FINITE ELEMENT ANALYSIS OF SOIL CUTTING AND TRACTION

by Alfred W. Hanna

SOIL CUTTING AND TRACTION

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements of the Degree of Doctor of Philosophy

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ABSTRACT

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A thesis presented by A.W. Hanna in partial fulfilment for the degree of Doctor of Philosophy

Department/of Civil Engineering and Applied Mechanics McGill University Montreal

May 1975

The purpose of this study is to provide a rational analytical means for predicting the performance of a cutting or a traction tool, using parameters that describe the soil response due to interaction with the tool. The analytical techniques examined have the objective of deriving statically possible stresses compatible with kinematically possible strains while satisfying the boundary conditions.

Due to the extent of the overall problem, the study is limited in scope to the verification of the validity of the application of the finite element technique to the analysis of simplified cutting and traction elements interacting with cohesive soils under plane-strain conditions. The solution provides detailed stress and deformation fields within the loaded soils, as well as contact stresses at the soil tool interface, for various tool positions. Consequently, a relatively complete description of the load-deformation behavior, as the tool advances in the soil, is obtained.

The applicability of the proposed analytical model is verified by the successful prediction of tool developed forces and soil deformation fields. In addition, through the application of the principle of conservation of energy to the cutting and traction element-soil systems, the energy dissipated in the soil deformation process is calculated, using the visioplasticity method. The energy values obtained are shown to provide reasonably good correlations with the experimentally measured and the finite element calculated energy components.

PRECIS

L'ANALYSE DE LA TRACTION ET DE LA TRANCHEE DES SOLS PAR LA METHODE DES ELEMENTS FINIS

Thèse présentée par Alfred W. Hanna faisant partie des conditions requises pour le titre de Docteur de Philosophie

Département de Génie Civil et Mécanique Appliquée Université McGill Montréal

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Le but de cet étude est de pourvoir un moyen analytique rationnel qui puisse prédire la performance d'un outil de tranchée ou de traction, et ceci en utilisant des paramètres qui décrivent la réaction des sols due à l'interaction avec l'outil. Les techniques examinées ont pour objectif de dériver des forces statiques compatibles avec des déformations cinématiques possibles, tout en satisfaisant les conditions de limite.

Etant donné l'étendue du problème global, l'étude est limitée à la vérification de la validité de l'application de la technique des éléments finis, à l'analyse des éléments simiplifiés de traction et de tranchée et leur interaction avec des sols cohésifs sous les effets de déformations à surface plane. La solution donne des forces et des champs de déformation détaillés à l'intérieur des sols chargés, ainsi que des forces de contact à la surface commune de l'outil avec le sol, et ceci pour diverses positions de l'outil. Conséquemment, on obtient, durant l'avancement de l'outil dans le sol, une description relativement complète des caractéristiques forces-déformations:

La validité du modèle analytique proposé est vérifiée par la bonne prédiction des forces développées par l'outil et des déformations du sol. En plus, en appliquant le principe de la conservation de l'énergie au problème et en utilisant la méthode de la plasticité visuelle, on peut calculer l'énergie dissipée dans le processus de déformation du sol. Les valeurs de l'énergie ainsi obtenues, donnent de bonnes correlations avec colles mesurées expérimentalement ainsi qu'avec les valeurs obtenues par la méthode des éléments finis.

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#### NOTATION

The symbols adopted in this thesis are defined as they are first used. The principal ones are listed below.

- area of i<sup>th</sup> quadrilateral of inscribed grid
- a,b empirical coefficients representing the intercept and the slope of the shear stress-displacement curve
  - grouser or blade width
    - soil cohesion

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- soil-metal adhesion
- deformation energy loss
  - elastic modulus
    - initial elastic modulus
      - slope of the deviator stress,  $(\sigma_1 \sigma_3)$ , versus principal strain,  $\epsilon_1$ , curve
      - lumped nodal point forces
      - body force field
      - grouser depth.
      - strain rate invariant
      - element stiffness matrix
      - von Mises yield function
      - element stiffness per unit length in the normal direction
      - element stiffness per unit length in the tangential direction
      - initial tangent stiffness modulus for joint element .
      - grouser or blade length

## NOTATION (continued)

total lateral pressúre.

lateral pressure at depth h below the soil surface

surcharge pressure

surface force field

U,V velocity components

displacement field

u,v displacement or velocity components

work done

strain energy

s i nkage

D

P<sub>h</sub>

a

T<sub>1</sub>

U

Z

۲

YXY

blade inclination angle with vertical

soil density

shear strain,

sofl-metal friction angle

average relative normal displacement across joint element

average relative shear displacement across joint element

(1=1,2,3) major, intermediate and minor principal strains, respectively

effective stress

normal strains

plasticity modulus

spectric mass

friction seels

coversities a second of the note prints

## NOTATION (continued)

normat<sup>es</sup>stresses on failure plane

a effective stress

 $\sigma_i(i=1,2,3)$  major, intermediate and minor principal stresses, respectively

σ<sub>x</sub>, σ<sub>y</sub> normal stresses

shear stress

τ<sub>1</sub> stress tensor

ν

τ<sub>XY</sub> shear stress component

> Poisson's ratio

relative displacement vector for joint elements

## ABBREVIATIONS

| •       |
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### CHAPTER 1

#### INTRODUCTION

#### 1.1 SUMMARY OF THE GENERAL PROBLEM

Cutting and traction tools are mechanical devices used to apply forces to the soil to cause some desired effect such as cutting, movement of soil, or the production of adequate traction for suitable trafficability. For purposes of definition, a tool will be considered a single soil-working element whereas an implement or machine will be considered a group of soil working elements. Although tillage and traction are nearly always affected with a machine, the emphasis here will be on the performance of a single tool rather than implements and tracked vehicles.

problem is shown in Fig. 1.1. It is appreciated that this description centers on the manipulation of soil by machanical forces, and the results of the final soil condition and the reaction of soil to forces are of primary importance. Thus, primary emphasis is placed on the soil response to an imposed set of loading parameters.

Traditionally, implement and track designers relied on empirical rules to develop earth-moving equipment and off-road vehicles. These empirical methods are trial and error attempts; the tool or track element [grouser] is varied in some manner, and acceptable designs are identified when the results are judged to be satisfactory. Quantitative descriptions or representations of the final soil conditions are seldom



 $\langle j \rangle$ 

used and, in addition, the forces required to move the tools or grousers are frequently not quantitatively assessed. Generally, no effort is made to describe the reactions of the soil. Gill and Vanden Berg (1969) present an excellent review of the empirical methods being used at the present time for design purposes. The following is a brief summary of the developments as well as the problems encountered in soil-cutting and soilgrouser interaction analyses:

### 1.1.1 Soil Cutting

The knowledge of soil mechanics has only been recently applied to the study of the problem of soil cutting. In the early part of the century, research in the United Kingdom and the U.S.A. was confined to `the investigation of the draft of tillage implements. The inability of researchers to isolate the relevant soil parameters made it difficult for them to visualize the possibility of a theoretical analysis in terms of classical soil mechanics.

The history of the development of a quantitative analysis of the action of cutting tools in soil has been described by Hettiaratchi (1965). Following the work of Payne (1956) on the action of agricultural times and Bekker's (1956) success with the study of vehicle performance, Osman (1964) showed that the retaining wall theory developed by Ode (1938) could accurately predict the forces required to cut a wide range of soils. Reace (1965) put forth an equation, which was similar in form to Terzaghi's bearing capacity equation, to predict the force acting on a blade. This equation was later modified by Hettiaratchi et al. (1966). A summary of the reported investigations in soil cutting

. 3

is presented in Appendix C.

In reviewing the literature, the various methods attempted to provide a solution for the blade problem appear to fall in four groups; methods relying on dimensional analysis [Wismer and Forth (1969) and Wismer and Luth (1970)], rigid body statical techniques [Osman (1964)], plasticity techniques such as those using a form of the Prandtl solution, specialized for bearing stability [Osman (1964) and Reece (1965)], and methods relying on the principle of limit equilibrium of the soil [Yong et al. (1969) and Yong and Chen (1970)].

It must be realized that in employing dimensional analysis techniques, using laboratory model tests, a required assumption is that soil properties can be adequately scaled. The difficulties surrounding the scaling of soil, or the derivation of appropriate scaling laws for soils, are most complex [Yong et al. (1967)]. In addition to the problems of separate examination of component parts, one must recognize that the problem of a moving rigid blade in soil is an interacting phenomenon and, therefore, should be considered as an interdependent system. The behavior of the soil mass in front of the moving blade is conditioned not only by the geometry of the blade itself, but also by the driving forces associated with the blade. In turn, the progress of the blade in the soil is controlled or influenced by the manner in which the soil will deform, the boundary conditions, and the constitutive makeup of the soil itself.

.1.2. Soil-Grouser Interaction

In the past decade, a number of research groups have begun
intensive investigations into the problems associated with soil-wheel interaction [e.g. Reece (1965), Freitag (1965), Yong (1969-1970) among others]. The same cannot be said for those problems associated with soil-grouser interaction. Some attempts have been made at examining the geometry of the failure surface beneath a moving rigid grouser [e.g. Bekker (1960) and Haythornthwaite (1961)] but apparently investigations into the mode and mechanisms of failure have been limited. Intensive research efforts are necessary in order to define the influence of such parameters as track type, grouser spacing, grouser geometry and grouser size on the magnitude of the forces exerted on the grouser plate by the soil.

As a consequence of the fact that the locomotive ability of any vehicle is dependent on the soil response, it would seem logical that in any attempt to describe the overall behavior of a tracked vehicle in soil, a clear understanding of the fundamental interaction process between grouser and soil is necessary. The little research which has been done on the problem has been oriented towards the prediction of macroscopic effects and has been directed more towards vehicular response than towards soil response.

Previous to the second world war, the design of tracked vehicles was largely an empirical process. Some research must undoubtedly have been carried out before this, but apparently was not reported in the available literature. The first systematic attempt at providing a solution to the overall problem was made by Micklewait (1944). He reported an empirical equation describing the tractive effort developed by a tracked vehicle moving on soft solls, an equation

which formed the basis of design until Bekker (1956, 1960, 1969) examined the problem from a more rigorous point of view.

With the assumptions that the grouser plate could be approximated by a strip footing, and an elastic stress distribution in the soil, Bekker was able to derive a theoretical expression relating the horizontal thrust on the grouser to the grouser parameters. By optimizing the grouser spacing and summing the horizontal forces operative on each grouser plate in the track, he was then able to predict the horizontal thrust exerted on a tracked vehicle by the soil. The equations for the horizontal and vertical forces on a grouser are given as:

$$H = b(n_c lc + \gamma n_q lz + \gamma n_\gamma l^2) \sin \theta \qquad (1.1)$$

(1.2)

$$W = b(\eta_c \ lc + \gamma \ \eta_q \ lz + \gamma \ \eta_\gamma \ l^2) \ \cos \theta$$

where

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b = grouser width, in inches.

n mensionless trafficability factors which are

dependent on  $\phi$ ,  $\theta$  [shown in Fig. 1-2] and the ratio 1/h.

1 = grouser length, in inches.

n = grouser depth, in inches.

c = cohesion, in psi.

z = sinkage, in inches.

The geometry of the forces is as shown in Fig. 1-2 in which the imaginary strip footing is represented by line AB sloped to the morizontal at an angle of:



[Arter BERKER (1960)]

## $\theta = \operatorname{arc} \operatorname{tan} (H/W)$

and the bearing capacity of the soil under the footing is given as  $P_n$ .

Despite the fact that no experimental evidence was cited in support of his theoretical conclusions, Bekker's equations formed the basis for the design of tracked vehicles until very recently, at which time an extensive research programme was entered into by the U.S. Army Waterways Experiment Station at Vicksburg. The results to date of this programme have dealt primarily with the response of soils to the action of rigid wheels [e.g. Freitag (1965),(1965a),(1965b),(1968)], and an absence of reported data on the response of soils to grouser action is still evident on an examination of the available literature. A summary of the reported investigations has been given in Appendix C.

### 1.2 PURPOSE OF STUDY

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Most of the soil cutting and traction research conducted to date have been based on empirical approaches using the results of a large amount of experimental data obtained from tests to develop methods of analysis and design. While such approaches may have been necessary in the past, the advent of digital computers and the development of modern methods of numerical analysis now provide the necessary tools to obtain analytical solutions which can replace much of the empirical testing carried out in the past. However, such analytical solutions must be checked by a selected, but smaller number of experimental tests to verify their accuracy.

The problem of soil-machine interaction has been the subject of a rigorous study under a research programme in operation at the

Soil Mechanics Laboratory of McGill University since 1963. This programme can be divided into two distinct phases. Investigation of the behavior of soil under driven rigid wheels [Yong and Webb (1969), Yong and Windisch (1970) and Windisch and Yong (1970)], and the study of the performance of an isolated element [tractive or cutting] moving through soil [Yong and Chen (1970), Yong et al. (1969) and Yong and Sylvestre-Williams (1969)].

The present study is a continuation of the second phase of the overall McGill programme. Its purpose is to provide a rational analytical means for predicting the performance of a cutting or a tractive tool, using parameters that describe the soil response due to interaction with the tool. It is to be appreciated that an accurate prediction of machine-soil response behavior would provide a sound basis for the evaluation of the efficiency and economy of soil cutting and mobility. Consequently, the computer solution technique developed herein can be used to aid in the designing of the tool or the interacting unit, since the various machine and soil parameters input to the computer code can be varied and the resultant output evaluated. This philosophy is demonstrated in schematic form in Fig. 1-3.

1.3 SCOPE OF STUDY

The factors considered pertinent in soil cutting and traction experiments relate to:

- (a) Soil Type, density, and shear resistance parameters.
- (b) Cutting or traction tool Geometry, depth of cut,

speed of travel and interfacial characteristics.



(c) Forces - Developed forces [horizontal and vertical].

In general, the variations with regard to the above are concerned with the specification of the desired condition, i.e.:

- Specified constant speed and constant depth of cut. This will yield developed forces on the tool, which may subsequently be decomposed into horizontal and vertical components.
- (2) Specified constant horizontal force and constant depth of cut. The measured variables in this instance are speed and developed vertical forces.
- (3) Specified constant horizontal and vertical forces. In this particular case, both speed and depth of cut are the measured variables.

To allow for a rational approach in the analysis of results, the experiments performed in the course of this study are limited to the first condition [i.e. specified constant speed and constant depth of cut]. The procedure employed accounts for measurement of developed forces [both horizontal and vertical], accompanied by photographic recording of soil distortion.

The scope of this study is limited to verifying the validity of the application of the finite element technique to the analysis of simple problems of soil-machine interaction in nearly-saturated kaolinite clay under plane strain conditions. Comparisons between theoretical and experimental results are made to assess the validity

of the assumed model. The approach adopted can be easily extended to field problems where the soil-machine interaction is more complex.

# 1.4 ANALYSIS OF THE PROBLEM

Within the broad definition of the problem, there are numerous paths that can be followed according to emphasis and assumptions made. Figure 1-4 shows a schematic diagram of a number of available solution procedures.

If soil deformation is neglected, rigid body forces and theories of classical soil mechanics can be used in attempting to calculate the developed reactions. Forces are evaluated by studying the static equilibrium of an assumed failure surface which is chosen to satisfy the limiting stress condition of a Coulomb material. These theories, however, neglect the soil deformation and therefore are not sufficiently accurate to be acceptable.

If the soil is assumed to be perfectly plastic with a Coulomb, or any other yield surface, there would be no difficulty, in principle, in computing reactions. The theorems of limit analysis [upper and lower bound theorems] will give bound on the answer. Yong et al. (1969) and Yong and Chen (1970), have successfully used the method of limit equilibrium to predict the force required to move a blade through a frictional material. Yong and Sylvestre-Williams (1969) adopted the same approach to study the traction of grousers. Limit equilibrium analysis uses a statically admissible stress field, giving lower bounds.

A lower bound solution requires an assumption of a statically



admissible stress field, while an upper bound solution requires a kinematically admissible displacement or velocity field. In a mixed boundary-value problem, there is no apparent independence between the two fields, and compatibility between the two fields is the essential final justification that the solution obtained is, in fact, the correct one.

Until quite recently, an important defect in the theory of earth pressure lay in its development without reference to stress-strain relations, the theory being based upon the concept of limiting equilibrium satisfying Coulomb's law of soil failure in conjunction with an extremum principle. This procedure neglects the important fact that stress-strain relations are an essential constituent of a complete theory of any branch of the continuum mechanics of deformable solids [Morgenstern and Eisenstein (1970)].

Semi-analytical techniques such as the visioplasticity method were investigated at McGill University. Yong and Webb (1969) used this method for determining the useful output energy for a rigid moving wheel. Yong and Windisch (1970) used it for determining the interfacial and subsoil stresses under a towed rigid wheel. In the visioplasticity method, the displacement field is recorded experimentally, from which a stress field is determined using a constitutive relationship. This method is only applicable to small scale testing [assuming steady-state conditions] and cannot be used to predict field conditions.

Based on the above discussion, it was concluded that a management of the stress distribution and

the soil deformation resulting from a cutting or a tractive tool would have a place in soil-machine mechanics. Such a method should take into account the non-linear behavior of soil and the effect of large deformation due to the implement movement.

### .5 PROCEDURE FOR DEVELOPING A RELIABLE NUMERICAL TECHNIQUE

For a given problem, development of a reliable numerical technique involves various steps as depicted in Fig. 1-5. These steps essentially represent a trial and error procedure which requires the examination of factors such as idealization of the problem as a discretized body, numerical characteristics and constitutive laws. In the Figure, the first two factors are indicated by dashed lines, whereas the trial and error procedure for constitutive laws is shown by solid lines [Desai (1972)].

A numerical technique for solving soil-machine problems can be developed in progressive stages. The purpose of the technique is to quantitatively describe the action of the machine on the soil. In the initial recognition phase, the action is observed and noted to be repetitive. The recognition phase is gradually supplanted by an "equivalent" model. For complicated problems, the idealization stage can be difficult and would require a number of trials before a model of acceptable accuracy can be evolved. The final model may be arrived at after a number of trials.

The second step of developing a solution technique is arriving at a representative constitutive law. A constitutive law for soil is



usually dependent on a number of factors such as density, stress history, water content, and existence of discontinuities. The constitutive relation can be established through the application of several distinct phases of study. First, some specific behavior is observed and studied. Second, having noted the behavior, factors involved in the behavior are identified and their relation ascertained in a causeand-effect manner. Mathematical equations are required to quantitatively describe the cause-and-effect relation and, hence, the behavior. Resorting to mathematical equations is possible only when both input and output quantities can be expressed in some form of numerical description.

With reasonably accurate constitutive equations, a complete analytical technique can be developed to describe machine actions. A specific machine tool has a fixed geometrical shape that can be expressed by appropriate equations. An overall coordinate framework can be established in which the direction of travel and the path of tool motion, the orientation of the tool, and the continuous nature and profile of the soil can be described. Specifying the path of motion of the tool in the reference framework thus produces the boundary conditions necessary to define the problem. Simultaneous solution of the system of governing equations utilizing the boundary conditions provides a quantitative solution to the problem.

Many numerical techniques can be attempted in developing a solution for a particular soil-machine interaction problem; among them are the limit equilibrium [classical soil mechanics solution], the finite difference, and the finite element method [Figure 1-4].

Adopting the limit equilibrium approach, Sokolovski (1960) developed the mathematical methods that made it possible to solve numerically the equations of equilibrium to obtain the force required to fail soil by loading an interface. In a plane problem, there are three unknown stresses and two equations of equilibrfum. If the soil is assumed to be in a state of failure, the Coulomb relationship could therefore be introduced as the third equation. In three-dimensional problems there are six unknown stresses and only four equations; a solution is therefore impossible - without the introduction of stressstrain and compatibility relationships. It must be pointed out that if the problem is statically determined [i.e., boundary conditions are only given in terms of stresses], the equilibrium equations and the Coulomb failure condition are sufficient to give the stress distribution without any reference to the stress-strain relations. However, if displacements or velocities are specified over part or all of the boundary, then the stress-strain relations must be used to relate the stresses to the strains and the problem becomes much more complicated and must usually be solved by trial and error. A stress field satisfying all stress boundary conditions is assumed. The velocities are then computed and a check made to see if the velocity boundary conditions are satisfied. If not, the stress field is modified and the procedure is repeated as often as necessary. In addition to all these difficulties, the solution obtained is valid only for the case of incipient plastic flow; once plastic flow progresses, the shape of the boundaries changes considerably and it becomes necessary to satisfy the boundary conditions on the deformed boundary. This makes it virtually impossible to obtain the load-deformation history of a continuously deforming soil.

The basic difference between the finite difference and the finite element methods lies in the approaches used in arriving at the node point [or discrete mass] equilibrium equations. In the usual finite difference techniques, the governing system of differential equations is approximated by difference equations, which in essence require an assumption of the displacement form between neighboring node The restriction applied by this approach is the relative points. uniformity of node point spacing which yields solutions at only a fixed number of points in the domain of interest, and may require additional interpolation for solutions at other points. Also, the finite difference method can be cumbersome for handling irregular boundaries and nonhomogeneities. In the finite element technique, on the other hand, the soil mass is divided into various small elements, with each element connected to its neighboring elements at their node points. Over each element, approximate displacement functions are defined. In this manner, the finite element method recognizes the continuity of masses, and doës not require separate interpolations for extension to The use of separate approximating models for each other points. finite element permits greater flexibility in tackling masses with extensive nonhomogeneities, complex realistic geometries and mixed Since the main advantage of the finite element boundary conditions. method lies in its capacity of handling relatively complex problems, the method was chosen in this study to investigate the subject of simple cases of soil-machine interactions.

### 1.6 ORGANIZATION OF THE THESIS

2.

The Thesis is divided into two separate parts: The first part deals with the development of the analytical model used in this study, together with the results of the experimental program. In addition, comparisons between theoretical, experimental and analytical results are presented to assess the validity of the assumed model.

The second part of the thesis, which consists of five appendices, concerns itself mainly with providing the pertinent information necessary for a complete appreciation of the computational and experimental techniques.

The first part, which deals mainly with the introduction, appreciation, application, and verification of the proposed analytical model, is subdivided into eight chapters [see Fig. 1-6].

<u>Chapter 1</u>, of which this Section is a part, is an introductory chapter in which a statement of the problem is presented.

<u>Chapter 2</u> describes the finite element technique and the proposed model adopted in this study.

<u>Chapter 3 provides a brief description of the experimental</u> facilities and techniques used, together with some initial experimental data.

<u>Chapter 4</u> contains results of the cutting and traction experimonts performed, and results of the strength tests. In addition, this



Chapter provides a development of the visioplasticity method as applied to the present study, together with an appreciation of its applicability to the problem by means of the invoked assumptions.

<u>Chapter 5</u> is concerned with the presentation and discussion of the finite element results of soil cutting analysis, and comparisons with the experimental results.

<u>Chapter 6</u> presents the finite element results of soil traction analysis accompanied by comparisons with the experimental results.

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<u>Chapter 7</u> discusses the applicability of the proposed analytical solution by examining the significance of implied conditions and requirements in relation to observations and results. This is accomplished by dividing this Chapter into two main Sections:

1. finite element analysis, employing the proposed model,
I of a long vertical wall retaining clay, and comparisons
with a closed-form solution scheme, and

2. comparisons of soil cutting and traction analytical and experimental results, obtained in this study, with

results computed from existing theories.

Chapter 8 contains the summary and conclusions.

The second part of the thesis is composed of the experimental and data reduction techniques, as well as computer program descriptions and other pertinent material required to provide the input for the experimental-theoretical study presented in the first part of the thesis. This part consists of:

|   | Appendix A        | - | experimental considerations.                                        |
|---|-------------------|---|---------------------------------------------------------------------|
| # | Appendix B        | - | data reduction techniques.                                          |
|   | <u>Appendix C</u> | - | review of previous work.                                            |
| J | Appendix D        | - | solution of linear equations by direct Gaussian elimination method. |
|   | Appendix' E       | - | computer program listings.                                          |

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## CHAPTER 2

# FINITE ELEMENT METHOD AS APPLIED TO THE PRESENT PROBLEM

# 2.1 INTRODUCTION

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Analyses of soil-structure interaction problems are of considerable importance in investigations concerned with soil-implement and soil-vehicle mechanics. The calculation of earth pressures on structures has been given detailed attention by researchers, and there now exists a wealth of both theoretical and experimental knowledge on this subject. These sources are continuously being investigated with a view to possible adaptation and improvement to meet the more specialized requirements of soil-machine problems. As an example of this approach, the familiar . cases of two-dimensional soil response encountered in long retaining walls and strip footings bear a close parallel to wide cutting blades and track-laying tractor running gear, respectively. This analogy is not limited to the actual physical similarity between these structures but extends to the more significant factors associated with the problem boundary conditions, the soil mode of deformation and the actual failure surface geometry involved.

It must be emphasized, however, that the mechanics of soil cutting and traction is much more complex than that of the soil-structureinteraction, as there is more than one process in operation. The resistance of soil to the forward motion of a tool is caused by shearing action, friction and adhesion between the soil and the tool, raising

and accelerating the soil, and cracking if the tensile strength is exceeded.

The problem at hand is so complex that an acceptable general solution technique capable of handling a wide variety of soil-machine interaction problems is not anticipated for some time to come due to:

- The difference in soil response to the action of an implement. This can range from shear failure for cohesionless soils to brittle behavior for a nonplastic soil to flow in the case of wet cohesive soils.
- 2] The different functions which determine the shape of the implements, their manner of movement [such as depth and speed], orientation and path of motion.

Within these limits the problem can range from investigating a case of a simple tool moving in a homogeneous soil with controlled properties to evaluating performance of complicated machinery designed to perform in different soils. With this in mind, the scope of this study as stated in Chapter 1 is to investigate a specific simplified problem under certain established conditions. While these conditions and hence the approach adopted may seem to be restrictive as to render a solution technique too specialized to be of immediate practical use, it is believed that a proposed technique that possesses a potential for extension to similar and more difficult problems with some or little modifications will ultimately have practical usefulness. Furthermore, such a technique can be very instrumental in investigating and understanding the fundamental mechanisms involved in the case of simplified cutting and tractive tools moving through soils.

1. .

No. W. State

In the specific problem of a soil-tool interaction, an accurate analytical determination of soil reactions as well as the internal stress and deformation fields in the soil mass throughout the loading sequence is complicated by a number of factors. Some of these factors are:

- 1] The system is composed of two materials, soil and metal, having in most instances complex interface geometries.
- 2] The system has a continuously changing topology caused by the movement of the tool in the soil. This will have the effect of introducing cracks or discontinuities in a brittle or frictional soil or flow in a plastic soil.
- 3] The stress-strain relationship for soil is nonlinear and is a function of many variables. Constitutive relationships and failure criteria for soils under combined stress states are difficult to obtain.
- 4] Soil behavior is dependent on loading rate and sequence.
- 5] The characteristics of the soil-metal interface in terms of the degree of soil slip and the nonlinearity in the relationship between interface shear stresses and shear displacements add to the complexity of the problem.

One of the factors that requires special consideration in the construction of a realistic analytical model for soil cutting and traction is the effect of the progressive cutting of the soil at the tool tip with the possible development of failure surfaces wherever the shear strength of the soil is exceeded. Figure 2-1 illustrates the general mechanisms operating in cases of soil cutting [constant depth of cut] and soilgrouser systems [constant depth of embedment].



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In view of the great complexities mentioned above, the problem can be classified from the continuum mechanics point of view as an inelastic, nonlinear analysis of a nonhomogeneous anisotropic system. An analysis to determine stresses and deformations throughout the soil medium by a direct application of the classical theories of continuum mechanics can be extremely difficult. However, if by an adoption of a numerical technique such as the finite element method, detailed stress and deformation fields could be determined for various tool positions, studies or the basic interaction behavior would be immeasurably aided.

## 2.2 IDEALIZATION

In developing an analytical model for problems of soil machine mechanics, it is essential that proper appreciation be given to the material performance and boundary conditions. The appropriate framework defined by using realistic similarities between physical and mathematical boundary conditions will ensure a higher order of predictability with the developed analytical model. The observation of soils deformation and failure patterns during a loading process often provides the basis for the development of valid models feading to solutions of forces and stress fields.

Classical soil mechanics idealizes soils as a rigid plastic frictional material [Chapter 1]. That is a material which supports loads without any deformation until a certain shear stress is reached, whereupon total failure occurs. This maximum stress is described by Coulomb's equation:

 $\tau_{\max} = C + \sigma \tan \phi$ 

and where the shearing occurs against a rigid interface by

 $\tau_{max} = C_a + \sigma \tan \delta$ 

The strength properties of the soil model are defined by the three parameters, cohesion C, angle of internal friction  $\phi$ , and density  $\gamma$ .  $\delta$  is the angle of soil interface friction and  $C_a$  soil interface adhesion. As previously mentioned in Chapter 1, this model as well as the theory of limit equilibrium has been taken to a proper logical conclusion by Sokolovski (1960). Failure patterns predicted by this approach are shown in Fig. 2-2a for a cutting blade and in Fig. 2-2b for a grouser.

It should be pointed out that the limit equilibrium model leads to a solution by predicting the shape of the regions of soil sheared off from the main body. In practice, however, the soil in the failure zone does not shear all at the same time. Due to the gradual increase in the stresses with increasing strain, the conditions for the transition into the passive state are not realized. In this event, shear failure occurs locally and the slip lines do not propagate This type of failure is termed progressive failure. to the surface. Furthermore, the limit equilibrium model provides a solution for the forces up to the formation of the first shear plane or failure surface with no provisions for extending the solution beyond this stage. Another limitation in the application of this approach is that an assumption has to be made regarding the degree of mobilization of the soil-rigid interface friction and adhesion.



While the limit equilibrium approach was utilized successfully for predictions of forces on cutting blades [Yong et al. (1969)], and grousers [Yong and Sylvestre-Williams (1969)], it is argued that a development of a finite element model to handle some of the cutting and traction problems can quite easily overcome most of the above limitations.

With this background, it is now possible to examine the deformation mechanism operative in a tool-soil system. Figure 2-3 divides the loaded soil into three distinct regions for ease of analytical treatment. These regions are typified by elements A, B and C. The first of these represents an interfacial element in which sliding of the soil on the rigid interface does occur. The second element [B] is a cutting element in which large shear distortions caused by the tool cutting action develop. Finally, element [C] represents a region in which plastic deformation takes place with possibilities of development of localized or general shear failures. While this representation may seem to oversimplify the soil response behavior, such philosophy does, in fact, take into account all the operative factors in the deformation process. It now remains to idealize these three elements to arrive at a viable finite element model for the problem at hand.

The initial step in developing an analytical model using the finite element approach consists of idealization of the problem by drawing a finite element mesh which simulates the presence of the soil mass and the tool. The construction of the finite element mesh requires that the type and number of elements included should be adequate to attain the correct flexibility of the continuum.



To idealize a simple soil-tool interaction problem by a finite element model, certain characteristics must be incorporated in such a model so that it can represent the various elements shown in Fig. 2-3. Some of these characteristics are:

1]

Relative displacements occur across a thin discontinuity at the tool tip level, for tool fixed depth of embedment, due to the cutting action caused by the tool movement in the soil mass. Above this discontinuity the soil is displaced by the tool while below it very little deformation occurs.

- 2] On the interface between soil and tool, relative displacements do occur and play an important role in the interaction between the two materials. The nature of the interface behavior depends upon the roughness of the tool and the friction and adhesion of the soil. Most finite element analyses have been performed using one of the two following limiting assumptions concerning the characteristics of a soil-rigid interface interaction:
  - (1) that the interface is perfectly rough, with no possibility for slip between the rigid interface and the soil, or
    - (11) that the interface is perfectly smooth, with no possibility for shear stresses which would retard relative movements between the rigid interface and the sofl.

Experimental and actual field evidence show that these assumptions are not realistic.

For a realistic analysis of the problem, it is essential that any relative displacement or discontinuity in the deformation field should be taken into consideration. It is obvious from the above discussions that the plane strain continuum elements used in the finite element analysis [constant strain triangular element, for example] cannot satisfactorily model the soil deformation behavior in a case where discontinuities may develop. These elements are assumed to be connected at the nodes preventing any slip or separation behavior. However, if an idealized material element that can transmit shear stress parallel to its direction - providing this does not exceed the frictional resistance - is incorporated in the overall model, one will be able to adequately include such behavior features as failing in shear and development of discontinuity surfaces.

Previous attempts have been made to develop discrete elements to represent discontinuities embedded in a continuous system [Goodman et al. (1968) and Zienkiewicz et al. (1970)]. In the following section a review of the research that has been done to simulate a discontinuity in the finite element analysis is presented, followed by the approach adopted in the present study to deal with such behavior.

## 2.2.1. Idealization of Discontinuities

Researchers in the fields of reinforced concrete and rock mechanics have investigated the possibility of modelling discontinuities in the deformation field by the finite element method. In reinforced concrete, the combination of steel and concrete, by itself, presents no difficulty in the analysis. However, the means of modelling the

behavior at the interface between the two materials require special attention. In the first application of the finite element method to reinforced concrete, Ngo and Scordelis (1967) developed a linkagé element consisting of two orthogonal springs to which stiffness was ascribed to represent other than a perfectly rigid connection between two nodes of adjacent elements. This element, shown in Fig. 2-4, has been used by many investigators, such as Ngo et al. (1967) and Nilson (1968), to simulate the bond-slip relationship between a reinforcing bar and the surrounding concrete.

With respect to cracking, Ngo and Scordelis (1967) studied the stress distribution in singly reinforced, simply supported beams into which they had incorporated predefined crack patterns. Nilson (1968) extended the work by allowing cracking to take place along the common edge between the elements where the principal tensile stresses exceeded the modulus of rupture of concrete. The crack was represented by altering the topology of the discretization by disconnecting cracked elements at their common nodes. In addition, Nilson introduced nonlinearities in the material properties and in the relationship between bond stress and bond slip. The loading was applied incrementally and the behavior studied up to the ultimate load.

In rock mechanics, a number of approximate models [or theories] have been proposed to represent the behavior of jointed media. These theories incorporate analyses of intact material, pre-existing or in situ joints or fractures, closing-opening and propagation of cracks, and sliding behavior of joints interpreted in terms of contact and interlocking of asperities.

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In order to account for a fault, Anderson and Dodd (1966) used a pin-ended one-dimensional element, Fig. 2-5. This element can allow transfer of compressive stresses across a fault, but cannot sustain shear or tensile normal stresses. Duncan and Goodman (1968) proposed three different procedures: - ubiquitous joint, orthotropic continuum and single joint analysis, shown in Fig. 2-5. The ubiquitous joint analysis is based on the continuum approach in which the induced shear stresses are computed on a large number of plane orientation. Then the likelihood of slip or opening of joints that really exist is The orthotropic continuum approach is based on linear evaluated. elastic theory in which equivalent elastic parameters are computed for the parent mass influenced by three orthogonal joint sets. In the single joint analysis, Figs. 2-5d and 2-5e, stiffness formulation is obtained by considering the joint as either one- or two-dimensional. The stiffness of a joint is defined in terms of its normal and tangential stiffnesses. This approach is a modification of the concept proposed by Ngo and Scordelis (1967) for cracking in concrete elements.

The one-dimensional single joint proposed by Goodman et al (1968) and Heuze et al. (1971) is defined by four nodal points, Fig. 2-5d; with its thickness in the normal direction assumed as zero. This joint element, when inserted between two portions of the parent mass, can per-

In application to soi]-structure interaction problems, Clough and Duncan (1971) performed analyses of retaining walls using the onedimensional finite elements to simulate the interface between the wall

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and the backfill. The analyses were performed in a series of increments, adjusting the properties of the interface and the backfill in accordance with the stresses for each increment to approximate nonlinear behavior. このでは見たいよ

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### 2.2.2 Idealization Adopted in the Present Study

The model adopted in the present study incorporates a predefined discontinuity at the level of the tool tip. This discontinuity is positioned on the cutting surface shown in Fig. 2-3. The purpose of including the cutting plane discontinuity in the finite element model is to represent the action of the cutting element, shown as element B in Fig. 2-3, where severe relative displacements and separation of soil blocks take place. Such discontinuity can be visualized as a thin soil layer on which the soil above slides on the soil mass below. This sliding behavior is governed by the soil constitutive shear stressrelative displacement relationship. It must be emphasized here that it is essential to consider such sliding action if an investigation is to be made of a continuous soil deformation process.

The discontinuity location was predetermined in this study due to the fact that the tool is assumed to be moving at a constant elevation. Such a predefined discontinuity plane is not to be confused with a failure plane which can initiate at the tool tip at any angle with respect to the horizontal depending on the direction of the maximum shear stress.

The horizontal movement of a cutting or a traction tool often produces a series of failures in the soil which are usually induced from the level of the tool tip to the soil surface. While these failure

surfaces could be modelled also as discontinuities, a prior specification of failure surfaces will limit the usefulness of the proposed model. Location of the failure zones or surfaces in the soil medium is determined in this study, by examining the maximum shear stress induced in each finite element after each increment of tool displacement. If the stress is found equal to or greater than the shear strength of the soil at that location, the stiffness values for this element are reduced to small magnitudes, and this element is considered to have failed in shear. It becomes essential now to point out that such an approach for determination of failure zones or surfaces does not allow cracking to take place, and hence, sliding along a series of failure surfaces is not possible. Such behavior was not included in the proposed model partly because it did not take place in the experimentally observed deformation field, as will be shown later, and partly because of the large amount of computer memory and time required for such an analysis. However, in case sliding along a failure surface is found to be of importance in describing the 'soil behavior, an approach similar to that of Nilson (1968) could be adopted in which the topology of the discretization is altered by disconnecting cracked elements at their common nodes and inserting a form of a joint element, similar to those described in the previous section, along the cracked elements' common edge. By allowing these joint elements to transfer compressive stresses but not shear or tensile normal stresses, one will be able to represent the propagation of failures surfaces, and subsequently sliding along these surfaces.

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As previously stated, in conventional finite element theory the displacements along the boundary between adjacent finite elements are
required to be compatible, i.e., no gaps may open or relative displacements may occur between adjacent elements. It has also been pointed out that during the soil deformation process, relative displacements do occur on the interface between the soil and the tool representing a discontinuity in the finite element displacement field. Such discontinuity, is presented in Fig. 2-3 as element A. Since the relative displacements occur in the tangential direction at the interface, the joint element, presented by Goodman et al. (1968), can be inserted between the tool surface and the soil mass, Fig. 2-6, to allow for soil slipping along the metal interface.

A similar approach is employed to model the cutting plane discontinuity in view of the fact that the deformation mechanism of this plane, presented in Fig. 2-3, by element B, is similar to that of a rock joint in that relative displacements occur across a thin discontinuity. Thus the simulation of the assumed discontinuity can be the same as that employed for rock joints where the joint elements are placed to model the separation of the two blocks of continuum adjacent to the discontinuity surface which were initially in contact.

Summarizing all of the above points, the finite element idealization adopted in this study, shown in Fig. 2-6, for a blade-soil system, consists of:

'l] Continuum elements [constant strain triangles] representing the soil mass.

2] Interface discontinuity employing joint [interface] elements to represent the soil-tool interface characteristics.

3] Cutting discontinuity modelled by joint [cutting] elements inserted between the continuum elements to represent the



shearing or cutting of the soil caused by the tool

#### 2.3 FORMULATION OF THE PROBLEM

The analysis of plane strain problems by the finite element method has been fully described in many publications [Zienkiewicz (1971)]. The derivations will not be presented here, only the general formulation and the essential features of the procedure required for the analysis of the present problem will be discussed.

From basic energy principles, for a body to be in equilibrium, its potential energy expressed as a functional II should assume a stationary value in a class of admissable variations ( $\delta U_i$ ) of the displacements  $U_i$  of the equilibrium state. The functional II is given by:

$$\Pi(U_{\star}) = Y - W$$

where

Y = strain energy, and

W = work done.

In a detailed form the above equation can be written as:

$$\Pi(U_{i}) = \int \frac{1}{2} \tau_{i} \varepsilon_{i} dV - \int F_{i} U_{i} dV - \int T_{i} U_{i} dB \qquad (2.1)$$

where

 $\tau_i = stress tensor.$  $\epsilon_i = strain tensor.$ 

 $F_i = body force field$ 

 $T_i = surface force field, and$ 

B, V represents the body boundary and volume, respectively.

In a matrix notation Eq. (2.1) becomes:

$$\Pi(U_{i}) = \int_{V} \frac{1}{2} \tau_{E}^{T} \varepsilon dV - \int_{V} \bigcup_{V}^{T} \varepsilon dV - \int_{B} \bigcup_{V}^{T} \tau_{A} dB \qquad (2.2)$$

Using a stress-strain relationship of the form:

 $\tau = \mathcal{L}^{\dagger} \cdot \mathcal{L}$ 

Where  $C^{i}$  is a stress-strain matrix at stress level 1, Eq. (2.2) can now be written as:

$$\pi(U_{i}) = \int_{V} \frac{1}{2} \varepsilon^{T} c^{i} \varepsilon^{d} V - \int_{V} U^{T} F^{d} V - \int_{B} U^{T} T^{d} B \qquad (2.3)$$

Assuming a displacement field given by:

$$U = \Phi \alpha \qquad (2 \cdot 4)$$

where  $\Phi$  is the coordinate matrix of the nodal points, and  $\Phi$  are generalized coordinates.

It is possible to represent  $\alpha$  in terms of  $\phi$  and U by premultiplying both sides of Eq. (2.4) by  $\phi^{-1}$ , giving:

 $\alpha = h U$ 

where

The strain vector can now be obtained by differentiating the displacement vector. U with respect to,  $\phi$  and can be expressed as

(2.5)

s = • h U

where  $\Phi'$  is the  $\Phi$  matrix after the necessary differentiation. Substituting Eq. (2.5) into Eq. (2.3) yields:

$$\Pi(U_{i}) = \frac{1}{2} \int_{V}^{U} \tilde{U}^{T} \tilde{U}^{T} \tilde{\psi}^{T} \tilde{\zeta}^{i} \tilde{\psi}^{i} \tilde{U} \tilde{U} dV - \int_{V}^{U} \tilde{U}^{T} \tilde{U} dV - \int_{B}^{U} \tilde{U}^{T} \tilde{U} dB \qquad (2.6)$$

After proper integration and conversion of the body forces F and surface traction. T to nodal forces, Eq. (2.6) can be written as:

$$\pi(\underline{U}_{1}) = \frac{1}{2} \underbrace{U}^{T} \underbrace{K} \underbrace{U}_{2} - \underbrace{U}^{T} \underbrace{f}_{2}$$
(2.7)

where f are the lumped nodal point forces.

From the theorem of minimum potential energy, in an equilibrium state the variation of the functional II vanishes, i.e.

$$\delta \Pi(U_{1}) = \frac{\partial \Pi(U_{1})}{\partial U_{1}} = 0$$
 (2.8)

Applying the condition set by Eq. (2.8) to Eq. (2.7), yields

$$\delta \Pi(U_i) = K U - f = 0$$

or K

(2.9)

where K is the element stiffness/matrix.

Solving Eq. (2.9), subject to the boundary conditions, provides both the stress and deformation fields.

2.3.1 Joint Element Stiffness Formulation.

A joint element was developed by Goodman, Taylor and Brekke (1958) and applied to several rock mechanics problems: sliding of joint with a tooth, behavior of joint intersections, tunnel in a system of staggered rocks. Héuze and Goodman (1967) also used it to simulate the behavior of mine roofs.

The following is a derivation of the stiffness properties of a joint element as presented by Goodman et al. (1968). This element, shown in Fig. 2.7 in a local coordinate system with the x-axis along the length, has a length, L, but very small width. The origin is at the center.

The stored energy,  $\Phi$ , in such an element is due to the applied forces per unit length acting through the displacements and must be summed through the element. Thus,

$$\Phi = \frac{1}{2} \int_{-L/2}^{L/2} \omega_{j} P_{j} dx \qquad (2.10)$$

in matrix notation

$$\Phi = \frac{1}{2} \int_{-L/2}^{L/2} (\omega)^{T} (P) dx$$

in which  $\omega$  ( $\omega$ ) = the relative displacement vector given by

 $(\omega) = \begin{bmatrix} \omega_s^{\text{Top}} & - \omega_s^{\text{Bottom}} \\ \omega_s^{\text{Top}} & - \omega_s^{\text{Bottom}} \\ \alpha_n^{\text{n}} & - \alpha_n \end{bmatrix}$ 

d (P) = p

P<sub>s</sub>

the vector of force per unit length

(2.13)

(2.11)

(2.12)



The vector, (P), may be expressed in terms of a product of unit joint stiffness and displacement

$$(P) = (k) (\omega)$$

in which (k) = a diagonal material property matrix expressing the element stiffness per unit length in the normal and tangential directions,

(2.14)

Substituting Eq. (2-15) in Eq. (2-14), gives

$$\Phi = \frac{1}{2} \int_{-L/2}^{L/2} (\omega)^{T} (k) (\omega) dx \qquad (2.16)$$

The displacement ( $\omega$ ) may be expressed in terms of the nodal point displacements (U) through a linear interpolation formula. Let U<sub>i</sub> and V<sub>i</sub> be displacements in the tangential and normal directions, respectively, at nodal point i along the bottom of the element

$$\begin{bmatrix} \omega_{s}^{bottom} \\ u_{n}^{bottom} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 - \frac{2x}{L} & 0 & 1 + \frac{2x}{L} & 0 \\ 0 & 1 - \frac{2x}{L} & 0 & 1 + \frac{2x}{L} \end{bmatrix} \begin{bmatrix} U_{1} \\ V_{1} \\ U_{2} \\ V_{2} \end{bmatrix}$$
(2-17)

and along the top of the element.

 $\begin{bmatrix} \omega_{a}^{Top} \\ u_{a}^{Top} \\ u_{n}^{Top} \\ u_{n}^{Top} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 + \frac{2x}{L} & 0 & 1 - \frac{2x}{L} & 0 \\ 0 & 1 + \frac{2x}{L} & 0 & 1 - \frac{2x}{L} \\ 0 & 1 + \frac{2x}{L} & 0 & 1 - \frac{2x}{L} \end{bmatrix} \begin{bmatrix} U_{3} \\ V_{3} \\ U_{4} \\ V_{4} \end{bmatrix}$ (2.18)

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(2.21)

Thus the relative displacement in the element is

Where -

$$A = 1 - \frac{2x}{L}$$
, and  $B = 1 + \frac{2x}{L}$ .

Symbolically

 $(\omega) = \frac{1}{2} (D) (U)$  (2.20)

 $= \frac{1}{2} \int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{1}{2} (U)^{T} (b)^{T} (k) (D) (U) dx$ 

Substituting and simplifying, the expansion  $\hat{\sigma}f$  Eq. (2.21) gives

$$\Phi = \frac{1}{2} L(U)^{T}(K)(U)$$
 (2.22)

in which

$$\left( K \right) = \frac{1}{5} \begin{bmatrix} 2k_{s} & 0 & k_{s} & 0 & -k_{s} & 0 & -2k_{s} & 0 \\ 0 & 2k_{n} & 0 & k_{n} & 0 & -k_{n} & 0 & -2k_{n} \\ k_{s} & 0 & 2k_{s} & 0 & -2k_{s} & 0 & -k_{s} & 0 \\ 0 & k_{n} & 0 & 2k_{n} & 0 & -2k_{n} & 0 & -k_{n} \\ -k_{s} & 0 & -2k_{s} & 0 & 2k_{s} & 0 & k_{s} & 0 \\ 0 & -k_{n} & 0 & -2k_{n} & 0 & 2k_{n} & 0 & k_{n} \\ -2k_{s} & 0 & -k_{s} & 0 & k_{s} & 0 & 2k_{s} & 0 \\ 0 & -2k_{n} & 0 & -k_{n} & 0 & k_{n} & 0 & 2k_{n} \end{bmatrix}$$
 (2.23)

K = the joint element stiffness per unit length

The element stiffness matrix has 32 nonzero terms but it depends on only two quantities, the unit joint stiffness in the normal and tangential directions.

The last step in the derivation is to place the element in a coordinate system for the entire structure. Adopting a global coordinate system X, Y as shown in Fig. 2-5, the transformation takes the following form:  $\checkmark$ 

$$\begin{bmatrix} x \\ y \end{bmatrix} \begin{bmatrix} \cos \theta & \sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$
 (2.24)

where

x and y = local coordinates in the tangential and normal directions, respectively.

### 2.3.2 Boundary Conditions

In the two-dimensional problem considered in this study, the boundary conditions can be either specified forces, specified displacements or both. Assuming direction of tool motion to be horizontal, the boundary conditions at the tool surface are specified horizontal displacements: The top soil surface is considered a stress-free boundary unless there is a vertical load distributed-uniformly on a grouser [tool (a) - Fig. 3-1 for example]. At a reasonable distance from the +ool, the bottom boundary is assumed to move only in the xdirection, while the sides are smooth in the y-direction but fixed in the x-direction. The assumed boundary conditions are shown in Fig.2-6.

If the boundary condition is that of an applied load, the value of the load is simply added to the appropriate components of the vector f in Eq. (2.9). Equivalent nodal point forces due to body forces and surface tractions are calculated and assembled concurrently with the element stiffnesses. The body forces in a triangular element due to gravity are lumped as one - third values at each nodal point comprising the triangle.

In case displacement or kinematic boundary conditions are specified, as in the present study, the stiffness matrix K has to be suitably altered to account for the specified displacements. If the  $i^{th}$  element of the deflection vector U is specified to be  $\Delta$ , the corresponding row of the stiffness matrix is made zero and the diagonal term is made unity, i.e.,

 $k_{13} = 0^{\circ}$  for  $i \neq j, j = 1, ..., .$ 

K<sub>11</sub>

(2.25)

The corresponding force element,  $f_i$ , is then set equal to the prescribed displacement value  $\Delta$ . One major disadvantage of this procedure is that the altered stiffness matrix, K is no longer symmetrical leading to added storage requirements while solving for the unknown displacements. An additional modification, however, will restore the symmetry of the K matrix as outlined below.

In addition to satisfying Eq. (2.25), all elements in the  $i^{th}$  column, except the diagonal element  $k_{ii}$ , are set equal to zero as in Eq.(2.26)the symmetrical nature of the K matrix is retrieved.

$$k_{ii} = 1$$
 (2.26)  
 $k_{ji} = 0$  for  $i \neq j$ ,  $j = 1, ..., n$ 

The force vector f on the righthandside of Eq. (2.9) now has to be altered as:

 $f_{i} = \Delta$  (2.27)  $f_{j} = f_{j} - k_{ji} \Delta$ , for  $i \neq j$ , j = 1, ..., n

Thus, Eqs.(2.25), (2.26) and (2.27) can be used together to achieve the desired purpose. The method is discussed in more detail in Zienkiewicz' book (1971); It is very easy to program and is adopted in the computer program developed in this work.

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### 2.3.3 Solution Method

Equation (2-9) after being modified for necessary boundary conditions represents a set of linear simultaneous equations. Various solution schemes that utilize certain special characteristics of the coefficient matrix have been used successfully in computer programs for the finite element. The banded nature of the matrix has led to the use of iterative methods of solution with over-relaxation factors [Fox (1965)]. The coefficient matrix has been decomposed into block tri-diagoral form and subsequently solved by elimination procedure, [McCormick (1963)]. Recursive techniques have also been used [Girijava-1]abhan (1967)]. The direct Gaussian elimination is simple and seffective to program [Zienkiewicz (1971)]. It has been adopted in the program developed in the present study. A detailed discussion of the technique is presented in Appendix D.

### 2.4 CONSTITUTIVE RELATIONSHIP FOR SOILS AND FINITE ELEMENT NONLINEAR ANALYSIS

In the previous section, the finite element formulations were derived assuming that the stress-strain behavior of the material is known. A set of equations that defines the stress-strain behavior of a material represents the constitutive law for the material. Constitutive relations for soils are derived, based on some simplified assumptions for the behavior of the material. The number of variables occurring in the law would depend upon the complexity of the model chosen to simulate soil behavior. Nonlinear analysis by the finite element method or other numerical techniques will be influenced by the nature of the model chosen. In general, the more complex the model, the more the number of variables

to be taken into account and the more involved the nonlinear analysis. Moreover, for a realistic analysis, it must be possible to obtain values for the constants involved in the constitutive law from laboratory experiments.

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## 2.4.1 Remarks on Constitutive Relations

The simplest constitutive law will be the one that assumes that soil behavior can be represented by a linear, elastic material. This linear, elastic model has been used by many research workers in their investigations. Other workers have considered soil to be elasto-plastic or nonlinearily elastic.

The elasto-plastic approach idealizes the stress-strain curve for the soil, and uses the equations of elasticity in the elastic range and the equations of plasticity in the plastic range. The nonlinear elastic approach, on the other hand, does not idealize the stress-strain curve, but uses the equations of elasticity to solve for the stress state even after yielding has occurred in the soil. Any degree of nonlinearity can be accounted for in this approach. The elasto-plastic approach appears sound from a theoretical standpoint, but the practical problems involved in defining a yield limit and a flow law are quite a handicap. In as much as the nonlinear elastic analysis represents the actual stress-strain relation obtained from tests, it seems reasonable to expect fairly good results from this type of analysis.

It is to be recognized that anisotropy in materials can be of two types. Material anisotropy represents different elastic properties in different directions. In nonlinear materials, stress-induced aniso-

tropy always exists and this may be coupled with material anisotropy. The principal stresses under a loaded condition will seldom be the same, and this will result in different elastic values in different directions depending on the stress level. This causes stress-induced anisotropy. It is generally difficult to take this type of anisotropy into account without elaborate testing or simplifying assumptions.

## 2.4.2 Solid Elements Constitutive Behavior

In the computer program developed in this study, the stressstrain relations obtained from laboratory plane-strain tests were used in the finite element analysis to predict the load deformation behavior of the continuum.

The nonlinear analysis in the finite element method is conducted as a series of linear analyses by an iterative or a step-by-step procedure, or a combination of both. Methods developed to obtain such solutions are described in the next section. However, both methods require procedures to compute values of E and v, elastic modulus and Poisson's ratio, for the soil during any state of loading. The procedure that is used to obtain these values from plane-strain test results will be first outlined.

### Evaluation of E and v from plane-strain triaxial test results:

Hooke's law for an isotropic, linear, elastic material in a principal plane can be written as:

$$\varepsilon_{1} = \frac{\sigma_{1}}{E} - \frac{v}{E} (\sigma_{2} + \sigma_{3})$$

$$\varepsilon_{2} = \frac{\sigma_{2}}{E} - \frac{v}{E} (\sigma_{1} + \sigma_{3})$$

$$\varepsilon_{3} = \frac{\sigma_{3}}{E} - \frac{v}{E} (\sigma_{1} + \sigma_{2})$$

where

 $\sigma_i$  (i = 1,2,3) are the major, intermediate and minor principal stresses, respectively.

 $\varepsilon_i$  (i = 1,2,3) are the major, intermediate and minor principal strains, respectively.

For the case of plane strain

ε<sub>2</sub> = 0

and the second equation in Eq. (2.28) reduces to

 $\sigma_2 = v(\sigma_1 + \sigma_3)$ 

for an incompressible material v = 0.5, and from the first equation of (2.28) it can be shown that

$$\varepsilon_1 = \frac{3}{4E} (\sigma_1 - \sigma_2)$$

 $E = \frac{3}{4} \frac{\sigma_1 - \sigma_3}{\varepsilon_1}$ 

 $E = \frac{3}{4}E_{T}$ 

 $\vec{T}_{i,i}$ 

(2.29)

(2,28)

The  $\frac{\sigma_1 - \sigma_3}{\varepsilon_1}$  term in Eq. (2.29) represents the slope  $E_T$ of the deviator stress,  $(\sigma_1 - \sigma_3)$ , versus principal strain,  $\varepsilon_1$ , curve. Thus in the plane strain case

(2.30)

### 2.4.3 Joint Elements Constitutive Relationship

As mentioned earlier, the cutting phenomenon caused by the tool movement in the soil mass is idealized by inserting joint elements between the solid elements. In evaluating the stiffness of these elements, it is assumed that both normal and shear displacements vary linearly along the length of the element, which is compatible with the external boundary displacements of the continuum elements used herein.

The properties of these elements consist of a normal stiffness,  $k_n$ , and a shear stiffness,  $k_s$ , which are related to the normal and shear stresses acting on the element by

and

where  $\Delta_n = average$  relative normal displacement across the element, and  $\Delta_s = average$  relative shear displacement along the element.

The values assigned to k<sub>s</sub> can be determined from the results of direct shear tests. The nonlinear tangential stress-displacement Curves shown in Fig. 2-8 may be approximated by hyperbolae having equation of the form

$$\tau = \frac{\Delta_c}{a + b\Delta_s}$$

 $k_n \Delta_n = \sigma_n$ 

k<sub>s</sub> Δ<sub>s</sub> = τ

where

 $\tau$  = cutting stress,

= shear displacement,

and a,

= ampirical coefficients whose values are determined experimentally.

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(2.31)



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The values of the coefficients (a) and (b) may be determined most easily if the stress-displacement data are transformed to another set of axes, on which the hyperbolae plot as straight lines. By transposing Eq. (2.32), the following relationship may be obtained

$$\frac{\Delta_{s}}{\tau} = a + b \Delta_{s}$$
 (2.33)

If values of  $\Delta_s'/\tau$  are plotted against values of  $\Delta_s$ , as shown in Fig. 2-8, the resulting variation will be a straight line if the shear stress varies hyperbolically with displacement. It may be shown from the form of Eq. (2.33) that coefficient (a) is the intercept, and coefficient (b) is the slope of the straight line on this transformed plot.

The reciprocal of coefficient (a) is the initial slope of the shear stress displacement curve, and is analogous to the initial tangent modulus of a stress-strain curve. The quantity called herein the initial "shear stiffness,  $K_{si}$ , has units of force per cubic length, or pounds per cubic inch for the curves shown in Fig. 2-8. The reciprocal of coefficient (b) is the asymptote approached by the shear stress displacement curve at very large values of displacement.

Tangent stiffness values, representing the slope of a tangent to the shear stress displacement curve, may be readily found by differentiating Eq. (2.33) with respect to  $\Delta_s$ , and, eliminating  $\Delta_s$  from the resulting equation, the tangent stiffness value may be expressed as

 $K_{st} = \frac{1}{a} (1 - \tau b)^2$ 

(2-34)

Possible modes of behavior for the joint element are shown in Fig. 2-9. It can be seen that in the compression and combined modes the adjacent continuum elements tend to overlap, a condition which occurs because compressive stresses require compressive relative displacements across the element, which, for purposes of analysis, is assumed to have very small thickness.

The stiffness values assigned to these elements varied depending on the mode of behavior and the element stresses. For compression, the value of  $k_n$  was made equal to the initial elastic modulus of the continuum elements, and the value of  $k_s$  was calculated using Eq. (2.34). After an element had failed in shear, with the element still in compression,  $k_s$  was reduced to a negligible value but the value of  $k_n$  was kept constant.

Both the shear stiffness,  $k_s$ , and the shear strength of the cutting zone depend on the value of the normal stress existing on this layer. The tangential stiffness values assigned to these elements varied depending on the element normal stress. This was done by conjustering the values of the coefficients (a) and (b) as a function of the normal stress existing in the element.

In a similar fashion, the properties assigned to the interface elements are determined from the results of direct shear tests consisting partly of soil and partly of tool material. Equation (2.34) is again used to predict the tangent stiffness modulus provided that (a) and (b) coefficients are obtained from a soil-metal interaction test.



### 2.5 METHOD OF ANALYSIS

In this particular study, nonlinearities occur in two different forms. The first is material or physical nonlinearity, which results from nonlinear constitutive laws [Section 2-4]. The second is geometric nonlinearity, which derives from finite changes in the geometry of the deforming body [Desai and Abel (1972)].

Material nonlinearity alone encompasses problems in which the stresses are not linearily proportional to the strains, but in which small displacements and small strains are considered. Displacements refer to the changes in the overall geometry of the soil body, whereas strains are related to internal deformations. Because of the small displacements encountered in some cases, local distortions of an element can be ignored and the areas of the original, undeformed element can be used in computing stresses. In this case the linear strain-displacement equations written for plane strain problems as:

$$\epsilon_{x} = \frac{\partial u}{\partial x} \qquad \epsilon_{y} = \frac{\partial v}{\partial y} \qquad (2.35)$$

$$\epsilon_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$$

where  $\varepsilon_v$  and  $\varepsilon_v$  are the normal components of strain,

 $\gamma_{XY}$  is the component of shear strain,

u and v are the displacement components in the x- and y-directions, are used.

Problems involving geometric nonlinearity arise both from nonlinear strain-displacement relations, written for a plane strain case as:

 $\varepsilon_{\chi} = \frac{\partial u}{\partial x} + \frac{1}{2} \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial x} \right)^2 \right]$  $\varepsilon_{\chi} = \frac{\partial v}{\partial y} + \frac{1}{2} \left[ \left( \frac{\partial u}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right]$ 

 $\gamma_{XY} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial u}{\partial x} \frac{\partial y}{\partial y} + \frac{\partial v}{\partial x} \frac{\partial v}{\partial y}$ 

and from finite changes in geometry. In other words, this category encompasses large strain and large displacements.  $(2 \cdot 36)$ 

The most general category of nonlinear problems is the combination of the material and geometric nonlinearities. It involves nonlinear constitutive behavior as well as large strains and finite displacements. This Section begins with the explanation of the computational procedure adopted to treat material nonlinearity, followed by a brief discussion on geometric nonlinearity.

2.5.1 Material Nonlinearity

Nonlinear stress-strain behavior may be approximated in finite element analyses by assigning different modulus values to each of the elements into which the soil is subdivided for purposes of analysis, as shown in Fig. 2-6. The modulus value assigned to each element is selected on the basis of the stress or strain in each element. Because the modulus values depend on the stresses, and the stresses in turn depend on the modulus values, it is necessary to make repeated analyses to insure that the modulus values correspond to the stress conditions for each element in the system.

Two techniques for approximate nonlinear analyses by the finite element method have been tried [Desai and Abel (1972)]. These

Direct iteration method, shown in Fig. 2-10. By this method, the same change in soil external loading is analyzed repeatedly. After each analysis the values of stress and strain within each element are examined to determine if they satisfy the appropriate nonlinear stress-strain-relationship. If the values of stress and strain do not correspond, a new value of modulus is selected for that element for the next analysis. The main advantage of this technique is the capability of the procedure to represent stress-strain relationships in which the stress decreases with increasing strain after reaching a peak value. The shortcoming of the iterative procedure, is that it can only give the solution for the final level of applied load, and cannot consider the load and deformation history pf the soil.

Incremental method, shown in Fig. 2-11. In this procedure, on the other hand, the soil loading is considered to be applied in small increments. If the state of stress and strain at the start of an increment is known in each element, the state at the end of the increment can be found by an addition of incremental changes. The constitutive relationship to be used for each element may be determined at the beginning of each interval. Thus the nonlinear stress-strain relationship is approxi-

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mated by a series of straight lines. The principal advantage of this procedure is that it provides a relatively complete description of the load-deformation behavior, as results are obtained for each of the intermediate states corresponding to an increment of loading.

In the present study, it is essential that the soil deformation and stress fields are obtained and examined as the tool advances in the soil. For this purpose the incremental procedure was employed.

The incremental technique adopted in the analysis makes use of the plane-strain triaxial stress-strain curves to compute the value of the elastic modulus, E, during each increment. The value of Poisson's ratio v is kept constant in the analysis.

The starting value of the modulus,  $E_0$ , is taken as the initial slope of the plane-strain triaxial stress-strain curves at zero confining pressure. With the assumed value of Poisson's ratio, the stresses or strains in each element due to the first increment of displacement is computed using the elastic analysis. A new value of the modulus to be used in the second increment is computed by using the nonlinear curves. Either the stresses or strains computed in the elements can be used in the nonlinear curves to obtain the E\_values. The modified constitutive relation is used in the next increment of deformation. The process is continued until the desired total deformation is obtained.

The modulus value, E, is calculated in each increment as:

$$E = \frac{2(\sigma_1 - \sigma_3) \mathbf{i} - 2(\sigma_1 - \sigma_3) \mathbf{i} - 1}{(\epsilon_1)_{\mathbf{i}} - (\epsilon_1)_{\mathbf{i}} - 1}$$
(2.37)

where i represents the current increment state, and i = 1 represents the previous increment stage. Figure 2-11 illustrates the incremental procedure.

There are several possible ways by which the solutions obtained by the incremental method can be improved. Since for every increment the elastic constants used are from the previous increment, it is necessary that the increments be quite small to obtain good results. Further, if there are abrupt slope changes in the stress-strain diagram, the method is likely to give unsatisfactory results. One of the ways to reduce some of these errors is to iterate a few times after each increment to bring the assumed E values close to the actual values. This procedure would also allow taking larger load increments in the analysis. The incremental-iterative method suggested is used in the computer program developed in this study.

In most problems, it is found sufficient to iterate two to three times at each increment to obtain compatible stresses and strains. The number of iterations at each increment may be reduced by predicting the value of E for a load increment based on the stresses or strains attained in the previous increment, and by using this value of E as a first trial in the computations. Linear and parabolic predictions were programmed in this study and gave very satisfactory performance for a faw idealized example problems. For soil stress-strain curves, it is

felt that the parabolic prediction will work much better than the linear one. Figure 2-12 diagrammatically illustrates the working of the linear prediction method.

# .5.2 Geometric Nonlinearity

In the previous subsection [2.5.1], the material or physical nonlinearity arising from material properties was considered. It is recalled that in the case of material nonlinearity, both strains and displacements are assumed to be small, but stresses are not proportional to strains. In this particular study, in addition to material nonlinearity, geometric nonlinearity occurs due to the finite changes in the geometry of the deforming soil in front of the cutting or traction tool. Combination of both nonlinearities is particularly simple if an incremental procedure is adopted.

If a full load-deformation study is required it is common practice to proceed with small loading increments and treat for each such increment the problem as a piece-wise linear one with the tangential stiffness matrix evaluated at the start of the increment. If the nodal coordinates are continuously/updated the calculation follows precisely the same pattern as used in small displacements-infinitesimal strain analysis. Updating for a plane strain case takes the form:

 $\overline{y}_{1} = y_{1} + v_{1}$ 

= x<sub>4</sub> + u<sub>4</sub>



Slope of OA - first trial value for E without prediction for second increment. Slope of AB - first trial value for E with linear prediction for second Slope of AC - actual E value for second increment after iterations.

FIGURE 2-12

INCREMENTAL-ITERATIVE METHOD WITH PREDICTION  $\overline{x}_i$ ,  $\overline{y}_j$  are the updated nodal coordinates at the end of the i<sup>th</sup> increment.

x<sub>i</sub>, y<sub>i</sub> are the nodal coordinates at the beginning of the i<sup>th</sup> increment.

u<sub>i</sub>, v<sub>i</sub> are the i<sup>th</sup> displacements in the x- and ydirections, respectively, associated with the nodes.

Strains are now determined by the derivatives of displacements with respect to the updated coordinates.

It is possible to use the general definition of strains. known as the Green's strain tensor, which is valid whether displacements or strains are large or small. For plane strain case the Green strain is defined by Eq. (2.36). If displacements are small the general firstorder linear strain approximation is obtained by neglecting the quadratic terms [Eq. (2.35)]. Because the loading increments are small, it is assumed that the strain increments may be regarded as infinitesimal in In such case, the linear strain approximation the usual sense. [Eq. (2.35)] can be used. It is recognized, however, that the same may not be true of the accumulated values. In the limit of infinitesimal increments of loading, it may be shown that this procedure gives the socalled logarithmic strains; rather than simple displacement gradients [Fong (1965)]. While this is admittedly an approximation to the more formal definition of large strains, Eq. (2.36), the degree of approximation appears to be consistent with that of the overall method.

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### CHAPTER-3

### EXPERIMENTATION

### 3.1 INTRODUCTION

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The analysis described in the previous Chapter solves approximately the problem of a simplified cutting or traction element interacting with soils. Two kinds of unavoidable approximations were introduced into the analysis, namely the insertion of the cutting [joint] elements in the finite element model to represent the tool cutting effect, and the adoption of a numerical solution [incremental finite element] technique. The combined effect of all approximations can be investigated by comparing the results of the analysis with experimental measurements. Therefore, the purpose of the experimental programme carried out during the course of this study was to provide data on the interaction of the chosen cutting and traction elements with cohesive soils under plane strain conditions, which could be compared with the analytical results. Mainly the following facts were investigated:

(1) The load-displacement, response of the soil.

(2) The soil deformation fields.

(3) Failure mechanisms.

In simulating traverse motion of a cutting or tractive element, it is common practice in laboratory experimentation to control:

(a) Depth of element travel - i.e. variable vertical

force resulting therefrom.

(b) Applied vertical force - i.e. variable depth of element motion.

The resultant forces developed for situation (a) are obviously different from those of (b) - due to the different boundary conditions developed. The actual field problem however, involves neither situation (a) nor situation (b), i.e. neither vertical loads nor elevations are controlled.

While in traction analysis the constant pressure approach [situation (b)] intends to simulate a portion of the vehicle weight applied to the top of the grouser and maintained throughout the entire test, it could be argued that this is not the case in reality as the vertical pressure on the grouser changes in magnitude while the track is moving. And since the actual field situation in traction involves multiple grousers on a link or a belt system, the prediction of mobility for track systems based on single grouser analysis must suitably account for multiplicity of grouser action. Track analysis however constitutes a separate problem and is not covered within the scope of this study.

Most of the work done up to the present time on the analysis of the problem of soil cutting assumes a constant depth of cut [Osman (1964), Reace (1965), Hettiaratchi et al. (1966) and Yong et al. (1969)]. This condition was maintained in both the cutting and traction test series conducted in this study. The reason for adopting such a condition

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in the traction series was to apply similar boundary-conditions as those assumed for the soil cutting case, thus obtaining a unified method of analysis.

The tests performed in the course of the investigation may be divided into two categories:

- (a) Cutting tests, in which a series of straight blades with different angles of inclination were moved through the soil. Vertical movements of blades were not permitted so as to produce a constant depth of cut condition.
- (b) Traction tests, in which grousers with different
   geometries were moved in the soil at a constant
   height relative to the initial soil surface.

In both cases, the measured parameters were: the horizontal and vertical forces, and the tool horizontal displacement. All measurements were made on a time base which allowed for the determination of the horizontal carriage velocity. A complete description of the experimental facility and procedures used in the experimental phase of the study is provided as Appendix A.

Briefly, the experimental facility consisted of a toolcarriage assembly moving through a soil sample contained in a bin with transparent lucite side walls. Two soil types were employed during the course of investigation. These were kaolinite clay, with a specific gravity of 2.62 and a liquid limit and plastic limit of 54.5 and 37.5 per cent, respectively, and an artificial, oil base, clay [trade name "Plasticine"]. In all cases, the dimensions of the test specimens were such as to permit full development of the failure zones without interference occurring between the deforming zones and the ends of the sample holder.

As a means of specifying the deformation history during the deformation process, a network of lines was inscribed on the side surface of the test specimens. The inscribed lines provided a grid of one-half-inch squares and photographs of the deforming grid were taken every five seconds of tool motion. Subsequent plotting and superposition of the sequential photographs provided the history of the deformation process over a range of tool movement of three inches.

#### 3.2 CUTTING AND TRACTION TOOL GEOMETRIES

The intent of this study is not to compare different tool geometries for the purpose of establishing suitability, efficiency or performance, but rather to develop an analytical method capable of predicting the interaction behavior of a wide spectrum of cutting and traction element geometries. Therefore, a number of tool geometries were chosen and tested to evaluate the applicability of the proposed method of analysis.

In case of the cutting experiments, four aluminum blades each measuring four inches wide by four inches long were utilized. The blades were set at angles of 10°, 20°, 40° and 50° with regard to the vertical.

As for the traction experiments, the groupings were separated in terms of the shape of the traction element and consisted of:

- (1) Right Angle Plate Grousers [R.A.P.G.], [Fig. 3-1a] with aspect ratios h/l of 0.5 and 0.833. The length l was maintained constant at 3.0 inches, while h was varied to provide the differences in h/l.
- (2) Straight-Edge Wedge Grousers [S.E.W.G.]. Only one tool was utilized with a height of 2.32 inches and tip angle of 45°, Fig. 3-1b.
- (3) Curved-Edge Wedge Grousers [C.E.W.G.]. Two geometries were utilized to provide different boundary conditions.
   The dimensions of the C.E.W.G. are shown in Fig. Nos.
   3-1c and 3-1d.

These grouser shapes simulate the most common boundary conditions of individual grousers which can arise in practice, and the results obtained from their analysis should therefore be representative of the behavior of the soil mass under typical loading systems.

### 3.3 EXPERIMENTAL PROGRAMME

The experimental research programme can be subdivided into the phases, namely, cutting and tractive elements, testing, and soil strength testing.

### 3.3.1 Cutting and Tractive Elements Testing

This phase consisted of two distinct groups. The groupings were separated in terms of the type of experiment, whether cutting or traction. In addition, two soils were used: an artificial, oil based,

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# GROUSER GEOMETRIES








clay and a kaolinite clay soil. The artificial clay was preferred in the initial test series due to the fact that preparation of the samples did not require water content control as they merely required moulding in the test bin and subsequent compaction. This permitted the development and debugging of test equipment and experimental techniques. The tests were continued to provide information regarding the interaction behavior of a cutting or tractive element with a plastic material. The conventional engineering properties of the kaolinite soil tested may be found in Appendix A, together with a description of the artificial, oil based, clay.

To minimize the number of experimental variables, the tools were tested at constant rate of horizontal movement of about 1.0 inch/ minute. The various experiments performed are listed in Table 3-1 for soil cutting tests, and in Table 3-2 for traction tests. It will be noted here that the horizontal speed fluctuated between 0.85 and 1.05 inches/minute. The torque output produced by the varying speed DC-motor, utilized in the experimental facility, was found to be very sensitive to the input current at low speeds, making it difficult to reproduce any desired torque. This resulted in difficulties in maintaining the same horizontal speed throughout the duration of the experimental program. However, the speed was constant during any one test.

Included in Table 3-1 and Table 3-2 is a listing of the applicable bulk densities and water contents for each of the reported experiments. Examination of these values will show that both were very reproducible over the entire experimental series. Finally, Fig. 3-2 shows the density variations encountered in both the cutting and traction test series for the kaolinite clay, reported in terms of dry

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# TABLE 3-1

# INITIAL DATA FOR SOIL CUTTING EXPERIMENTS

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|     |                                                                                                                  | <u> </u>                                                                                                        |                                  |                |                       |   |
|-----|------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|----------------------------------|----------------|-----------------------|---|
|     | TEST<br>Number                                                                                                   | ANGLE OF BLADE<br>WITH VERTICAL                                                                                 | HORIZOŃTAL<br>SPEED<br>inch/min. | DENSITY<br>PCF | WATER<br>CONTENT<br>% |   |
|     | ARTIFIC                                                                                                          | IAL CLAY TESTS                                                                                                  |                                  |                |                       | 1 |
|     | 8                                                                                                                | · 10°                                                                                                           | 0.85                             | 110.0          | -                     |   |
|     | 9                                                                                                                | 10°                                                                                                             | 1.084                            | 110.90         | -                     |   |
|     | 21                                                                                                               | 10°                                                                                                             | 0.98                             | 108.0          |                       |   |
| •   | 3                                                                                                                | 20°                                                                                                             | 1.0 -                            | 109            | -                     | 1 |
|     | 4                                                                                                                | <sup>ໍ</sup> 20°                                                                                                | 0.95                             | 109.5          | -                     |   |
| L   | 12                                                                                                               | 20°                                                                                                             | <b>.0.98</b> '                   | 111.0          | -                     |   |
|     | 10                                                                                                               | 40°                                                                                                             | 1.05                             | 110.2          | -                     |   |
|     | 23                                                                                                               | 40°                                                                                                             | 0.95                             | 109.0          | -                     |   |
|     | 6                                                                                                                | 50°                                                                                                             | 1.0                              | 108.5          | -                     |   |
|     | . 7                                                                                                              | 50°                                                                                                             | 0.97                             | 110.0          | -                     |   |
|     | 22                                                                                                               | 50°                                                                                                             | 1.03                             | 109.3          | · - ·                 |   |
|     | NATURAL                                                                                                          | [KAOLINITE] CLÀ                                                                                                 | Y TESTS                          |                |                       |   |
|     | 27                                                                                                               | ` 10°                                                                                                           | 1.05                             | 101.00         | 53.75                 |   |
| ,   | 30                                                                                                               | 10°                                                                                                             | 0.90                             | 102.80         | 52.15                 |   |
|     | 28                                                                                                               | 20 <b>°</b>                                                                                                     | 1.0                              | 101.80         | 51.49                 |   |
|     | 35                                                                                                               | 20°.                                                                                                            | 1.05                             | 102.40         | 52.50                 |   |
|     | 26                                                                                                               | 40° '                                                                                                           | 0.98                             | 102,25         | <b>50.9</b> 0         |   |
|     | 36                                                                                                               | 40°                                                                                                             | 1.03                             | 99.96          | 51.30                 |   |
| •   | 29 🕥                                                                                                             | 50°                                                                                                             | 1.0                              | 100.80         | 53.20                 |   |
|     | 31                                                                                                               | 50°                                                                                                             | 1.0                              | 101.75         | 53.60                 |   |
| - 1 | and the second | In the second |                                  |                |                       | 1 |

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TABLE 3-2

# INITIAL DATA FOR TRACTION EXPERIMENTS

| Aity Water<br>Content<br>X<br>.31 -<br>.0 -<br>.7 - |
|-----------------------------------------------------|
| .31 -<br>.0 -<br>.7 -                               |
| .31 -<br>.0 -<br>.7 -                               |
| .0 –<br>.7 –                                        |
| .7 –                                                |
|                                                     |
| .5 -                                                |
| .0 -                                                |
| .92                                                 |
| .57 –                                               |
| .0 –                                                |
| .35 -                                               |
| .21 ′ -                                             |
| .65 -                                               |
|                                                     |
| .40 52.80                                           |
| .00 53.20                                           |
| .2 52.6                                             |
| .0 51.2                                             |
| .80 53.35                                           |
| .10 50.95                                           |
| .22 52.57                                           |
| .10 51.79                                           |
|                                                     |

Notes: Traction tools indicated by the letters -

R.A.P.G. - denote Right Angle Plate-Grouser C.E.W. - denote Curved-Edge Wedge Grouser S.E.W. - denote Straight-Edge Wedge Grouser

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density. In addition, it is observed that the kaolinite soil samples used in these experiments generally achieved a degree of saturation of the order of 95 per cent. >

## 3.3.2 Soil Strength Tests

In addition to the cutting and traction experiments, strength tests were performed on compacted soil samples to obtain the stressstrain relationships required for the analytical solution. The results of these tests will be presented in the following Chapter, and complete descriptions of the techniques and apparatus are given in Appendix A. Briefly, however, two types of tests were performed.

#### (a) <u>Tests to determine the stress-strain relationships for the soil</u> represented by continuum elements in the analytical solution

After the cutting and traction tests were completed, undisturbed blocks of the soil were taken from the test bin at various locations away from the region of loading. These samples were subjected to two loading conditions, the first being testing of prismatic samples under plane-strain conditions in a modified triaxial chamber. The second consisted of the application of axisymmetric loading to a cylindrical soil sample placed in a standard triaxial cell. Some preliminary studies were conducted with a view to finding the effect of the rate of strain on the strength properties of the soil. Triaxial tests at three different rates of speed [0.1, 0.5 and 1.0 inch/minute], and three different confining pressures [0, 2.5 and 5.0 psi] were run on duplicate samples.' The results showed some gain in strength with speed, Fig. A-5, Appendix A.



It was therefore decided to use the triaxial test results obtained at the same speed at which the cutting or traction element is loaded in the model test.

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### (b) <u>Tests to determine the properties of the joint elements used in</u> <u>idealizing the cutting and interface behavior</u>

As mentioned previously [Chapter 2] joint elements are utilized in the analytical solution to simulate the discontinuities in the finite element model proposed in this study. The properties of the joint elements consist of a shear stiffness,  $k_s$ , and a normal stiffness,  $k_n$ . These coefficients ( $K_s$  and  $K_n$ ) express the rate of change of shear stress with shear deformation and of normal stress with normal deformation. The nonlinear, stress dependent, joint behavior may be conveniently obtained by performing direct shear tests due to the fact that the relative displacement in this test occurs along a predetermined plane which can be visualized as a discontinuity reflecting the behavior of a joint element: Two types of direct shear tests were performed.

- (1) <u>Cutting tests</u> The soil was tested in a direct shear machine to obtain the stiffness values assigned to the joint elements inserted between the continuum elements to simulate the tool cutting action.
- (ii) <u>Interface tests</u> In these tests, the lower part of the direct shear box consisted of a specimen of aluminum, the same material used in the fabrication of the cutting and traction tools, and the soil was compacted in the upper part of the shear box. The gap between the

upper half of the shear box and the aluminum base was kept as small as possible, and the tests were interpreted assuming that the relative displacements between the upper and the lower parts of the box were due entirely to interface movements.

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Furthermore, to account for the dependence of the shear stiffness modulus,  $k_s$ , on the normal stresses, the normal load, in both test series, was varied through the values 0, 2.5 and 5.0 lb.

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#### CHAPTER 4

#### EXPERIMENTAL RESULTS AND ANALYSIS

SECTION A - EXPERIMENTAL RESULTS

#### 4.A.1 GENERAL CONSIDERATIONS

A soil-tool interaction prediction must be based on quantitative descriptions of the forces applied by the tool and the resulting behavior of the soil. The actions recognized as being present in soil cutting and traction must be separated into simple behavior, which can be studied. Simple behaviors include, for example, stress-strain relations, soil-metal friction and adhesion, and yield by shear.

As previously stated, descriptions of behavior can be established through the application of several distinct phases of study. First, some specific behavior is observed and studied. Second, having noted the behavior, factors involved are identified and their relation ascertained in a cause-and-effect manner. Analytical techniques are required to quantitatively describe the cause-and-effect relation, and, hence, the behavior. The sequence adopted in the presentation of the test results and the methods of analyses in the present, and the following Chapters are shown in Fig. 4-1. In this Figure, the separation of the distinct phases of the study is clearly evident.

One of the difficulties in understanding a soil-tool action is that every behavior is not always operative. A behavior may appear



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EXPERIMENTAL RESULTS AND ANALYTICAL SOLUTION

intermittently, and its presence may be difficult to detect or assess. For example, a dry cemented soil does not exhibit plastic flow behavior or even compression failure to any great extent. Similarly, a wet saturated soil may exhibit great plastic flow but little shear Elijah and Weber (1968) identified four distinct types of failure. soil failure for flat cutting blades. They were designated as "shear plane", "flow", "bending", and "tensile" failures. This terminology was created by the authors as the most descriptive of the patterns They have stated that "Predicting the type of failure in involved. a given soil with a given tool will require some new soil parameters, ones that will distinguish quantitatively some of the soil characteristics that are now expressed in qualitative terms".

The results and associated discussions presented in this study deal mainly with plastic soils interacting with a number of The soil deformation behavior observed during the tool geometries. experimental investigation is of a plastic flow nature. The solution technique, in turn, is oriented towards analyzing interaction problems involving the plastic flow soil failure, and therefore cannot be considered a general solution technique covering the wide soil behavior However, in the analytical approach adopted it is essential. spectrum. that proper appreciation of the constitutive performance of the material and boundary conditions be obtained and subsequently applied. Such rigorous requirements should provide for more general behavior predictions by the analytical method.

## 4.A.2. TYPICAL EXPERIMENTAL RESULTS

## 4.A.2.1 Soil Cutting Results

The soil cutting tests which were carried out in the course of the experimental programme are listed in Table 3-1. Prior to presentation and examination of test results some points should be discussed in order to arrive at a better insight and evaluation of these results.

The entire test series was performed at a constant rate of blade motion [about 1.0 inch/minute]. Although many studies have shown that the forces acting on soil-engaging tools increase with the increase in speed [Rowe and Barnes (1961), Olsen and Weber (1966) and others], no satisfactory explanation of this phenomenon has been reported. This increase in force has been attributed to acceleration of the soil, increased shear strength, and increase in length of the failure path [Siemens (1963), Shone (1956)]. Rowe and Barnes (1961) and Olsen and Weber (1966) studied the effects of speed on the draft of an inclined flat blade and concluded that increase in draft with increase in speed was primarily due to increased soil shearing strength. Some of the conclusions reached by Olsen and Weber were:

- acceleration of the loaded soil segment was not a significant contributing factor to the increase in tool force with increase in speed,
- there was no significant change in length of the failure path or angle of inclination of the failure plane with change of speed for the soil tested, and

 the shape of the stress-strain curve of a soil seems to be a determining factor in the magnitude of the increase in tool force with increase in speed.

In view of the above findings, it was argued that there was no need for examining the effect of speed on the developed forces since such effect is already included in relating the stress to the strain for the soil used in the experimental investigation. It will be recalled that the stress-strain relations obtained from laboratory planestrain tests, performed at the same speed at which the cutting or traction element moved in the soil, are used in the finite element analysis to predict the load-deformation behavior of the soil. ' While realizing that the strain-rate dependence of a certain soil may vary with the test constraints [i.e., the difference between the boundary conditions of a plane-strain triaxial test and the model tests] which may lead to some error in prediction, such error should not diminish the effectiveness of the above technique, since by adopting a more appropriate framework defined by using more similarities in boundary conditions ensures a higher order of/predictability.

The draft force is usually taken as the maximum force produced during the cutting operation. It is easy to determine the draft force if the material fails in shear and the draft-displacement curves exhibit peak values at small displacements. However, if the draft force gradually increases with tool displacement, the cutting forces should be computed at a specified-value of displacement. Contrary to most of the previous research which was directed towards the measurement and prediction

of the maximum draft forces regardless of the displacements at which these forces were attained, the present study is concerned with the prediction of the force-displacement history. For this purpose, the tool was moved in the soil for a distance of 3.0 inches, and the forces and displacements were recorded.

It has been previously mentioned that the model tests were performed for the purpose of checking the validity of the analytical approach. With this in mind, the experimental results should be viewed not as a study of the various factors influencing soil cutting, but rather as data gathered for the purpose of verifying the applicability of the predictive technique adopted.

A sample of the results showing measured horizontal and vertical forces for blades with inclination angles of 10°, 20°. 40° and 50° with the vertical are shown in Figs. 4-2 and 4-3 for the kaolinite clay, and in Appendix A for the artificial, oil based, clay, It should be noted here that the blades employed in this study wene of a constant length of 4.0 inches which resulted in a depth of cut varying with the blade inclination angle. Such variation in the depth of cut makes it difficult to compare the forces developed by the various blades. It is argued that a normalization of the results by comparing the forces per unit depth of cut is not a viable approach since interaction forces cannot be assumed, without experimental evidence, to be directly proportional to the depth of cut for a particular blade. Any conclusion derived from a normalization technique employing such an assumption, without experimental verification, can be greatly misleading.





It has been mentioned in Section 2.2.2. [Chapter 2] that during the cutting process no distinct failure planes were developed in the loaded soil; instead continuous failures took the form of Such behavior was observed during the deformation process bulging. using the glass-sided soil bin [Chapter 3], and is confirmed from the plots of draft forces versus displacement, Fig. 4-2, for the various blades employed in this investigation. These plots show a nonlinear load-displacement relationship exhibiting no peaks that can indicate the formation of shear or failure planes. Yong and Chen (1970) observed in their investigation that the force-displacement plots for cutting blades in sand and  $C - \Phi$  soils exhibited a first peak representing the major or maximum force development at first failure and subsequent perturbations which generally show higher values, corresponding to the subsequent development of secondary shear planes. In the case of clay soils tested in this study, no such peaks were recorded and the draft values are shown to keep on increasing with blade movement, an indication of the surcharge accumulation effect in front of the moving blade.

The development of the vertical forces, presented in Fig. 4-3, shows that the sense of the vertical force changes from downward [positive] on the blades with inclination angles greater than 10° to upward [negative] for the 10° inclined blade. Such behavior is consistent with the concept put forward by Osman (1964) stating that in the absence of much blade friction [or adhesion] the vertical force acts downwards for small blade rake angles, changing to upwards at a certain point as the rake angle increases. The friction [or adhesion]

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force always acts upwards along the blade because this is the direction of relative soil movement. The effect of friction [or adhesion] is therefore to diminish the downward force on low rake blades, increase the upward force on near vertical blades.

The influence of the angle of blade inclination on the developed horizontal and vertical forces at 1.0 inch displacement is illustrated in Fig. 4-4, for both kaolinite and artificial soils. Discussion relative to the above and also the following results will be developed in Chapters 5, 6 and 7. For continuity, the material presented at this point will relate primarily to the presentation of results, in a form which is amenable for examination and evaluation.

#### 4.A.2.2 Traction Results

Regarding the traction test results, while the intent of the experiments is similar to that of blade testing, the results [in terms of developed forces and soil deformation] must be viewed from a different perspective. The purpose of using lugs or grousers on traction devices is to cause deformation of soil in a certain manner as to develop adequate traction capacity for a grouser. The deformation of a particular soil plays a very important role in the production of adequate traction for a single grouser. The deformation characteristics could be manipulated by changing the geometry of the traction tool in order to produce enough interaction for efficient performance, To this end, the purpose of performing the traction experiments was to investigate the influence of the tool boundary conditions on the interaction process in order to arrive at desirable developed forces for efficient



conversion of traction into pull.

This study is concerned with the mechanics of a single grouser acting on clay soils as a phase of the study of track-soil interaction. Again, the intent here is to provide information on the physical behavior of the action of the moving grouser in order to formulate the necessary mathematical model and boundary conditions. Grouser action is defined in this study as the motion of the grouser in the soil to create a failure condition in the soil. Thus, the limits of the magnitudes of the horizontal and vertical forces defined for the action of the grouser serve to identify the maximum forces that can be applied to provide for forward motion of the tracked vehicle. Having established the viability of a certain predictive technique, further studies on The end purpose of multiple grouser multiple grousers can be initiated. study is to determine optimum spacing to admieve best total aggressive grouser motion.

With this appreciation of the problem, it will be recalled that grouser tests may be divided into two categories [Chapter 3], viz:

1. Constant vertical load tests

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In this type of test a constant vertical load intended to simulate a portion of the vehicle weight is applied to the top of the grouser and maintained throughout the entire test. Since the grouser is mounted on a carriage, it is free to translate both vertically and horizontally but is restrained against rotation. The measurable response parameters during this type of test

are the horizontal displacement, the horizontal force and the vertical displacement.

2. Constant elevation tests

In this type of test, the grouser is restrained in the vertical direction and is only free to translate horizontally. The method of restraint is to keep the grouser at a constant height in relation to the initial surface throughout the duration of the test.

These two types of tests simulate most situations which arise in practice and the results obtained therefrom should be representative of the behavior of the soil mass under the most common loading systems which can be applied to a grouser. As previously mentioned, in this study the latter condition was chosen for simplicity in specifying the boundary conditions.

Typical results from the traction experiments listed in Table 3-2 are shown in Figs. 4-5 and 4-6. In Fig. 4-5 both the horizontal and vertical forces developed on the plate grousers [R.A.P.G.] are plotted as a function of the distance travelled. In this Figure the results are shown for two grousers with aspect ratios (h/1) of 0.5 and 0.833, tested in the kaolinite clay. Similar results are shown for the artificial clay in Appendix A. It must be noted that while the number of grousers tested does not permit a good comparison of the developed forces based on the aspect ratio (h/1), the results shown indicate that there seems to be no linear correlation between the grouser aspect ratio (h/1) and the developed forces. In Fig. 4-6





similar plots are shown for the C.E.W. and the S.E.W. grousers tested in the kaolin clay. The corresponding plots for the artificial clay are shown in Appendix A.

Table 4-1 presents a comparison of typical forces developed on the various grousers employed after a travel distance of 1.0 inch.

|                      | Kaolin Clay         |                   | Artificial Clay     |                   |
|----------------------|---------------------|-------------------|---------------------|-------------------|
| Grouser Type         | Horizontal<br>Force | Vertical<br>Force | Horizontal<br>Force | Vertical<br>Force |
| R.A.P.G.(h/1)= 0.5   | 38.5                | 18                | 30                  | 11.5              |
| R.A.P.G.(h/1)= 0.833 | 47.0                | 25.5              | 40                  | 18.2              |
| C.E.W. type (1)      | 45.5                | · 22              | 38,2                | 17.5              |
| S.E.W.               | 44.0                | 19                | 35,5 -              | 14.9              |
| C.E.W. type (2)      | 40,0                | 13.5              | 33.6                | 11.0              |

Typical Developed Forces (in 1b) for Various Grousers Tested at 1.0 inch Displacement

(Constant Elevation Tests)

With the exception of the R.A.P.G. with an aspect ratio (h/1)of 0.5 [h=1.5", 1=3.0"], the rest of the grousers employed in this investigation have approximately the same depth of cut [2.5 inches for the R.A.P.G. with h/1 of 0.833 and 2.32 inches for the wedge grousers]. Consequently, direct comparison of the developed forces as a function of grouser geometry is possible. It is shown from Figs. 4-5 and 4-6 and Table 4-1 that the plate grouser [h/1 = 0.833] develops maximum traction, i.e., horizontal as well as vertical forces. The development of the large forces may be attributed to the soil deformation behavior' in front

## TABLE 4-1

of this grouser. From an examination of the displacement patterns as well as the velocity fields of the grid nodes [shown in a later section of this dissertation], it was noted that the soil confined by the plate grouser moves coherently with the grouser, leading to differential deformation between this and the surrounding soil. This effect is similar to the "dead" zone postulated by Terzaghi (1944) in his analysis of bearing capacity, and to the "dead" zone postulated by Yong and Sylvestre-Williams (1969) in studying grouser thrust on sand, see Fig. 2-1(t). It is believed that the existence of a similar "dead" zone in the present investigation extended the region of influence of the grouser resulting in larger developed forces. On the other hand, the wedge grousers' deformation fields indicated very small or no "dead" zones, and the regions of influence of such grousers were found to be smaller than those of the plate grousers.

Comparing the forces developed on the wedge grousers, it is noted that the C.E.W. type (1) grouser produces the largest forces [both horizontal and vertical]. While the depth of embedment is the same for all the wedge grousers, the contact surface area is larger for the C.E.W. type (1) grouser due to the wedge **em**rvature and also due to the contact of the top horizontal plate with the sofl, see Fig. 3-1, resulting in more soil interacting with the tool.

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The effect of the curvature of the grouser interface on the developed forces can be seen from a comparison of the C.E.W. type (1) grouser results with those of the S.E.W. grouser. Both systems are similar in dimensions except for the curvature of the C.E.W. type (1) grouser surface. This curvature results in an increase in developed forces.

It seems, however, that the effect of the grouser top horizontal plate being in contact with the soil on the developed forces is much more pronounced. The C.E.W. type (2) grouser shown in Fig. 3-1(d) has a curved interface but the top horizontal plate does not touch the soil surface. This grouser produces the lowest forces.

Finally, from examination of the displacements of the surface grid, the geometry of the deformed soil mass subjected to the aggressive action of the different grousers showed no development of distinct failure surfaces in the initial three inches of grouser travel. This behavior resembles the deformation observed in the cutting tests which is attributed to the plasticity of the soils tested.

#### I.A.3 STRENGTH TEST RESULTS

For many soil-structure interaction problems, it is necessary to know, or to predict with a reasonable degree of accuracy, the strength and deformation characteristics of soil under load. The acceptability of a theory for predicting the stress-strain relationship for soil depends on the accuracy of the assumptions and the approximations made regarding the actual behavior of the soil. The simplest assumption that can be made is that a given soil can be classified as linear elastic, rigid plastic, or elasto-plastic. However, soil behavior is a function of mineral composition, stress level, density, strain conditions, etc., and, unlike most engineering materials, can neither be linear nor compatible with elastic, plastic, or elasto-plastic classification.

### (a) <sup>\*</sup><u>Plane-strain and axisymmetric</u> triaxial test results

It was felt that the best way to incorporate a constitutive behavior was to perform tests that reproduce as much as possible the assumed conditions during the cutting and traction tests. For this purpose, prismatic samples of nearly saturated remolded clay were prepared, and triaxial tests were conducted under plane-A given sample was installed into a modified strain conditions. triaxial cell between two polished and lubricated brass plates. The axial [vertical] load was applied through a lubricated rectangular platen of the same dimensions as the initial sample The apparatus used, together with the procedures, is section. described in Appendix A. The testing was conducted under different confining pressures of 0, 2.5 and 5.0 lb/in<sup>2</sup>, and at axial strain-rates of 0.1, 0.5 and 1.0 inch/minute. Typical test results are shown in Fig. 4-7 for kaolinite clay and in Appendix A for the artificial clay. , Analogous axisymmetric, triaxial tests were performed on cylindrical samples 1.4 inches in diameter. These tests were performed in order to verify the fact that the nonexistence of a well defined failure condition i.e., absence of strain softening behavior, is not a result of the plane strain, "True Triaxial", test restraints (Fig. 4-8).

It may be noticed that the stress-strain curves do not exhibit a definite peak to define failure, but instead the stress difference  $(\sigma_1 - \sigma_3)$  keeps on increasing with axial strain for both soils tested. The finite element analysis in this investigation is performed by an increasing procedure, and in such a





case, it is difficult to account for a drooping stress-strain curve. The observed rising of the stress-strain curves eliminated the need for an approximation to the stress-strain curves to avoid the numerical difficulties arising from strain softening behavior. Since no definite peak was evidenced, an axial strain of 20% was chosen to define failure.

There are two common procedures for incorporating a nonlinear stress-strain law into a finite element formulation for The stress-strain law derived from a digital computations. laboratory test can be used directly in a tabular or digital form. Several points on the curve are selected and are input in the form of number pairs denoting stress and strain at those points. The variable material parameters such as E and v are obtained from such curves by suitable interpolation. If the behavior is represented by a single stress-strain curve, stresses are obtained by interpolation for a calculated state of strain. If the behavior is represented by several curves, interpolation must also be done between two curves for different confining pressures.

In the alternative procedure, the laboratory stress-strain relationship is expressed in the form of a suitable mathematical function. The material parameters for the nonlinear analysis are again obtained on the basis of the state of stress or strain.

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The tabular or digital procedure was utilized in this .study to represent the constitutive behavior of the soil modelled .by continuum [triangular] elements in the analytical solution. To

start the analysis, initial values of the modulus of elasticity, E, and Poisson's ratio v, are required. The clays used can be considered to be fairly incompressible as they were nearly Therefore, it would be reasonable to choose the saturated. value of the Poisson's ratio of the soils close to 0.50. In the present study. v, was assumed to be 0.48 for both the kaolinite and artificial clays. Furthermore, the value of v was assumed to remain constant throughout the entire deformation process. Similar assumptions have been made by others earlier [Clough and Woodward (1967), Girijavallabhan and Reese (1968)]. The nonlinear analysis was based directly on the plane-strain triaxial The starting value of the modulus,  $E_0$ , was taken as curves. the initial slope of the stress-strain curve at zero confining This value, obtained from Fig. 4-7, is 90 lb/in<sup>2</sup> pressure. for the kaolinite clay.

In an axisymmetric triaxial stress condition, the intermediate and minor principal stresses are the same, and the confining pressure for the sample is equal to the minor principal stress,  $\sigma_3$ . In the actual problem, however, these conditions are not strictly valid as; in general, the magnitudes of the intermediate and minor principal stresses in an element will be different. This is particularly true in a plane-strain condition where the intermediate principal stress is given by the relation:

$$v_2 = v_1(\sigma_1 + \sigma_3) \qquad (4.1)$$

For special cases only will Eq. (4.1) yield  $\sigma_2 = \sigma_3$ .

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However, it seems reasonable to express the confinement in an element, for the sake of computations, as the average of the magnitudes of the intermediate,  $\sigma_2$ , and minor,  $\sigma_3$ , principal stresses induced at the centroid of the element. The analysis developed in this study adopts this approximation.

The finite element analysis first computes the values of the stresses, strains, and confining pressures in each element. In a general case, three interpolations are required to compute the state of stress  $(\sigma_1 - \sigma_3)$  corresponding to a state of strain,  $\epsilon_1$ , in an element from a set of nonlinear curves. Interpolations are performed to compute intermediate values in a curve and also between curves at different confining pressures. In the computer program "MAIN-2" developed in this study, stress values were computed from strain values obtained in the analysis. The details of the computer prorambare given in Appendix E.

(b) <u>Direct shear test results</u>

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As previously mentioned in Chapter 3, two types of direct shear tests were performed to determine the properties of the joint elements used in idealizing the cutting and the interface behavior. The first type was a conventional direct shear test which is referred to as a soil-to-soil shear mode, while the second test type was conducted with the lower part of the shear box consisting of an aluminum plate representing a soil-to-metal shear mode.

The shear stress-displacement curves for the soil-to-soil mode are shown in Fig. 4-9, and for the soil-to-metal mode in Fig. 4-10 for the kaolinite clay. In both Figures, it is seen that the shear stress values increase with increasing displacement reaching maximum values for relative displacements of approximately 0.2 inch, after which the shear stresses remain nearly constant. It may also be noted that both the steepness of the stress-displacement curves and the maximum values of shear stresses increase with increasing normal stress for both the soil-to-soil and soil-to-metal modes, Fig. 4-11.

The ratio of the peak stress in the soil-to-metal mode to the peak stress reached in the soil-to-soil mode is plotted in Fig. 4-12 as a function of the applied normal load. The relationship indicates that the ratio approaches unity at zero normal load, and decreases with increasing normal load up to a point after which it remains constant. While the reason for such behavior is not obvious, it appears that at low normal stresses the shearing does not occur at the soil-metal interface where the angle of metal friction is operative, but rather in the soil itself. This results in a condition approaching that of the soil-to-soil shearing mode, accounting for the high ratio. Increasing the normal load forced the soil to slide on the metal surface and a constant ratio of peak stresses is achieved.

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The nonlinear shear stress-displacement behavior shown in Figs. 4-9 and 4-10 may be conveniently represented by a rectangular hyperbola, Eq. (2.32), repeated here for convenience:





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where (a) and (b) are parameters whose values depend on the material tested and the normal stresses applied (the symbols in the above equation are defined in Chapter 2). As explained earlier, the above equation can be simplified by expressing  $\Delta_s/\tau$  as a linear function of  $\Delta_s$ , which would enable direct evaluation of the parameters (a) and (b) as depicted in Fig. 2-8. The linear form of Eq. (2.32) is given as Eq. (2.33) and repeated here:

 $\frac{\Delta_{s}}{\tau} = a + b\Delta_{s}$ 

 $\dot{\tau} = \frac{\Delta_{\rm s}}{a + b\Delta_{\rm c}}$ 

where (a) is the intercept and (b) is the slope of the line. Thus by plotting the experimental data in the transformed form, the corresponding values of (a) and (b) are easily obtained. The results of Figs. 4-9 and 4-10 plotted in the transformed form are shown in . Fig. 4-13 for the soil-to-soil mode, and in Fig. 4-14 for the soil-tometal mode. As can be seen, the observed points can be approximated by a straight line for any applied normal load and, therefore, the assumption of a hyperbolic shear stress-displacement relationship throughout the entire displacement range is valid. Table 4-2 lists the values of the intercept (a) and the slope (b) of the straight line in the transformed plot as obtained from Figs. 4-13 and 4-14





| I | ŀ | BL | <b>E</b> 4 | 4-2 |  |
|---|---|----|------------|-----|--|
|   |   |    |            |     |  |

|               | р                 |        | ``     |       |        |
|---------------|-------------------|--------|--------|-------|--------|
| NORMAL LOAD   | 0 16              | 2.0 lb | 5.0 lb | 10 Ib | î15 lb |
| Soil-to-seil  | a = 0.022         | 0.02   | 0.0185 | 0.017 | 0.015  |
| mode          | b = 0.78          | 0.695  | 0.64   | 0.60  | 0.59   |
| Soil-to-Metal | a = 0.025         | -      | 0.024  | 0.023 | 0.02   |
| mode          | b = 0 <u>.</u> 81 |        | 0.77   | 0.75  | 0.72   |

PARAMETERS (a) AND (b) FOR THE CASES OF SOIL-TO-SOIL AND SOIL-TO-METAL SHEAR MODES

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#### SECTION B - EXPERIMENTAL ANALYSIS

#### 4.B.1 APPLICATION OF THE METHOD OF VISIOPLASTICITY TO THE PRESENT PROBLEM

In an interaction study, it is reasoned that the forcing function [i.e. blade or grouser load pattern] and the response function [i.e. soil response behavior] are suitably related and modified through some correlating function. Thus, if one can describe or evaluate the response function characteristics, and if the correlation functions are known, it becomes obvious that the surficial load parameters will be identified and accounted for.

In view of the differences in the deformation processes occurring in the faces of various cutting and traction tools, a solution must be sought in terms of a common parameter which will be relatively unaffected by the geometrical changes in the deformation fields and boundary conditions. The energy fields existing in these deformation processes represent a parameter common to all systems. Moreover, this parameter is a scalar quantity and as such the work output of two dissimilar systems, exhibiting differences in their stress fields and boundary conditions, can be compared without explicit account being taken of these differences.

Experience has shown that the soil response to an imposed loading can be described in terms of the conservation of energy of the system. Results reported by Yong and Webb (1969) indicate that the application of this principle to the rigid wheel-soil system allows ' for good predictions of the useful work output or drawbar-pull. A similar philosophy can be adopted for the tool-soil system. In this case, the statement of the conservation of energy will be of the form:

(4.2)

or Work Input = Deformation + Interfacial energy loss energy loss

F ds =

where 💡

F = applied load or developed force
s = distance travelled.

Unlike the wheel-soil interaction problem, there appears to be very little slip energy [interfacial energy] loss vis-a-vis toolsoil interfacial performance [slip loss in a track system however still exists]. Thus, in terms of analytic modelling, the prime requirement is in regard to a proper description of the deformation energy loss.

In order to describe the dissipation process associated with the plastic deformation of the soil in the face of a cutting or a traction tool, the following field equations are necessary:

- (a) a yield criterion describing the stress state existing in the soil at yield,
- (b) a constitutive relationship between the stress and associated strain in the loaded soil, and

(c) continuity conditions.

The lack of an applicable load-deformation relationship relating the stresses and strains in the soil necessitates the use of empirical relationships in order to calculate the operative stress and energy fields.

Moreover, with the knowledge that clays undergo or sustain irrecoverable deformation under very small applied loads, and according to the definition of yield [i.e. onset of irrecoverable deformation], yielding therefore may be considered to begin virtually at the onset of shear stressing and continues throughout the loading process [Yong and Warkentin (1966)]. For the above two reasons, it may not be unreasonable to assume the material to follow a rigid perfectly-plastic model. This model was adopted by Yong and Webb (1969) in studying the plastic deformation of clay soil under the action of a moving rigid wheel, and by Sylvestre-Williams (1973) in analyzing the energy dissipation in indenter-soil systems. This model demands the following conditions:

(a) the application of a yield criterion,

- (b) the measurement of a deformation field from experiments and calculations of the resultant
  - strain rate fields within the loaded soil, and
- (c) selection of plasticity flow rules consistent with the choice of the yield criterion.

An examination of these requirements suggests that the method of visioplasticity is directly applicable to the present problem. The method, as developed by Yang and Thomsen (1953) and reported by Thomsen et al. (1965), is described in Fig. 4-15. It is apparent that the theoretical development permits the calculation of the plastic work rate, and hence the deformation energy, either directly or by means of a prior determination of the stress distribution within the soil. These two paths are denoted as (1) and (2) in Fig. 4-15. The subsequent theoretical development follows the former path.



In the next several subsections, the various elements shown in Fig. 4-15 will be developed separately.

## 4.B.1.1 Definition of Strain Rate Components

In order to follow the deformation history of a given point, one of two coordinate systems may be used. The first of these, the Lagrangian space, describes the instantaneous particle location in terms of its original position. The second system, known as the Eulerian description, specifies the particle position in terms of its current coordinates. Thus, for a point with initial coordinates  $[a_1, a_2, a_3]$  moving to new coordinates  $[x_1, x_2, x_3]$  in time t, a Lagrangian description would be of the form:

 $x_{i} = \overline{x}_{i}(a_{1}, a_{2}, a_{3}, t)$ 

where  $\overline{x}_i$  are single-valued continuous functions. The Eulerian description would use  $[x_1, x_2, x_3]$  and the time, t, as independent variables [Fung (1965)].

In the present instance, the incremental velocities and strain rates are more readily determined if expressed in terms of the original coordinates of any given point rather than as a function of the instantaneous position of that point. As a result, a Lagrangian space is selected, in preference to an Eulerian space, as a means of following the deformation history of a selected point.

In terms of Cartesian coordinates within this space, the strain rate components are written as:

$$\dot{\varepsilon}_{x} = \frac{\partial u}{\partial x} + \frac{1}{2} \left[ \left( \frac{\partial u}{\partial x} \right)^{2} + \left( \frac{\partial v}{\partial y} \right)^{2} \right]$$
  
$$\dot{\varepsilon}_{y} = \frac{\partial v}{\partial y} + \frac{1}{2} \left[ \left( \frac{\partial u}{\partial x} \right)^{2} + \left( \frac{\partial v}{\partial y} \right)^{2} \right]$$
(4.3)

 $\dot{\varepsilon}_{Xy} = \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) + \frac{1}{2} \left( \frac{\partial u}{\partial x} \cdot \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \cdot \frac{\partial v}{\partial y} \right)$ 

where

- $u = \frac{dx}{dt} =$ instantaneous particle velocity in the X-coordinate direction.
- $v = \frac{dy}{dt}$  = instantaneous particle velocity in the Y-coordinate direction.

It has been noted [Thomsen et al. (1965), Mendelson (1968)] that if the derivatives of the velocity components shown in Eqs. (4.3) are small, the strain rate components may be approximated by Cauchy's infinitesimal Strain rate tensor, given in plane strain as :

$$\dot{\varepsilon}_{y} = \frac{\partial v}{\partial y}$$

$$\dot{\varepsilon}_{xy} = \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)$$

(4.4)

Thomsen et al. (1965) have shown that the possible error of estimate involved in neglecting the quadratic terms of Eqs. (4.3) is of the order of 0.5% per 1% increase of strain rate. The strain rates encountered in the present study are sufficiently small to ensure that the errors involved in the estimation of the strain rate fields are of acceptable magnitude [of the order of 1%]. As a result, Eqs. (4.4)

are used in preference to Eqs. (4.3). By means of these relations the strain rate distributions within the loaded soil mass can be obtained from the experimentally measured deformation patterns.

#### 4.B.1.2 Selection of a Yield Criterion

In the present study, the soil is assumed to form a part of an undrained system, in the light of the rapid load application. As a consequence, the loaded soil, assumed to be saturated, will show no dependence on the mean normal stress [Yong and Warkentin (1966)] and it can further be assumed that the behavior will be entirely cohesive with  $\phi = 0$ , i.e. a total stress analysis is valid.

Invoking these assumptions requires that the material exhibit no permanent volume change effects on load application. The similarity between this type of soil behavior and the behavior of ductile metals has been pointed out by several investigators [Haythornthwaite (1963), Bishop and Henkel (1957) and Abbott (1966)]. Consequently, in view of the widely successful application of the von Mises yield criterion in the field of metal plasticity, it is reasonable to assume that the stress state in the loaded soil, at yield, is adequately described by this condition.

The von Mises theory [also associated with Hencky] assumes that yielding occurs when the distortion energy equals the distortion energy at yield in simple tension and is expressed as:

 $\frac{1}{2} \left[ (\sigma_{1} - \sigma_{2})^{2} + (\sigma_{2} - \sigma_{3})^{2} + (\sigma_{3} - \sigma_{1})^{2} \right] = \sigma_{0}^{2}$ 

(4.5)

where

 $\sigma_{n}$  = yield stress in simple tension.

Owing to the difficulty of conducting simple tension tests on soils,  $\sigma_0$  has generally been defined as the yield stress in composition, in soil mechanics [Webb (1969)]. Equation (4.5) may then be rewritten as:

$$\frac{1}{6} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] = \frac{1}{3} \sigma_0^2$$
(4.6)

Equation (4.6) can be also written as:

J

$$= \frac{1}{3} \sigma_{0}^{2}$$
  
= k<sup>2</sup> (4.7)

where  $J_2$  is the second invariant of the stress deviator tensor and the scalar constant k may be identified as the yield stress in pure shear [Mendelson (1968)].

The magnitudes of the actual volume changes encountered in the. test programme are presented in Section [4.B.3]. It will then be apparent that they are small enough so as not to invalidate the assumptions.

# 4.B.1.3 Selection of Associated Plasticity Relations

The Lévy-Mises equations of plasticity have been shown to be valid for ductile materials where the elastic component of the strain increment vector is of negligible magnitude [1111 (1950) and Mendelson (1968)]. The equations are given as:

where  $d\lambda$  is a non-negative scalar constant which may vary throughout the loading history and which relates the strain increment vector to the gradient of the loading surface defined by the yield function:

$$f(J_2, J_3) = 0$$
 (4.9)

(4.8)

(4.10)

Similar equations may be derived from the relationship between the strain rate vector and the instantaneous value of the stress deviation, viz:

$$\dot{\epsilon}_{ij} = \dot{\lambda} \dot{\sigma}_{ij}$$

In unabridged notation, under conditions of plane strain, the Lévy-Mises equations are written as:

 $\dot{\epsilon}_{x} = \dot{\lambda} \sigma_{y}^{\dagger}$ 

where

$$f_{xy} = 2 \dot{\varepsilon}_{xy} = (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})$$

XY

represents the total shear distortion experienced by any point within the deforming sample.

It can be readily shown [Mendelson (1968)] that the compliance  $\dot{\lambda}$  is given by:  $\dot{\lambda} = \frac{3}{2} \cdot \frac{\dot{\xi}}{2}$ (4.11)

where  $\dot{\epsilon}$  and  $\bar{\sigma}$  are Hencky effective stress and strain rate parameters given as:  $\overline{\sigma} = \frac{1}{\sqrt{2}} \left[ \left( \sigma_{x} - \sigma_{y} \right)^{2} + \left( \sigma_{y} - \sigma_{z} \right)^{2} + \left( \sigma_{z} - \sigma_{x} \right)^{2} + 6 \left( \tau_{xy}^{2} - \sigma_{y}^{2} \right)^{2} \right]$ +  $\tau_{xz}^{2} + \tau_{yz}^{2}$ ]<sup>2</sup> = /3J  $\ddot{\varepsilon} = \frac{\sqrt{2}}{3} \left[ (\dot{\varepsilon}_{\chi} - \dot{\varepsilon}_{\chi})^2 + (\dot{\varepsilon}_{\chi} - \dot{\varepsilon}_{\chi})^2 + (\dot{\varepsilon}_{\chi} - \dot{\varepsilon}_{\chi})^2 + 6(\dot{\varepsilon}_{\chi\chi}^2)^2 \right]$  $+ \varepsilon_{yz}^2 + \varepsilon_{zx}^2)]^{\frac{1}{2}}$  $=\sqrt{\frac{4}{3}I_2}$ 

 $J_2$  and  $I_2$  are the second invariant of the stress deviator tensor and the second invariant of the strain rate tensor, respectively. Combining Eqs. (4.11), (4.10) and (4.7) yields:

(4.12)

$$\dot{\varepsilon}_{x} = \frac{\sqrt{T_{2}}}{K} \sigma'_{x}$$
$$\dot{\varepsilon}_{y} = \frac{\sqrt{T_{2}}}{K} \sigma'_{y}$$
$$\dot{\gamma}_{xy} = \frac{2\sqrt{T_{2}}}{K} \tau_{xy}$$

If reference is made to Fig. 4-15, it can be seen that the theoretical means of specifying the strain rate distributions have now been provided. In addition, a valid yield function, as well as the

plasticity equations associated with this yield function, has now been specified. With these elements, it is now possible to develop the equations necessary for the calculation of the plastic work rate and hence of the deformation energy.

#### 4.B.1.4 Plastic Work Rate Determination

The rate at which stresses do work in connection with the plastic distortion of an incompressible material is given as:

$$\dot{\mathbf{w}} = \sigma'_{\mathbf{ij}} \dot{\mathbf{e}}_{\mathbf{ij}}$$
 (4.13)

The rate of total energy dissipation with the soil is then:

$$\dot{D} = \int_{V} \dot{W} \, dV$$

$$= b \int_{X_1}^{X_2} \int_{y_1}^{y_2} (\sigma_x \dot{\varepsilon}_x + \sigma_y \dot{\varepsilon}_y + \tau_{xy} \dot{\gamma}_{xy}) \, dx \, dy \qquad (4.14)$$

in plane strain, where b is the width of the sample under test.

Substituting Eqs. (4.12) into Eqs. (4.14) yields:

 $\mathbf{\dot{H}} = [d_{\chi}^{2} \mathcal{A}_{2} + d_{y}^{2} \mathcal{A}_{2} + 2\tau_{\chi y}^{2} \mathcal{A}_{2}] \frac{1}{K}$ 

$$= \frac{\sqrt{I_2}}{k} \left[ \sigma_{\chi}^2 + \sigma_{y}^2 + 2\tau_{\chi y}^2 \right]$$

(4.15)

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The second invariant of the stress deviator tensor  $J_2$  can be written for the case of plane strain as:

$$J_{z} = \frac{1}{2}(\sigma_{x}^{'2} + \sigma_{y}^{'2}) + \tau_{xy}^{2}$$

Equation (4.15) can now be written as:

$$W = 2k \sqrt{T_a}$$

and by integration in time, the total work done, and hence the energy dissipated in accomplishing plastic deformation, is found to be:

$$D = 2b \int_{1}^{t_2} \int_{1}^{x_2} \int_{1}^{y_2} k \sqrt{I_2} dx dy dt$$
(4.17)

Equation (4.17) is sufficient to calculate the deformation energy component of the total energy in the tool-soil system, provided that the deformation fields within the loaded soil sample are experimentally specified.

## 4.B.2. DATA REDUCTION TECHNIQUE

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Accepting that the proposed visioplasticity solution is a valid one, it becomes necessary to obtain data in an expedient and acturate manner in order to satisfy the theoretical requirements. The system of data retrieval used to reduce the experimental results of the soil cutting and traction tests required the manual plotting of the sequential positions of a number of grid nodes from projected 35 mm negative slides. Figure 4 -16 shows particle path trajectories [translation patterns] for a R.A.P.G. - soil interaction process. The coordinate pairs corresponding to each of the plotted points were then obtained with the aid of an x-y recorder and a process control computer. The resulting data were input to a computer routine, listed in Appendix E as program "FIT". With this routine, the corrected particle

(4.16)



coordinates, the incremental particle velocities, the instantaneous strain rate components and the rate of plastic energy dissipation were. calculated. A schematic of the procedure used in the calculation is shown in Fig. 4-17.

An examination of Fig. 4-17 will show that the developed procedure provides a rapid and expedient means of obtaining data from the measured experimental results. A more comprehensive account of the data reduction technique is provided in Appendix B.

#### 4.B.3. NO VOLUME CHANGE ASSUMPTION

The assumptions and constraints inherent in the visioplasticity technique have been discussed in Section 4.B.1. It was noted that an essential requirement of the theory is that the soil exhibits no permanent volume change characteristics when loaded. As a means of verifying the validity of this assumption, the actual volume changes occurring during the tests were obtained from the experimentally measured tool-soil deformation fields. In order to obtain the required data, the principle of conservation of mass was applied to elemental areas within the deforming field. These elements were each defined by four adjacent node points of the inscribed grid and were followed throughout the deformation history of the four relevant points. The method is shown schematically in Fig. 4-18.

Application of the principle of conservation of mass to these areas results in:

 $\rho_1 A_1 = \rho_2 A_2 = \rho_3 A_3$ 

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(4.18)





Equation (4.18) can also be written as:

$$\frac{\rho_{i}}{\rho_{j}} = \frac{A_{j}}{A_{i}}$$

where

 $P_i$  = mass density or specific mass of the ith elemental area. A<sub>i</sub> = area of the ith element.

(4.19)

Machine computation of the areas, carried out by program "FIT" shown in Appendix E, allowed for a comparison of the mass densities of the deforming soil through successive grid positions. The results of these computations are shown in Table 4-3 for the various kaolinite clay tests performed:

The permanent volume distortions reported are in terms of the average value over the entire deforming field, throughout the deformation Evidently, the average values do not necessarily reflect the process. magnitude of the peak local values since positive and negative values may tend to compensate each other. In Fig. 4-19, the volume changes computed indicate local volume changes up to five per cent. In the final analysis, however, the overall influence of the volume change on the exhibited behavior of the tool-soil system is a function of the entire deforming field and, consequently, the average values reported in Table 4-3 should be representative of this influence. In view of this, the small values reported here '- of the order of two per cent imply that the constant volume assumption invoked in the theoretical development is a justifiable one.

# TABLE 4-3

VOLUME CHANGES

|   | , I               | Natural (Kaolinite) Clay | ٨                     |
|---|-------------------|--------------------------|-----------------------|
| 9 | <u>Tool</u>       | Test No.                 | Average Volume Change |
|   | 10° Blade         | 27                       | - 0 <b>.57</b>        |
|   | ,<br>,            | 30                       | . 0.45                |
|   | 20° Blade         | 28                       | 0.89                  |
| • |                   | 35                       | 1.05                  |
| ŀ | 40° Blade         | 26                       | - 0.69                |
|   |                   | - 36                     | 1.25                  |
|   | 50° Blade         | 29                       | 0.78                  |
|   |                   | 31                       | 0.90                  |
|   | Plate Grouser     | 32                       | 2.01                  |
|   | (K.A.P.G.)        | 37                       | - 0.99                |
|   | S.E.W. Grouser    | 33                       | 0.77                  |
| • | <b>x</b>          | 38                       | 0.91                  |
|   | C.E.M. Grouser    | <b>34</b>                | 1.52                  |
|   | * <b>rype (2)</b> | 39                       | • <b>- 0,71</b>       |

Notes:

(1) Positive volume changes denote dilation.

(2) Negative volume changes denote compression.

(3) Average values represent the algebraic average over four images.

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4.B.4. DETERMINATION OF THE LIMITING SHEAR STRESSES

The strength parameter, k, is defined in Eq. (4.7), viz:

 $J_{2} = k^{2}$ 

Here  $J_2$  is the second invariant of the stress deviator tensor and the above equation can be written in detail as:

$$J_{2} = \frac{1}{6} [(\sigma_{1} - \sigma_{2})^{2} + (\sigma_{2} - \sigma_{3})^{2} + (\sigma_{3} - \sigma_{1})^{2}] = k^{2}$$

For the case of plane strain deformation, with no permanent volume change occurring, the intermediate principal stress is given by [Mendelson (1968)]:

$$\sigma_{2^{1/2}} = \frac{\sigma_1 + \sigma_3}{2}$$

Use of these two equations, together with the experimentally measured stress-strain curves, permits the calculation of k. An axial strain of 20% was chosen to define failure since no definite peaks were evidenced in the measured stress-strain curves, Figs. 4-7 and 4-8.

#### 4.B.5. PREDICTION OF THE DEFORMATION ENERGY BY VISIOPLASTICITY

The influence of the tool geometry on the Energy required for motion is shown in Fig. 4-20 for the cutting blades and in Figs. 4-21 and 4.22 for the R.A.P.G. and the wedge grousers, respectively. The curves represented by solid lines indicate measured values obtained from the integration of the areas beneath the experimentally measured force-displacement curves. In addition, the theoretically calculated values of the dissipation energy are shown for comparative purposes by

broken lines. These values were obtained by means of the applicationof Eq. (4.17) together with the appropriate values of k obtained from the results of the plane-strain triaxial tests as outlined in the previous section. Comparisons of these results with those obtained from the measured force-displacement curves are also shown in Table 4-4, for cutting tests, and in Table 4-5 for traction tests. The comparisons are made in terms of measured and calculated values, referring to those results obtained from experimental curves and by means of Eq. (4.17), respectively, and are reported at 0.25 inch intervals over a displacement of 1.0 inch. The deviations between the two sets of values, expressed as a percentage of the applicable experimental values, are also shown in these Tables.

Examination of these data indicates that the analytical solution, as expressed by Eq. (4.17), provides reasonable estimate of the energy dissipated in the soil for tool displacement in excess of 0.25 inch. For displacements in excess of 0.25 inch, the average error in energy prediction is of the order of ten per cent, while the maximum error is of the order of 20 per cent. However, at 0.25 inch displacement the error of estimate is significant, with an average of 36.5 per cent, while the maximum error is some 75 per cent. These differences can be attributed to errors due to the assumptions made in the determination of the limiting shear stresses. Since no definite peaks were evidenced in ... the measured stress-strain curves, Figs. 4-7 and 4-8, an axial strain of 20 per cent was chosen to define failure. The stress values corresponding to the failure strain were used to calculate the value of the von Mises yield function, k. While this procedure implies a rigid plastic material, the stress-strain curves, Figs. 4-7 and 4-8, show a







|       |                                    |                                   |             | 4           | COMPARISON<br>DEFOR | OF MEASUR           | RED AND CALCU | ILATED VALU | ies of     | \$         | ł        |            |                |  |  |
|-------|------------------------------------|-----------------------------------|-------------|-------------|---------------------|---------------------|---------------|-------------|------------|------------|----------|------------|----------------|--|--|
| TEST  | ANGLE OF<br>BLADE WITH<br>VERTICAL | DEFORMATION ENERGY IN.LB/IN.WIDTH |             |             |                     |                     |               |             |            |            |          |            |                |  |  |
| 1900  |                                    | Measured                          | Calculated  | Difference  | Measured            | Calculate           | Difference    | Measured    | Calculated | Difference | Measured | Calculated | Difference     |  |  |
|       |                                    | Tool Dis                          | placement:d | =0.25 ,1nch | , d                 | = 0.50 fr           | ich           | 6           | = 0.75 in  | ich `      |          | d = 1.0 in | ch             |  |  |
| Artif | fcial Clay T                       | ests ~                            | •           |             | •                   | -                   |               |             |            |            | ŀ        |            |                |  |  |
| 21    | 10*                                | 1.47                              | 1.90        | +29.2       | 4.05                | 4.45                | + 9.87        | 7.03        | 7.90       | +12.3      | 10.24    | 11.32      | +10.5          |  |  |
| 12    | 20*                                | 1.42                              | 1.80        | +26.7       | 3.81                | 4.1                 | + 7.61        | 6.28        | 6.68       | + 6.36     | 9.14     | 9,816      | + 7.39         |  |  |
| 23    | - 40°                              | 1.10                              | 1.40        | +27.2       | 2.91                | 3.2                 | + 9.95        | 5.02        | 5,48       | + 9,16     | 7.36     | 7.99       | + 8.55         |  |  |
| ° 22  | 50°                                | 1.05                              | 1.30        | +23.8       | 2.6                 | 2.9                 | +11.53        | 4.3         | 4.85       | +12.7      | 6.16     | 6.899      | + 7.39         |  |  |
| Natur | al (Kaolinit                       | e) Clay                           |             | ,           |                     | · _                 |               |             | -          |            | -        |            |                |  |  |
| 27    | 10•                                | 1.32                              | 1.95        | +47.7       | 3.92                | 4.60                | -+17.3        | 7.65        | 8.35       | + 9.10     | 12.05    | 12.62      | ' <b>+ 4</b> 7 |  |  |
| 30    | 10° -                              | 1.2                               | 2.05        | +70.8       | 3.86                | 4.56                | +18.1         | 7.40        | 8.25       | +11.48     | 11.71    | 12.50      | + 6.7          |  |  |
| - 28  | 20°                                | 1.01                              | , 1.72      | +70.2       | 3.194               | <sup>*</sup> 2.83 ) | -11.3         | 6.0         | 6.93       | +15.5      | 9.42     | 10.5       | +11.4          |  |  |
| 35    | 20°                                | 1.15                              | 1.60        | +39.1       | 3.33                | 3.61                | + 8.4         | 6.31        | 7.00       | +10.9      | 9.55     | 10.7       | +11.4          |  |  |
| 26    | 40*                                | 1.061                             | 1.39        | +31.0       | 2.90                | 3.10                | + 6.9         | 5.12        | 5,61       | + 9.57     | 8.0      | 8.5        | + 6.25         |  |  |
| 36    | 40°                                | 0.97                              | 1.20        | +23.71      | 2.96                | 3.27                | +10.4         | 5.00        | 5.60       | +12.0      | 8.3      | 8.7        | + 4.81         |  |  |
| 29    | 50°                                | 0.92                              | 1.23        | +33.6       | 2.436               | 2.737               | +12.3         | 4.3         | 4.95       | +15.1      | 6.57     | 7.50       | +14.1          |  |  |
| 31    | 50° .                              | 0.88                              | 1.17        | +32,9       | 2.65                | 2.91                | + 9.81        | 4.1         | 4.65       | +13.4      | 6.90     | 7,55       | + 9.42         |  |  |
|       |                                    | L                                 |             |             |                     |                     | 1             | 1           |            |            |          |            |                |  |  |

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TABLE 4-4

15 A.E.

 Measured values denote values obtained from the experimental force-displacement curves.
 Calculated values denote theoretically calculated values obtained from Equation (4.17).
 Difference expressed in percentage of measured values. Notes:

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|                                                | •                  |                          | بد        |              | UEFURMAL | IUN ENERGY     | FUR TRACTION | TESTS    |             |                 |          | ,             | ſ          |
|------------------------------------------------|--------------------|--------------------------|-----------|--------------|----------|----------------|--------------|----------|-------------|-----------------|----------|---------------|------------|
| TEST GROUSER DEFORMATION ENERGY IN.LB/IN.WIDTH |                    |                          |           |              |          |                |              |          |             |                 |          |               |            |
|                                                | •<br>•             | Measured                 | Calculate | d Difference | Measured | Calculate      | d Difference | Measured | Calculated  | Difference<br>% | Measured | Calculated    | Difference |
| -                                              |                    | Tool Dis                 | lacement: | d=0.25 Inch  |          | d=0.50 inc     | :h           |          | d=0,75 inch |                 |          | d=1.0 inch    |            |
| Artif                                          | icial Clay Tests   | $\langle \gamma \rangle$ |           |              |          |                | •            |          |             |                 |          | <b>~~</b>     |            |
| 18                                             | R.A.P.G.h/1=0.83   | 1.7 \                    | 2.11      | +24.1        | 4.42     | 4.67           | +10.6        | 7.21     | 7.79        | + 8.04          | 10.03    | 11.13         | +10.9      |
| 19                                             | R.A.P.G.h/1=0.5    | 1.29                     | 1.56      | +20.9        | 3.17     | 3.12           | - 1.5        | 5.18     | 5.45        | + 5.2           | 7.29     | 7,79          | + 6.85     |
| 40                                             | C.E.W.type(1)      | . 0. 94                  | 1.33      | +41.4        | 2.99     | 3.14           | + 5.0        | 5.5      | 5.84        | + 6.18          | - 8.2    | 8,99          | + 9.6      |
| 14.                                            | C.E.W.type(2)      | 0.69                     | 1.02      | +47.8        | 2.33     | 2.56           | + 9.87       | 4.48     | 4.76        | + 6.25          | 6.85     | 7.33          | + 7.0      |
| 16                                             | S.E.W.             | 0.83                     | 1.15      | +38.5        | 2.69     | <b>, 2.8</b> 0 | + 4.0        | 5.02     | 5.25        | + 4.58          | 7.55     | 8.02          | + 6.22     |
| Natur                                          | al (Kaolinite) Cla | 1<br>Y.                  |           |              |          |                | 0            |          | ,           |                 |          |               |            |
| 34                                             | R.A.P.G.h/1=0.88   | 1.56                     | 1-1.90    | ( +22.06     | 4.26     | 4.445          | + 4.34       | 7.343    | 8.255       | +12.41          | 11.14    | 12.70 -       | +14.00     |
| 39                                             | R.A.P.G.h/1=0.5    | 1.33                     | 1.44      | + 8.27       | 3.51     | 3.36           | - 4.27       | 6.015    | 6.24        | + 3.70          | 8.85     | 9.60          | + 8,47     |
| 42                                             | C.E.W.type(1)      | 1.22                     | 1.74      | +42.6        | 3.75     | 4.07           | + 8.53       | 6.79     | 7.56        | +11.31          | 10.57    | .11.63        | +10.0      |
| 43                                             | C.E.W.type(1)      | 1.31                     | 1.8       | +37.4        | 3.65     | 4.15           | +13\.6       | 6.5      | 7.32        | +12.6           | 10.7     | 11.33         | + 5.60     |
| <b>33</b> <sup>1</sup>                         | C.E.W.type(2)      | 0.821                    | 1 44      | +75.3        | 2.76     | 3.36           | +21.7        | 5.278    | 5.24        | +18.22          | 8.57     | 9.6           | +12.0      |
| 38                                             | C.E.W.type(2)      | 0.95                     | 1.34*     | +41.0        | 3.1      | 3.4            | + 9.6        | 5.91     | 6.35        | + 7.45          | 8.70     | 9.4           | + 8.04     |
| 32                                             | S.E.W.             | 1.31                     | 1.70      | +29.8        | 3.79     | 3.97           | + 4.74       | 6.72     | 7.38        | + 9.82          | 10.29    | <b>'11.35</b> | +10.3      |
| 37                                             | S.E.W.             | 1.42                     | 1.79      | +26.0        | 3.4      | 3.9            | +14.7        | 6.51     | 7.12 🎢      | + 9.37-         | 10.6     | 11.71         | +10.4 .    |

COMPARISON OF MEASURED AND CALCULATED VALUES OF PERMITIAN ENGAN FOR TRADES ......

TABLE 4-5

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 Measured values denote values obtained from the experimental force-displacement curves.
 Calculated values denote theoretically calculated values obtained from Equaltion (4.17).
 Difference expressed in percentage of measured values. Notes:

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nonlinear behavior which could be idealized by a work-hardening material. With the adoption of the stress values corresponding to 20 per cent strain, an overprediction of the dissipated energy would be expected. This explains the higher values obtained from the analytical solution in almost all the calculations performed.

Finally, Fig. 4-23 shows the distribution of the deformation energy as a function of depth for the various blade inclinations adopted in the experimental investigation. These distributions are instantaneous quantities in that they represent the deformation energy distributions at the specified instantaneous blade positions. In Chapters 5 and 6, the soil deformation energy results obtained by the method of visioplasticity as outlined in this Section, are compared to the work 4 input computed from the integration of the areas under the experimentally measured load-displacement curves as well as the work output as determined from the finite element model proposed in this study.



#### CHAPTER 5

# FINITE ELEMENT ANALYSIS OF SOIL CUTTING PROBLEM

Following from Fig. 4-1, this Chapter provides the development and presentation of the results of the finite element model used for solution of the stated problem, and a discussion of these results. In addition, comparisons between the finite element results of the soil cutting problem and the experimental results previously reported in Further appreciation of the solution technique Chapter 4 will be made. is achieved in Chapter 7 through a parametric study of the familiar case of two-dimensional soil response encountered in long retaining walls, Recognizing that the retaining wall when yielding in a passive sense. problem bears a close parallel to wide cutting blades moving in soils, it is believed that by comparing the results obtained from the analysis. with the classical earth pressure theory, a better insight into the rationality of the solution technique will be accomplished. In the second part of Chapter 7, soil cutting and traction analytical and experimental results reported in this thesis are compared with the results computed from existing theories.

### 5.1 MESHES, AND BOUNDARIES

The cutting tests described in the previous Chapters were modelled by the finite element method for solution in the digital computer [Chapter 2]. The boundary conditions for the problem are

easily fixed since the laboratory tests were done in a box of known dimensions.

The meshes adopted for the 10° and 50° inclined blade problems are shown in Figs. 5-1 and 5-2. In the idealization of the 10° blade problems 266 elements and 176 nodal points were used, while 199 elements and 136 nodal points were used for modelling the 50° blade problem. The mesh patterns were so arranged that smaller elements were employed near the blades and larger elements in regions away from them.

As mentioned earlier, constant strain triangle elements were employed in these models to represent the soil mass with joint [interface] elements inserted between the soil and the blades to simulate the interface characteristics. In addition j joint [cutting] elements were placed on the plane on which cutting progresses, as shown in Fig. 2-6.

Since the sides and the bottom of the box containing the soil were greased, it is reasonable to assume that these boundaries are smooth. In the finite element idealization, the boundaries were placed on rollers so that the horizontal movement was restrained on the sides and the vertical movement on the bottom boundary. The load setup in the laboratory was so designed as to insure uniform blade movement in the soil. In the analysis, the blades were considered rigid. Uniform horizontal rigid displacements were applied at all nodal points. The displacements were increased in 10 equal increments of 0.10 inch for a total displacement of 1.0 inch. The self weight of the soil was considered in all the analyses made.




## 5.2 DISPLACEMENT AND VELOCITY PATTERNS

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The displacement fields in the soil mass are computed from the magnitudes and directions of the vertical and horizontal displacements at the nodal points. Figures 5-3 and 5-4 show the displacement fields for the 10° and 50° inclined blades, respectively, at a displacement of 0.50 inch.

The displacement patterns indicate the existence of two zones. In the zone above the cutting plane, the soil undergoes large deformations resulting from the blade motion. In this region, the soil is moved forward and upward relative to the original blade position. These motions indicate that shear distortions occurred throughout the On the other hand, the region below the cutting plane is shown zone. to experience very little deformation. The discontinuity in the deformation field is shown to occur on the cutting plane, discontinuity that results from the relative displacements between the top and the bottom surfaces of the cutting [joint] elements. It must be noted, however, that according to the assumed model, the soil is displaced by continuous deformation rather than by sliding along a series of specific failure surfaces. Furthermore, it is seen that such a model allows for a build up of a surcharge as the blades progress in the soil.

The deformation patterns for the 10° and 50° inclined blades are generally the same. However, the zone of shearing deformation adjacent to the blade is found to be larger for the 10° inclined blade by approximately the volume of the soil enclosed within the projection of the blade face.



151 DISPLACEMENT FIELD FOR THE 50° INCLINED BLADE-SOIL SYSTEM (BLADE DISPLACEMENT = 0.50 fnch) 14, 1 Scale: 1 inch = 0.65 inch.\ / / FIGURE 5-4 Direction of Notion

Regarding the interface displacements, it is shown in Figs. 5-3 and 5-4 that a certain degree of slip occurs between the blade surface and the adjacent soil. At 0.50 inch of blade displacement, the interface element nodal points attached to the triangular elements move upward relative to the nodal points fixed to the blade surface. In the case of the 10° blade deformation field, the magnitude of the soil slip is smaller near the blade tip and increases along the surface of the blade, reaching a maximum at the intersection of the \_soil surface with the blade. On the other hand, the magnitude of the soil slip along the 50° blade surface appears to be more uniform. Such difference in the slip behavior is attributed to the difference in the tangential stress distributions developed in the interface elements along both the 10° and 50° inclined blades. The contact stresses will be presented in a later section with a discussion on the observed differences.

Finally, the plots of the horizontal and vertical components of the nodal point velocities are shown in Fig. 5-5 for the 10° inclined blade and in Fig. 5-6 for the 50° inclined blade-soil system. These iso-velocity contours serve to show the effect of the insertion of the cutting elements on the development of discontinuities in the velocity fields. In Section [5.6.2] the displacement fields obtained by means of the finite element model proposed will be compared to those obtained from the experimental analysis described in Chapter 4, in order to establish the similarity between the corresponding fields.

## 5.3 STRAIN RATE DIRECTIONS

The directions of the principal strain rates are obtained on





FIGURE 5-6 VELOCITY FIELDS FOR THE 50° INCLINED BLADE-SOIL SYSTEM DURING THE FIRST DISPLACEMENT INCREMENT OF 0.10 INCH

[CONTOUR VALUES ARE IN INCHES/MINUTE]

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the basis of the strain rate components, calculated by dividing the incremental strain components  $\delta \varepsilon_x$ ,  $\delta \varepsilon_y$  and  $\delta \varepsilon_x$  by the time increment  $\delta t$ , or

 $\dot{\epsilon}_{x} = \frac{\delta \epsilon_{x}}{\delta t}$   $\dot{\epsilon}_{y} = \frac{\delta \epsilon_{y}}{\delta t}$  and  $\dot{\epsilon}_{xy} = \frac{\delta \epsilon_{xy}}{\delta t}$  (5.1)

However, due to the approximations involved in the formulation of the constant strain triangle elements employed in this study, it is logical to use some average value of strain [or stress] as representative for the element. The most common method of averaging is to use the strain at the centroid of the element, since the strains [or stresses] are constant over the element. For better averaging, an alternative procedure is admissible. Instead of averaging the strain [or stress] over the element to obtain a centroidal value, the strain at a particular node may be taken as the average value at that node among all the adjacent elements. This procedure has the double advantage of:

1] avoiding unacceptable discontinuities in the stress, velocity and strain rate fields: most elements currently in use exhibit discontinuities in stresses from one element to another, although the stresses in two adjacent elements often straddle the true stress curve [Zienkiewicz (1971)], and

2] simplifying data interpretations and presentations, as

it is easier to visualize the results at the nodal points rather than at the elements' centroids.

In the present study all the stresses, strains, strain rates and velocities are averaged at the nodal points. The averaging procedure

is carried out by subroutine "AVER" in program "MAIN -2", in Appendix E.

At every nodal point the strain rate components are calculated by Eq. (5.1), and the directions of the principal strain rate components as well as those of the maximum shear strain rates are determined as shown in Fig. 5-7. The network of the principal strain rate and the maximum shear strain rate directions are shown in Figs. 5-8 and 5-9 for the  $10^{\circ}$  and  $50^{\circ}$  blade problems, respectively.

Since the soil undergoing deformation in front of a moving blade constitutes essentially a closed system as far as water content is concerned, the loading being characterized by its short duration, it is relevant, as discussed previously, to base the analysis on a total stress approach with the friction parameter  $\phi$  taken as zero. This reasoning indicates that the similarity in mechanical behavior of clay in front of a moving tool and ductile metals has a rational basis. According to these considerations, Saint Venant's postulates already accepted to be valid for ductile metals can also be accepted for clays subjected to short duration loading conditions. The postulate states that: "In a plastic material, the principle directions of strain rate coincide with the principal directions of stress". The directions obtained in Figs. 5-8 and 5-9 can therefore be assumed to coincide with those of the principal stresses and maximum shear stresses.

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.4 STRESS ANALYSIS

The distributions of the horizontal, vertical and shear soil







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stresses in front of a moving cútting blade are presented in this Section. The stress contours for the 10° and 50° inclined blade problems are plotted at displacements of 0.1 and 0.50 inch. The stress contours for the 10° blade problem are shown in Figs. 5-10 and 5-11. For the 50° blade case, the contours are plotted in Figs. 5-12 and 5-13. The 0.1 inch blade displacement is typical of stress distributions in the elastic range, while the 0.5 inch plots are considered to indicate the distributions in the plastic range in the vicinity of the ultimate stresses.

The contours shown in these Figures seem to maintain the same general shapes with increasing blade displacement. Furthermore, the results clearly indicate the discontinuity in the stress distribution within the soil mass due to the effect of the cutting [joint] elements inserted at the level of the blades' tips. It must be kept in mind, however, that these elements were inserted, in the first place, to produce discontinuities in the stress and deformation fields similar to those occuring in the physical situation. Correlations between the analytical and experimental results are the final justification that the assumed analytical model with its assumed discontinuities can be employed with reasonable accuracy to predict the physical response. Correlations between analytical results and the experimental results obtained from the model tests performed are attempted in Section 5.6.

Examination of Figs. 5-10 through 5-13 leads to the following observations:

1] Stress concentrations at the tip of the blades are

indicated in all cases. Horizontal,  $\sigma_x$ , vertical,  $\sigma_y$ ,



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and shear,  $T_{Xy}$ , stress values are highest in the vicinity of the blade tip. Such concentrations are also characterized by a singular behavior where a change in the magnitudes and, in some instances, in the directions of the stresses above and below the blade tip-point result.

Comparison of the patterns of the horizontal stress,  $\sigma_{\chi}$  distribution in front of the 10° and 50° inclined blades shows no significant differences. However, while the stress values in the vicinity of the blades are similar in the two cases, it may be noted that, distant from the blade, the soil is subjected to higher horizontal stresses in the case of the 10° blade than in the case of the 50° inclined blade.

The effect of the plane of cutting elements on the horizontal stress distribution is to divide the stress field into two differently stressed regions:

(a) The upper field, where the compressive stresses
are high near the blade surface and decrease
with distance from that surface;

 (b) The lower field, where lower stresses, partly tensile and partly compressive, are developed.
The compressive stresses increase with distance from the blades, while a zone of tensile horizontal stresses develops in the soil below the blade tip in the two cases studied.

2]

3]

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5]

The vertical normal stress,  $\sigma_y$ , distributions, show the existence of a zero vertical stress contour in the upper part of the soil mass in both the 10° and 50° blade distributions. With the blade progressing in the soil, this contour shifts downward, resulting in larger zones of vertical tensile stresses. This behavior is attributed to the restraining influence of the fixed vertical end boundary which induces action that results in larger zones of tensile stresses. As in the case of the horizontal stress field, the lower part of the soil mass [below the cutting plane] experiences a change from tensile stress below the blade tip to compressive stress away from the blade.

The shear stress contours, indicate a zone in front of the blade tip experiencing high shear stresses. The shear stresses in this zone are positive, thus the shearing is a clockwise shearing action as would be These zones could be termed the "active" expected. shear zones as the shear stresses@keep on increasing Above the "active" shear zones, with blade movement. there exists zero shear stress contours with zones of 🤟 negative shear stresses, i.e., shearing is anticlockwise above the zero contour. These zones are found to expand with larger negative values in the 0.5 inch plots, indicating an upward action that explains the formation of the surcharge.

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Figures 5-14 through 5-19 demonstrate the behavior of the joint elements placed on the cutting plane at 0.1, 0.3, 0.6 and 1.0 inch of blade displacement for the 10° and 50° inclined blade models, respectively. Figures 5-15 and 5-18 show how the average relative shear displacements at the centroids of the cutting elements vary as a function of the horizontal distance from the blade leading edges. The variation of the tangential stress,  $\tau$ , as obtained from the hyperbolic Eq. (2.32) with the coefficients (a) and (b) obtained from Fig. 4-13, is plotted in Figs. 5-14 and 5-17. The variation of the tangential stiffness values,  $k_s$ , is presented in Figs. 5-16 and 9-19.

As indicated in Chapter 2, the relationship between shear stress and relative displacement on the interface between blade and soil is nonlinear and dependent upon the developed normal stress. In other words, the constitutive relationship for the yield point in soil shear at the blade-soil interface is assumed to take the form  $\tau_s(P, \Delta_s)$ . P is the normal pressure acting on the interface and  $\Delta_s$  is the relative displacement between the soil and the blade surface. The tangential stress,  $\tau$ , can then be defined in the following manner:

This follows because the shear stress of a point in the thin surface layer of soil adjacent to the blade surface is less than on a slipping surface at this point. The equality holds if the surface of contact is a slip surface, that is, the maximum value of the tangential stress is given by the relation:

 $|\tau| \leq \pi_{s}(P, \Delta_{s})$ 

 $\tau = \tau_{e}(P, \Delta_{e})$ 

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(5.3)

(5.2)













The results demonstrating the behavior of the interface elements in the finite element analysis of soil cutting are shown in Figs. 5-20 and 5-21. They show the shear displacements and the stresses in the interface elements [inserted between the rigid blades and the clay soil] at blade displacements of 0.1, 0.3, 0.6 and 1.0 inch, respectively. As mentioned previously, the interface elements were assigned properties determined from the direct shear test results of the soil-metal mode, shown in Fig. 4-10. The hyperbolic formulation [Section 7.4.3] was again included to allow the stiffness of these elements to simulate the interface behavior.

It is observed from Figs. 5-20 and 5-21 that the distributions of the tangential relative displacements and stresses along the interface elements are markedly different in the two cases. In both cases the soil moved up the blade surface. Whereas in the case of the 10° inclined blade the tangential displacements and pressures are minimum near the blade tip and increase with distance from the blade tip, the distributions of the tangential displacements and stresses along the 50° inclined interface are shown to be very nearly uniform. In other words, the soil in the case of the 50° inclined blade moved uniformly upward along the blade surface, while in the case of the 10° blade, which penetrated deeper in the soil, the soil near the surface moved upward much more than the soil near the blade tip, creating a situation of variable slip rate along the surface of the blade. These results configm the observations made by Kostritsyn (1956) who noted that near the surface, sold would rupture or move upward, but at deeper depths the movement was parallel to the direction of travel of the cutter.





As mentioned earlier, failure zones are located by examining the maximum shear stress induced in each element after each increment. If this stress is equal to or greater than the shear strength of the soil at that location, the modulus value, E, for the element is reduced to a small magnitude indicating failure. Thus, the extent of the failed zone is established on the basis of these elements in which the induced stresses equalled or exceeded the limiting stresses at 20% strain obtained from the stress-strain curves presented in Fig. 4-7.

It must be emphasized, however, that this presentation is not an indication of the establishment of failure or separation surfaces since the criterion of exceeding the shearing strength of the soil is obtained from the plane strain test results where the strength of the soil is taken as the maximum value obtained at 20% strain. In the strength tests, the samples did not fail along distinct planes but exhibited bulging deformation. The failed elements should, therefore, be considered as the elements where failure planes would develop if the soil exhibited failure along shear planes rather than flow.

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The development of the failure zones for the 10° and 50° inclined blade idealizations are shown in Figs. 5-22 and 5-23, respectively. The elements failure started in increment No. 7 [0.7 inch of blade displacement] for the 10° blade problem, and in increment No. 5 [0.5 inch of blade displacement] for the 50° blade idealization. The failure patterns show that the failed elements started at the leading edge of the blade and progressed toward the soil surface. The effect of the blade inclination on the shape and progress of the failure zones







INCREMENT No. 9 - BLADE DISPLACEMENT = 0.90 inch.

FIGURE 5-23 (CONT'D)

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DEVELOPMENT OF FAILURE ZONES FOR THE 50° INCLINED BLADE - KAOLIN CLAY SYSTEM



INCREMENT No. 10 - BLADE DISPLACEMENT = 1.0 inch

FIGURE 5-23

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DEVELOPMENT OF FAILURE ZONES FOR THE 50°

is clearly demonstrated in these Figures. While in the 10° blade case the elements are shown to fail in clusters starting at the blade tip and progressing toward the soil surface, the 50° blade figures show single elements failing along a well-defined plane. The correlation of these failure zones and actual experimental observations needs further documentation; however, they appear to be indicative of actual progressive failure.

## 5.5 NORMAL PRESSURE DISTRIBUTION

Normal pressures on the surface of the blades, as displacements are increased, are shown in Figs. 5-24 and 5-25. Figure 5-24 shows the distributions for the 10° inclined blade at displacements of 0.1. 0.3, 0.6 and 1.0 inch. The normal pressure distributions, in this case, are seen to be uniform over about three-quarters of the blade Near the blade tip, however, the pressure increases to surface. about 145 to 165 per cent of the average pressure over the whole surface. The shape of the distribution curve remains the same throughout the entire loading range. Figure 5-25 shows the normal pressure distributions on the 50° inclined blade at similar displace-In this case, the normal pressures increase near the tip of ments. the blade to about 200 to 300 per cent of the average pressure over the whole blade surface.

Another look at Figs. 5-24 and 5-25 will show that in the case of the 10° inclined blade, the pressure increases proportionally with increasing blade displacement. However, this is not the case for the 50° blade, as the pressure is shown to increase at a much higher




rate near the tip than in the middle and upper locations.) Eurthermore, the data shown indicate that the upper one-half of the 50° blade does not materially add to the draft, while in the case of the 10° blade the whole surface contributes to the developed forces.

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In general, the smaller the forces or pressures developed on the cutting tool the better the performance. But the extent of soil manipulation must also be considered because it may alter any conclusions that are based on pressures alone. At the present time, no information is available to indicate what magnitude or distribution of pressure can be considered to be good performance. Certainly, however, criteria could be developed and performance measured in terms of the distribution and magnitude of pressure on the soil-engaging surface of cutting tools, provided that the degree of soil manipulation is taken into consideration.

## 5.6 COMPARISON OF ANALYSIS WITH EXPERIMENTAL RESULTS

10 m 1 m

This Section presents comparisons between the soil cutting experimental data reported in Chapter 4, and the finite element analysis presented in the previous Sections of this Chapter. Such comparisons permit a rational assessment of the admissibility and viability of the finite element method as a means of predicting the performance of a cutting tool - the stated aim of the current study [Chapter 1]. In addition, this Section examines the constraints and requirements implied by the proposed analytical technique. The discrepancies between the theoretical model and the physical conditions are also avaluated and their significance discussed. As mentioned earlier [Chapter 1], the problem at hand is a mixed boundary value problem with the boundary conditions specified in terms of both displacement and stress. In such problems, the stress and velocity fields must be compatible as there is no apparent independence between the two fields. Therefore, it is essential to establish separate correlations of both the stress distribution and the soil deformation with the physical measurements, before the technique is judged to be satisfactory. In the present study, the correlation is done in the following fashion:

- The calculated blade reactions [both vertical and horizontal] obtained from the finite element solution are compared with the experimentally measured forces. Such correlation is an indication of the extent of similarity between the stress fields.
- 2. The contours of the nodal displacements obtained from the finite element model proposed are superimposed on<sup>3</sup> the contours obtained from the recorded grid deformation to demonstrate the similarities and discrepancies in the deformation patterns.
- 3. Finally, as differences in the stress and deformation fields are reflected on the scalar values of the energy field, it is reasoned that the examination of the deformation energy values would provide a rational and expedient means of evaluating and comparing the analytical solution with the values obtained from experiments and experimental analysis

### 5.6.1 Comparison of Measured and Calculated Forces

The load-displacement curves as obtained from the finite element analysis based on the proposed model are shown in Fig. 5-26 for the horizontal force and in Fig. 5-27 for the vertical load for both the 10° and 50° inclined blades, respectively. The experimental results are also plotted on the same Figures for comparison.

The agreement between the experimental and the finite element results is very satisfactory in the case of the horizontal forces for the two blade inclinations analyzed. In case of the 50° blade, the difference is about 3 pounds over the whole displacement range analyzed, with the analytical results lying always below the experimental curve. For the 10° blade, the errors are found to be almost negligible up to blade displacement of 0.4 inch, beyond which the analytical and test results diverge, with the predicted results again lying below the experimental values.

The vertical forces computed from the finite element analysis, shown in Fig. 5-27, are seen to be smaller than the measured values. A more complete comparison of the analytical results with those obtained from the measured force-displacement curves is presented in Table 5-1. The comparisons are made in terms of measured and predicted values and are reported at 0.25 inch intervals over a total blade displacement of 1.0 inch. The deviations between the two sets of values, expressed as a percentage of the applicable experimental values, are also indicated.

No analyses are presented here for blade inclinations lying between the 10° and the 50° angles. It was reasoned that these angles





# TABLE 5-1

# COMPARISON OF MEASURED AND PREDICTED VALUES OF DEVELOPED FORCES ON THE 10° AND 50° INCLINED BLADES

| Test<br>No. | Angle of<br>Blade with | Tool<br>Displacement | Hor               | izontal For | ce (1b)      | Vertical Force (1b) |           |              |  |
|-------------|------------------------|----------------------|-------------------|-------------|--------------|---------------------|-----------|--------------|--|
|             | Vertical               | (d) inch             | Measured Predicto |             | % Difference | Measured            | Predicted | % Difference |  |
| 27          | 10°                    | 0.25                 | 29.8              | 31.6        | + 6.0        | -2.13               | - 0.8     | -62.4        |  |
| · ·         |                        | 0.50                 | 40.8              | 42.46       | + 4.0        | -2.75               | - 1.75    | -36.3        |  |
|             | -                      | 0.75                 | 52.0              | 49.5        | - 4.8        | -2.85               | - 2.05    | -28.0        |  |
| `           |                        | 1.00                 | 56.1              | 54.07       | - 3.6        | -2.7                | - 2.15    | -20.3        |  |
| 30          | 10°                    | 0.25                 | 30.5              | 31.6        | + 3.6        | -1.95               | 0.8       | -64.1        |  |
| ,           |                        | 0.50                 | 44.0              | 42.46       | - 3.5        | -2.13               | 1.75      | -17.8        |  |
| -           |                        | 0.75                 | 53.5              | 49.5        | - 7.47       | -2.25               | - 2.05    | - 8.9        |  |
|             | •                      | . 1.00               | 60.0              | 54,07       | - 9.9        | -2.30               | - 2.15    | - 6.5        |  |
| 29          | 50°                    | 0:25                 | 20.0              | 17.5        | -12.5        | 9.3                 | 8.1       | -12.9        |  |
| ١.          |                        | 0.50                 | 24.0              | 21.25       | -11.45       | 12.2                | 10.9      | ÷10.7        |  |
|             | ς . τ                  | 0.75                 | 26.0              | 24.2        | - 6.92       | 13.8                | 12.3      | -10.9        |  |
| -           |                        | 1.00                 | 28.2              | 26.07       | - 7.55       | 14.2                | 13.2      | - 7.0        |  |
| 31          | 50°                    | • 0.25               | 20.5              | 17.5        | -14.6        | 12.0                | 8.1       | -32.5        |  |
|             | · · ·                  | 0.50                 | 24.3              | 21.25       | -12.6        | 13.1                | 10.9      | -16.8        |  |
|             |                        | 0.75                 | 26.5              | 24.2        | - 8.7        | \13.8               | 12.3      | -10.9        |  |
|             |                        | 1.00                 | 29.0              | 26.07       | -10.1        | 14.13               | 13.2      | - 6.6        |  |
|             | I                      | I                    | 1                 | •           |              |                     | 1         | 1            |  |

Notes: (1) Predicted values refer to values obtained from the finite element analysis.

(2) Difference expressed in percentage of measured values.

represent a bound on the verification of the proposed model, and, if the technique is found suitable for these inclinations, it could be assumed that it may be used successfully for any blade inclination within these limits.

Examination of the data in Figs. 5-26 and 5-27 and Table 5-1 indicates that the analytical model provides reasonable estimates of the developed forces on the cutting tools analyzed. This is particularly true of the horizontal forces, in which the average error of estimate is of the order of 8%, while the maximum error is some 15%. For the vertical forces, the values obtained from the theoretical solution are, however, more subject to variation from the experimentally deduced values especially in the case of the 50° inclined blade. Such differences in the vertical forces can be attributed to the effect of the soil deformation behind and below the blades, effect that has not been considered in the finite element idealization.

### 5.6.2 Comparison of Analytical and Experimental Deformation Fields

It will be recalled that photographic records were made of the deforming grid at 5-second intervals of tool motion. With the aid of an x-y plotter and a process control computer, the coordinate pairs corresponding to each of the plotted points were obtained. The particle displacements, over successive grid positions, were then calculated on the basis of the change of the particle position in the coordinate directions. These calculations were performed by the initial section of program "FIT" Appendix E. A more comprehensive

account of these techniques are provided in Appendices B and F.

The experimentally measured displacement fields are plotted in Figs. 5-28 to 5-31 together with the analytical fields obtained from the finite elements nodal displacements, for a tool displacement of 1.0 inch. These deformation fields are presented in terms of horizontal and vertical displacements and are shown for the 10° inclined blade in Figs. 5-28 and 5-29, and for the 50° inclined blade in Figs. 5-30 and 5-31, respectively. As a means of facilitating comparisons, the results are illustrated in contour forms plotted in the undeformed position.

In these Figures, the discontinuity in displacements at the level of the blade tip is clearly demonstrated in the experimental However, a close examination of the morizontal displacement plots. fields reveals that the contours are only discontinuous in the vicinity of the blades, while at a distance they are seen to be continuous above and below the cutting plane. Such behavior implies that the discontinuity propagates with the blade movement. This is not the case in the finite element solution where the discontinuity is assumed to extend all the way to the end boundary. Moreover, the deviation between the experimental and the analytical horizontal displacement fields indicates that the finite element solution underestimates the horizontal displacements in the zone near the soil surface, while it overestimates wines soil mass situated directly above the cutting plane.

Examination of the vertical displacement fields, Figs. 5-29 and 5-31, indicates a significant deviation in the location of the zero



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vertical displacement contour dividing zones of upward and downward movements. It is shown that the experimental zero contour lies above the cutting plane for both the 10° and 50° inclined blades. The corresponding line from the analytical analysis, however, takes a different shape and lies below the experimental one for both cases. Nevertheless, the qualitative agreement between the two fields [experimental and analytical] is seen to be generally satisfactory.

## 5.6.3 Prediction of Deformation Energy

1.

It has already been noted [Section 4.8.5] that the deformation energy results shown so far have been experimental in nature, in that they were obtained by:

> the application of the visioplasticity method to the experimentally recorded deformation fields with the assumption that the stress-deformation behavior of the soil can be described by a rigid plastic model. This model in turn demands the following conditions:

(a) the application of a yield criterion,

- b) the measurement of a deformation field from experiments and calculations of the resultant strain rate fields within the loaded soil, and
- (c) the selection of plasticity flow rules consistent with the choice of the yield criterion.

 the integration of the areas under the experimentally measured force-displacement curves.

It will be recalled that the proposed energy budget for the tool-soil system, given as Eq. (4.2), was written as:

As the system is in a state of dynamic equilibrium such that the input energy is expended completely in producing plastic deformation with no work output and with negligible interfacial energy losses, the above equation can be reduced to:

$$\int_{S} F \, ds = D$$

Energy models for the analysis and the prediction of tool-soil interaction performance will rely on the ability to measure [or determine] response function performance. So, while the results of integrating the areas under the experimentally measured force-displacement curves can be considered as a measure of the work input, the response function is characterized by the work output or the energy dissipated in the system. The work output is determined by two methods: one by using the visioplasticity method, the other by using the finite element stress and strain fields.

# First Method

For a material which follows the von Mises yield criterion, the total work done, and hence the total energy dissipated in plastic deformation under plane-strain conditions was expressed previously by Eq. (4.17), and repeated here for convenience as:

$$D = 2b \int_{t_1}^{t_2} \int_{x_1}^{x_2} \int_{y_1}^{y_2} K \sqrt{T_2} dx dy dt$$
 (5.4)

(5.5)

#### Second Method

The deformation energy during a time interval can be evaluated from the finite element solution by the following equation [Desai and Abel (1972)]:

$$D = \int \int [\sigma]^{T} d[\varepsilon] dt dv$$

where

 $[\sigma] = element stress matrix.$ 

d[c] = element incremental strain matrix.

t = increment duration.

/ = element volume.

These two methods are used to calculate the deformation energy of the tool-soil system. The results obtained from their application are shown in Figs. 5-32 and 5-33 for the 10° and 50° inclined blade problems, respectively. Comparisons of these results with those obtained from the integration of the areas under the experimentally



0.8

0.9

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COMPARISON OF MEASURED AND CALCULATED VALUES OF DEFORMATION ENERGY FOR THE

10° INCLINED BLADE - KAOLIN CLAY SYSTÉM

200

FIGURE 5-32

0

Û.5

0.6

DISTANCE TRAVELLED, INCHES.

13

12

11

10

9

8

7

DEFORMATION ENERGY, IN.LB/IN.WIDTH



measured force-displacement curves are also shown. The information is reported in Table 5-2 at 0.25 inch intervals of tool displacement of 1.0 inch. The deviations between the values obtained from the application of the two methods outlined above, expressed as a percentage of the applicable measured input energy, are indicated in Table 5-3.

As pointed out earlier in Section [4.B.5], the visioplasticity method which assumes a rigid plastic model overpredicts the deformation energy, esnecially in the initial stages of the deformation process. It is reasoned that replacing the work-hardening form of the stressstrain curves shown in Section [4.A.3] by a rigid plastic idealization should be expected to result in the overestimation of the deformation energy, particularly in the present case of gradual load application.

In the finite element analysis of the present problem, the soil was treated as a non-linear-elastic-strain hardening material subject to boundary conditions of an incremental form, thus permitting calculations to be made for the description of the growth of stresses within the loaded soil from initial to final states. A solution of this form should be expected to provide better estimates of the energy dissipated within the soil, subject to the approximations made in the theoretical development. Comparisons of the finite element calculated with the experimentally obtained energy values demonstrate that the developed analytical model provides reasonable prediction of the energy dissipated in the soil. The average error of estimate is of the order of 10%, while the maximum error is 18%.

# TABLE 5-2

# COMPARISON OF THE DEFORMATION ENERGY VALUES OBTAINED BY VARIOUS METHODS FOR THE 10° AND 50° INCLINED BLADE PROBLEMS

| Test     | Angle of Blade | Deformation Energy in.lb/in.width |              |      |               |                       |               |                    |               |      |                |                |       |
|----------|----------------|-----------------------------------|--------------|------|---------------|-----------------------|---------------|--------------------|---------------|------|----------------|----------------|-------|
| No.      | with Vertical  | Tool Displacement                 |              |      |               |                       |               |                    |               |      |                |                |       |
| •        | -              | d =                               | 0.25 1       | nch  | d = 0.5 inch  |                       |               | d = 0.75 inch      |               |      | d = 1.0 inch   |                |       |
| •        |                | a                                 | b            | ° C  | à             | b                     | с             | a                  | b             | с    | a              | b              | С     |
| 27<br>30 | 10°<br>10°     | 1.32<br>1.20                      | 1,95<br>2,05 | 1.39 | 3.92<br>3.86  | <b>4.6</b> 0<br>~4.56 | 4.06          | ,<br>7.65`<br>7.40 | 8.35<br>8.25  | 7.32 | 12.05<br>11.71 | 12.62<br>12.50 | 11.04 |
| 29<br>31 | 50°<br>50°     | 0.92<br>0.88                      | 1.23<br>1.17 | 0.79 | 2.436<br>2.60 | 2.737<br>2.91         | 2 <b>.</b> 17 | 4.3<br>4.1         | -4.95<br>4.65 | 3.83 | 6.57<br>6.90   | 7.50<br>7.55   | 5.61  |

Notes:

(1) Columns headed with the letter (a) denote values obtained from the experimental force-displacement curves.

(2) Columns headed with the letter (b) denote calculated values obtained from Eq. (4.17).

(3) Columns headed with the letter (c) denote values obtained from the finite element solution.

# TABLE 5-3

# ERRORS OF ESTIMATES OF DEFORMATION ENERGY VALUES FOR THE 10° AND 50° INCLINED BLADE PROBLEMS

| Test |                    | Deformation Energy in.1b/in.width |                               |                    |                                  |                               |                    |                                         |                               |                    |                                  |                               |  |
|------|--------------------|-----------------------------------|-------------------------------|--------------------|----------------------------------|-------------------------------|--------------------|-----------------------------------------|-------------------------------|--------------------|----------------------------------|-------------------------------|--|
| NU.  | Measured<br>Values | Error of<br>Visio-<br>plasticity  | Estimate<br>Finite<br>Element | Measured<br>Values | Error of<br>Visio-<br>plasticity | Estimate<br>Finite<br>Element | Measured<br>Values | <u>Error of</u><br>Visio-<br>plasticity | Estimate<br>Finite<br>Element | Measured<br>Values | Error of<br>Visio-<br>plasticity | Estimate<br>Finite<br>Element |  |
|      | d = 0.25 inch      |                                   |                               | d = 0.5 inch       |                                  |                               | d = 0.75 inch -    |                                         |                               | d = 1.0 inch       |                                  |                               |  |
| 27   | 1,32               | + 47.7                            | + 5.3                         | 3.92               | + 17.3                           | + 3.60                        | 7.65               | + 9.10                                  | - 4.13                        | 12.05              | + 4.7                            | - 8.4Ŏ                        |  |
| 30   | 1.20               | + 70.8                            | + 15.8•                       | 3.86               | + 18.1.                          | + 5.20                        | 7.40               | + 11.48                                 | - 1.1                         | 11.71              | + 6.7                            | - 5.70                        |  |
| 29   | 0.92               | + 33.6                            | - 14.1                        | 2.436              | + 12.3                           | - 10.75                       | 4.3                | +_15.1                                  | -10.9                         | 6.57               | + 14.1                           | - 14.6                        |  |
| . 31 | ÷ 0.83 ,           | + 32.9                            | - 10.2                        | 2,60               | + 11.92 ·                        | - 17.4                        | 4.1                | + 13.4                                  | - 6.6                         | 6.90               | + 9.42                           | - 18.71                       |  |
|      | <u></u>            |                                   |                               |                    |                                  | a<br>                         | <u>k</u>           |                                         |                               |                    | •                                |                               |  |

# Notes:

(1) Errors expressed in percentage of measured values.

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(2) Measured values refer to values obtained from the integration of the areas beneath the experimentally measured force-displacement curves.

### CHAPTER 6

# FINITE ELEMENT ANALYSIS OF SOIL-GROUSER INTERACTION PROBLEM

A solution of the traction problem - that is, obtaining adequate traction at a suitable speed in a practical manner and at a reasonable cost - lies in an understanding of:

1. the manner in which stresses are applied to the soil, and

2. the reaction of the soil to the applied stresses.

Bearing in mind this understanding; which is necessary to deal with an interaction process, a direction of approach may be established.

As previously mentioned [Chapter 4], while soil cutting and traction problems can be considered to be one problem in principle, [both situations requiring analyses of soil stresses and deformations, as well as the evaluation of developed reactions on the cutting or traction devices], the purpose of a traction device is to cause deformation of soil in a certain manner as to develop adequate traction capacity [optimum developed reactions]. To achieve this, it is necessary to change the geometry of the traction tools, or, in other words, the interacting boundary conditions, in order to reach the manner of soil manipulation for the production of adequate traction. The importance of accurate specifications of boundary conditions cannot be overemphasized.

Three illustrative examples are studied in this Chapter to demonstrate the validity of the proposed method. Three grouser geometries were chosen for modelling by the finite element method. These grousers are the place grouser [R.A.P.G.] with an aspect ratio

[h/1] of 0.833, the C.E.W. type (2) grouser, and the S.E.W. grouser, shown to scale in Fig. 3-1, Chapter 3. The reason for the choice of these grousers was based on the fact that they represent different geometries and therefore different boundary conditions.

#### 6.1 MESHES AND BOUNDARIES

The meshes adopted for the three grousers chosen for the finite element analysis are shown in Figs. 6-1, 6-2 and 6-3. The material is again assumed to be nonlinear elastic with constitutive behavior derived from the stress-strain results discussed in Section 4.A.3. The initial modulus of elasticity,  $E_0$ , is assumed to be equal to the slope of the initial tangent of the zero confining pressure stress-strain curve shown in Fig. 4-7, and the Poisson's ratio, v, is kept constant at 0.48 through the entire deformation process.

As mentioned earlier, plane strain condition is assumed in cross-section, and constant strain triangles are employed to represent the soil mass. Some objectives in subdividing the mass by C.S.T. [constant strain triangle] elements are the following:

- (a) Small triangles in the areas of most interest.
- (b) All triangles approximately equilateral.
- (c) Less than 400 total triangles and 200 nodes to keep, computer storage requirements down.
- (d) No more than six elements incident to any one node to keep computer storage requirements down.
  (e) Uniform meshes as to facilitate plotting and inter-

polation of results.







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In all the idealizations, Figs. 6-1 to 6-3, cutting [joint] elements are placed on the plane where the cutting is anticipated. This cutting plane is assumed to start in all cases at the level of the grouser tip. It is realized that such an assumption can lead to a certain degree of error as the soil is forced to separate on a particular plane having a fixed position and direction. Comparisons with the available experimental deformation fields, as well as the overall performance, are essential before judging the extent of the validity of such an assumption on the solution technique.

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Figure 6-1 presents the idealization adopted for the R.A.P.G. As previously mentioned, observations of with  $\lceil h/1 \rceil$  ratio of 0.833. both the experimental soil displacement and velocity patterns indicated that the soil situated in the rectangle formed by the two sides of the grouser experiences very little displacement relative to the grouser, with virtually no soil slip on the grouser interface. This zone was termed the "dead" zone in Chapter 4 and is presented in Fig. 6-4 as zone 'ABCD'. This no-slip condition eliminated the need for placing interface elements between the soil and the grouser interface. However, it was observed that, while the dead zone does not experience any appreciable slip on the grouser interface, relative displacements [or slip] do occur between the soil in the "dead" zone and the surrounding soil mass. Jhese relative displacements occur on the outer edge of the "dead" zone represented by plane 'BC' in Fig. 6-4. It was found out that in order to account for such a discontinuity in the deformation field, joint [interface] elements must be inserted on the plane 'BC'. Fig. 6-4. A computer analysis performed on the idealization that did not include



such discontinuity showed that both the deformation field and the predicted forces do not correlate with the experimental results.

In Fig. 6-2, the idealization of the C.E.W. type (2) grousersoil system is shown with interface elements inserted on the grousersoil interface. In modelling the S.E.W. grouser, Fig. 6-3, it was found that interface elements are not required as the horizontal plate placed on top of the grouser creates a no-slip condition, similar to that observed in the R.A.P.G. case.

The sides and bottom boundary conditions are similar to those adopted in the soil cutting analysis. It is assumed that the side and bottom boundaries are placed on rollers. The horizontal movement is restrained on the sides and the vertical movement is prevented on the bottom. Uniform horizontal displacement is applied to all the nodes on the grousers' surfaces. The displacements are increased in ten equal increments of 0.1 inch each for a total displacement of 1.0 inch.

# 6.2 DISPLACEMENT AND VELOCITY PATTERNS

The nodal displacement patterns for the R.A.P.G.-soil system are shown in Figs. 6-5 and 6-6 for grouser displacements of 0.5 and 1.0 inch, respectively. From these plots the displacement patterns could be divided into three distinctive zones:

1. <u>The "dead" zone</u>. The material adjacent to the grouser interface is seen to behave as a rigid body with very little deformation. The rigid body zone can be approximately defined as the material occupying the





triangle 'ACD' in Fig. 6-4. In the remainder of the "dead" zone 'ABC' in Fig. 6-4, the nodal displacements indicate compression of material with downward motion.

- 2. The soil occupying the area above the cutting plane between the "dead" zone and the side boundary. The nodal displacements indicate mostly an upward movement with the exception of the area adjacent to the "dead" zone where the nodes are seen to continue moving downward. The upward motion of the top surface nodes in this zone clearly indicates the gradual formation of surcharge.
  - The soil lying below the cutting plane. This material experiences very little deformation with downward motion below the "dead" zone, and upward displacement for the soil situated on the right.

The general displacement pattern suggests that the soil deformation changes from downward motion in the grouser vicinity to upward motion away from it, and the cutting plane seems to deform accordingly. Also, the effect of the interface elements placed on plane "BC', Fig. 6-4, on the displacement pattern is evident—in the nodal displacement plots, Figs. 6-5 and 6-6. In These Figures it is shown that the soil on the righthandside slides upward on this plane [BC], creating a discontinuity in the deformation field which is compatible with experimental observations as will be shown in a later Section. All of these findings could be confirmed from the plots of the horizontal and vertical nodal points' velocity contours shown in Fig. 6-7. —These velocity contours represent the soil velocity during the first increment of deformation [0.1 inch grouser displacement]. It can be also seen that the vertical interface elements create a discontinuity in the horizontal velocity field. This behavior is to be expected since the direction of the velocity vector outside the "dead" zone changes to an upward position resulting in a sudden reduction of the horizontal velocity is downward in the "dead" zone, with the zone confined by the two sides of the grouser experiencing negligible velocity [rigid body zone defined in Fig. 6-4 by area 'ACD'].

The horizontal and vertical velocity contours for the C.E.W. type (2) and the S.E.W. grousers are plotted in Figs. 6-8 and 6-9. From these Figures the following observations could be made:

In the case of the C.E.W. type (2) grouser, the horizontal velocity above the cutting plane is shown to decrease with increasing distance from the grouser interface. Below the cutting plane, the soil velocity is in the direction of the grouser motion. The highest velocity occurs in a zone near the grouser tip, with decreasing values behind the grouser and close to the righthandside boundary.

From the plots of the vertical velocity field of the C.E.W. type (2)-soil system, Fig. 6-8, it may be seen that a contour of zero vertical velocity intersects the grouser

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interface. Below the cutting plane, this contour is displaced to the right due to the influence of the cutting action. Below and behind these zero vertical velocity contours the material experiences downward motion while above and in front the soil moves upward.

The plot of the horizontal velocity of the S.E.W. grousersoil system, Fig. 6-9, indicates the existence of a small "dead" zone located between the soil-grouser interface and the top horizontal plate. With the exception of this "dead" zone, the x-velocity field for this grouser is similar in pattern to that of the C.E.W. type (2) grouser. However, the horizontal velocity at any specific distance from the soil-grouser interface is found to be lower for the case of the C.E.W. type (2) grouser system, when compared with the values of the S.E.W. field. This is again attributed to the existence of a "dead" zone in the S.E.W. system which creates a rigid body zone, having about the same velocity as the grouser.

In the vertical velocity plot of the S.E.W. system, Fig. 6-9, the zero vertical velocity contour is seen to start from the leading edge of the top horizontal plate, creating a larger zone of downward moving soil. Again, all the material below and behind the zero contour moves downward, while above and in front the soil moves upward.

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#### 6.3 STRESS ANALYSIS

As was discussed in Section 6.1, it was found from the examination of the experimental displacement fields that there is no need for placing interface elements along the soil-metal interface for the R.A.P.G. The interface boundary conditions are assumed as fixed in the system. x-and y-directions for the nodes connected to the vertical side of the grouser. However, the nodes attached to the horizontal interface are assumed to be fixed only in the vertical direction, but free in the It was reasoned that these assumptions for the horizonta: direction. interface conditions would lead to reasonable stress distributions and consequently developed reactions. The distributions of the horizontal, vertical and shear stresses in the soil obtained for the finite element idealization of the R.A.P.G.-soil system shown in Fig. 6-1 are plotted in Figs. 6-10 and 6-11. Figures 6-10 and 6-11 show, respectively, the stress contours for grouser displacement of 0.1 inch and 0.5 inch.

A close look at these plots will reveal the following illustrative points;

- . The largest horizontal compressive stresses occur in the "dead" zone with stress concentrations at the bottom of the vertical interface.
- 2. In addition to the discontinuity in the horizontal stress field occurring across the cutting plane elements, the vertical interface elements plane [placed on plane 'BC' in Fig. 6-4] produce another discontinuity. Such discontinuity, however, seems to result in no sudden change in the horizontal stress magnitudes.

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It is shown that while the horizontal compressive stresses above the cutting plane decrease with increasing distance from the grouser-soil interface, the reverse occurs below the cutting plane. This behavior is attributed to the fact that the material located in the zone directly underneath the grouser is subjected to horizontal tensile stresses. These tensile stresses gradually change into compressive stresses which increase until they reach values similar to the stresses developed above the cutting plane near the righthandside boundary.

It is indicated that the material confined by the grouser sides is subjected to very high vertical compressive stresses  $(\sigma_y)$ , Figs. 6-10 and 6-11. Outside the "dead" zone the stresses suddenly drop to a little more than half the magnitude. Further, the shape of the contours in the "dead" zone indicates the influence of the grouser sides, while outside it the contours change to a shape similar to what would be expected from a material with a free top surface boundary.

An examination of the shear stress plots, indicates that the zone 'ACD' in Fig. 6-4 experiences very little shear distortion. A zero shear stress divide is shown to occur on the boundary of this zone; to its left the material is shearing in a clockwise [positive]

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direction, while to its right the shear is negative [anticlockwise direction].

The zone of maximum shear stresses initiates at a distance from the grouser toe level in the initial loading stage, Fig. 6-10, and is shown to be moving forward with increasing grouser displacement, Fig. 6-11. From the plots of the failed elements, Fig. 6-16, it will be established that the zone of maximum shear stress moves outside the "dead" zone at larger grouser displacements.

The distributions of  $\sigma_{x}$ ,  $\sigma_{y}$ , and  $\tau_{xy}$  stresses for both the C.E.W. type (2) and the S.E.W. grouser-soil systems are presented in Figs. 6-12 to 6-15. Again, the stress contours for these systems are plotted at 0.1 and 0.5 inch of tool displacements. Examination of the horizontal and vertical stresses of the two systems suggests that, with the exception of the zone adjacent to the grouser interface, the horizontal as well as the vertical stress distributions seem to be similar. Moreover, the contours maintain the same general shapes with increasing grouser displacement.

Comparisons of the stress fields in front of both grousers show that the stress values near the toe of the S.E.W. grouser are higher than those occurring in front of the C.E.W. type (2) grouser. The difference in stress magnitudes is attributed to the difference in the grousers' toe geometries. The attack angle [angle between bottom portion of the interface and the cutting plane] of the C.E.W. type (2)









grouser is 90°, while it is only 67.5° for the S.E.W. system, Fig.3-1. Due to this variation, one would expect higher stress concentrations for the acute grouser attack angle. Another dissimilarity is the higher horizontal and vertical stresses developing under the top horizontal plate of the S.E.W. system. These stresses are caused by the confining influence of this plate on the adjacent material.

Finally, the plots of the shear stresses,  $\tau_{\chi\gamma}$ , for the S.E.W. system, Figs. 6-14 and 6-15, show a zero shear stress divide which indicates the existence of a small "dead" zone similar to the one observed in the R.A.P.G. stress fields. This zone can be approximately defined by the area located between the grouser interface and the line connecting the grouser toe with the leading edge of the top horizontal plate. Inside this area the material is shown to have negative shear [i.e., clockwise] values - near the grouser interface. No indication of any similar zone is observed in the C.E.W. type (2) grouser stress fields.

The development of the failure zones for the R.A.P.G., the C.E.W. type (2), and the S.E.W. grouser-soil systems is shown in Figs. 6-16, 6-17 and 6-18, respectively. For the R.A.P.G.-soil system, yielding occurs in two different locations, Fig. 6-16. At the toe of the grouser, the adjacent element fails in increment No.8. In subsequent increments, only one additional element is added to this zone. This suggests that this zone represents a localized shear area caused by stress concentrations due to the cutting action. The main failure in the material occurs outside the so-called "dead zone". It is seen that failure starts in two elements just outside the "dead" zone in







increment No.8 and then moves upward and forward with increasing grouser displacement. While in the shear stress plots of Figs. 6-10 and 6-11 the region of maximum shear stresses is located within the lower part of the "dead" zone, it is shown to be moving forward with increasing grouser displacement. The actual failure occurs outside this zone starting in increment No.8.

For the C.E.W. type (2) and the S.E.W. system, the failed zones, as shown in Figs. 6-17 and 6-18, do not start at the grousers' toes, but at approximately the same distances where regions of maximum shear stresses occur, [Figs. 6-12 to 6-15]. Of interest is the localized failed areas near the point of intersection of the grouser interface with the free soil surface. Again these zones can be considered as localized areas of maximum shear due to stress concentrations. However, it is seen that in increment No.10 these localized failed areas join with the Another point of interest is the extension of the main failure zones. failure zone back to the grouser toe in the case of the C.E.W. type (2) system, a phenomenon that is not exhibited in the S.E.W. system. This observation substantiates the fact that a small "dead" zone experiencing very little shear distortion exists in front of the S.E.W. grouser.

## 6.4 CONTACT PRESSURE DISTRIBUTION

The normal pressure distributions on the R.A.P.G.-soil interface are plotted in Fig. 6-19 at grouser displacements of 0.1, 0.3, 0.6 and 1.0 inch. These results are obtained by dividing the reactions, developed at the interface nodal points by the areas of influence of each modal reaction. The plots indicate that the maximum pressure on



the vertical side of the grouser occurs at the grouser toe where a region of stress concentration develops. At a distance of approximately half an inch above the toe, the normal pressure is found to drop to approximately half the value of the cutting pressure. It is also seen from this Figure that in the initial stages of deformation [0.1 Inch grouser, displacement] no pressure peak develops on the horizontal interface. However, with increasing grouser displacement a pressure peak starts to form on the leading edge. This behavior is attributed to the formation of a stress concentration zone, below the leading edge, caused by the confining effect of the horizontal interface. No tangential stress distributions are drawn for this grouser for it was assumed that the nodes on the horizontal interface are free to move in the horizontal direction [smooth boundary], resulting in zero tangential stresses on this interface. The values of the tangential stresses on the vertical side were found to be of very small magnitudes.

Figures 6-20 and 6-21 show the normal pressure distributions on the C.E.W. type (2) and the S.E.W. grousers, respectively. The C.E.W. type (2) grouser normal pressure distributions are of parabolic shape with peaks at the toe and at the leading edge. Larger peak values develop on the leading edge, accounting for the appearance of failed elements near this edge before the toe failure commences, Fig. 6-17. The same argument is true for the S.E.W. system, Fig. 6-21, with the exception that the leading edge, in this particular case, is the top horizontal plate.

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The corresponding tangential stress distributions on these





grousers are plotted in Figs. 6-22 and 6-23. In both systems the shear stress changes direction at a certain point on the soil-grouser inter-But, while the shear direction is negative [anticlockwise] on face. the bottom half of the C.E.W. type (2) grouser interface, and positive on the top part, the reverse occurs on the S.E.W. grouser interface. As the tangential reactions are obtained from resolving the horizontal and vertical reactions in the tangential direction, the direction of the tangential reaction is expected to depend upon the relative magnitudes of the x- and y-reaction components. The curvature of the C.E.W. type (2) interface results in a continuous variation in the angles made between the x- and y-reactions and the interface. This causes a change in the magnitudes of the tangential components contributed by each of the horizontal and vertical reactions along the curved interface. Moreover, the presence of the top horizontal plate in the S.E.W. system influences the direction of the reaction on the interface nodal points, resulting in a negative [downward] shear along approximately the top twothirds of the inclined interface.

#### 6.5 COMPARISON OF ANALYSIS WITH EXPERIMENTAL RESULTS

#### 6.5.1 Comparison of Measured and Calculated Forces

The force-displacement relations obtained from the finite element analysis for the various grouser-soil systems are shown in Figs. 6-24 to 6-26, inclusive. The idealizations, assumptions, and the boundary conditions adopted for the analyses of these systems were discussed in Section 6.1. Plotted on the same Figures are typical load-displacement records obtained from the traction series. For the





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sake of comparison, both the analytical and experimental forces are also reported in Table 6-1 at 0.25 inch intervals over a total grouser displacement of 1.0 inch, together with the difference between the two sets of values expressed as a percentage of the experimental value.

The agreement between the experimental and the finite element results, considering the numerous assumptions made, is generally very satisfactory. The analytical and test results, however, show better agreement in the case of the horizontal forces, for which the percentage difference rarely exceeds 10%. In the case of the vertical forces the average error of estimate is in the order of 20%, while the maximum error is some 40%. It must be noted that the trend of better predictions of horizontal forces was also observed in the soil cutting results,

### 6.5.2 <u>Comparison of Analytical and</u> Experimental Deformation Fields

Typical deformation fields for the traction test series are shown in Figs. 6-27 to 6-32, plotted at 1.0 inch grouser displacement. The analytical fields obtained from the finite element nodal displacements are also plotted on the same Figures for comparison.

Figures 6-27 and 6-28 illustrate the horizontal and vertical displacement fields for the plate grouser-soil system. From the examination of these Figures the following observations could be made:

 Generally the correspondence between the analytical and the experimental fields for both the horizontal and vertical displacements is satisfactory. The

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| , | DEVELOPED FORCES FOR TRACTION TESTS |                           |                                |                              |                                |                                    |                               |                                  |                                      |
|---|-------------------------------------|---------------------------|--------------------------------|------------------------------|--------------------------------|------------------------------------|-------------------------------|----------------------------------|--------------------------------------|
| 1 | TEST<br>No.                         | GROUSER<br>TYPE           | GROUSER DISPLACEMENT<br>(inch) | HORIZONTAL FORCE (1b)        |                                |                                    | VERTICAL FORCE (1b)           |                                  |                                      |
|   |                                     |                           |                                | Measured                     | Predicted                      | Difference<br>%                    | Measured                      | Predicted                        | Difference<br>%                      |
| - | 34                                  | R.A.P.G.<br>(h/1 = 0.833) | 0.25<br>0.50<br>0.75<br>1.00   | 33.5<br>41.2<br>44.5<br>47.0 | 32.4<br>41.47<br>48.0<br>52.5  | - 3.3<br>+ 0.6<br>+ 7.9<br>+ 11.70 | 13.1<br>18.0<br>21.8<br>25.2  | 17.20<br>23.63<br>27.43<br>29.43 | + 31.3<br>+ 31.3<br>+ 25.8<br>+ 16.7 |
|   | 33                                  | C.E.W.type(2)             | 0.25<br>0.50<br>0.75<br>1.00   | 21.0<br>32.0<br>38.0<br>40.0 | 26.0<br>                       | + 23.8<br>+ 9.0<br>+ 6.3<br>+ 8.63 | 8.9<br>11.0<br>12.2<br>13.6   | 7.9<br>12.71<br>14.9<br>15.4     | - 11.2<br>+ 15.5<br>+ 22.1<br>+ 13.2 |
|   | 38                                  | C.E.W.type(2)             | 0.25<br>0.50<br>0.75<br>1.00   | 23.0<br>31.0<br>37.3<br>41.3 | 26.0<br>34.88<br>40.4<br>43.78 | + 13.0<br>+ 12.5<br>+ 8.3<br>+ 6.0 | 8.5<br>11.7<br>, 13.1<br>14.3 | 7.9<br>12.71<br>14.9<br>15.4     | - 7.0<br>+ 8.6<br>+ 13.7<br>+ 7.7    |
|   | <b>32</b>                           | S.E.W.                    | 0.25<br>0.50<br>0.75<br>1.00   | 30.0<br>38.8<br>42.5<br>44.0 | 29.0<br>37.98<br>43.8<br>46.97 | - 3.3<br>- 2.1<br>+ 3.0<br>+ 6.8   | 9.70<br>14.7<br>16.4<br>19.0  | 13.9<br>18.2<br>20.9<br>21.53    | + 43.2<br>+ 23.8<br>+ 27.4<br>+ 13.3 |
|   | 37                                  | S.E.W.                    | 0.25<br>0.50<br>0.75<br>1.00   | 27.0<br>35.0<br>41.1<br>42.9 | 29.0<br>37.95<br>43.8<br>46.97 | + 7.4<br>+ 8.5<br>+ 6.6<br>+ 9.4   | 11.3<br>15.9<br>18.8<br>20.1  | 13.9<br>18.2<br>20.9<br>21.53    | + 23.0<br>+ 14.5<br>+ 11.2<br>+ 7.1  |

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COMPARISON OF MEASURED AND PREDICTED VALUES OF DEVELOPED ENDIES END TRACTION TESTS

TABLE 6-1

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finite element model, however, is seen to possess more rigidity in the x-direction, and more flexibility in the y-direction, when comparing nodal displacements with those measured during the test 'series.

There appears to be no discontinuity in the measured horizontal displacement fields, Fig. 6-27, across the position of the interface elements placed at the outer edge of the rectangle formed by the two sides of the grouser, line BC, Fig. 6-4. Such discontinuity is shown, however, to occur in the experimental vertical displacement field near the soil surface, Fig. 6-28. Such performance substantiates the reasoning for placing interface elements on this plane.

Examination of the experimental vertical displacement field confirms the fact that the soil located below the grouser moves downward, while the soil in front of the grouser moves upward. Such performance corresponds to that obtained from the analytical solution, shown in Figs. 6-5 and 6-6. A significant deviation between the two fields, however, is shown in the location of the zero vertical displacement contour dividing zones of upward and downward movements.

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In comparing the computed deformation fields with the measured ones for both the C.E.W. type (2) grouser and the S.E.W. grouser-soil systems, Figs. 6-29 to 6-32, the following points could be made:

1. The computed horizontal deformation fields for the two systems are shown to correspond very closely with the experimentally measured fields, with the finite element results again indicating higher model rigidity than that of the physical system.

2.

- From the vertical displacement plots, Figs. 6-30 and 6-32, the downward motion of the C.E.W. type (2) system is shown to be localized in a very small region below the toe of the grouser, while in the case of the S.E.W. system the corresponding region is shown to be much larger, signifying the confining effect of the top horizontal plate, Fig. 3-1.
- 3. The location of the zero vertical displacement contour-line for both systems is again shown to differ when comparing the computed with the measured fields. The measured fields indicate larger zones of downward motion than those obtained from the analytical model. This is believed to be due to the predefinition of the cutting plane discontinuities in the finite element model.





(GROUSER DISPLACEMENT = 1.0 INCH)





# 6.5.3. Prediction of Deformation Energy

As outlined in Section 5.6.3, the deformation energy of the tool-soil system is obtained by various methods. These methods were classified as follows:

Experimental - by integration of the experimentally measured forcedisplacement'relationships,

<u>Semi-analytical</u> - by application of the visioplasticity method to the experimentally recorded deformation fields, <u>Theoretical</u> - by calculating the deformation energy of the finite element idealizations proposed in this study.

The results computed using these methods are plotted in Figs. 6-33, 6-34 and 6-35 for the plate (R.A.P.G.), the C.E.W. type (2) and the S.E.W. grouser-soil systems, respectively. In Table 6-2 the energy values are reported at 0.25 inch intervals of tool displacement of 1.0 inch. The deviations between the semi-analytical and theoretical values of deformation energy, expressed as a percentage of the values obtained from the integration of the areas under the measured forcedisplacement curves, are shown in Table 6-3. It is seen from these results that, as in the case of the soil cutting comparisons, Section 5.6.3. the visioplasticity method overestimates the deformation energy in all cases, while the finite element results show a better correlation with the measured input energy. The reasons given in Section 5.6.3 for the discrepancies between the two predictive methods also apply to the above results.

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## TABLE 6-2

## COMPARISON OF THE DEFORMATION ENERGY VALUES OBTAINED BY THE VARIOUS METHODS FOR TRACTION TESTS

| TEST | GROUSER                   | Þ.                                           | DEFORMATION ENERGY IN.LB/IN.WIDTH  |                                    |                                   |  |  |  |  |
|------|---------------------------|----------------------------------------------|------------------------------------|------------------------------------|-----------------------------------|--|--|--|--|
|      |                           | <pre>- Tool Displacement d * 0.25 inch</pre> | Tool Displacement<br>d = 0.50 inch | Tool Displacement<br>d = 0.75 inch | Tool Displacement<br>d = 1.0 inch |  |  |  |  |
|      |                           | abe                                          | a b c                              | .abc                               | abc                               |  |  |  |  |
| 34   | R.A.P.G.<br>(h/1 = 0.833) | 1.56 1.90 1.40                               | <b>4.26 4.445 4.05</b>             | 7.343 8.255 7.21                   | 11.14 12.70 10.85                 |  |  |  |  |
| 33   | C.E.W.type(2)             | 0.821 1.44                                   | 2.76 3.36                          | 5.278 6.24                         | 8.57 9.6                          |  |  |  |  |
| . 38 | C.E.W.type(2)             | 1.09<br>0.95 1.34                            | 3.32<br>, 3.10 3.4                 | 6.01<br>5.91 6.35                  | . 9.05<br>8.70 9.4 <sup>-</sup>   |  |  |  |  |
| 32   | S.E.W.                    | 1.31 1.70                                    | 3.79 3.97                          | 6.72 7.38                          | 10.29 11.35                       |  |  |  |  |
| 37   | <b>S.E.W.</b>             | 1.35<br>1.42 1.79                            | 3.//<br>3.4 3.9                    | 6.70<br>6.51 7.12                  | 9.94<br>10.6, 11.71               |  |  |  |  |

### Notes:

(1) Columns headed with the letter (a) denote values obtained from the experimental force-displacement curves.

(2) Columns headed with the letter (b) denote calculated values obtained from Equation (4.17).

(3) Columns headed with the letter (c) denote values obtained from the finite element solution.

| · · · · · · · · · · · · · · · · · · · |                    |                                          |                         | · · · · · · · · · · · · · · · · · · · |                                          | · · · · · · · · · · · · · · · · · · · | <u>.</u>           |                                       |                         |                    | •                                          |                        |
|---------------------------------------|--------------------|------------------------------------------|-------------------------|---------------------------------------|------------------------------------------|---------------------------------------|--------------------|---------------------------------------|-------------------------|--------------------|--------------------------------------------|------------------------|
| TEST No.                              |                    | DEFORMATION ENERGY IN.LB/IN.WIDTH        |                         |                                       |                                          |                                       |                    |                                       |                         |                    |                                            |                        |
|                                       | Measured<br>Values | - <u>Error of</u><br>Visio-<br>plasticit | Estimates<br>F.E.<br>ty | Measured<br>Values                    | <u>Error of E</u><br>Visio-<br>plasticit | <u>stimates</u><br>F.E.<br>Y          | Measured<br>Values | <u>Error of</u><br>Visio-<br>plastici | Estimates<br>F.E.<br>ty | Measured<br>Values | <u>Error of Es</u><br>Visio-<br>plasticity | <u>timates</u><br>F.E. |
|                                       | đ                  | = 0.25 incl                              | h,                      | 9                                     | <u>1 = 0.5 inch</u>                      |                                       | <u>d</u>           | = 0.75 in                             | <u>ch</u>               | <u>d</u>           | = 1.0 inch                                 | 1. 8                   |
| 34                                    | 1.56               | +22.06                                   | -10,25                  | 4.26                                  | · + 4.34                                 | - 4.95                                | 7.343              | +12.41                                | - 1.8                   | 11.14              | +`14.0                                     | - 2.6                  |
| 33                                    | 0.821              | +75.3                                    | +32.7                   | 2.76                                  | +21.7                                    | +20.1                                 | 5.278              | +18.22                                | +13.8                   | 8.57               | + 12,0                                     | + 5.5                  |
| 38                                    | 0.95               | +41_0                                    | +14.7                   | 3.10                                  | + 9.6                                    | + 6.51                                | 5,91               | + 7.45                                | + 1.70                  | 8.70               | + 8.04                                     | + 4.0                  |
| , 32                                  | 1.31               | +29.8                                    | + 3.0                   | 3.79                                  | + 4.74                                   | - 0.5                                 | 6.72               | + 9.82                                | 30                      | 10.29              | + 10.3                                     | - 3.4                  |
| 37                                    | 1.42               | <u>.</u>                                 | - 4.9                   | 3.4                                   | +14.7                                    | +10.8                                 | 6,51               | + 9.37                                | + 2.90                  | 10.6               | + 10.4                                     | - 6.2                  |

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TABLE 6-3

## ERRORS OF ESTIMATES OF DEFORMATION ENERGY VALUES

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FOR TRACTION TESTS

6.6 A

## ANALYTICAL TECHNIQUE SENSITIVITY TO STRENGTH TESTS LOADING CONDITION

It is recalled that the stress-strain relationships for the soil represented by the continuum elements in the finite element solution were obtained by subjecting prismatic samples to a plane-strain loading condition in a modified triaxial cell [Appendix A]. These tests were performed in order to reproduce as closely as possible the plane strain conditions applicable to the soil cutting and traction experimental boundary conditions adopted in this study. In addition to these tests, an axisymmetric loading condition was applied to cylindrical samples placed in a standard triaxial cell. The main objective for conducting the axisymmetric tests was, as mentioned previously, to verify the fact that the nonexistence of a well-defined failure condition is not a result of the plane strain "True Triaxial" test constraint [Section 4.A.3.].

The application of axisymmetric triaxial loading condition is considered a standard testing procedure, requiring no special devices. This is not the case with the plane strain loading condition which is viewed as a special type of test. Due to this fact, it is of interest to examine the sensitivity of the proposed finite element analysis to the strength test loading condition, as well as its effect on the predicted results. For this purpose the artificial clay-grouser interaction problems were analyzed, employing the input stress-strain curves of both loading conditions. The stress-strain curves obtained from both the axisymmetric and plane strain loading conditions for the artificial clay are shown in Fig. A-6, Appendix A. The artificial clay was chosen for the sensitivity analysis as the performance of this clay is not influenced by the magnitude of the confining pressure, Appendix A, and hence one stress-strain curve is employed for each loading condition. Moreover, such analysis leads to further verification of the validity of the proposed analytical technique when applied to tool interaction with a purely plastic material.

It has been shown in Section 2.4.2 that for a plane strain loading condition of an incompressible material (v = 0.5), Hooke's Law, Eq. (2.28), gives:

 $\frac{\sigma_{1} - \sigma_{2}}{\varepsilon_{1}} = \frac{\sigma_{1} - \sigma_{2}}{\varepsilon_{1}}$ 

with the term  $(\sigma_1 - \sigma_3)/\epsilon_1$  representing the slope of the secant modulus, (E<sub>T</sub>), of the deviator stress,  $(\sigma_1 - \sigma_3)$ , versus principal strain,  $\epsilon_1$ , curve obtained under plane strain loading condition. Equation (2.28) simplifies to:

 $E = \frac{2}{4} E_{T}$ 

(6.1)

It should be pointed out here that E represents the elastic modulus of the material which is a material property and should not depend on the loading condition: On the other hand, the modulus  $E_T$ , is obtained, in this case, from the stress deviator-principal strain curve resulting from plane strain loading.

In the axisymmetric triaxial compression test,

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Applying Hooke's Law, for an isotropic, linear, elastic material, in a principal plane, Eq. (2.28) reduces to:

$$\varepsilon_{1} = \frac{\sigma_{1}}{E} - \frac{2^{\nu}\sigma_{3}}{E} = \frac{1}{E} (\sigma_{1} - 2^{\nu}\sigma_{3})$$
(6.2)

$$\epsilon_2 = \epsilon_3 = \frac{\sigma_3}{E} - \frac{v}{E} (\sigma_1 + \sigma_3)$$
(6.3).

For an incompressible material v = 0.5, and from Eq. (6.2),

$$E = \frac{\sigma_1 - \sigma_3}{\varepsilon_1}$$
 (6.4)

Also, in an unconfined compression test  $\sigma_s = 0$ , and from Eq. (6.2),

$$\mathbf{E} = \frac{\sigma_1}{\varepsilon_1} \tag{6.5}$$

Equations (6.4) and (6.5) represent the slope  $E_T$  of the deviator stress,  $(\sigma_1 - \sigma_3)$ , versus principal strain,  $\varepsilon_1$  for the axisymmetric triaxial and unconfined compression curves, respectively. Thus in these two cases,

E

Employing Eq. (6.1) and Eq. (6.4) together with the appropriate stress-strain curve for the artificial clay, shown in Fig. A-6, Appendix A, the problems of the R.A.P.G., the C.E.W. type (2), and the S.E.W. grousers; were analyzed. The idealizations presented in Section 6.1, Figs. 6-1, 6-2 and 6-3, were adopted. The predicted forces, obtained from: (1) the analysis employing the axisymmetric stress-strain curve and Eq. (6.6), (2) the analysis using the plane-strain curve and Eq. (6.1), and (3) the experiments, are plotted as a function of grouser displacement in Figs. 6-36, 6-37 and 6-38 for the three grousers. It can be seen from

these Figures that employing the plane strain curve results in lower predicted horizontal and vertical forces when compared with those obtained from the analysis adopting the axisymmetric triaxial curve. This behavior can be explained by the fact that while the plane strain loading condition produces a stress-strain curve exhibiting higher stresses, Fig. A-6, Appendix A, the elastic modulus, E, in the finite element analysis employing the plane strain curve is taken equal to three-quarters that of the curve secant value,  $E_T$ , Eq. (6.1). In case of the analysis using the axisymmetric curve, on the other hand, the E values are taken equal to the secant values of the axisymmetric curve, Eq. (6.1). This resulted in slightly lower E values for the plane strain case, and hence lower predicted forces. The difference in E values resulting from the two loading conditions is attributed to the non-uniform and dissimilar distributions of stresses and strains within the cylindrical and prismatic samples due to the effect of the end restraints, and side restraints in the case of plane strain loading Finally, it is of interest to note that while both techniques condition. predict horizontal forces which agree closely with the measured values, the vertical forces obtained from the analysis employing the plane strain curve correlate better with the measured vertical forces.







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#### CHAPTER 7

## COMPUTER SOLUTION AND COMPARISON WITH ANALYTICAL RESULTS

#### 7.1 INTRODUCTION

In Chapters 5 and 6 the results of the soil cutting and traction experiments, conducted during the course of this study, were compared with the finite element analyses. The agreement was found to be satisfactory. Following from Fig. 4-1, the purpose of this Chapter is to establish the validity of the developed solution technique by presenting a number of verifications of the solution against conventional methods based on closed-form solution schemes.

A typical example of a nonlinear plane-strain problem is the load-deformation characteristics of a long vertical retaining wall with soil mass on one side. The determination of the actual earth pressure on the wall is extremely complicated, because it depends on the relative mevement of the wall and the soil. This relative movement mobilizes frictional and/or adhesional forces along the soil-wall interface which affect the earth pressure magnitude and direction. Although many experiments have been carried outs on the load-deformation characteristics of walls, there is no widely accepted theory to determine the loaddeformation relationship.

While the present study is mainly concerned with the analyses of simple soil cutting and traction problems, the familiar case of twodimensional soil response encountered in long retaining walls when

yielding in a passive sense bears, a close parallel to wide cutting This is particularly true as the term "passive blades moving in soil. earth pressure", in the broadest sense, indicates the resistance of a mass of soil against displacement by lateral pressure. Bearing this in mind, the passive earth pressure behind a model retaining wall has been calculated by a nonlinear analysis with differing boundary conditions employing the developed computer program. The results obtained from this analysis are compared in this Chapter with results obtained from the classical theory of earth pressure. The assessment of the admissability and viability of the solution technique is carried out through a parametric study to establish the relative importance of the various features and assumptions implemented in the finite element technique.

The second part of this Chapter is devoted to comparisons of soil cutting and traction analytical and experimental results obtained in this study with results computed from existing theories. The sequence in presentation of results and related discussions for this part is consistent with the earlier separation of the overall problem under study into two principal parts, i.e. soil cutting and traction.

#### 7.2 LOAD-DEFORMATION CHARACTERISTICS FOR A STRIP OF LONG VERTICAL WALL RETAINING. CLAY

7.2.1 Background

The case of a simple retaining wall and its interaction with a soil was treated by Coulomb (1776) and Rankine (1857), and the

theories developed have continued to be used with remarkable success up to the present time as the most common basis for the design of retaining walls. From these theories the resultant of the earth pressure acting on the wall at some limiting conditions can be obtained, without, however, any information as to the deformation of the wall or earth. In both theories the earth mass is assumed to behave as a rigid-plastic material governed by a Mohr-Coulomb failure criterion, and the structure itself is assumed perfectly rigid.

Only through experimental work such as that of Terzaghi (1932, 1934, and 1936) and more recently Rowe and Peaker (1964), and James and Bransby (1970), an insight was gained into the wall deformations associated with the limit conditions and the dependence of earth pressure on mode of wall deformation. To account for the effect of the mode of wall deformation, more sophisticated limit theories have been developed [Hansen (1953), Drucker (1953), and Sokolovski (1965)] which have application to a much wider class of problems than the simple Elastic solutions have also been derived which can retaining wall. account for the flexibility of the structure [Hetenyi (1964) and Finn In either type of solution however, the material behavior (1963)]. is highly idealized; in the first instance the earth mass is assumed to be a rigid-plastic material governed by a Mohr-Coulomb failure criterion, while in the second it is assumed to be homogenous, isotropic and linearly elastic, regardless of the stress level.

Girijavallabhan and Reese (1968) first demonstrated the successful simulation of a retaining wall problem by finite element techniques. They analyzed two model retaining wall tests in which

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the wall was forced into first a loose, and then a dense, backfill by pure translation. A nonlinear elastic model was employed for the soil and the interface between the wall, and the backfill was assumed perfectly smooth. Remarkable agreement was obtained when comparing the predicted and observed results.

Morgenstern and Eisenstein (1970) conducted finite element analyses to investigate the effects of the foundation deformations as well as those of excavation on retaining wall behavior. Two problems were analyzed - in the first, the wall was assumed smooth and unmoving, the interface between the soil and the wall smooth, and the soil to be linear elastic. The foundation layer underlying the wall varied from zero thickness to a thickness equal to the height of the wall. Relative to a normal linear k, distribution, their analyses showed that the earth pressure near the bottom of the wall was increased and at the top decreased, in some cases going into tension, as the thickness of the foundation layer increased. In the second set of analyses, the wall was allowed to yield in an active and passive sense by 0,0025 In this case they noted that the boundary conditions  $p^{\Lambda}$ of wall height. between the foundation layer and the rigid base have a significant effect on the earth pressures, the pressure distribution on the wall becoming nonlinear with a rough boundary for both the active and passive analyses,

Analyses of retaining walls were performed by Clough and Duncan (1971) using the one-dimensional element of Goodman et al. (1968) to simulate the interface between the wall and the backfill. The wall was assumed to be either perfectly rough ( $\delta = \phi$ ), perfectly smooth ( $\delta = 0$ )

or moderately rough ( $\delta = 2/3 \phi$ ), and it was displaced by rotation and translation in both the active and passive senses. The minimum active and maximum passive pressures calculated in these analyses were found to be in good agreement with the results of the classical earth pressure theory, and the amount of movement required to reach the full active and full passive conditions were found to be in agreement with the results of the model retaining wall tests performed by Terzaghi (1934).

# 7.2.2 Finite Element Analysis of the Retaining Wall Problem

Several analyses were conducted to Idealization: (a) evaluate the effectiveness of the analysis procedures described previously, using the rigid wall and backfill shown in Fig. 7/1. Beginning from initial at-rest pressure condition, the wall was moved toward the backfill in a series of increments, adjusting the properties of the elements in accordance with the stresses for each increment to approximate nonlinear behavior [Chapter 2]. The wall was assumed to be either perfectly rough [i.e. no possibility for slip between wall and soil], perfectly smooth [no shear stresses at the fnterface], or moderately rough [soil-wall adhesion case governed by nonlinear, stress dependent interface behavior]. The moderately rough [soil-wall adhesion] case was simulated in the finite element analysis by inserting interface elements between the soil and the wall; The boundaries were placed on rollers such that 'horizontal Fig. 7-1. displacements were prevented on the sides and no vertical movement was allowed on the rigid base.



To examine the influence of the cutting plane adopted in the finite element idealization on the developed forces and pressure distributions, one of the idealizations analyzed did not include a cutting plane. It should be recalled that these planes were included in the formulation to account for the severe relative displacements at the wall base, especially at large wall deformation.

An incremental-iterative method of nonlinear analysis was This method of analysis was described utilized to solve the problem. in detail in Chapter 2, and used in the soil cutting and traction The nonlinear plane-strain triaxial stress-strain curves analyses. shown in Fig. 4-7 for the kaolinite clay were used in the analysis to represent the constitutive behavior of the constant strain triangular For the interface and cutting elements the hyperbolic elements. relationships of the tangential stress-displacement curves, shown in Fig. 4-13, for the soil-to-soil mode, and in Fig. 4-14 for the soil-to-The shear strength of the clay was about metal mode, were utilized. 1.16 psi, and an initial elastic modulus of 90 psi was adopted. The Poisson's ratio, v, was kept constant at 0.48 in all the problems. A total wall movement of 0.5 inch was applied in ten equal increments Three iterations were performed during each increment. of 0.05 inch each.

(b) <u>Variables studied</u>: One of the purposes of analyzing the retaining wall problem was to study the influence of the boundary conditions on earth pressure and soil deformation. Knowledge of the boundary conditions is as essential for the reliable estimate of lateral loads and deformations as both the initial conditions and the constitutive relations. These boundary conditions must represent the interaction

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between the soil and the wall rather than be simple analytical conditions such as "rigid, perfectly rough" or "perfectly smooth" [Clough and Duncan (1971)].

Another purpose of this study is to demonstrate the significance of specifying the boundary conditions at the base of the wall. In view of the marked difference in the soil deformation above and below the level of the wall base, a discontinuity in the finite element idealization must be incorporated at this level in order to account for the relative displacements occurring in the soil media, especially at large wall deformation. Such discontinuity is essential as there is no provision in the oonventional finite element theory for relative displacements to occur between adjacent elements. It will be recalled that the discontinuity behavior as adopted in this study is governed by the soil constitutive shear stress-relative displacement relationship.

The significance of providing such discontinuity can be demonstrated with reference to Morgenstern and Eisenstein (1970) results. Figure 7-2 shows a set of results obtained for conditions of passive pressure where the wall is pushed into an elastic medium by a distance equal to 0.0025 of wall height. It is seen that the passive resistance is increased substantially by the presence of a rough rigid base at the bottom of the excavation. Moreover, the influence of conditions along the rigid base decreases with increasing distance from the bottom of the excavation. Morgenstern and Eisenstein concluded that the boundary conditions between the rigid base and the foundation layer have a significant effect on earth pressures, the pressure distribution on the wall becoming nonlinear with a rough boundary. It is argued here that such



FIGURE 7-2 LATERAL PRESSURE DISTRIBUTIONS FOR DIFFERENT BOUNDARY CONDITIONS WHEN THE WALL YIELDS 0,0025 H IN THE PASSIVE SENSE.

> (After Morgenstern and Eisenstein, 1970)

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an effect resulted from inadequacy of the proposed finite element model to deal with relative displacement at the bottom of the excavation. In their model the wall has to drag all the foundation layer as it moves, which results in very high pressures at the base of the wall as shown in their pressure distributions. More appreciation of this point will be gained in the next section with the presentation of results and related discussion.

With this understanding of the problem, four analyses of walls translating in a passive sense were performed. Table 7-1 lists the different schemes employed in the analysis of these problems.

## 7.2.3. Results and Discussion

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where

(a) <u>Total lateral pressures</u>: The total lateral pressures for a 4.0 inch model retaining wall are plotted in Fig. 7-3 as a function of the wall displacement toward the backfill. Each of the pressure displacement curves is labelled according to the problem boundary conditions adopted [Table 7-1]. On the same Figure the classical passive earth pressure value for a smooth wall is also plotted. According to the Coulomb and the Rankine theories, a soil with no friction ( $\phi = 0$ ) but with cohesion (C > 0) will offer resistance to lateral displacements expressed by:

$$P_{p} = \frac{1}{2} \gamma H^{2} + 2CH$$
 (7.1)

(7:2)

At depth h below the soil surface, the lateral resistance will be

| · * *                | TABLE 7-          | <u>ŀ</u>     | . <b>.</b> . |    |
|----------------------|-------------------|--------------|--------------|----|
| CLASSIFICATION OF SC | HEMES EN          | PLOYED IN    | ANALYSES     | 0F |
| 1                    | The second second | -X-Y-X-X-T-7 |              | _  |

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RETAINING WALL PROBLEM

| Problem<br>No. | Interface<br>Condition | Cutting<br>Plane | Total<br>No. of<br>Elements | No. of<br>Interface<br>El <u>ements</u> | No. of<br>Cutting<br>Elements | Noof<br>Nodes | Total<br>Wall<br>Displ.<br>Inch | No. of<br>Incre-<br>ments | No. of<br>Iter-<br>ations | Material<br>Properties |
|----------------|------------------------|------------------|-----------------------------|-----------------------------------------|-------------------------------|---------------|---------------------------------|---------------------------|---------------------------|------------------------|
| · 1            | Rough                  | No               | 302                         |                                         | -                             | 178           | 0.5                             | 10                        | ر<br>۲                    | E <sub>o</sub> = 90psi |
| <b>2</b>       | Rough *                | Yes              | 316                         | <b>-</b>                                | ° 14₁                         | 193           | 0:5                             | . 10                      | 3                         | ν = 0.48               |
| 3              | Wall adheston          | Yes -            | 324                         | 8                                       | 14                            | 202           | 0.5                             | 10                        | 3                         | γ = 100 pcf            |
| 4              | Smooth                 | ° Yes            | <sup>-</sup> 316            | <b>-</b>                                | 14                            | 193           | 0.5                             | 10                        | . 3                       | C = 1.16 ps1           |
|                |                        |                  | ;                           |                                         | 5                             |               |                                 |                           |                           | φ = 0                  |

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- P<sub>n</sub> = total lateral pressure on the wall, lb.
- $\gamma$  = soil density, pcf.
- H = wall height, feet.
- P<sub>h</sub> = lateral pressure at depth h below the soil surface, psf.

The data in Fig. 7-3 show that the classical passive earth pressure is reached at different values of wall movement, depending on the boundary conditions assumed. At an inward movement of the wall,  $\Delta$ , of only 0.11 inch [or at a  $\Delta$ /H ratio of 0.0275], the perfectly rough wall-no cutting plane model reaches the value predicted by the classical <u>earth pressure theory</u>. For the smooth wall-cutting plane model, the passive condition is reached at the largest wall movement  $\Delta$  of 0.05875 of wall height. The perfectly rough wall-cutting plane and the wall adhesioncutting plane models lie in between the above two limits.

Table 7-2 presents a summary of the total lateral pressures calculated by the finite element analyses as a percentage of the classical earth pressure value for a smooth wall. From this Table, and also from Fig. 7-3, the following observations can be made:

> The effect of the cutting plane is to reduce the total lateral pressure on the wall. The reduction varies from 32.5% for  $\Delta/H$  of 0.025 to 28.5% for  $\Delta/H$  of 0.125. Such reduction is caused by the decrease in the magnitude of pressure developing at the bottom of the wall [shown in the pressure distribution diagrams, Figs. 7-4 and 7-5].

|   | •              |                                                        |                                | (                          |                            | •                         | · · ·                      | <b>1</b><br>20  |
|---|----------------|--------------------------------------------------------|--------------------------------|----------------------------|----------------------------|---------------------------|----------------------------|-----------------|
|   |                | SIBMADY OF                                             | TABI                           | 5.7-2<br>DBESSIDE HT       |                            |                           |                            | ·<br>· · ·<br>· |
| · | -              | AS A PERCENTAGE OF                                     | TED BY THE F                   | INTE ELEMEN<br>TH PRESSURE | T ANALYSES<br>VALUE FOR A  | SMOOTH WAL                | <b>L</b>                   | -               |
|   | Problem<br>No. | Boundary Conditions                                    | $\frac{\Delta}{H} = 0.025^{*}$ | $\frac{\Delta}{H} = 0.05$  | $\frac{\Delta}{H} = 0.075$ | $\frac{\Delta}{H}$ = 0.10 | $\frac{\Delta}{H} = 0.125$ |                 |
|   | 1              | Perfectly rough wall<br>No cutting plane               | - 94                           | ¥<br>134 <u>.</u> 4        | ີສ<br>159.7                | 177.8                     | <b>%</b><br>192            | `~~             |
| • | 2              | Perfectly rough wall<br>Cutting plane                  | 71.4                           | 102.2                      | 121.7                      | 136.2                     | 147.5                      |                 |
|   | 3              | Wall adhesion<br>(interface element)<br>Cutting plane  | 64.9                           | 98.6                       | 119.1                      | 133.8                     | 145.4                      |                 |
|   | 4              | Smooth wall<br>Cutting plane                           | 64.8                           | 92.0                       | 111.4                      | 126.3                     | 137.9                      |                 |
|   |                | <pre>▲ = Wall movement<br/>H = Total Height of W</pre> | ka11                           |                            |                            |                           | <u> 8</u>                  | ,               |

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As would be expected, wall translation with full adhesion [perfectly rough case] increases pressure on the back of the wall, while the case of no wall adhesion [smooth] gives the minimum pressure. The wall adhesion [i.e. interface element] model is seen to lie between the two limiting assumptions.

(b) <u>Wall pressure distributions</u>: The lateral earth pressure distributions for the four cases being discussed are shown in Figs. 7-4 to 7-7, inclusive. These pressure distributions are plotted for various amounts of wall translation and each of the pressure-depth curve shown is labelled according to the amount of inward wall movement  $\Delta$ , as a ratio of wall height, H. In these Figures the lateral passive earth pressure distribution computed from the classical theories of Coulomb and Rankine, Eq. (7.2), is also plotted.

It is of interest to note that a strongly nonlinear distribution arises in the case of a perfectly rough wall with no cutting plane, Fig. 7-4. Such nonlinearity is shown to be due to the development of substantial lateral pressure along the base of the wall. This distribution, when compared with the distribution of the perfectly rough wallcutting plane model, Fig. 7-5, indicates close similarity for the upper three-quarters of wall height. In the lower quarter of the wall a reduction in pressure of more than 50% resulted when including a cutting plane in the finite element analysis. It is seen that, without taking into consideration the wall interface characteristics, the cutting plane model indicates closer agreement with the classical theory distribution.

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Examination of Figs. 7-5, 7-6 and 7-7, discloses the influence of soil-wall interface characteristics on the shape of the lateral pressure distribution. The main difference between the various shapes is exhibited in the nonlinearity of the diagrams near the soil surface. When the wall is considered perfectly rough the pressure reaches a minimum near the wall mid-height and then increases approaching the soil surface. In the cases of the smooth wall and the wall adhesion models, the pressures are seen to be minimum at the soil surface, with lower values for the smooth wall. Closer agreement between the pressure distribution of the wall adhesion case and the classical distribution is again observed.

The tangential pressure distributions are plotted in Figs. 7-8, 7-9 and 7-10 for the perfectly rough-no cutting plane, perfectly roughcutting plane and wall adhesion-cutting plane models, respectively. It is seen from these figures that the direction of the tangential pressure is mostly downward except at the base of the wall where it reverses to upward. The existence of a cutting plane is shown to reduce the upward tangential stresses at the wall base. Finally, the wall adhesion model is seen to exhibit very little upward pressure at the wall base, and smaller tangential pressures along the wall.

(c) <u>Stresses in soil</u>: Since the stress distribution may be used as the basis for predicting the locations of the failure zones, it is of interest to compare the influence of the boundary conditions on the distribution of stresses in the soil mass, for the cases studied. Three examples of contours of horizontal, vertical and shear soil stresses







are shown in Figs. 7-11 to 7-13 for the perfectly rough-cutting plane, wall adhesion-cutting plane and smooth-cutting plane models. These examples are all for wall movement,  $\Delta$  of 0.05 of wall height, and therefore the differences arise from the boundary conditions. It is seen from these Figures that substantial differences exist in the stress distributions for the three cases. The horizontal, vertical and shear stresses developed for the case of perfectly rough wall are shown to be much higher than those developed in front of a smooth wall, with the stresses for the wall adhesion case lying in between. Also, while the contours of the horizontal normal stress,  $\sigma_y$ , seem to maintain the same general shapes for the three cases, the vertical stress,  $\sigma_v$ , distribution for the case of a smooth wall differs from the other two cases. A large zone of the soil in front of the smooth wall experiences zero vertical stresses or very slight tension. This behavior was also observed in case of cutting blades, Section 5.4, at a larger blade dis-It may be recalled that all the cutting blade placement of 0.5 inch. analyses were performed with interface elements which suggest that the effect of the roughness of the moving element [on the upward tangentia] stresses] is to retard the formation of zones of vertical tensile stresses.

In case of shear stress distributions, it is seen that the stresses developed in the wall adhesion case are very similar to those existing in front of the perfectly rough wall. Much lower shear stresses are developed when the wall is smooth. It is clear from the above discussion that the effect of soil-wall interface condition is very pronounced on the development of stresses in the soil mass.






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### 7.2.4. / Summary

The study described in this Section was performed to obtain comparisons between the finite element results derived from the idealizations and the solution technique developed with a conventional method based on a closed-form solution. To this end a typical example of a nonlinear problem of a long vertical retaining wall with cohesive soils on one side was analyzed. Four schemes were adopted to examine the influence of the soil-wall interface characteristics and the effectiveness of inserting a cutting plane at the base of the excavation. Examination of the results reported in this Section shows that:

- (a) The effect of the cutting plane is found to reduce the magnitude of the high pressures developed at the wall base caused by the inadequacy of the conventional finite element idealization to account for the soil relative displacements at the bottom of the excavation.
- (b) The soil stress distributions are shown to depend on the soil-wall interface condition. The soil stresses for the case of the perfectly rough wall are shown to be the highest, followed by the soil-wall adhesion case, and then the smooth wall scheme.
- (c) With regard to the wall pressure distribution as influenced by the different schemes of soil-wall interface characteristics, it has been shown that the soil-wall adhesion finite element scheme [employing interface elements] provides the closest correspondence to the classical earth pressure distribution.

## 7.3 <u>SOIL CUTTING PROBLEM</u> -COMPARISONS WITH RESULTS COMPUTED FROM THE PREVIOUS THEORIES OF SOIL CUTTING

The problems of soil cutting have been studied by several investigators [Appendix C]. Most of the theories developed to predict the forces on two-dimensional cutting blades were based on the assumption of a slip surface along which the failure of the soil mass takes Osman (1964) has shown that the method due to Ode (1938) for place. the solution of the plastic equilibrium of the mass of soil within a curved failure boundary yielded accurate correlation with experimental observations in three types of soil [viz. a purely frictional, a purely cohesive, and a C- $\phi$  type of soil]. A similar investigation carried out by Siemen's et al. (1964), when re-assessed on the soil values worked out by Bailey (1964), also showed that the logarithmic spiral method gave good correlation with experimental observations. Some of the widely used relations are due to Reece (1965) and Hettiaratchi et al. (1966), which also use the analytical solution due to Ode for computing the forces on blades. In this Section, the results obtained from the finite element analysis and the experimental data will be compared with those obtained from Reece and Hettiaratchi et al. methods of computation.

Reace (1965) proposed an equation similar to that of Terzaghi's bearing capacity equation [Terzaghi (1944)], to compute the draft forces on a two-dimensional blade. This equation has the form:

(7.3)

F 1b/ft = 2CbN<sub>c</sub> +  $2b^2\gamma N_{\gamma}$  +  $2bqN_{q}$  + C bN<sub>a</sub>

where

F = force per unit width.

b = a characteristic dimension.

: • cohesion.

r = soil density.

q = surcharge pressure.

 $C_{a} = soil-metal adhesion.$ 

 $N_{c}, N_{\gamma}, N_{q}, N_{\alpha}$  = dimensionless factors depending on shape of soil failure surface.

In Eq. (7.3) the four terms on the righthandside represent the effect of the soil's cohesion, its weight, any surcharging load that is present, and the adhesion that develops between the soil and the blade surface. The N-factors are dimensionless numbers describing the shape of the soil failure surface. They, therefore, depend on the angle of internal friction,  $\phi$ , the angle of wall friction,  $\delta$ , and the shape of the structure and soil mass involved in the system.

It must be pointed out here that Reece's equation is not based on any rigorous mathematical proof. In addition, the failure zone chosen, as Reece admits, does not even fulfil the conditions of static equilibrium [it results in an impossible stress situation at the actual blade surface], let alone kinematic requirements. The simple four-part equation [Eq. (7.3)] with its dimensionless N-factors are shown to be dependent on the main variables [density  $\gamma$ , cohesion C, admesion C<sub>a</sub>, and surcharge q], leading to a certain degree of error. The magnitudes of error in predicting the forces on cutting blades, employing Reece's equation, were evaluated by Hettiaratchi et al. (1966). While Eq. (7.3) includes terms for soil-metal adhesion and surcharge effect, Reece (1965) presented charts for the determination  $\delta K$  the N<sub>c</sub> and N<sub>y</sub> factors only [i.e., soil weight and cohesion effects).

The cohesion value for the kaolinite clay used in this study was found to be 1.16 psi [Fig. A-5, Appendix A]. This value, together with an average value of soil density of 0.060 lb/in? was used for the calculation of forces on the blades employing Eq. (7.3), with the soil adhesion and surcharge terms omitted. The computed horizontal and vertical forces are compared with the finite element and experimental results in Fig. 7-14 and Table 7-3. Examination of these results are presented later on in this Section.

An investigation was undertaken by Hettlaratchi et al. (1966) to check the solution of the passive earth pressure problem as proposed by Reece (1965) and to present computed values of his N-factors for the solution of simple two-dimensional soil cutting problems. Briefly, the logarithmic spiral method as used by the authors assumes a composite failure boundary composed of a curved part 'BC' [Fig. 7-15] and a plane section 'CD'. The latter is the last slip plane of the Rankine passive zone 'ACD' which joins up with the failure plane containing the lower edge of the loaded interface. Thus 'CD' and 'AC' make an angle of  $(45 - \frac{1}{2})$  with the horizontal free soil surface. The curved part 'BC' is assumed to be part of a logarithmic spiral represented by  $r = r_0 e^{\omega tan\phi}$ where  $r_n^{(1)}$  is the initial radius 'OB' and  $\omega$  is the spiral angle 'BOC'. The pole 0 of the spiral is assumed to line on 'CA' or 'CA' produced. Evidently there is an infinite number of possible failure surfaces for given interface geometry consistent with the location of the pole at



# TABLE 7-3

# COMPARISON OF HORIZONTAL AND VERTICAL FORCES ON

| s .                                        | HORIZONTAL FORCE                   |               |                                    | VERTICAL FORCE |                  |                  |                             |                 |
|--------------------------------------------|------------------------------------|---------------|------------------------------------|----------------|------------------|------------------|-----------------------------|-----------------|
|                                            | ANGLE OF BLADE INCLINATION-DEGREES |               | ANGLE OF BLADE INCLINATION-DEGREES |                |                  |                  |                             |                 |
| •                                          | 10                                 | 20            | 40 _                               | 50             | 10               | 20               | 40                          | 50              |
| Reece's Equation                           | · 32.2                             | 27.8          | 20.6                               | 18.8           | - 9.9            | - 6.2            | - 2.8                       | - 1.45 .        |
| Hettiaratchi et al.<br>Equation            | 40.6                               | 36.8          | 25.95                              | 22.05          | - 8.45           | - 2.94           | + 1.73                      | + 2.38          |
| Finite Element at<br>0.5 inch Displacement | 42.46                              | •             | , <b>-</b>                         | 21.25          | - 1.75           | -                | <b>-</b> ,                  | +10.90          |
| Experiment at<br>0.5 inch Displacement     | 40.8<br>44.0                       | 39.0<br>•35.5 | 27.8<br>29.0                       | 24.3<br>24.0   | - 2.13<br>- 2.75 | + 0.50<br>+ 1.20 | + 7.90<br>+ 7.0             | +12.2<br>+13.1  |
| Finite Element at<br>1.0 inch Displacement | 54.07                              | -             | -                                  | 26.07          | - 2.15           | -                | -                           | +13.2           |
| Experiment at<br>1.0 inch Displacement     | 56.1<br>60.0                       | 49.0<br>46.4  | 32.1<br>36.3                       | 29.0<br>28.2   | - 2.3<br>- 2.7   | + 1.7<br>+ 4.1   | + 9.3 <sup>+</sup><br>+12.4 | +14.2<br>+14.13 |

SOIL-CUTTING BLADES BY DIFFERENT METHODS

- Negative values indicate upward forces.



FIGURE 7-15

DETERMINATION OF PASSIVE EARTH PRESSURE BY THE LOGARITHMIC SPIRAL METHOD

[After Hettiaratchi et al. (1966)]

some point on 'CA'. The required failure surface boundary is the one that gives the minimum force on the loaded interface 'AB'. Thus, for "any given location of the pole 0 at a distance say  $\lambda$  from A along 'CA', the total soil reaction P on the plane 'AB' can be evaluated by considering the equilibrium of the soil within the segment 'ABCE'. The correct value of P can be found for that value of  $\lambda$  which satisfies the condition  $\frac{dP}{d\lambda} = 0$ . As the calculation of P for even a single value of  $\lambda$  is extremely tedious, the authors proposed an alternative method. From Fig. 7-15, P is found to be equal to the sum of  $P_{\gamma}$ ,  $P_{c}$ ,  $P_{a}$  and  $P_{q}$ , or

 $P = P'_{Y} + P_{c} + P_{a} + P_{q}$ 

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=  $\gamma Z^2 N_{\gamma}$  +  $C Z N_c$  +  $C_a Z N_{\alpha}$  +  $q Z N_q$ 

where  $P_{\psi}$ ,  $P_{c}$ ,  $P_{a}$ ,  $P_{q}$  are the soll reactions on the interface due to weight, cohesion, adhesion and surcharge, respectively.

The value of  $N_{\gamma}$ , in the above equation, can be obtained simply by considering a soil with no cohesion, adhesion or surcharge. Thus, the force P acting on a particular interface under these conditions can be computed for arbitrary values of  $\gamma$  and Z over the entire range of variables [ $\phi$ ,  $\delta$  and Z]. Values of  $N_c$  can be obtained by calculating fresh values of P taking into account cohesion as well as weight. In a similar manner values of  $N_{\alpha}$  and  $N_{q}$  are obtained. Hettiaratchi et al. (1966) computed the four N-factors for a complete range of values of  $\phi$  for the two extreme values of  $\delta$ , that is,  $\delta = 0$  and  $\delta = \phi$ , for values of rake angles varying from 45 -  $\phi/2$  to 135 -  $\phi/2$ .<sup>\*</sup> They also produced suitable interpolation formulae and graphs showing the rupture distance as a function of the soil and blade variables.

In applying the method suggested by Hettiaratchi et al. to the problem under study, the following values are used:

Soil properties:C = 1.16 psi $\phi = 0 \rightarrow \gamma = 0.060 \text{ lb/in}^3$ Soil-metal values: $\delta = 0$  $C_a = 1.16 \text{ psi}$ 

The horizontal and vertical forces computed, using the N-factors presented by Hettiaratchi et al., are plotted in Fig. 7-14 and shown in Table 7-3, as a function of blade inclination angle.

According to the mathemátical model of limit equilibrium, the soil is rigid up to the point of failure, whereupon it flows steadily at constant stress. This would result in a definite failure load at zero displacement, which then increases linearly with the displacement as the surcharge builds up. The theory would predict the initial force value. In practice, however, this is not the case. The force-displacement results shown in Figs. 4-2 and 4-3 indicate that the force records reach their maximum values at very considerable values of strain. Moreover, the force records have no peaks, indicating failure at maximum density, nor valleys, signifying reduced resistance offered by the soil after it has failed.

It was thought that a decision as to which point on the force record should be taken could perhaps be made by noting when the first shear plane emerged at the surface. However, as mentioned earlier, the soil tested did not exhibit distinct failure planes.

It must be mentioned here that it is not always possible to

obtain information on first peaks in many reported studies for comparison purposes. It is expected that the asymptotic value of the force record may be the one generally used. In that regard, the limit equilibrium approach to the analysis of the problem would in general underestimate the total draft or horizontal force in view of the marked change in the geometry of the deforming soils.

For lack of a more definite criteria to define failure in the experimental force records reported in this study, computed forces using<sup>6</sup> Reece's and Hettiaratchi et al. limiting equilibrium approach are compared with the finite element and experimental forces obtained at 0.5 and 1.0 inch of blade displacements. While such a choice may raise questions, any other failure definition is just as arbitrary. Such inability to correlate between forces developed in a continuous deformation process and forces predicted by the limit equilibrium theorems is due, as pointed out earlier, to the development of the limit equilibrium approach without reference to the stress-strain relations and kinematic considerations.

The analytical methods suggested by Reece (1965) and Hettiaratchi et al. (1966) for computing the theoretical forces may be examined, using the test results obtained from this study as a base for comparison. In Fig. 7-14 and Table 7-3, these comparisons are shown together with the present finite element approach computations for forces acting on the 10° and 50° inclined blades. It is seen that the predicted horizontal forces using Hettiaratchi et al. data show good agreement with the forces obtained from the actual test results as well as the finite element analysis obtained at 0.5 inch of blade displacement. On the

other hand, Reece's method is found to underestimate the draft forces.

The divergence between Reece's and Hettiaratchi et al. results can be accounted for by considering the following factors:

1. While Reece presented Eq. (7.3) with the four terms representing the gravitational, cohesive, adhesive and surcharge components of the soil reaction, he only provided data for obtaining N<sub>Y</sub> and N<sub>C</sub>. Thus, Eq. (7.3) reduces in fact to the following form:

 $P = \gamma Z^2 N_{\gamma} + C Z N_{C}$ 

Whereas the surcharge effect can be considered to be negligible in the present case, eliminating the soil-metal adhesion term leads to a large error, especially when dealing with a purely cohesive soil as in the present investigation. The value of the adhesion term  $C_a ZN_{\alpha}$ , with the magnitude  $N_{\alpha}$  obtained from Hettiaratchi et al. charts, of was added to Reece's results. This resulted in a very close agreement with the horizontal forces obtained from Hettlaratchi et al. data for the 10°, and to a certain extent, the 20° inclined blades. However, in case of the 40° and 50° inclined blades appreciable differences remained even after adding the adhesion term to Reece's equation.

In the case of a cohesive soil, the largest contribution to the draft force results from the cohesion term CZN<sub>c</sub>. The N<sub>c</sub> values obtained for the different inclined blades are as follows:

| Blade angle<br>with vertical              | 10°  | 20°  | <b>4</b> 0° | 50°  |
|-------------------------------------------|------|------|-------------|------|
| N <sub>c</sub> [Reece]                    | 1.75 | 1.45 | 1.00        | 0.90 |
| N <sub>c</sub> [Hettiaratchi<br>` et al.] | 1.75 | 1.65 | 1.45        | 1.35 |

It is seen that while the  $N_c$  values obtained from the two methods are the same for the 10° blade, Reece's  $N_c$  values are smaller than those of Hettiaratchi et al. for the rest of the blade angles. The deviation between the  $N_c$  values is seen to increase with the blade inclination. This results in lower values for Reece's cohesion term (CZN<sub>c</sub>), and hence smaller predicted forces.

The above two reasons account fully for the difference between the forces predicted by Reece's data and those obtained using Hettiarat-. chi et al. method of computation.

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No. Contraction

In comparing the developed forces obtained from the limit equilibrium approach [Reece and Hettiaratchi et al. methods], Table 7-3 lists both the experimental and the finite element results at 0.5 and 1.0 inch of blade displacements. A closer examination of the values in this Table reveals that the forces reported at 0.5 inch of blade displacement are seen to provide a better degree of correspondence with those computed using

the limit equilibrium methods. As pointed out earlier in this Section, the limit equilibrium approach assumes that the soil is rigid up to the point of failure. This would result in a definite failure load at zero blade displacement which then increases with displacement as the surcharge builds up. Such an assumption is not realistic especially in the case of a plastic soil where the failure occurs at a very considerable value of strain. Taking this consideration into account, it was decided that the 0.5 inch blade displacement is large enough to produce failure conditions similar to those of the limit equilibrium model, and is small enough not to include the surcharge effect.

From Fig. 7-14 and Table 7-3 it is noted that while both the experimental and theoretical horizontal forces [developed at 0.5 inch of blade displacement] reported in this study do agree with those computed by Hettiaratchi et al. method, it is not the case with regard to the vertical forces. It is perhaps instructive at this point to note that Reece's equation [Eq.(7.3)] computes the total resultant force P per unit width of the interface, Fig. 7-15. This force acts at angle  $\delta$  with the normal to the interface. If, however, the vertical force is required, it is computed as the resultant of the vertical component of the force P and the appropriate component of the adhesion force R<sub>a</sub> Fig. 7-15, which acts upwards along the interface. The adhesion force R<sub>a</sub> is equal to:

# $R_a = C_a x I$

where

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 $C_{1}$  = adhesion,  $1b/in^{2}$ 

Inches.

In the application of the limit equilibrium approach it is assumed that the soil directly in front of the blade is in a state of failure and that the full adhesion value,  $C_a$ , is developed along the interface. Harrison (1973) has shown that this is often not so. The adhesion value of the kaolin clay, as measured by the soil-to-metal direct shear test presented in Section 4.A.3, is shown to be lower than the clay strength or the cohesion value, Fig. 4-11. It has also been found that the tangential stress values, or adhesion, on the soil-metal interface increases with increasing displacement reaching maximum values at relative displacements of approximately 0.2 inch, Fig. 4-10. Moreover, the adhesion values are shown to depend on the normal stresses, ranging from 93% of the cohesion value under zero normal load to about 82% for a normal load of 5.0 lb or more, Fig. 4-12. While the adhesive forces should be independent of the normal load, it should be recalled that such dependence was already shown to be due to the change of failure mode along the interface from a soil-to-soil shear under low normal stresses to a soil-to-metal failure when the normal stresses are increased.

Applying all these findings to the problem at hand, it has been made clear from the finite element analysis that the mobilization of the soil adhesion is a function of the relative displacements between the soil and the blade, or, in other words, a function of the blade displacement. Figures 5-20 and 5-21 show that the full value of adhesion is mobilized at a blade displacement of about 1.0 inch. These Figures also show that the mobilization of the soil adhesion is a function of the blade rake angle as the distributions of the tangential stresses are markedly different along the 10° and 50° inclined blade surfaces. Such

complex behavior sheds doubt on the validity of Hettiaratchi et al. assumption of constant uniform adhesion along the blade surface, and hence the computed vertical forces.

# 7.4 <u>SOIL-GROUSER INTERACTION PROBLEM</u> -/ COMPARISONS WITH RESULTS COMPUTED FROM THE <u>PREVIOUS THEORIES OF SOIL-GROUSER INTERACTION</u>

Most of the research done to date on the grouser-soil interaction problem has been oriented towards investigating the performance of the plate-grousers, either individually or in groups, Appendix C. The intensive research on the interaction of this grouser with soil is mainly due to the wide use of such an element in tracked-vehicles. As warranted as this may be, it is still necessary to examine other grouser geometries and their tractive efforts. It is precisely in this area that there appears to be a great lack of experimental or theoretical research work. Bearing this in mind, the examination and comparison of the traction results will be divided into two parts, those of the wedge grousers [i.e., C.E.W. and S.E.W. grousers], followed by those of the plate-grousers [R.A.P.G.].

#### a) Wedge Grousers

The wedge grouser-soil interaction process can be considered as a lateral earth pressure problem involving backward raked soil interfaces [i.e., rake angle > 90°]. In other words, the analysis can be performed considering the grousers as cutting elements with their lower edges trailing. Hettiaratchi et al. (1966) pointed out that lateral earth pressure problems involving backward raked soil interfaces [ $\alpha > 90^{\circ}$ , Fig. 7-16], have not yet been investigated experimentally, and that therefore the soil failure mode is not known. They postulated that under these conditions the interface "converts" itself by means of soil wedge ['ABG', Fig. 7-16], into a perfectly rough interface 'AG' having a smaller rake angle  $\alpha'$ . They proposed that the solution



## FIGURE 7-16

HETTIARATCHI ET AL. (1966) PROPOSED FAILURE SURFACE FOR LATERAL EARTH PRESSURE AT LARGE RAKE ANGLES

to this problem could be obtained using their method [Section 7.3] in conjunction with an appropriate modification factor. They also <u>stated that suitable modifications</u> and simplifications are required in using their method of solution to deal with problems of curved elements.

Investigating the draft of curved blades, Osman (1964) considered any curved blade to be one of a family of blades of increasing curvature, starting from the straight blade forming the chord between the cutting edge and the soil surface. While realizing that increasing curvature will cause increasing draft because shear strains must occur throughout the soil mass in front of the

blade, he postulated that the draft cannot increase beyond that required to cause the soil to flow up the straight line forming the chord across the blade between the cutting edge and the top This is because it is postple for the soil to fill up. edge. the curve, transforming the blade into a straight one with the same depth and rake angle, which results in a condition where  $\delta = \Phi$  and  $C_a = C$ . Such reasoning enabled Osman to put forward and experimentally verify the hypothesis that the draft of a curved blade must lie between two limits. The lower limit corresponds to a hypothetical plate blade forming the chord across the curved blade and having the friction and adhesion values of the curved blade surface. The upper limit is represented by the same straight blade but with the angle of soil-metal friction increased and the adhesion,  $C_a$ , to the value of soil cohesion, C.

By considering the wedge grousers to act as cutting elements with backward raked soil interfaces, the predictive methods of Reege (1965) and Hettiaratchi et a]. (1966) [Section 7.3] may be used to compute the developed forces on these elements to compare with those reported in this study. For the curved-edge wedge grousers [C.E.W. type (1) and C.E.W. type (2), Fig. 3-1], the hypothesis made by Osman (1964) is adopted to account for the effect of element curvature on the developed forces. It must be pointed out at this stage that these methods will not account for the effect of the horizontal plate, placed on top of the S.E.W. and the C.E.W. 'type (1) grousers, on the developed forces. The influence of these plates is to change the problem boundary condit-

ions from those similar to a lateral earth pressure problem where soil failure takes place due to a horizontal movement of the soil interface, to a problem combining the effect of lateral pressure with surface bearing capacity. Such change in boundary conditions should be expected to lead to errors in prediction.

In applying the methods of Reece and Hettiaratchi et al. for predicting the forces on the wedge grousers, the following assumptions and approximations are made:

> The failure boundary is composed of a curved part 'BC' Fig. 7-15, and a plane section 'CD'. The latter is the last slip plane of the Rankine passive zone 'ACD' which joins up with the failure plane containing the lower edge of the loaded interface. This assumption is subject to further experimental evidence.

 The curved grouser-soil interfaces are dealized by flat surfaces having the same depth and rake angle [Osman (1964)].

3. The soil-metal adhesion is equal to the value of the soil cohesion, and the angle of metal friction δ = 0. According to Osman's hypothesis, such an assumption represents
 an upper bound on the draft values.

The results computed employing Reece's and Hettiaratchi et al. methods, with the adoption of the above approximations, are shown in Table 7-4 for the three wedge grousers analyzed in this study, together with the finite element results and the experimental measurements obtained at 0.5 inch of grouser displacement. The reasons for the choice of the 0.5 inch grouser displacement criterion for comparison with the limit equilibrium results were discussed earlier in Section 7.3.

Examination of the results in Table 7-4 shows that, as in the case of soil cutting discussed in Section 7.3, Reece's method predicts smaller forces than those computed from Hettiarat-The lower values obtained from Reece's analysis chi et al. data. are again attributed to the omission of the soil-metal adhesion term,  $C_abN_{\alpha}$ , and to lower values of the cohesion term, CZN<sub>c</sub>, Eq. (7.3). It is also observed that Reece and Hettiaratchi et al. methods of computations, with the adoption of Osman's hypothesis, give the same forces for both the S.E.W. and the C.E.W. type (1) grouser-The same forces on both systems resulted since, by soil systems. adopting Osman's hypothesis, the /C.E.W. type (1) grouser, when idealized by a flat surface, wi/11 / have the geometry of the S.E.W. Moreover, even with the assumption of the metal-soil grouser. adhesion value equal to the soil cohesion, which is supposed to give an upper bound on the measured forces, the computed horizontal force for the C.E.W. type (X) growser is shown to be less than the measured Obviously, these results are in contradiction with Osman's one. hypothesis in that the /increase of element surface curvature increases the soil-metal contact area, and consequently the strains and stresses developed in the soil, which should lead to larger computed draft forces. It is only in case the soil-metal adhesion value is considerably less than the soil cohesion would such a hypothesis lead

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TABLE 7-4

COMPARISON OF HORIZONTAL AND VERTICAL FORCES ON

WEDGE GROUSERS BY DIFFERENT METHODS

|                                            | HORIZONTĄL FORCE |                    |                    | VERTICAL FORCE |                    |                    |  |
|--------------------------------------------|------------------|--------------------|--------------------|----------------|--------------------|--------------------|--|
| •                                          | GROUSER FYPE     |                    |                    | GROUSER TYPE   |                    |                    |  |
| • • •                                      | S.E.W.           | C.E.W.<br>Type (1) | C.É.₩.<br>Type (2) | S.E.W.         | C.E.W.<br>Type (1) | C.E.W.<br>Type (2) |  |
| Reece's Equation                           | -<br>24.92       | 24.92              | 23.19              | -22.91         | -22.91             | -22.61             |  |
| Hettiaratchi et al.<br>Method              | 33.42            | 33.42              | 32.04              | -26.43         | -26.43             | -25.86             |  |
| Finite Element at<br>0.5 inch Displacement | 37.98            | ` <b>-</b>         | 34.88              | -18,2          | -                  | -12.71             |  |
| Experiment at<br>0.5 inch Displacement     | 35.0<br>38.8     | 40.0<br>39.0       | 31.0<br>32.0       | -15.9<br>-14,7 | -16.5<br>-17.2     | -11.0<br>-11.70    |  |

- Negative values indicate upward forces.

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to an upper bound on the draft forces.

Comparing the developed forces computed by the various methods, with all the above points taken into consideration, it is seen that the horizontal forces predicted by Hettiaratchi et al. method show a fairly good degree of correspondence with the experimentally measured horizontal forces. However, the method is shown to overestimate the vertical forces. The reasons for such divergence were previously discussed in Section 7.3 and can be summarized, with regard to the traction results, in the following points:

- While the methods of limit equilibrium assume full mobilization of the soil-metal adhesion forces, it has been shown that the mobilization of adhesion is a function of the relative displacement between the soil and the metal interface, Section 7.3.
- 2. It has been shown from the finite element analysis, Fig. 6-22 and 6-23, that the shear stresses on the soil-metal interfaces change direction at a certain point on the interface. This finding is in contradiction with the limit equilibrium models proposed by Reece and Hettiaratchi et al. in which the adhesion force is assumed constant and acting upwards along the interface.

Finally, in general it is observed that the agreement between the finite element and the experimental results is very satisfactory for the two soil-grouser systems analyzed by the finite element method.

#### b) Plate Grousers

Regarding the developed forces on the plate grousers, results computed from Bekker's equations [Bekker (1960)] are compared with both the theoretically computed and the measured values in Table 7-5. In the Bekker equations [Eqs. (1.1) and (1.2) in Chapter 1 and also in Appendix C], the horizontal and vertical forces, H and W, are not expressed explicitly in terms of system parameters but are rather proportional to an angle 0 defined by:

 $\theta$  = arctan H/W -

where

 $H = b(n_c^{1}c + \gamma n_q^{1}z + \gamma n_Y^{1^2}) \sin \theta$  $W = b(n_c^{1}c + \gamma n_q^{1}z + \gamma n_Y^{1^2}) \cos \theta$ 

It is seen that H and W are dependent on such dimensionless trafficability factors as  $n_q$ ,  $n_c$ , and  $n_\gamma$ , all of which in themselves are dependent on  $\phi$ ,  $\theta$  and the ratio of 1/h, (Fig. 7-2).

In view of the above considerations, the two equations for H and W do not permit a direct determination of these forces but instead, must be solved by an iterative process, see Appendix C. In the case of a grouser moving at a constant elevation, an estimate for either H or W must be made to arrive at an estimate for  $\theta$ . The experimentally measured values of the vertical forces obtained at 0.5 inch of grouser displacement were substituted in Bekker's equations, and the corresponding horizontal forces were computed. The results of these computations are shown in Table 7-5, and it is seen that the deviation between Bekker's and the experimentally measured values is of the order of 6% for grouser aspect ratio h/l

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of 0.5 and about 18% for grouser with an aspect ratio (h/l) of 0.833.

Harrison (1973) developed a theory that predicts the passive pressure on a rough two-dimensional interface with one edge in the soil surface. The theory is based on slip line fields including wedges of soil that are in equilibrium, not failing, but in a stress state of incipient failure. The slipline fields vary with the interface angle  $\alpha$  and the angle of internal shearing resistance  $\phi$ , and are a function of the direction of motion of the interface 0. The detailed mathematical expressions for the horizontal and vertical forces acting on a plate grouser are given in Forces computed from Harrison's equations [Eq. (C.3), Appendix C. Appendix C], are compared in Table 7-5 with both the finite element and the experimentally measured forces obtained at 0.5 inch of grouser displacement. From-this Table, it is shown that Harrison's results deviate appreciably from the measured values. It is interesting to note that when examining Harrison's results for the case of constant grouser elevation [i.e.  $\theta = 0$ ], large discrepancies are found between the measured and the theoretically calculated forces. These discrepancies are reported in both the loam and clay series, while in the sand series good correlations are obtained. This behavior suggests that Harrison's hypothesis of the existence of a wedge-shaped zone of soil fixed to the interface, forming pseudo interface along which actual failure occurred, is not valid for the case of constant elevation tests in cohesive soils.

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# COMPARISON OF HORIZONTAL AND VERTICAL FOPCES ON RIGHT ANGLE PLATE GROUSERS BY DIFFERENT METHODS

| ***                                        | Grouser Aspect R | atio h/l = 0.5   | Grouser Aspect Ratio h/l = 0.833 |                |  |
|--------------------------------------------|------------------|------------------|----------------------------------|----------------|--|
|                                            | Horizontal Force | Vertical Force   | Horizontal Force                 | Vertical Force |  |
| Harrison's Equation                        | 48.62            | - 81.16          | ِ<br>58.57                       | - 64.0         |  |
| Bekker's Equation                          | 35.60            | - •              | 49.84                            | a •            |  |
| Finite Element at<br>0.5 inch Displacement | •<br>•<br>•      | -                | 41.47                            | - 23.63        |  |
| Experiment at 0.50 inch Displacement       | 33.2<br>34.1     | - 13.9<br>- 14.3 | 41.20<br>43.0                    | 18.0<br>- 19.2 |  |
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- Negative Values Indicate Upward Forces

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#### CHAPTER 8

## SUMMARY AND CONCLUSIONS

#### 8.1 SUMMARY

The primary goal of the problem examined in this study was to look into the possibility of providing a rational analytical means for predicting the performance of a number of cutting and traction tools, using parameters that describe the soil response due to interaction with the tool. The review of past work revealed the need for an analytical technique that can be efficiently employed in predicting both the stress distribution and the soil deformation resulting from a cutting or a traction tool loading, by taking into consideration the nonlinear behavior of soil and the effect of large deformation due to implement movement.

The field of research was shown to be extensive and of many dimensions. The scope of the study was therefore limited to verifying the validity and applicability of the suggested analytical model [finite element model] to the analysis of the problem of simplified cutting and traction elements interacting with a nearly-saturated kaolinite and an artificial-oil based clays under plane-strain conditions. The purpose of the experimental program was, therefore, to provide data on the interaction process which could be compared with the analytical results. The experimental investigation was divided into cutting tests and traction tests. In the former phase a series of flat blades with different angles of inclination were moved through the soil. On the

other hand, the traction study was concerned with the influence of grouser geometries on the developed forces. Both phases of the study were performed at specified constant speed and constant depth of cut.

An analytical model was developed using the finite element method to provide a theoretical solution to the soil cutting and traction problems. The developed model takes into account the effect of the progressive cutting of the soil at the tool tip, with the possible development of failure zones wherever the shear strength of the soil is exceeded. The solution provides detailed stress and deformation fields within the loaded soil, and contact stresses at the soiltool interface for various tool positions. Consequently, a relatively complete description of the load-deformation behavior as the tool advances in the soil was obtained.

The main features of the finite element model adopted in this study can be summarized as follows:

- a) Idealization
  - 1. The model incorporates two discontinuities. A cutting plane discontinuity positioned at the level of the tool tip representing the action of the cutting element, where severe relative displacements and separation of soil blocks take place. The second discontinuity is a soil-tool interface discontinuity representing the relative displacements occuring between the soil and the tool surface.

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2. The soil mass is modelled by plane-strain continuum elements representing a region in which plastic deformations take place with possibilities of localized or shear failures.

b) Boundary Conditions

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The boundary conditions for the analytical model can be either specified pressure, specified displacement, or both. Thus, the model is capable of handling mixed boundary value problems. Moreover, relative displacements occurring across a thin discontinuity are included in the formulation to account for different degrees of interfacial slip.

## c) Nonlinear Analysis

In the model developed, the stress-strain relations obtained from laboratory tests are used in the analysis to predict the load-deformation behavior of the soil. The tabular [direct digital] form is used to incorporate the constitutive law into the finite element model. The solution is obtained by the incremental method of analysis improved by iterating a few times in each increment of loading.

The application of energy conservation principles to soil cutting and soil traction problems provided a technique for a check on the finite element solution. Application of the visioplasticity method to

the experimentally recorded deformation fields, with the assumption that the stress-deformation behavior of the soil could be described by a rigid plastic model, enabled the calculations of the deformation energy fields of the loaded soils. These energy values were compared to those obtained from the finite element model.

The applicability of the proposed solution technique was further examined in order to assess the significance of the implied conditions and requirements. The examinations were conducted by:

> Firstly, applying the solution technique to the familiar problem of a long retaining wall, yielding in a passive sense. This constituted a parametric study to establish the relative importance of the various features and assumptions implemented in the finite element technique. • The results were compared with the conventional solution. A summary and findings of this study are presented in Section 7.2.4, Chapter 7.

Secondly, comparing the soil cutting and traction [analytical and experimental] results presented in this Thesis with results computed from existing theories.

### 3.2 CONTRIBUTION

This study contributes to the field mainly by having shown that the soil cutting and traction problems can be dealt with through an analytical approach which has the objective of deriving statically possible strains while, at the same time, satisfying some average boundary conditions, even though numerous assumptions and approximations needed to be made, especially regarding the mathematical modelling of the deforming medium.

Specific contributions are:

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- 1. The development of an analytical technique for the determination of the soil stress and deformation fields as well as contact stresses on the soiltool interface, thus providing a relatively complete description of the load-deformation behavior as the tool advances in the soil.
- The successful application of the method of finite element to the study of soil cutting and traction, and the verification of correspondence between measured and computed values.
- 3. The successful application of the principle of energy conservation to the cutting and traction element-soil systems. The developed solution, using the method of visioplasticity, provides reasonably good predictions of the experimentally measured energy components.

To the author's knowledge, the above has not been available in past published work and, in the author's opinion, contributes to the field of soil-machine interaction analysis.

8.3 CONCLUSIONS

On a long term basis, the present study may be looked upon as a step in the direction of an improved method for soil machine-interaction analysis. In its immediate application, the proposed method may contribute to a systematic study of cutting and traction elements travelling in clays by a rational scanning of all pertinent parameters. Eventually, it could be attempted to rationalize the deformation patterns and stress fields in terms of significant soil and tool parameters, and hence establish a complete and unified theory for cutting and traction in clay soils.

The following is a short summary of the conclusions arrived at in this study concerning the soil cutting and traction problems:

A. Soil Cutting Problem

ation.

Regarding the soil cutting developed forces it was found that:

1. The agreement between the experimentally measured and the finite element calculated forces is very satisfactory in the case of the horizontal forces for both the blade inclinations analyzed; the average error of estimate is of the order of 8%, while the maximum error is some 15%. With regard to the vertical forces, the values obtained from the analytical solution are, however, more subject to variation. The differences in the vertical forces can be attributed to the effect of the soil deformation behind and below the blades which has not been considered in the finite element ideamiz-

Regarding the deformation fields it was found that:

- The discontinuity in displacement at the level of the blade tip [on the cutting plane] is clearly demonstrated from the experimental plots. However, the experimental horizontal displacement fields reveal that the displacement contours are only discontinuous in the vicinity of the blade while at a distance they are shown to be continuous above and below the assumed cutting plane. Such behavior implies that the discontinuity in displacement propagates with the blade movement.
- 2. Examination of the experimental and the analytical horizontal displacement fields indicates that the finite element solution underestimates the horizontal displacements in the zone near the soil surface, while it overestimates in the soil mass situated directly above the cutting plane.

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In the vertical displacement fields a deviation between the experimental and analytical fields was observed in the location of the zero vertical displacement contour dividing zones of upward and downward movements.

The gualitative agreement between the experimental and the analytical deformation fields, taking all the above points into consideration, is found to be very satisfactory.

Régarding the deformation energy fields it was found that: The visioplasticity méthod as applied in this study, with the assumption of a rigid plastic model, overpredicts the deformation energy calculated from the integration of the experimentally measured load-deformation relationship, especially in the initial stages of the deformation process. On the other, hand, the finite element model developed in this Thesis, which treats the soil as a nonlinear strain-hardening material subject to boundary conditions of an incremental form, provides better estimates of the energy dissipated within the soil. The Tinite element average error of estimate, compared to the experimentally obtained energy values, is of the order of 10%. The maximum deviation is about 18%.

<u>Comparison with results computed from the previous theories</u> of soil cutting indicated that:

- The predicted horizontal forces using Hettiaratchi et al. (1966) data show good agreement with the forces obtained from the test results as well as from the finite element analysis at.
   0.5 inch of blade displacement. On the other hand, Reece's method is found to underestimate the draft forces.
  - The vertical forces [experimental and analytical] deviate. significantly from those computed from Hettiaratchi et al. method. This deviation is attributed to the fact that the mobilization of the soil-blade adhesion is a function of:

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- i) the relative displacements between the soil and the blade, or in other words, a function of blade displacement, and
- ii) the blade rake angle. The distributions of the tangential stresses are markedly different along the 10° and 50° inclined blade surfaces.
  This finding is in contrast to Hettiaratchi et al. and Reece's assumption of constant uniform adhesion along the blade surface.

### B. Soil-Grouser Interaction Problem

Regarding the developed forces on the various grousers it was found that:

Concerning the measured developed forces on the various 1. grousers employed in this study, the plate grouser. [R.A.P.G.] with an aspect ratio h/l of 0.833 was found to develop the highest horizontal as well as vertical forces when compared to the wedge grousers. This is attributed to the soil deformation behavior in front of the plate grouser where a rigid zone, similar to  $\Im$ the "dead" zone postulated by Terzaghi (1948) for bearing capacity, was observed. The compression in this zone extends the region of influence of the grouser, resulting in larger developed forces. In the wedge grouser experiments, very small or no rigid zones were observed, and the regions of influence of such grousers were found to be smaller than those of the plate grouser [R.A.P.G.].

2. The agreement between the experimentally measured and the finite element calculated forces, considering the assumptions made, is generally very satisfactory. The analytical and test results, however, show better agreement in the case of the horizontal forces, for which the percentage difference rarely exceeds 10%. In the case of the vertical forces, the average error or estimate is of the order of 20%, while the maximum error is some 40%.

Regarding the deformation fields it was found that: Generally the correspondence between the analytical and the experimental deformation fields for both the horizontal and vertical displacements is judged to be Satisfactory. The finite element model, however, is found to possess more regidity in the x-direction and more flexibility in the y-direction, when comparing dfsplacements with those measured.

Regarding the deformation energy fields it was found that: in the case of the soil cutting comparisons, the visioplasticity method overestimates the deformation energy in all cases, while the finite element results show a better correlation with the measured input energy.
Comparison with results computed from the previous theories of soil-grouser interaction indicated that:

- By considering the wedge grousers to act as cutting elements with backward raked soil interfaces, the predictive methods of Reece (1965) and Hettiaratchi et al. (1966), together with the hypothesis put forward by Osman (1964) to account for the effect of element curvature, could be used to compute the developed forces on these elements.
- 2. The horizontal forces predicted by Hettiaratchi et al. method of computation show a fairly good degree of correspondence with the measured forces for the wedge grousers. With regard to the vertical forces, a significant deviation is obtained between the calculated and the measured values. The deviation is attributed to the facts that:
  - The mobilization of adhesion is a function of the relative displacement between the soil and the metal interface.
  - ii) The shear stresses on the soll-metal interfaces change direction at a certain point on the interface.

3. When comparing the developed forces on the plate grouser ... [R.A.P.G.] with Bekker's equations, the deviation between Bekker's and the experimentally measured values is found to be of the order of 6% for grouser aspect ratio [h/1] of 0.5 and about 18% for the grouser with a ratio [h/1] of 0.833.

4. Forces computed from Harrison's equations (1973) deviate considerably from those measured or computed. However, when examining Harrison's results for the case of constant grouser elevations, large discrepancies were also found between his measured and his calculated values. This sheds doubt on the validity of his hypothesis for the case of grousers tested under constant elevation condition in cohesive soils.

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## APPENDIX A

## SECTION A

#### EXPERIMENTAL CONSIDERATIONS

## A.1 DESCRIPTION OF THE TEST FACILITY

A.1.1 / Apparatus

As constructed, the apparatus consisted of a tool plate rigidly attached to a carriage which allowed it to translate both horizontally and vertically but which permitted no angular rotation, Fig. A-1 and Plate A-1.

The carriage itself was mounted on roller bearings which travelled in polished guide rails. The rails were machined to a tolerance of 0.003 inches, and as a consequence the frictional resistance of the system was reduced to a minimum, the force required to overcome this resistance being typically of the order of two per cent to four per cent of the total measured horizontal force.

The drive mechanism of the apparatus consisted of a threaded shaft which was, in effect, a worm gear. This was driven by a 1/2-horsepower varying speed electric motor and a V-belt pulley assembly through a system of gears.

The carriage and tool assembly were mounted on a frame in such a position that it was directly above a soil bin whose dimensions were 22 1/2 ins. x 4 ins. in planform and which usually accommodated a

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depth of clay of the order of nine inches. The bin was equipped with removable lucite side walls and was mounted on castors to facilitate its removal from under the carriage. The carriage and bin are shown in Fig. A-1.

#### A.1.2 Measuring and Recording Devices

All forces and displacements were measured by means of electrical transducers. The horizontal and vertical force transducers were of 0-100 lb capacity, and were manufactured by the Dynisco Division of the Abex Corporation. They were both excited by a 6-volt direct current voltage and had a full range sensitivity of the order of 3.5 mv/volt of excitation.

The horizontal displacement transducer was of the linear displacement type, utilizing a moving core in an electro-magnetic field. This transducer also required a 6-volt direct current excitation signal and had a maximum stroke of 1.5 inches.

The output of the transducers were fed into a 6-channel Sanborn Series 850 Recording System. The signals from the force transducers were fed into series 850-1800 preamplifiers with a sensitivity range of 0-100 mv/cm of deflection, while the displacement transducer signal was fed into series 850-1300 preamplifier with sensitivity range of 0-50 volts/cm in ten steps.

A 35 mm Pentax type SV Camera with Kodak Plus-X Panachromatic film was used to record grid distortions.

A.2 SAMPLE PREPARATION

The soil was prepared for placement in the soil bin by the following steps:

Soil Mixing [in the case of the natural kaolinite clay]. Dry

kaolinite in powder form [stored in approximately 50-pound bags] was deposited in 50-pound lifts forming approximately two inch deep layer in a batching reservoir. Each lift was sprinkled with sufficient water to bring the soil to the desired water content. The water was allowed to soak in and the next lift was added. The wet soil was allowed to stand in the batching bin for seven days. At the end of this period the soil was mechanically mixed to improve homogeneity.

Soil Placing The removable side of the bin was first taken off

and the inner surfaces of the remaining open box were coated with vaseline. Remoulded kaolinite of water content of  $52.5\% \pm 1.0\%$  was manually deposited in small lumps, tamped and rolled in one inch lifts. When the sample thickness was a little over the thickness of the bin, the excess was trimmed off with a wire saw and the surface smoothed over with a trowel.

Grid Placing Once the soil sample had been prepared, the

selected tool [cutting blade or grouser] was embedded in the clay at a specified location. The various grousers employed during the course of this investigation are shown in Plates A-2 to A-4, inclusive. A grid network of one-half-inch squares was then made on the soil surface with a black pen and a





plotted lucite sheet, This was done by first placing the plotted lucite sheet in one direction and drawing lines in the slots. The lucite sheet was then turned 90 degrees, and the procedure was repeated until a grid of one-half-inch squares resulted. The bin lucite front was then lubricated with vaseline and placed on the soil surface, and the aluminum frame bolted back on.

## A.3 TESTING PROCEDURE

Ence the soil sample had been prepared, it was placed under the carriage and the tool was attached to the carriage system by a nutand-bolt system. Care was taken not to disturb the sample during this operation.

At this point, the tool speed desired [generally 1.0 inch/ minute] was preset on the motor control box. An initial photograph of the undeformed grid was taken and the carriage was then set in motion. During the course of the test, further photographs of the deforming grid were taken at five-second intervals. A photographic record of a soil cutting test is shown in Plate A-5.



PLATE A-5

PHOTOGRAPHIC RECORD OF A SOIL CUTTING TEST

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# SECTION B

## SOIL PROPERTIES

The natural clay used in both phases of the experimental study [i.e. cutting and traction tests] was an "English China Clay" formerly designated "5-187" and now known as "Lee Moor SPS". The predominant clay mineral constituent was kaolinite, as shown by the chemical analysis of samples. The complete chemical analysis, by weight, as provided by the supplier, is given as:

| SiO <sub>2</sub>   | 47.39% |
|--------------------|--------|
| A1203              | 37.94% |
| $Fe_2^{0}$         | 0.36%  |
| 1 <sup>110</sup> 2 | 0_05%  |
| Mg0                | 0.18%  |
| CaO                | 0.32%  |
| k <sub>2</sub> 0   | 1.17%  |
| Na20               | 0.07%  |
| ,                  | 6      |

Loss on ignition

13.02%

An X-ray diffraction revealed that the clay was primarily kaolinite [approximately 93% by weight] with some illite [about.7%].

The soil was in part donated by, and in part purchased from Domtar Fine Papers Ltd. and was found to have the following engineering properties, as determined from laboratory tests:

Liquid limit Plastic limit Specific gravity

Particle size distribution 74% finer than 2 microns A complete grain size distribution is shown in Fig. A-2.

54.5%

37.5%

2.62

The artificial clay employed during the investigation was "Plasticine" [trade name] as manufactured by Harbutts Ltd. of England. Although the manufacturer's specifications stated that the material was temperature insensitive, such did not prove to be the case with regard to stress-strain performance. For this reason all the tests were conducted within a temperature range of  $70^{\circ}$ - $75^{\circ}$ F. A small amount [about 3% by weight] of petroleum jelly was added to the clay to reduce its strength.

The static stress-strain curves of the prtificial clay are shown in Fig. A-6. The particle size distribution of the solid residue reported by Japp (1967) is shown in Fig. A-3. Japp found that approximately 20% by weight is of clay size fraction. An X-ray diffraction study revealed that no clay minerals were present, and that the solid phase was primarily quartz.

At a loading velocity of 1.0 inch/minute, triaxial tests were conducted on confined and unconfined specimens. The results of these tests revealed that the performance of the artificial clay is not influenced by the magnitude of the confining pressure and hence a  $\varphi = 0$ analysis is valid [Japp (1967)].





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#### SECTION C

## SHEAR STRENGTH TESTS

"True Triaxial" tests were performed under plane strain conditions in order to reproduce as closely as possible the assumed conditions existing in the cutting and traction tests. In this case. prismatic samples [2 ins.  $x \mid 1/2$  ins.  $x \nmid 1/4$  ins.] of both artificial clay and nearly saturated remoulded [kaolinite] clay were prepared in a similar manner to the compacted samples used in the cutting and traction tests. The prepared sample was placed in a modified triaxial chamber between two polished brass plates [see Fig., A-4]. The distance between the plates was adjusted so that no material deformation of the sample, normal to the plates, was permitted. The samples were then placed in a testing machine and axial loads applied. The tests were performed at three different cell pressures [0, 2.5 and 5.0 psi] and at axial loading velocities of 0.1, 0.5 and 1.0 ins/min. The results of the tests on the kaolinite clay have previously been shown as Fig. 4-7.

Similar tests were performed on cylindrical samples. These samples were 1.40 ins. in diameter and 3 1/8 ins. in length. Axisymmétric tests were performed in order to verify that the nonexistence of a well-defined failure conditions, i.e. no strain softening behavior, is not a result of the plane strain, "True Triaxial", test restraints. The results have been included in Fig. 4-8 for the natural kaolinite clay and in Fig. A-6 for the artificial clay employed during the initial stages of the experimental programme. Figure A-5 shows the effect of



the loading rate on the shear strength values for the kaolinite clay.

Finally, direct shear tests were performed on the compacted soil in both the soil-to-soil and the soil-to-metal modes. Sampleswere cut from clay compacted in the test bin and these were trimmed and tested, Section 4.A.3. The direct shear test results are shown in Fig. 4-9 for the soil-to-soil mode and in Fig. 4-10 for the soil-tometal mode.

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SECTION D

## ARTIFICIAL CLAY CUTTING AND TRACTION TEST RESULTS

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## APPENDIX B

## DATA REDUCTION TECHNIQUES

The basic steps adopted for data reduction of the soil cutting and traction experiments are described in this Appendix. The techniques were described briefly in Chapter 4 [Section 4-B-2]. The method adopted in this study is similar to those previously reported by Chen (1972) and by Sylvestre-Williams (1973). A flow chart of the various steps followed, in the reduction of experimental data, shown as Fig. 4-17, is given in Fig. B-1. In a phronological order these steps are:

Plotting of successive grid nodes.

Transfer of grid coordinate locations to Process Control Computer.

Grid adjustments.

Calculations of displacement and velocity components.

Calculations of strain rates and effective strain rates.

Estimation of volume changes. "

Calculation of power of deformation.

These steps are discussed in detail in subsequent sections of this Appendix.

## B.1 PLOTTING OF SUCCESSIVE GRID NODES

Selected frames from the photographic record of the grid nodes were projected and the grid displacement patterns at successive time intervals, together with the tool [blade or grouser] positions at these times, were plotted on paper [Fig. 4-16]. The grid nodes were taken



as the points of intersection of the horizontal and vertical lines. The plotted field for each image consisted of a network of ten horizontal points spaced at one inch intervals by 14 vertical points spaced at one-half inch intervals. This resulted in a rectangular network having a size of nine inches by six and one-half inches with the top lefthandside point taken as the closest node to the point of tool intersection with the original soil surface. As pointed out earlier, five image positions were recorded, representing respectively the initial position plus four subsequent positions at 0.25, 0.50, 0.75 and 1.0 inch tool displacement. These five images were then superposed on each other to provide a detailed description of the nodal displacement trajectories over a tool horizontal displacement of 1.0 inch.

#### **B.2** TRANSFER OF GRID COORDINATE LOCATIONS TO PROCESS CONTROL COMPUTER

The plotted grid images were placed on a Moseley Autograph Model 2D-2AN-X-Y recorder which was connected to a Canadian General Electric Process Control Computer, model GEPAC 4020. The plotted images paper was fixed in position on the X-Y recorder and the carriage needle moved manually, by adjusting two potentiometers to each node location. The grid points were then plotted row by row, image by image. The voltages corresponding to the horizontal and vertical coordinates of each location were input to an integrating digital voltmeter which fed into the computer logic circuits. By means of programme [25] shown in Appendix E, the input voltages produced by the X-Y recorder were converted into coordinate values [X and Y] in centimeters. The resulting coordinate values were then temporarily stored on a magnetic disc, from which

they were transferred to an IBM Magnetic Tape at the end of each test plot. The coordinate values stored on the magnetic tape were then transferred to punched cards by means of programme "TAPE 25" shown in Appendix E.

## B.3 GRID ADJUSTMENTS

As can be seen from Fig. 4-16, the undeformed grid is usually in a slightly distorted state. The distortion is due in part to the manual grid placing technique and soil heterogeneity, but it is mainly caused by the preparation and manipulation of the clay sample after the grid is placed. In order to ensure a regular interval between adjacent grid nodes which greatly facilitates the calculation of velocity and strain rate components, the initial undeformed and subsequently deformed plotted grids were subjected to approximate geo metrical adjustments shown in Fig. B-2. The method adopted by Windisch (1969) consists of the specification of arbitrarily defined grid coordinates to provide an adjusted undeformed grid of regular horizontal and vertical lines. This new network corresponds as closely as possible to the initial undeformed grid. Utilizing the following notation, the procedure is detailed below.

> XI, YI = original undeformed coordinates XIA, YIA = adjusted undeformed coordinates XX, YY = original deformed coordinates XXA, YYA = adjusted deformed coordinates

The adjustment to the abscissa of an undeformed grid point [I, J] is given as:



## $D_{1} = XIA(I,J) - XI(I,J)$

This value is then applied as a first adjustment to the corresponding grid point abscissa. The rate of adjustment along row J is:

$$C_{1} = \frac{XIA (I+1,J) + XI (I,J) - XIA (I,J) - XI (I+1,J)}{XI (I+1, J) - XI (I,J)}$$

If the constant,  $C_1$ , is regarded as being a gradient/along row J between adjacent points, a second adjustment can be made to the abscissa of the deformed grid point, viz:

 $D_2 = [XX (I,J,JS) - XI (I,J)] C_1$ 

Here JS represents the image at 0.25, 0.50, 0.75 and 1.0 inch tool displacement, and corresponds to the indices two, three, four and five.

The adjustment of any given grid point will, by necessity, depend on the location of adjacent undeformed grid points in the following row. Hence, the rate of adjustment of the abscissa along row J+1 can be expressed as:

 $C_{2} = \frac{XIA (I+1, J+1) - XI (I+1, J+1) - XIA (I, J+1) + XI (I, J+1)}{XI (I+1, J+1) - XI (I, J+1)}$ 

From this, a further adjustment is made to the deformed coordinate, of magnitude:

 $D_{9}^{1} = [XX (I, J+1, JS) - XI (I, J+1)] C_{2}$ 

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A third correction is the result of adjustments in the ordinate direction of the grid point, viz:

$$D_{g} = (D_{g}^{1} - D_{1}) \frac{YY (I_{s} J_{s} JS) - YI (I_{s} J)}{YI (I_{s} J^{+}) - YI (I_{s} J)}$$

The final adjusted abscissa value of the deformed grid point (I,J,JS). is then given as:  $XXA (I,J,JS) = XX (I,J,JS) + D_1 + D_2 + D_3$ Similar adjustments are performed on the plotted ordinate values of the

grid nodes.

The above calculations, given by Eq. (B-1) and by an analogous equation for the ordinate values, are performed by the first part of the Computer programme "FIT" given in Appendix E. It should be noted that in this computer routine, the following substitutions of symbols are made:

> XI (I,J) = XX (I,J,1) YI (I,J) = YY (I,J,1) XIA (I,J) = XXA (I,J,1) YIA (I,J) = YYA (I,J,1)

## B.4 VELOCITY CALCULATIONS

The particle valocities, over successive grid positions, were calculated on the basis of the time rate of change of the particle position in the coordinate directions. The velocity components are given as:

$$U_{IJK} = \frac{XXA (I_{J}J_{k} + 1) - XXA (I_{J}J_{k})}{TT}$$

$$V_{IJK} = \frac{YYA (I_{J}J_{k} + 1) - YYA (I_{J}J_{k})}{TT}$$
(B-2)

here

I.J = column and row indices; respectively

XXA, YYA = adjusted coordinates

# image number

U.V = velocity components in the x- and y- coordinate

directions, respectively

TT = time interval between successive images.

## B.5 STRAIN RATE COMPONENTS.

The strain rate components were calculated by the application of Eq. (4-4) repeated as:

(B-3)

(B-4)

$$\dot{\epsilon}_{y} = \frac{\partial v}{\partial y}$$
$$\dot{\epsilon}_{xy} = \frac{1}{2}(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})$$

 $\dot{\varepsilon}_{x} = \frac{\partial u}{\partial x}$ 

However, in the actual calculation, carried out by the digital programme "FIT" shown in Appendix E, the strain rate components were determined to be the average value of the quantities calculated for adjacent rows or columns. Thus, Eqs. (B-3) are written as:

$$\dot{\epsilon}_{X}^{(j)}XN, YN = \frac{1}{2} U (I+1, J,k) - U (I,J,k)$$
  
XXA (I+1,J,k) - XXA (I;J,k)

 $\frac{1}{2}$  U (I+1,J+1, k) - U (I, J+1, k) XXA (I+1, J+1,k) - XXA (I,J+1,k)

where

 $(\dot{\mathbf{e}}_{\mathbf{X}})_{\mathbf{X}\mathbf{N},\mathbf{Y}\mathbf{N}} = \dot{\mathbf{e}}_{\mathbf{X}}$  at the point (XN,YN) located at the center of area of the quadrilateral formed by the points (I,J,k), (I+1,J,k), (I+1, J+1, k) and (I, J+1, k).

I,J.= column and row numbers, respectively

k = image number

U = particle velocity in the x-direction

XXA = adjusted abscissa value of particle coordinates

Similar equations were used to determine the values of the other strain rate components.

The effective strain rate  $\dot{\epsilon}$  was obtained from the calculated strain rate components, viz:

$$\dot{\varepsilon} = \frac{2}{3} \left[ (\dot{\varepsilon}_{\chi})^2 + (\dot{\varepsilon}_{y})^2 - \dot{\varepsilon}_{\chi} \dot{\varepsilon}_{y} + \frac{3}{4} (\dot{\gamma}_{\chi y})^2 \right]^{\frac{1}{2}}$$

## B.6 VOLUME CHANGE CALCULATIONS

The method by which the permanent volume changes were estimated has been described in detail in Section 4.B.3. The results of these calculations, performed by programme "FIT" in Appendix E, have been presented as Table 4-3. In summary, however, the method makes use of the principle of the conservation of mass [Fung (1965)], applied to the elemental areas within the deforming field. If reference is made to Fig. B-3, it will be seen that the application of this principle results in:

$$\rho_1 A_1 = \rho_2 A_2 = \rho_3 A_3$$

for plane strain deformation. These equations may/be rewritten as:

(B.5)

(B.6)

$$\frac{P_1}{P_j} = \frac{A_j}{A_1}$$

#### where

 $P_1$  = mass density or specific mass of the ith elemental area.  $A_2$  = area of the ith element.



Machine computation of the areas, carried out by programme "FIT", permitted a comparison of the mass densities of the deforming soil through successive grid positions. Estimates of the volume changes were thus obtained.

## 8.7 CALCULATION OF POWER OF DEFORMATION AND TOTAL DEFORMATION ENERGY

The power of deformation at the coordinate location [XN, YN] is obtained from the application of Eq. (4,16) repeated as:

 $\hat{W} = 2k\sqrt{T}$ 

to form the product:

PD = W x A

where

PD = power of deformation at coordinate Tocation [XN, YN].

(B.7)

A = area of quadrilateral surrounding the point [XN, YN].

 $k^2 = J_2$  = second invariant of the stress deviation.

I = second invariant of the strain rate tensor.

The summation of the values of PD calculated at the various points given by [XN, YN], is carried out by means of Simpson's rule [Hildebrand (1965)] to yield the total energy dissipated in the plastic deformation of the soil.
#### APPENDIX C

#### REVIEW OF PREVIOUS WORK

# A. **INVESTIGATIONS ON SOIL CUTTING**

During the early part of the century [1918 to 1939], researchers in the United Kingdom and the U.S.A. apparently confined their work to the investigation of the draft of tillage implements. They could not, however, isolate the relevant soil parameters from their work because of the very large number of inter-related factors considered. For example, "no clear distinction was made between a directly involved soil property like cohesion and a characteristic such as colloidal content, which is only relevant insofar as it affects cohesion" [Hettiaratchi (1965)]. Consequently, it was impossible for them to conclude that a theoretical analysis/in terms of classical soil mechanics was possible.

An important and noticeable feature of all recent work in the field of soil cutting is the application of the theories of classical soil mechanics to greatly simplified soil working tools. It was felt by most researchers that once these problems were understood, it would not be unreasonable to extend the study to more complex and realistic problems.

Basically, the foundation of this work was laid by Coulomb, and the following factors were involved:

a) Soil parameters such as cohesion, internal friction, density.
b) Soil-metal properties such as soil-metal friction and adhesion.

c) Assumptions that the soil was rigid and incompressible. Forces were evaluated by studying the static equilibrium of an assumed failure surface which was chosen to satisfy the limiting stress condit ion of a Coulomb material.

Payne (1956) first confined his investigations to vertical He classified narrow tines as those having a shape factor tines. [depth/width ratio] greater than unity, and blades as those with shape factors less than 0.5. Although he analyzed the forces of his proposed complicated failure pattern in front of a narrow tine, he did not produce a solution in a readily usable form. Furthermore, the very complicated expression he derived for the force on the time was for an arbitrary failure surface; also such an expression "has to be further subjected to trial computations required in a minimizing process for conformity with the requirements of a minimum value postulate before the final value is obtained." [Hettjaratchi (1965)]. Payne's work was later extended by Payne and Tanner (1959), and by Tanner (1960) to cover the behavior of narrow times over a wide range of rake angles. Experimental observations were in good agreement with the complex failure shape proposed by Payne.

Osman (1964) analyzed very thoroughly the wide blade cutting problem. In his investigations, Osman used wide blades with varying rake angles. By using wide blades, he simplified the stress-field to a simple two-dimensional one, and his experimental work was carried out on dry sand, stiff clay, and a C- $\phi$  type of soil. He attempted to check two theories for passive pressure: a) Coulomb's solution for a granular material, and

b) Ode's logarithmic spiral method.

He concluded that Coulomb's wedge solution was only good for smooth blades of small rake angles working in cohesionless soils, and showed that Ohde's solution could accurately predict the forces required to cut a wide range of soils.

It has been pointed out by Ösman that the usefulness of his analysis is limited, in that it is a function of a large number of variables and it is necessary to have access to a computer to solve for each individual case. With a view to overcoming this difficulty, Osman made use of dimensional analysis and was able to write the following equation:

 $D/\gamma z^2 = f(\frac{c}{\gamma z}, \delta, \phi, \frac{Ca}{\gamma z}, \alpha, h/z)^2$ 

where

 $D/vz^2$  = ratio of draft to gravity forces

 $C_{/YZ}$  = ratio of cohesive to gravity forces

 $\delta$  = soil to metal frictional angle

= angle of internal friction

a = ratio of adhesive to gravity forces

α = rake ångle, degrees

n = height of surcharge, inches, and

z = blade depth, inches .

 $\alpha$  and h/z describe the geometry of the blade and the starge

0 sman presented charts that would enable the calculation of draft forces to be made for a range of soil types of practical interest.

Siemens and his colleagues (1964) conducted similar investigations but with fewer experimental variables, and they used a combination of Ode's retaining wall theory and a "free body" theory to compute theoretical loads on the blade. There was, however, poor agreement between predicted and experimental observations, the former being higher in value than the latter. This seemed to cast doubt on the validity of the Ohde logarithmic spiral solution. Subsequent measurements of soil parameters revealed that too high a value of cohesion had been used in the original computation. Predicted forces utilizing the revised value for cohesion showed good agreement with experimental results.

Selig and Nelson (1964) conducted qualitative investigations into the mode of failure of three types of soil under the action of flat blades, and, generally, their observations supported the idea that the failure geometry was in accordance with the postulated logarithmic spiral solution for retaining walls.

Reece (1965) proposed that the cutting force acting on a blade could be expressed by means of the following equation:

D = cutting force per unit width of blade and  $N_{c}$ 

 $D = \gamma z^2 N_{\gamma} + C z N_{c} + C_{z} Z N_{\gamma} + q z N_{c}$ 

where 🚊

are dimensionless numbers representing the boundary con-

ditions of the failure surface and functions of  $\phi$ ,  $\delta$ , blade geometry and failure boundary.

q'= the weight of the uniformly distributed surcharge due to piled-up soil.

Reece's equation is not only simple but it also applies to the computation of the force required to produce failure of the soil beneath any form of loading structure with a two-dimensional failure pattern.

However, as pointed out by Hettiaratchi (1965), this equation is not absolutely correct. Hettiaratchi et al. (1966) computed the four "N factors for a complete range of values of  $\phi$  for the two extreme values of wall friction  $\delta$ , that is,  $\delta = 0$  and  $\delta = \phi$ , for values of rake angle varying from  $(45^\circ - \phi/_2)$  to  $(135^\circ - \phi/_2)$ . They also produced suitable interpolation formulae and graphs showing the rupture distance as a function of the soil and blade variables.

O'Callaghan and Farrelly (1964) derived a simplified expression for the draft per unit width on the basis that two distinct regimes of deformation occur in vertical and horizontal planes. This expression appeared to give good correlation for cohesive soils but failed in cohesionless soils.

Hettiaratchi and Reece (1967) attempted to provide a useful solution which would enable certain symmetrical three-dimensional soil failure problems to be analyzed rapidly by the use of charts describing the failure geometry, together with some simple trigonometrical factors.

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Certain simplifying assumptions were made and their limitations pointed out. However, more experimental support was needed as pointed out by the authors.

Elijah and Weber (1968) conducted experiments using model and full-scale flat blades in artificial and field soils to determine the soil failure patterns and the distribution of normal and tangential These blades were designed so that pressures on the blade surface. the cutting edges were separated from the blade surface. In this work, four distinct failure patterns were identified. They were designated as "shear plane", "flow", "bending" and "tensile" failures. Elijah and Weber pointed out that there was a need for definition of new soil parameters in order to predict when these patterns will occur and what They found that the pressure distribution tool forces are involved. on the blade surface varied with the location on the blade and with the type of soil. Reasonably good agreement was obtained when the pressures were integrated and used to predict the total cutting force acting on the blade for the various soils.

Reece (1959) pointed out that while the methods of classical soil mechanics can solve the problem of wide cutting blade, time has come to make use of the theory of plasticity, with a proper description of the relation between stress and strain, in developing soil machine mechanics.

Wismer and Forth (1969) and Wismer and Luth (1970) derived prediction equations for the draft and vertical forces on blades operating in both sand and saturated clay. These equations were

developed by application of dimensional analysis and nonlinear curve fitting to experimental results for a wide range of blade sizes, angles, and operating speeds. In these experiments cone penetrometer measurements were made to determine the properties of the soil, and the soil strength was expressed in terms of the cone index of a standard cone instead of the more conventional terms of cohesion and angle of internal friction. For this reason, no quantitative comparisons with other investigations can be made since the relationship between the cone index and the conventional strength parameters depends on the soil type.

Yong et al. (1969) and Yong and Chen /(1970) employed the principle of limit equilibrium where the stability of the soil mass is controlled or affected by the moving blade. <sup>7</sup> The development of the solution technique was based on the following assumptions:

1] The stressed soil in front of the blade is divided into two regions: Region I being the radial shear zone and

Region II the simple passive Rankine zone, Fig. 2-2-A.

2] The soil mass is incompressible and is assumed to obey the Mohr-Coulomb yield function.

With the use of a similarity solution technique, the equations of equilibrium, and the Mohr-Coulomb yield condition, they were able to predict the forces on cutting blades in both cohesionless and C-\$ soils.

Yong and Chen (1970) showed that for conditions where limit equilibrium in the soil is approached, and for the purposes of predicting first failure in the soil under the action of a moving blade, the analytical technique developed, utilizing the method of characteristics for solution, gave a good correspondence between computed and measured values. Moreover, comparisons with reported values from other studies showed the applicability of the method to the solution of the problem.

#### B. INVESTIGATIONS ON SOIL-GROUSER INTERACTION

The first systematic attempt to provide a basis from which reliable predictions of vehicle behavior could be made was carried out by Micklethwait (1944). Based on his experimental work, Micklethwait proposed an equation expressing the maximum tractive effort of a tracked vehicle in cohesive soils of the form:

 $H = blc + W \tan \phi$ 

where

H = gross tractive effort in 1b

b = track width in inches

1 = track length in inches

c = cohesion in psi

W = vehicle weight in 16

This equation is very rarely used at the present time, but was the basis of vehicular design until Bekker (1956, 1960) examined the problem of soil-grouser interaction from a theoretical point of view. Bekker considered that Micklethwait's equation was incomplete in that several parameters were not taken into account. As a result, a pair of equations were proposed, the first of which described the horizontal thrust developed by a grouser in terms of track geometry, vehicular weight and the rate of slip. This equation was developed for use with the conven-

tional linked track, where a condition referred to as "grip failure" results, Fig. C-1. This condition occurs at very high values of the ratio of horizontal to vertical forces  $(H/_W)$  and rupture occurs along interface ab with the forces acting as shown. The relationship between H and W for this case/is given as:

$$H = W \frac{h + S \tan \phi}{S - h \tan \phi} + \frac{C(h^2 + S^2)}{S - h \tan \phi}$$
(C-1)

The second of these equations was applicable to a spaced link track, a system which is analogous to a series of isolated grousers moving through a soil. The condition of failure in this case was referred to as "ground failure". This equation expressed the horizontal thrust in terms of the grouser geometry and soil parameters, and was based on the assumption that the grouser plate could be approximated by a strip footing inclined to the horizontal at an angle given by:

 $\dot{\theta}$  = arc tan (H/<sub>W</sub>)

where

e.

H = horizontal thrust developed by grouser

W = applied vertical load

 $2P_p = b(n_1 t + \gamma n_q 1z + \gamma n_q 1^2)$ 

As a consequence of this assumption, the development of the equation follows the methods proposed by Terzaghi (1944) in that dimensionless constants analogous to bearing capacity factors were used. The equations and the force diagram have already been given in Chapter 1 as Eqs. (1.1) and (1.2) and Fig. 1-2 respectively, and were examined in Section 7-4. The resultant force  $2P_p$ , Fig. 1-2, is given by Bekker as:

(C-2)

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Equation (C-2) is used to plot a trafficability curve, Fig. C-2. The curve from point A to point B is generated by plotting polar coordinates of  $2P_p$  at  $\theta$  over cartesian coordinates of H and W. Point A is determined by the intersection of Eqs. (C-1) and (C-2), and point B is the ultimate bearing capacity under vertical load. From the traffic-ability curve one may obtain the optimum values of W and H for any given W/H ratio and for the plate grouser and soil strength parameters used.

Harrison (1973) pointed out two main objections to the approach proposed by Bekker. The failure pattern chosen is not compatible with the properties of a rigid Coulomb material, and the forces assumed to act on planes within the pattern are not reasonable. Nevertheless, the investigations carried out by Bekker represent an ambitious attempt to supply solutions to some of the problems associated with the soil-vehicle interaction process. Unfortunately, there appears to be a lack of firm experimental support of these theories reported in the readily accessible literature.

Haythornthwaite (1961) considered the problem of a grouser being driven through a soil possessing both cohesion and friction. In his analysis, Haythornthwaite utilized the methods of limit plasticity developed by Drucker and Prager (1952). With the assumptions of:

- a) a soil possessing both cohesion and friction,
  - b) the Coulomb yield criterion,

 $\tau = C + \sigma \tan \phi$ 

describing the stress conditions at failure, and c) a weightless, perfectly plastic model for the soil, a statically admissible stress distribution was postulated by means of which a lower bound solution was obtained. An upper bound solution was then inferred by calculating the dissipated energy along an assumed failure surface. Examples of upper and lower bound conditions as described by Haythornthwaite are shown in Figs. C-3a and C-3b respectively. A numerical solution to these assumed conditions is shown in Fig. 3-3c. In this approach through sophisication of the stress and flow pattern, the lower bound is maximized and the upper bound is minimized until the curves shown in Fig. C-3c coincide. A more sophisticated upper bound model chosen by Haythornthwaite is presented in Fig. C-3d.

The solutions arrived at by Haythornthwaite are severely restrictive. The calculation of the dissipation energy function for the upper bound was based on the failure hypothesis proposed by Drucker and Prager (1952) and is only valid for a material possessing cohesion. For a non-cohesive material, the dissipation energy and hence the upper bound is zero. In addition, as a consequence of the assumption of a perfectly plastic material, the solution will only be valid for soils which possess a very small angle of internal friction,  $\phi$ , since . . . "a material is only plastic to the extent that it is not frictional." [Drucker (1961)].

A main objection to the application of the limit analysis theorems as stated by Harrison (1973) is "The degree of probability that the two bounds can be made to coincide within a reasonable number of assumed flow and stress options. The intuition required to cause the upper and lower bound solutions to converge would conceivably require a considerable number of solutions or a knowledge of the stress-strain



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behavior of soils uncommon to the ordinary researcher."

The limit equilibrium approach has been successfully used by Yong and Sylvestre-Williams (1969). The analytical model adopted is shown in Fig. C-4. The following assumptions were made:

1] Admissibility of the Mohr-Coulomb failure criteria.

2] Rigidity of block ABCD.

3] Full failure development in the entire mass defined by zone CDE.

4] Insignificant volume change in zone ABCED.

In analyzing such a model, a similar approach to that of Yong et al. (1969) and Yong and Chen (1970), [a similarity solution technique together with the method of characteristics] was followed. Integration of the stresses over the length of CD [Fig. C-4] provided the forces on the grouser. Confirmation between analytical model prediction and physical performance was obtained, for grousers moving at controlled depth or under constant vertical loads in sand, by:

a) matching physical failure surface due to grouser action with theoretically computed failure characteristic, and

b) matching computed forces with physical values.

Comparing their results with those computed from Bekker's equations [e.g. Eq. (1.1) and (1. In Chapter 1] showed little agreement.

Harrison (1973), on consideration of the discrepancies between experimentally observed slip line fields and those predicted by the theory, came to the conclusion that these discrepancies were, to a large extent, due to the existence of a wedge-shaped zone of soil fixed to the interface,



forming a pseudo-interface along which actual failure occurs. He postulated that the interface shear zone transformed itself into a wedge if the direction of motion of the lower edge of the interface was at a smaller angle to the horizontal than the slip line at that point. Considering Fig. C-5a, wedge will form if the interface is driven forward at an angle smaller than  $\theta_c$ , where  $\theta_c = 90 + \phi - \beta$ , Fig. C-5b; otherwise the normal slip line will apply.

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Having made this postulate, Harrison analyzed the plate-grouser problem using a combination of Ohde's retaining wall theory and a "free body" theory to compute the loads on the grouser. The mathematical solution is based on the relationship between the horizontal force H, the vertical force V, and the direction of plate-grouser movement  $\theta$ , for a given set of soil strength parameters, and a given plate-grouser configuration. The solution requires that either V or  $\theta$  be known. The horizontal and vertical forces are given by Harrison as:

 $H = \frac{1}{2}\gamma S^{2}k_{\gamma} \sin (\beta - \Delta) + CS[k_{c} \sin (\beta - \Delta) + \tan \Delta \cot \phi]$   $V = \frac{1}{2}\gamma S^{2}[k_{\gamma}\cos((\beta - \Delta) - \tan \beta] + CS[k_{c} \cos (\beta - \Delta)$   $- \tan \beta \tan \Delta \cot \phi]$ (C-3)

 $\frac{\sin^2 \left(\frac{\beta+\theta}{\beta}\right)}{\cos^2 \beta \sin \left(\frac{\beta+\theta-\phi-\Delta}{\beta}\right)} \left\{ \frac{1}{8 \sin^2 \phi+1} \right| e^{i\omega} \tan \phi$ 

<u>sin (θ-φ) cos (β+θ-φ)</u> sin (β+θ) cos φ

 $\frac{(2 \sin \phi (\frac{1}{2} + 2 \sin \phi)}{\cos \psi} + 3 \tan \phi \sin (\theta - \phi) + \cos (\theta - \phi)$ 

where



$$c = \frac{1}{\cos \beta \sin (\beta + \theta - \phi - \Delta)} \left\{ \left| \frac{e^{2\omega} \tan \phi_{-1}}{\sin \phi} + e^{2\omega} \tan \phi \right| \right\}$$
  
sin (\beta + \theta) + cos (\beta + \theta - \phi)[1 + cot \phi tan\Delta] \right\}

$$\Delta = \arctan \frac{\sin \theta}{1 + \cos \theta} \sin \phi$$

 $p^{1} = 2(\beta + \theta) - (\dot{9}0 + \phi)$ 

$$\omega = \varepsilon + \theta = 45 - \phi/2 + \theta$$

= angle between specified radii of log spiral

 $\psi$  = angle 45+ $\phi/2$  degrees

 $\beta$  = characteristic angle of a plate-grouser [degrees], Fig. C-5c.

 $\theta$  = instantaneous direction of plate-grouser movement with

the horizontal at soil failure [degrees]

#### S = plate length in inches

r = soil bulk density, lb/in<sup>t</sup>

C = apparent cohesion, psi-

 $\phi$  = angle of soil shearing resistance [degrees].

Harrison conducted experiments on quite large grousers driven into a saturated clay, a dry sand and an intermediate loam. The experimental observations verified the postulated slip line fields. Moreover, there was fairly good agreement between the predicted forces and the experimentally measured ones, with the exception of the case of a horizontally moving grouser [i.e.  $\theta = 0$ ] driven in loam and clay where the difference between the predicted and the measured values was very significant.

Investigating the problem of traction from a macroscopic point of view, a great deal of work has been done in recent years by

the U.S. Army at the Waterway's Experimental Station in Vicksburg and at the OTAC at the Detroit arsenal. Studies on the trafficability of soils by both wheeled and tracked vehicles have been carried out by W.E.S., and a great deal of work has been done on the problem of soil wheel interaction. In the course of their research, W.E.S. have proposed formulae for the determination of a dimensionless Mobility Index based on the determination of the cone penetration resistance of the soil in question. The Mobility Index is an indication of the ability of the soil to allow fifty/passes of the vehicle under consideration without that vehicle being stuck. Some attempts at correlating the theories proposed by Bekker and the trafficability theories proposed by W.E.S. have been made by trafficability research teams of the Israeli Army [trafficability research team 1961] while Seia (1961) has provided a theoretical solution to Bekker's tractive effort-slip relationship.

It must be pointed out that most of the research done to date on the tracked vehicle-soil interaction problem has been oriented towards the provision of "go/no-go" criteria for given vehicles in given soils. As warranted as this may be, it is still necessary to understand the fundamental interaction process, and it is precisely in this area that there appears to be a great lack of experimental or theoretical research effort. In addition, reviewing the available literature it is evident that very little work has been done in investigating the interaction of grousers other than that of the plate-grouser with soil. As the problem of traction is related to the interaction of stress between the ground and the loading area, and the motion resistance depends on the relation between stresses and strains, studies of the effect of grouser

geometries on the loaded soil may lead to a grouser shape that produces a rather significant improvement in traction.

## APPENDIX D

# SOLUTION OF LINEAR EQUATIONS BY DIRECT GAUSSIAN ELIMINATION METHOD

The equilibrium equations for a continuum system may be written

| $A_{11}X_1 + A_{12}X_2 + A_{13}X_3 +$ | • • • • • • | + ATRXN = B1           | (D-la) |
|---------------------------------------|-------------|------------------------|--------|
| A. X. + A. X. + A. X. +               |             | $+ A_{a}X_{a} = B_{a}$ | (D-16) |

$$A_{31}X_1 + A_{32}X_2 + A_{33}X_3 + \dots + A_{3N}X_N = B_3$$
 (D-1c)

(D-1)

$$A_{N_1}X_1 + A_{N_2}X_2 + A_{N_3}X_3 + \dots + A_{NN}X_N = B_N$$
 (....)

\* or symbolically:

[A][X] = [B]

where

[A] = the stiffness matrix

[X] = the unknown displacements

[B] = the applied loads.

#### GAUSSIAN ELIMINATION METHOD

The first step in the solution of the above set of equations. Is to solve Eq. (D-Ta) for  $X_2$ , or

 $X_1 = B_1/A_{11} - (A_{12}/A_{11})X_2 - (A_{14}/A_{11})X_3 \dots (A_{1N}/A_{11})X_N (D-2)^2$ 

If Eq. (D-2) is substituted into Eqs. (D-7b, c, . . . N) a modified set of N-1 equations is determined.

386  $A_{22}^{1}X_{2} + A_{23}^{1}X_{3} + ...$  $A_{32}^{1}X_{2} + A_{33}^{1}X_{3} + / \dots / \dots / \dots + A_{3N}^{1}X_{N} = B_{3}^{1}$ (D-3b)  $A_{N2}^{1}X_{2} + A_{N3}^{1}X_{3} +$  $\therefore f_{1} \cdot \cdot \cdot + A_{NN}^{1} X_{N} = B_{N}^{1}$ where  $j, j = 2, \dots, N$  (D-4a)  $A_{11}^{1} = A_{11} - A_{11}A_{11}/A_{11}$  $B_{i}^{1} = B_{i} - A_{i}B_{i}/A_{i}$ ..., N (D-44) A similar procedure is used to eliminate  $X_2$  from Eq. (D-3), etc. A general algorithm for the elimination of  $X_n$  may be written 85:  $X_n^* = (B_n^{n-1}/A_{nn}^{n-1}) - \sum (A_{n,i}^{n-1}/A_{nn}^{n-1})X_i \qquad j = n+1, \dots, N \quad (D-5)$  $A_{i,i}^n = A_{i,j}^{n-1} - A_{i,n}^{n-1} (A_{n,j}^{n-1} / A_{n,n}^{n-1})$   $i,j = n+1, ..., N (D-6)^n$  $(B_{i}^{n} = B_{i}^{n-1} - A_{in}^{n-1} (B_{n}^{n-1}/A_{nn}^{n-1})$ i = n+1, . . . , N (D-7) Equations (D-5), (D-6), and (D-7) may be rewritten in compact form:  $x_n = D_n - \sum H_{nj} x_j$ j = n+1, ..., N (D-8)  $A_{i,i}^n = A_{i,i}^{n-1} - A_{i,n}^{n-1} H_{n,i}$ ·i,j = n+7, . . . , N (D-9)  $B_{t}^{n} = B_{t}^{n-1} - A_{tn}^{n-1} D_{n}$ 1 = n+1, . . . , N (D-TO)  $\mathbf{D}_{n} = \mathbf{B}_{n-1}^{n-1} / \mathbf{A}_{nn}^{n-1}$ 

 $H_{nj} = A_{nj}^{n-1} / A_{nn}^{n-1}$ 

0

•

After the above procedure is applied N-1 times, the original set of equations is reduced to the following single equation:

which is solved directly for  $X_N$ 

 $\mathbf{x}_{N-1} \mathbf{x}_{N} = \mathbf{B}_{N}^{N-1}$ 

 $X_{N} = B_{N}^{N-1} / A_{NN}^{N-1}$ 

 $X_N = D_N$ 

In terms of the previous notations, this is:

The remaining unknowns are determined in reverse order by the repeated application of Eq. (D-8).

# SIMPLIFICATION FOR BANDED MATRICES

For many situations it is possible to place the stiffness matrix in a "band" form which results in the concentration of the elements of the stiffness matrix along the main diagonal. Therefore, the following simplifications in the general algorithm [Eqs.(D-8), (D-9) and (D-10)] are possible:

 $X_{n} = D_{n} - \sum H_{nj}X_{j} \qquad j = n+1, \dots, n+M-1 \qquad (D-12)$   $A_{1j}^{n} = A_{1j}^{n-1} - A_{1n}^{n-1} H_{nj} \qquad i,j = n+1, \dots, n+M-1 \qquad (D-13)$   $B_{1}^{n} = B_{1}^{n-1} - A_{1n}^{n-1} D_{n} \qquad i = n+1, \dots, n+M-1 \qquad (D-14)$ 

where 'N = the band width of the matrix.

The number of numerical operations can further be reduced by recognizing that the reduced matrix at any stage of procedure is

symmetric. Accordingly, Eq. (D-13) may be replaced by the following equation:

(D-15)

$$A_{ij}^{n} = A_{ij}^{n-1} - A_{in}^{n-1} H_{nj}$$
  $i = n+1, \dots, n+M-1$   
  $j = 1, \dots, n+M-1$ 

Since

E 1

 $a_{ji}^n = A_{ij}^n$ 

The number of numerical operations required for the solution of a band matrix is proportional to  $NM^2$  as compared to  $N^3$  which is required for the solution of a full matrix. Also, the computer storage required by the band matrix procedure is NM as compared to  $N^2$  required by a set of N arbitrary equations. Equation (D-15) is utilized in Subroutine "SOLVE" of programme "MAIN", Appendix E, to solve for the unknown finite elements modal displacements.

# APPENDIX E

## SECTION A

# COMPUTER PROGRAMS - MAIN SERIES

During the course of the present study, several computer programs were developed to solve general nonlinear plane-strain problems occurring in soil mechanics. The programs were grouped under a series named "MAIN" and were based on Zienkiewicz's program (1971). All the programs can handle nonlinear material properties, and the different methods used to perform the nonlinear analysis and idealize the continuum usually classified the type of the program.

"MAIN 1" and "MAIN 2" [Figs. E-1 and E-2] use an incrementaliterative method without predictions [Chapter 2] to solve nonlinear problems (FClay. "MAIN 1" is a general routine developed to handle problems with no discontinuities in the deformation field, the joint analysis was incorporated in "MAIN 2" to handle such problems. The programs were written in the Fortran language for use on the IBM 360/75. computer. A brief outline of the working of the "MAIN 2" program is given here. A listing of the program, together with general flow charts for the various routines are included. A number of comment cards are added in the listing for better understanding of the mechanics of the program.

The computer time required for a problem usually depends on the number of elements and nodel points used in the idealization of the problem, the number of increments and iterations [Table E-1].





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| PROBLEM<br>WHBER | PROBLEM<br>DESCRIPTION                                  | No. OF CST<br>ELEMENTS | NO. OF JOINT<br>ELEMENTS | No. OF<br>NODES | , <b>BAND</b><br>WIDTH | NO. OF<br>INCREMENTS | NO. OF ITERATIONS<br>WITHIN EACH<br>INCREMENT | COMPUTER<br>TIME*<br>(Minutes) |
|------------------|---------------------------------------------------------|------------------------|--------------------------|-----------------|------------------------|----------------------|-----------------------------------------------|--------------------------------|
| 1                | Cutting blade-10°<br>with vertical                      | 237                    | 29                       | 176             | <b>78</b>              | 10                   | 3                                             | 9.10                           |
| 2                | Cutting blade - 50°<br>with vertical                    | 175                    | 24                       | 136             | 74                     | 10                   | 3                                             | 7.10                           |
| 3                | R.A.₽.G h∕L<br>= 0.833                                  | 228                    | 17                       | 156             | - 44                   | 10                   | 3                                             | 7.33                           |
| 4                | R.A.P.G h/1<br>= 0.833                                  | 228                    | 22                       | <b>162</b>      | 44                     | 10                   | 3                                             | · 7 <b>.45</b> ′               |
| 5                | S.E.W. Grouser                                          | 205                    | 13                       | 139             | 38                     | 10 .                 | 3                                             | 5.30                           |
| 6                | C.E.N. Grouser                                          | 199                    | 18                       | 144             | 36                     | 10                   | <b>3</b>                                      | 5.45                           |
| 7.               | Retaining well-Rough<br>Interface-No cutting<br>plane   | 302                    | -                        | 178             | 58                     | 10 .                 | · 3                                           | 9.25**                         |
| 8                | Retaining wall-Rough<br>Interface-cutting<br>plane      | 302                    | <b>14</b>                | 193             | 58                     | 10                   | 3                                             | 10.0                           |
| 9 ́              | Retaining wall-Inter-<br>face elements-cutting<br>plane | 302                    | ,                        | 202             | 58                     | 10                   | 3                                             | 10.75                          |
| * Doe            | es not include compilat                                 | ion time of            | 40 seconds.              | <u></u>         |                        |                      |                                               | / -                            |
|                  | ( second                                                |                        | TARI                     | É E-1           |                        |                      | N<br>I                                        | •                              |

COMPUTER TIME

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# A.1 GENERAL OUTLINE OF PROGRAM "MAIN 2"

The "MAIN 2" program consists of several subroutines and a brief description of the subroutines is given below.

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#### Main Program - "MAIN 2"

This is the main driver routine of the program. It calls two subroutines to handle the input data and calls several others to execute the problem. This routine initializes all nodal and element arrays, and specifies the size of the loading increment. All output with the exception of the reactions are printed out in the subroutines.

# Subroutines "GDATA 1" and "GDATA 2"

Since this program deals with nonlinear material properties, it was found most appropriate to provide two data input routines. Subroutine "GDATA 1" reads the basic data, which are:

- 1) Junction Coordinates and element characteristics.
- 2) Initial material properties for each element type.
- 3) Boundary conditions.
- Number of increments, and number of iterations in every increment required for execution of the problem.

Subroutine "GDATA 2" incorporates the nonlinear stressstrain data into the program. As mentioned earlier, the stress-strain laws derived from laboratory tests are used directly in a digital form. Several points on the stress-strain curve are selected as input to this noutine in the form of number pairs. The first half of this routine reads the selected input points on the stress difference  $(\sigma_1 - \sigma_2)$  vs axial strain  $(\varepsilon_1)$  curve for each confining pressure. The second half reads data for the joint elements nonlinear properties. The input data, in this case, are the hyperbolic coefficients (a) and (b), Eq. (2.32) for each normal pressure.

# Subroutine "STIFT 1(N)" and "STIFT 2(N)"

The purpose of these two routines is to create the element stiffness coefficients appropriate to the problem. They have all necessary data transmitted to them through common storage and passes the element stiffness matrix back to the calling routine "FORMK". The element stiffness matrix is generated using the constitutive relations of the material and the geometry of the element. Subroutine "STIFT 1(N)" computes the stiffness matrix for a joint element [cutting or interface element]. In case the element is of the constant strain triangle type, subroutine "STIFT 2(N)" is called to generate the stiffness matrix.

#### Subroutines "FORMK" and "MODIFY"

The "FORMK" routine assembles the total stiffness matrix for the entire continuum using the direct stiffness method. Because of the bonded form of the resulting total stiffness matrix, only the main diagonal elements and the lower triangle elements are stored in a rectangular matrix with a width of half the band, [Zienkiewicz (1971)].

The "FORMK" routine also generates the total nodal force vector. The applied nodal forces are added directly, while the total stiffness matrix is modified for the applied displacement conditions [Chapter 2] using subroutine "MODIFY". The body forces due to gravity are also added in this routine.

# Subroutine "SOLVE"

This routine uses Gaussian elimination method [Appendix D] and solves for the unknown displacements from the set of stiffness equations generated in "FORMK".

# Subroutine "STRESS" and "JSTRES"

These routines compute the stresses and strains at the center of each element using the nodal displacements obtained from "SOLVE". Subroutine "STRESS" is called for the determination of stresses and strains in the "CST" elements. The routine also computes the principal stresses and principal strains in each "CST" element. Moreover, it calls subroutine "NONLIN(N)" to update the "CST" elements' elastic properties.

Subroutine "JSTRES" is used for the computations of the average incremental shear and normal stresses across the joint elements and the accumulative corresponding values. This routine calls subroutine "JNONL(N)" for updating the stiffness values of the joint elements to be used in the subsequent increments.

# Subroutines "NONLIN(N)" and "JNONL(N)"

The nonlinear analysis is performed in these subroutines. In "NONLIN(N)" routine, values of E and v are computed for each element from the nonlinear stress-strain curves depending on the state of strain and confining pressure in each element. This nonlinear routine can handle several nonlinear curves for any number of different materials by suitably altering the dimension statements. Subroutine "JNONL(N)" interpolates for shear stiffness values  $(k_s)$  from the hyperbolic shear stress-relative displacement relationships. Values of the coefficients (a) and (b), Eq. (2.32), are computed for each cutting or interface element depending on the state of shear displacement and the normal pressure in the element. Again this routine can handle several nonlinear curves for any number of different joint behaviors by suitably altering the dimension statements.

### Subroutine "REAC"

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The neactions at certain nodal points resulting from specifying displacement boundary conditions for these nodes are determined in this routine. The reactions at the desired node are obtained by multiplying the nodal displacement vector of the element by the stiffness values of the particular node. The reactions obtained for any particular increment are then added to the cumulative values obtained in previous increments to obtain total reactions.

#### Subroutine "AVER"

In this subroutine output results are averaged at the nodes. The stresses, the strains, and the strain rates of all the elements connected to a node are summed and divided by the number of elements.

#### Subroutine / LARDEF\*

After each increment, the element nodal coordinates are updated. This is done in subroutine "LARDEF" by adding the nodal displacements to the element nodal coordinates to obtain new coordinates for the next increment [Chapter 2]. In addition, the velocity components of the nodal points are determined together with elements strain-rate components and their principal values and directions. The "LARDEF" routine also computes the incremental deformation energy and power of deformation and adds them to previously obtained values for determination of total deformation energy and power of deformation.

Subroutine "PRIN"

This routine evaluates the principal stresses [or strains] from the known nodal values.

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# A.2 FLOW CHARTS

# PROGRAM MAIN 2







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READ TOOL VELOCITY AND TRAVEL DISTANCE

READ PRESSURE BOUNDARY CONDITIONS

READ NUMBER OF INCREMENTS AND NUMBER OF ITERATIONS



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# SUBROUTINE GDATA 2



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#### SUBROUTINE STRESS









## SUBROUTINE REAC









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## SUBROUTINE JNONL(N)





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CODE

# A.3 IDENTIFIERS USED IN THE "MAIN 2" PROGRAM

Symbols and arrays appearing in the various routines of the program are listed below in the order in which they appear.

# COMMON BLOCK/CONTR/

|   | TITLE        | •  | Word title array.                       |
|---|--------------|----|-----------------------------------------|
|   | NP           | :  | Number of nodal points.                 |
| / | NE           | :  | Number of elements.                     |
| / | NB           | :  | Number of restrained boundary nodes.    |
| • | NDF          | :  | Number of degrees of freedom per node.  |
|   | NCN          | :  | Maximum number of nodes per element.    |
|   | NLD          | :  | Number of load cases.                   |
|   | NMAT         | :  | Number of element material types.       |
|   | NSZF         | \: | Number of equations in the system.      |
|   | LT.          | ł  | Load case counter.                      |
|   | .NT4 /       | :\ | Logical stands device numbers           |
|   | NT5          | :  | Lugical sublage sevice numbers.         |
|   | NOPC         | :  | Number of boundary pressure cards.      |
| ſ | NCMAT        | :  | Number of "CST" element material types. |
|   | COMMON BLOCI | YD | ATÁ                                     |
|   | CORD         | :  | Nodal point coordinate array.           |
|   | NOP          | :  | Element connection array.               |
|   | IMAT         | ·  | Element material type array.            |

: Restrained boundary node numbers.

: Code for various boundary conditions,

0.0 specified load in both X and Y directions
1.0 specified displacement in X-direction,

load in Y-direction.

= 2.0 specified load in X-direction, displacement in Y-direction. = 3.0 specified displacement in both X and Y directions. UX X-force or displacement at the nodal point. UΫ́ Y-force or displacement at the nodal point, **IBC** Nodal point I for the boundary pressure. Nodal point J for the boundary pressure. JBC : PRE Boundary pressure between I and J. Element thickness array. : **XDEN** Body forces in X-direction. YDEN Body forces in Y-direction. : ORX X-coordinate of element centroid. ORY Y-coordinate of element centroid. PRCORD Nodal point coordinate at previous increment. COMMON BLOCK/ANAL/ NOINC Number of increments. KOUNT Counter for number of increments. NTEST Alphanumeric identifier of type of problem. = 0 for linear problem. = 1 for nonlinear problem. LTEST Alphanumeric input to specify whether problem is linear or nonlinear. NOITER Number of iterations. NITER Counter for number of iterations executed: VĒL Tool velocity.

Tool total horizontal displacement.

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COMMON BLOCK/STIFF/

| ESTIFM         | : Stress-strain matrix, later used for element stiffness   |
|----------------|------------------------------------------------------------|
| e              | matrix.                                                    |
| Ă Î            | : Strain-displacement matrix.                              |
| B ×            | : Stress back-substitution matrix.                         |
| - SK           | : Rectangular matrix for equations.                        |
| AREA           | : Area of element.                                         |
| C              | : Initially contains nodal force vector for the total      |
|                | stiffness matrix, but displacement solution vector         |
|                | replaces it.                                               |
| R              | : Vector of element nodal displacements.                   |
| Н              | : Nodal displacement vector of joint elements in           |
|                | local coordinates.                                         |
| <b>WBAND</b> · | : Band width of the stiffness matrix.                      |
| D              | : Nodal force vector for the total stiffness matrix;       |
| e .            | replaces vector C before modifying for displacement        |
|                | boundary conditions.                                       |
| AR             | : Nodal reaction array.                                    |
| COMMON BL      | .OCK/STRES/                                                |
| DISTO          | : Total nodal displacement vector.                         |
| SIGTO          | : Total element stress vector.                             |
| STRTO          | : Total element strain vector.                             |
| SMAXTO         | : Total maximum principal stress.                          |
| smînto ·       | : Total minimum principal stress.                          |
| ANGTO          | : Clockwise angle from vertical to line of action of total |
| · • • • •      | maximum principal stress.                                  |

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| EANGTO . | : Clockwise angle from vertical to line of action       |
|----------|---------------------------------------------------------|
|          | of total maximum principal strain.                      |
| EMAXTO , | : Total maximum principal strain. 🔆 🐂 💡                 |
| EMINTO   | : Tótal minimum principal strain.                       |
| FORCE    | : Vector of element incremental stresses.               |
| STR      | : Vector of element incremental strains.                |
| PSIGTO   | : Total element stress vector at previous increment.    |
| PSTRTO   | : Total element strain vector at previous increment.    |
| PDIST0   | : Total modal displacement vector at previous increment |

COMMON BLOCK/NONLX

| NCUR   | : Vector of numbers of nonlinear curves input for each            |
|--------|-------------------------------------------------------------------|
|        | material.                                                         |
| CPR    | : Confining pressure for a nonlinear curve.                       |
| NPTS   | : Number of points on each nonlinear curve.                       |
| EG     | : Stress coordinate of the nonlinear curve for data.              |
| GAM.   | : Strain coordinate of the nonlinear curve for data.              |
| EY     | : Stress coordinate of the nonlinear curve.                       |
|        | = EG X AXMUL1                                                     |
| GAMOC  | : Strain coordinate of the nonlinear curve.                       |
| •      | = GAN X AXMUL2                                                    |
| PRESTR | : Principal strain at previous increment.                         |
| PREDEV | : Principal stress difference $(\sigma_1 - \sigma_2)$ at previous |
| 2<br>4 | fncrement.                                                        |
| CONPRE | : Element confining préssure.                                     |

|            | COMMON-BLOG  | <u>(/DEF/</u>                                                 |
|------------|--------------|---------------------------------------------------------------|
|            | DX           | : X-displacement of nodal point for a loading increment.      |
| J          | DY           | : Y-displacement of nodal point for a loading increment.      |
| r          | VX           | : Horizontal velocity of nodal point for a loading increment. |
|            | VY           | : Vertical velocity of nodal point for a loading increment.   |
|            | EPSX .       | : Horizontal strain rate for a loading increment.             |
|            | EPSY         | : Vertical strain rate for a loading increment.               |
|            | GANXY        | : Shear strain rate for a loading increment.                  |
| r          | EPSI 1       | : Major principal strain rate for a loading increment.        |
| ι,         | EPSI 2       | : Minor principal strain rate for a loading increment.        |
| المر       | P\$I         | : Clockwise angle from vertical to line of action of          |
|            |              | major principal strain rate.                                  |
| -<br>~     | CSUMPD       | : Total deformation energy.                                   |
|            | CSUMPW       | : Total power of deformation.                                 |
| x          | COMMON BLOC  | Z /ELAS/                                                      |
| ×          | E            | : Starting modulus of elasticity for the material.            |
|            | ENU          | : Poisson's ratio for the material.                           |
|            | EE\ °        | : Array of values of E modified for nonlinear analysis.       |
| ţ          | EC           | : Array of values of E determined from stresses and           |
| ,          | • \          | strains calculated in increment.                              |
|            | DKSIJ        | : Starting tangential stiffness value for cutting             |
|            | r            | joint elements.                                               |
| •          | DKNIJ        | : Starting normal stiffness value for cutting joint           |
|            | ;            | elements.                                                     |
| · .        | DKSI I       | : Starting tangential stiffness value for interface           |
| د،         |              | joint elements.                                               |
|            | 7<br>4 V     |                                                               |
| <i>~</i> ° | , <i>C</i> = |                                                               |
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|-----------------|-----------------------------------------------------|
| DKNII           | : Starting normal stiffness value for interface     |
|                 | joint elements.                                     |
| COMMON BLO      | CK/JOINT/                                           |
| ТI              | : Joint element transformation matrix from local    |
|                 | element axes to global axes.                        |
| BL              | : Working matrix for the transformation process.    |
| AL              | : Element length.                                   |
| ANG(N)          | : Angle element N making with horizontal.           |
| DKS(N)          | : Tangential stiffness coefficient for element N.   |
| D <b>KN(</b> N) | : Normal stiffness coefficient for element N.       |
| SD 🐂            | : A diagonal material property matrix expressing    |
| <i>,</i>        | • the joint stiffness per unit length in the normal |
|                 | and tangential directions.                          |
| W(N,1)          | : ) Incremental shear and normal displacements      |
| W(N,2)          | : ) for element N, respectively.                    |
| P(N,1)          | : ) Incremental shear and normal stresses           |
| P(N,2)          | : ) for element N, respectively.                    |
| V(N,1)          | : ¿Average incremental shear and normal             |
| V(N,2)          | : displacements for element N, respectively.        |
| AVP(N,1)        | : ) Average incremental shear and normal            |
| AVP(N.2)        | > )# tresses for element N, respectively.           |
| CV (N,1)        | : ) Cumulative average shear and normal             |
| CV (N,2)        | : displacements for element N, respectively.        |
| CAVP(N,1)       | : ¿ Cumulative average shear and normat             |
| CAVP(N,2)       | : Stresses for element N, respectively.             |

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| •          |   | matrix. [Designated as matrix D in Eq. (2.20)].  |
|------------|---|--------------------------------------------------|
| B1         | : | Relative element displacement-modal displacement |
| PCAVP(N,2) | : | ) the summation process                          |
| PCAVP(N,1) | : | ) Working vestors for                            |
| PCV(N,2)   | : | ) the summation process.                         |
| PCV(N,1)   | : | > Working vectors for                            |

# COMMON BLOCK/JNONL/

|             | NVAL      | : Vector of numbers of nonlinear curves input for each joint material. |
|-------------|-----------|------------------------------------------------------------------------|
|             | CNP       | : Array of normal pressures for nonlinear curves.                      |
|             | AH        | · Hyperbolic coefficient (a) array.                                    |
| !           | BH        | : Hyperbolic coefficient (b) array.                                    |
|             | COMMON BL | OCK /AVRG/                                                             |
| r<br>1<br>3 | AVSMAX    | : Average incremental maximum principal stress.                        |
|             | AVSMIN    | : Average incremental minimum principal stress.                        |
| -           | AVANG     | : Clockwise angle from vertical to line of action                      |
|             |           | of incremental maximum principal stress.                               |
|             | ANTINA .  | : Avérage total maximum principal stress.                              |
|             | AVTMN     | : Average total minimum principal stress.                              |
|             | AVTANG    | : Clockwise angle from vertical to Nine of action                      |
|             |           | of average total maximum principal stress.                             |
|             | AVSMX     | : Average incremental maximum principal strain.                        |
|             | AVSMN .   | : Average incremental minimum principal strain.                        |
|             | AVSANG    | : Clockwise angle from vertical to line of action                      |
|             | · ' .     | of average incremental maximum principal strain.                       |
| ľ,          | . AVSTMX  | : Average total maximum principal strain.                              |
|             | 1         |                                                                        |

 AVSTMN : Average total minimum principal strains.
 AVSTAN : Clockwise angle from vertical to line of action of average total maximum principal strain.
 AVPSI 1 : Average incremental maximum principal strain rate.
 AVPSI 2 : Average incremental minimum principal strain rate.
 AVPSI 1 : Clockwise angle from vertical to line of action of average incremental maximum principal strain rate.

### VARIABLE DEFINITIONS

#### PROGRAM MAIN

NPROB : Number of problems.

NRB

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Counter on number of problems.

SUBROUTINE GDATA

Il : Control for print of input data.

BANGLE : Angle of cutting blade [only in case of soil-cutting analysis] with vertical.

#### SUBROUTINE GDATA 2

 

 TMAT
 : Type of material.

 AXMUL1
 : Multiplier for the stress coordinate of the nonlinear curve.

 AXMUL2
 : Multiplier for the strain coordinate of the non 

linear curve.

#### SUBROUTINE STIFT 1(N)

I, J, K, L : Element connections, later used as loop counters.

#### SUBROUTINE STIFT 2(N)

I, J, K : Element connections, later used as loop counters. AJ,BJ,AK,BK : Local coordinates of triangles.

#### SUBROUTINE FORMK

NROWB

NCOLB : Variables defining location of element stiffness matrix. NCOL : )

#### SUBROUTINE SOLVE

N : Equation counter for elimination and back-substitution.

: Working variable for the elim/nation process.

#### SUBROUTINE STRESS

G

: Vector of displacement. DIS EQUIVALENCE statement allows array DSIS(2,200) to be used for the solution vector C(400). SMAX Maximum principal stress for element N. SMIN Minimum principal stress for element N. : ANG Clockwise angle from vertical to line of action of maximum principal/stress for element N. EMAX Maximum principal strain for element N. . Emiñ Minimum principal/strain for element N. : Clockwise angle/from vertical to line of action EANG of maximum principal strain for element N.

| SUBROUTINE | REAC |                    | •<br>•         | 1          |
|------------|------|--------------------|----------------|------------|
| J1,J2,K1,  | ://  | Element horizontal | and vertica    | reaction / |
| K2.1.1.12  | ./ / | directions corresp | onding the not | ,<br>loc   |

Vector of element nodal displacements.

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SUBROUTINE LARDEF Incremental deformation energy for the SUMPW entire continuum. Incremental power of deformation for the SUMPD entire continuum. DUP : Working variable for calculation of deformation energy for element N. Incremental deformation energy for element N. DUPV Incremental power of deformation for element N. PDOF SUBROUTINE AVER Working variable for summation of incremental SFORCE : stresses in elements connected at node, later used for average incremental stresses at node. Working variable for summation of total stresses in **SSIGTO** elements connected at node, later used for average total stresses at node. SSTRTO Working variable for summation of total strains in elements connected at node, later used for average total strains at node. Working variable for summation of incremental strains SSTR in elements connected at node, later used for average incremental strains at node. SESPSX Working variables for summation of incremental horizontal, vertical and shear strain rates, respectively, SEPSY in elements connected at node, later used for average SGAMXY . 0 încremental values at node.

NOEL

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: Counter for number of elements attached to node.

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# SUBROUTINE NONLIN

| EPRE   | : | E-value of an element at pre                                        | vious increment              |   |
|--------|---|---------------------------------------------------------------------|------------------------------|---|
| PRSTTO | f | Principal strain ( $\epsilon_{b}$ ).                                |                              | , |
| NC     | : | Nonlinear curve number.                                             | ,<br>N                       |   |
| BOTSTR | : | 2                                                                   | 1<br>2                       |   |
| TOPSTR | : | } Intermediate values in inte                                       | erpolation for               |   |
| STRNEW | : | $\begin{cases} stress difference (\sigma_1 - \sigma_3) \end{cases}$ | ) corresponding to strain, a | ÷ |
| DZNOM  | : |                                                                     | 1                            | - |
| FIMER  | • | <b>*</b> ,                                                          | •                            |   |

## SUBROUTINE JNONL

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TOWM

Ultimate strength of joint material employing the

hyperbolic formulation.

: Nonlinear curve number.

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Interpolated (at and (b) coefficients, Eq. (2.33).

A.4 LISTING OF PROGRAM "MAIN-2L"

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| FORTHAN IÝ 6 LEVEI                    | . 21 MAIN DATE                                         | 73195 04/43/41                             | PAGE 0001 |
|---------------------------------------|--------------------------------------------------------|--------------------------------------------|-----------|
| <b>∽ c</b>                            | **********************                                 | • • • • • • • • • • • • • • • • • • •      | •         |
| C                                     | ***************************************                | ******************************             |           |
| ¢                                     | NAIN-2L ,                                              |                                            |           |
| C.                                    | ******                                                 | ********************************           | • *       |
| с<br>. с                              | NOTE THAT ALL THE HESULTS ARE I                        | IN TERMS OF UNIT WIDTH                     | •         |
| с<br>с                                | PROGRAM CAPACITY                                       |                                            |           |
| C                                     | NUMBER OF NONLINEAR HATERIALS                          | =3                                         |           |
|                                       | NUMBER OF NONLINEAR CONTINUUM NATERIALS                | =1                                         | •         |
| τ.                                    | TOTAL NUMBER OF ELEMENTS                               | =450                                       |           |
| Ç Ç                                   | NUMBER OF TREANGULAR ELEMENTS                          | =400                                       |           |
| . C                                   | NUMBER OF JOINT ELEMENTS                               | *50                                        |           |
| C 1.                                  | W NUMBER OF NOTAL POINTS                               | =209                                       |           |
| C                                     | NUMBER OF SPECIFIED BOUNDARY CONDITIONS(LOAD           | OR DISPLACEMENTS) =50                      |           |
| , ς                                   | NUNBER OF SPECIFIED PRESSURE BOUNDARY CONDIT           | 10NS #10                                   |           |
| ) - C                                 | NUMBER OF NONLINEAR CURVES FUR EACH CONTINUE           | M MATERIAL -10                             | •         |
| C C                                   | NUMBER OF POINTS ON EACH NONLINEAR CONTINUUS           | CURYE #50                                  | /         |
| , c                                   | NUMBER OF NONLINEAR CURVES FOR EACH JOINT HA           | TERIAL #10                                 | •         |
| · · · · · · · · · · · · · · · · · · · | BAND WIDTH                                             | +80                                        |           |
| C                                     | CONTROL MAIN PROGRAM                                   |                                            |           |
| <b>***</b> 1                          | COMMON/CONTR/TITLE(12).NP.NE.NB.NOF.NCN.NLD.           | NMAT-NSZF-LESNT4-NTS                       |           |
|                                       | 3 - NOPC - NCHAT                                       | ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~    |           |
| , <b>0465</b>                         | COMMON/DATA/COND(200.2).NOP(450/4).1HAT(450)           | •NBC(50).CODE(200).UK                      |           |
|                                       | E(200) .UV(200) . (BC(10) . JBC(10) . PRE(10) . T(450) | }• XDEN• YDEN• ORX { 450 }•                | h         |
|                                       | 2077(450).PRCORD(200.2)                                | •                                          | •         |
| . 8003                                | COPHON/ANAL/NOINC.KOUNT.NTEST.LTEST.NITER.NC           | LITER.VEL.THO                              |           |
| 0004                                  | COPHON/ST[FF/EST[FH(12,12).A(3,6).B(3,6).SK(           | 400.80}.AREA(450},                         |           |
| ×                                     | 1C(400).R(8).H(85.WHAND.D(400).AR(400)                 |                                            |           |
| (VVS)                                 | COMMUN/STRES/DISTO(2.200).SIGTO(450,4).STRT            | 3(450,3),SMAXTD(450),                      |           |
| -                                     | 13#1#10(450); ANGIU(450); EANGIU(450); EFAXTO(45       | SOI . EMINICIASCI.FORCE                    | 0         |
|                                       | 11950191251#(450.3) #\$1610(450.4) PSTRTO(450.         | 3).POISTO(2.200)                           | _         |
|                                       |                                                        | 501-6AR(30)-                               |           |
|                                       | COMPON/OFF/OIL2001.07(2001.98(2001.98(2001.98)         |                                            |           |
|                                       | 16ANTY(A50) - FRET: (A50) - LOCI2(A60) - DEIIARO) - CO |                                            |           |
|                                       | COMMONANT ACAR, FMILTRELAGAL, MCLAGAL, DURAL ACAM      | NAL TO |           |
| 0009                                  | COMMONY (DINT/I) (8.8). (4.8). (1.60). (1.60).         | J.DKS[].DKN[]                              |           |
|                                       | 1(2.2) (\$60-2) P(650.2) . V(650.2) . AVP(650.2)       | CV(450-2).CAV0(450-3).                     |           |
|                                       | 2PCV(450.2).PCAVP(450.2).01(8.8)                       |                                            |           |
| 9919                                  | COMMON/ JHONE /HVAL (2). CNP(2.10). AM(2.10). BH(2     | (.10) e                                    |           |
| 6011                                  | COMMON/AVRG/AVSHAX(200) . AVSHIN(200) . AVANG(20       | 01.AVTH1(200).                             | •         |
|                                       | LAVTHN(200) . AVTANG(200) . AVS#X(200) . AVSHN(200)    | .AVSANG[200].                              |           |
|                                       | 2445THA(200) . AVSTHN(200) . AVSTAN(200) . AVPS11(2    | 00), AVPS12(200),                          |           |
|                                       | JAVPST(200)                                            | · · · · · · · · ·                          | •         |
| <b>11</b> 2 ~                         | INTEGER WBAND                                          |                                            |           |
| с.                                    |                                                        |                                            |           |
| _ C                                   | 1 INITALIZE JAPE NO.                                   |                                            |           |
| c                                     | AND NUMBER OF CORNER NODE MAX.                         |                                            |           |
| 0013                                  | NT4=[]                                                 | -                                          |           |
| <b>##1</b> 4                          | NT5=12                                                 | - <sup>1</sup>                             |           |
| 0415                                  | READ(5,1) NPROB                                        |                                            | •         |
| , c                                   | LOOP ON NO. OF PRUBLEMS                                |                                            |           |
| nn) 🔺                                 | EG 400 MPR#1.NPRON                                     |                                            |           |





| 1<br>roor   |            |                                     | Ň                          | •                           | ł           |           |        |     |
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| FORTAL      | •          |                                     | •                          |                             | ~           |           |        |     |
| -           | IV 6 LEVE  |                                     | NIM 2                      | DATE = 73195                | 1 */E ¥/ *0 | PAGE 0004 |        |     |
| 0107        | 90         | I CONTINUE                          |                            |                             |             |           | •      |     |
| 010         |            | D CONTINUE<br>D CONTINUE            |                            |                             |             |           |        |     |
|             | U          |                                     | TE REACTIONS               |                             |             |           |        |     |
|             |            | IF (NITER.ME.NOITE<br>NEITE (4.203) | EM) 60 TO 441              |                             |             |           |        |     |
| 0112        |            | 00 434 Kal. NG                      |                            |                             | ·           |           |        |     |
|             | ·          | 2120(X)                             | *                          |                             |             |           |        |     |
| 4110        |            | L=20M                               | ~                          |                             |             |           |        |     |
|             | U          | Abo<br>Abo                          | BOY FORCES TO F            | INST INCREMENT              |             |           |        |     |
| 0117        |            | AR(N) -AR(N)-D(N)                   |                            | •                           |             |           |        | ,   |
| • • • •     | <b>.</b>   | 60 10 503<br>1 17/005(m)_00.2.)     | ) 60 TO 502                |                             |             |           |        |     |
| 0110        | -          | AN(N)=AR(N)-D(N)                    |                            |                             | *           | •         |        |     |
|             |            | # AR(L)=AR(L)-0(L)<br>= churime     |                            | -                           |             |           |        |     |
| 0123        |            | s thrifte<br>urite(4+201) N.AA      | 1(M). AR(L)                |                             |             | •         |        | , . |
|             |            | CONTINUE                            | ·<br>·                     |                             |             |           | 7      | -   |
| 6125        | U          |                                     | VGE ELEMENT COORD          | INATES                      |             |           |        |     |
| 0120        | R.         | 3 IF (MDINC.EQ.1) GO                | 0 TO 712                   |                             |             |           |        |     |
| 0127        |            | CALL LARDEP                         |                            |                             |             |           |        | •   |
| ,<br>,<br>, | J U        |                                     | KANK SIMESKA . 4<br>Héntis | ter Alexia des chievie      |             |           |        |     |
| 0128        |            | CALL AVER                           | ĸ                          |                             |             |           |        |     |
|             | 20.        | á CDNTIMJE                          |                            | ,                           | ,           |           |        |     |
| 1010        | <b>.</b> . | P CONTINUE                          | •                          |                             |             |           |        |     |
| 2010        | ē<br>•     | D CONTINUE                          |                            |                             |             | 4         |        |     |
| 6133        | •          | I FORMAT(915)<br>• Framation 14.05  |                            |                             |             |           |        |     |
|             |            | I FORMAT(15.2F15.6)                 |                            |                             | ~~          |           | ,      |     |
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|             |            | 5700                                |                            | -X-#EVCI [CM2. • 1 6X• • A- |             |           |        |     |
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| PORTRAN IV & L                                                                                                                                                                                                                                                           | EVEL 21 -                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | GDATAL                                                                                                                                                                                                                          | DATE = 73195                                                                                                                              | 04/43/41          | PAGE 60     | 01                                    |  |
|                                                                                                                                                                                                                                                                          | SUDDON'T THE SOAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 7.8.1                                                                                                                                                                                                                           |                                                                                                                                           |                   | (           | •                                     |  |
| 0001                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | :***<br> 'YLF61234NP+NF-MB+                                                                                                                                                                                                     | NOF MEN NUM NEAT MEAT .                                                                                                                   | T-NTA-NTS         | · _ · ,     |                                       |  |
| VVVL                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                 |                                                                                                                                           |                   | •           |                                       |  |
|                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                 |                                                                                                                                           |                   | _           |                                       |  |
| <b>69</b> 03                                                                                                                                                                                                                                                             | COMMON/DATA/COM                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | CD(200+2)ANOP(430.                                                                                                                                                                                                              | 4). IWAT (450). NEC (50). C                                                                                                               | DE (200) . UX     |             |                                       |  |
|                                                                                                                                                                                                                                                                          | I (580) 104(580) 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | (BC(10)+JBC(10)+PH                                                                                                                                                                                                              | E(10) . I (430) . XDEN. TDEN                                                                                                              | UKX(450).         |             |                                       |  |
|                                                                                                                                                                                                                                                                          | 2011Y (450), PHCONC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 2200.23                                                                                                                                                                                                                         |                                                                                                                                           | -                 |             | -                                     |  |
|                                                                                                                                                                                                                                                                          | COPHON/ANAL/WU                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | MC KOUNT NIESTELT                                                                                                                                                                                                               | EST MITERANULTERAVELAT                                                                                                                    |                   |             |                                       |  |
| 4405                                                                                                                                                                                                                                                                     | COMMON/STIFF/ES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | ST [FH(]2.12).A(].0                                                                                                                                                                                                             | 7.0(3.6).SK(400,80).AR                                                                                                                    | EA(450).          |             |                                       |  |
|                                                                                                                                                                                                                                                                          | 1C(400).#(8).H(8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | 33 <b>, waand</b> , D(496)?AR                                                                                                                                                                                                   | (400)                                                                                                                                     |                   | 2           |                                       |  |
| 6804                                                                                                                                                                                                                                                                     | COMMON/ELAS/E.8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | ENU, EE(450].EC(450                                                                                                                                                                                                             | I. DKSIJ. DKN IJ. DKSII. DK                                                                                                               | •11 /             |             |                                       |  |
| 8967 ·                                                                                                                                                                                                                                                                   | INTEGER VBAND                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | •                                                                                                                                                                                                                               |                                                                                                                                           |                   | ,           | _                                     |  |
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| Ċ                                                                                                                                                                                                                                                                        | . <b>R</b> t                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | LAD AND PRINT TITL                                                                                                                                                                                                              | E AND CONTROL                                                                                                                             | -                 |             |                                       |  |
| 0001                                                                                                                                                                                                                                                                     | READ(5.7) TITLE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | (                                                                                                                                                                                                                               |                                                                                                                                           |                   |             |                                       |  |
| 400 <b>9</b>                                                                                                                                                                                                                                                             | W417E(4+109) TI                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | ITLE                                                                                                                                                                                                                            |                                                                                                                                           |                   |             |                                       |  |
|                                                                                                                                                                                                                                                                          | READ(5.1) NP.N                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | E. ND. NDF. NHAT. NCHA                                                                                                                                                                                                          | T.NOPC. XDEN. YDEN. 11                                                                                                                    |                   |             |                                       |  |
| 0011                                                                                                                                                                                                                                                                     | wRITEL6.9)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                 | -                                                                                                                                         |                   |             | •                                     |  |
| 0012                                                                                                                                                                                                                                                                     | WITELS.10) NP                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | NE .NB . HOF . HHAT . NC                                                                                                                                                                                                        | HAT, NOPC , XDEN , YDEN , II                                                                                                              |                   |             |                                       |  |
| · · ·                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | EAD AND PHINT MATE                                                                                                                                                                                                              | RIAL DATA                                                                                                                                 |                   |             |                                       |  |
| 6113                                                                                                                                                                                                                                                                     | BEAD(S.8) F.FM                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | PADKSTJADKNTJADKST                                                                                                                                                                                                              | LOKNII                                                                                                                                    | •                 |             |                                       |  |
| A014                                                                                                                                                                                                                                                                     | ARTE IA. I OAL                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                 |                                                                                                                                           | <b>`</b>          |             |                                       |  |
| 0015                                                                                                                                                                                                                                                                     | WEITEIA. BIF. MAN                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                                 | I-DKNII                                                                                                                                   |                   |             |                                       |  |
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| - A104                                                                                                                                                                                                                                                                   | READ(5.2) IN-(CO                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | MDIN.MIAMMIAZIAL                                                                                                                                                                                                                | L. SIP)                                                                                                                                   |                   |             |                                       |  |
| - 4                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | TAD FLED WIT DATA                                                                                                                                                                                                               | ******                                                                                                                                    |                   |             |                                       |  |
|                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                 | 7141. 7144                                                                                                                                |                   |             | -                                     |  |
|                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | ***************************************                                                                                                                                                                                         |                                                                                                                                           |                   |             |                                       |  |
| ,                                                                                                                                                                                                                                                                        | COOSed a cost                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | THE LOAD THE PLAN                                                                                                                                                                                                               | × 01050110                                                                                                                                |                   |             |                                       |  |
|                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                 |                                                                                                                                           |                   |             |                                       |  |
|                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | FIED DISPLACEMENT                                                                                                                                                                                                               | IN A DIRECTION- CORD IN                                                                                                                   | T DIMECTION       |             |                                       |  |
|                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | FIED CURP IN A UIN                                                                                                                                                                                                              | CUTTOR- DISPLACEMENT I                                                                                                                    | I DIRECTION       |             |                                       |  |
|                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | TEO DISPLACEMENT                                                                                                                                                                                                                | THE X AND Y DEMECTIONS,                                                                                                                   |                   |             |                                       |  |
| 9919                                                                                                                                                                                                                                                                     | HEAD(5+12) (NO(                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | C(1)+1=1+NH)                                                                                                                                                                                                                    |                                                                                                                                           |                   |             |                                       |  |
| ****                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                 |                                                                                                                                           |                   |             |                                       |  |
| 6019                                                                                                                                                                                                                                                                     | DO 800 K=1.NB                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                 | •                                                                                                                                         |                   |             |                                       |  |
| 6019<br>6629                                                                                                                                                                                                                                                             | DO 800 K=1.NB                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                 | •                                                                                                                                         |                   |             |                                       |  |
| 4019<br>4 <del>029</del><br>6021                                                                                                                                                                                                                                         | DO 800 K=1.NB<br>NM=NBC(K]<br>800 READ(5.13) COOR                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | E ( NN ) JUX ( NN ) JUY ( NH                                                                                                                                                                                                    | •                                                                                                                                         |                   |             |                                       |  |
| 6019<br>6620<br>6071                                                                                                                                                                                                                                                     | DO 800 K=1,NS<br>NM=NBC(<)<br>800 READ(5,13) CODE<br>READ(5,13) CODE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | E(M) SUX(M) SUV(M)<br>EAD BLADE VELOCITY                                                                                                                                                                                        | ))<br>' AND HOREZONTAL TRAVEL                                                                                                             |                   |             | -                                     |  |
| 6019<br>6629<br>6621<br>6621<br>(                                                                                                                                                                                                                                        | DO 800 K#1.NB<br>NM=N8C(K]<br>800 READ(5.13) CODE<br>READ(5.8) THD:1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | E(NN) JUX(NN) JUY(NN<br>EAD BLADE VELOCITY<br>VEL-BANGLE                                                                                                                                                                        | D .<br>AND HORIZONTAL TRAVEL                                                                                                              | DISTANCE          |             |                                       |  |
|                                                                                                                                                                                                                                                                          | DO 800 K=1.NB<br>NH=HBC(K)<br>800 READ(5.13) CODI<br>READ(5.8) THD.4<br>READ(5.8) THD.4<br>READ(5.8) THD.4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | E(NN) JUX(NN) JUY(NN<br>EAD WLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND                                                                                                                                                  | 18<br>- AND HOREZONTAL TRAVEL<br>NARY CONDECTONS                                                                                          | DISTANCE          | Ţ           | ۰<br>۲                                |  |
| 6019<br>0020<br>0021<br>0022<br>0022                                                                                                                                                                                                                                     | DO 800 K=1.NB<br>NH=H6C(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO:<br>100 READ(5.8) THO:<br>100                                                   | E(MN) UX(MN) UV(MN<br>EAD WLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110                                                                                                                                       | 1)<br>AND HOREZONTAL TRAVEL<br>NARY CONDETIONS                                                                                            | DISTANCE          | ·           | ,                                     |  |
| 6019<br>6624<br>6621<br>6622<br>6622<br>6022<br>6024                                                                                                                                                                                                                     | DO 800 K=1.NB<br>NH=H6C(K]<br>800 READ(5.13) CODE<br>READ(5.8) THD.N<br>1f(HOPC.EQ.D).C<br>DO 470 L=1.NOPC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | E(NN) UX(NN) UV(NN<br>EAD BLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C                                                                                                                                  | 1)<br>1 AND HORIZOHTAL TRAVEL<br>1ARY CONDITIONS                                                                                          | DISTANCE          | ·           | γ                                     |  |
| 4010<br>0020<br>0021<br>0022<br>0023<br>0024<br>0025                                                                                                                                                                                                                     | DO 800 K=1.NB<br>NM=HBC(K]<br>800 READ(5.13) CODI<br>81<br>READ(5.8) THD.1<br>1P(HOPC.EQ.0) (<br>DG 470 L=1.NOOM<br>READ(5.118) ID(                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | E(NN) UX(NN) UV(NN<br>EAD WLADE VELOCITY<br>Vel.Bangle<br>EAD Pressure Bound<br>Go to 110<br>C<br>C<br>C(L), JUC(L), PHE(L)                                                                                                     | -<br>AND HORIZONTAL TRAVEL<br>DARY CONDITIONS                                                                                             | DISTANCE          | •           | ۲<br>۲                                |  |
| 6010<br>6020<br>6021<br>6022<br>6023<br>6023<br>6024<br>6025<br>0026                                                                                                                                                                                                     | DO 800 K=1.NB<br>NH=H8C(K]<br>800 READ(5.13) CODI<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.118) ID(<br>490 CONTINUE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | E(NN) JUX(NN) JUY(NN<br>EAD BLADE VELOCITY<br>Vel.BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L), JBC(L) PRE(L)                                                                                                         | AND HOREZONTAL TRAVEL                                                                                                                     | DISTANCE          | •           | ۲<br>۲                                |  |
| 6010<br>6020<br>6021<br>9522<br>0023<br>6024<br>6025<br>0026                                                                                                                                                                                                             | DO 800 K=1.NB<br>NH=H6C(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO.4<br>17(HOPC.EQ.0)/<br>DO 470 L=1.NOPC<br>READ(5.116) ID(<br>490 CONTINUE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | E(INN) UX(INN) UV(INN<br>EAD BLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L) JBC(L) PHE(L)<br>EAD NO. OF INCREME                                                                                   | AND HORIZONTAL TRAVEL<br>NARY CONDITIONS                                                                                                  | DISTANCE          | •<br>•      | · · · · · · · · · · · · · · · · · · · |  |
| 4019<br>0020<br>0021<br>0022<br>0023<br>0024<br>0025<br>0026<br>0026                                                                                                                                                                                                     | DO 800 K=1.NB<br>NH=H6C(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO:<br>17(HOPC.EG.0) (<br>DO 490 L=1.NOPC<br>READ(5.11A) 10(<br>490 CONTINUE<br>110 READ(5.4) NOIN                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | E(NN) UX(NN) UV(NN<br>EAD BLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L) USC(L) PRE(L)<br>EAD NO. OF INCREME<br>C.NOITER                                                                          | AND HOREZONTAL TRAVEL<br>NARY CONDITIONS                                                                                                  | DISTANCE          | · ·         | ۲ :<br>۲ :                            |  |
| 4010<br>0021<br>0021<br>0023<br>0024<br>0025<br>0026<br>0026                                                                                                                                                                                                             | DO 800 K=1.NB<br>NM=HBC(K]<br>800 READ(5.13) CODI<br>(<br>READ(5.8) THD.1<br>(<br>10 (HOPC.EQ.0).(<br>DO 400 L=1.NOM<br>READ(5.118) ID(<br>490 CONTINUE<br>110 READ(5.4) NOTION<br>400 IF(11.NE.0) GD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | E(MN) UX(MN) UV(MN<br>EAD WLADE VELOCITY<br>VEL.BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L).JUC(L).PHE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO 500                                                                | AND HORIZONTAL TRAVEL<br>DARY CONDITIONS<br>INTS AND NO. OF STERATE                                                                       | DISTANCE          | ,<br>,<br>, |                                       |  |
| 6010<br>6020<br>6021<br>9022<br>0023<br>0024<br>6025<br>0026<br>6025<br>0026<br>6027<br>0028                                                                                                                                                                             | DO 800 K=1.NB<br>NH=H8C(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.11A) IO<br>490 CONTINUE<br>110 READ(5.4) NOIN<br>400 IF(J1.NE.0) GD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | E(NN) UX(NN) UY(NN<br>EAD WLADE VELOCITY<br>VEL.BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L).JUC(L).PNE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO SOO<br>RINT INPUT DATA                                             | AND HOREZONTAL TRAVEL<br>DARY CONDETIONS<br>NTS AND NO. OF STERATE                                                                        | DISTANCE<br>      | •           | ۲<br>۲<br>۲                           |  |
| 6010<br>6020<br>6021<br>6022<br>6023<br>6023<br>6024<br>6025<br>0026<br>6027<br>6026<br>6029                                                                                                                                                                             | DO 800 K=1.NB<br>NH=HBC(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>READ(5.16) ID(<br>490 CONTINUE<br>110 READ(5.4) NOTH<br>490 IF(J1.NE.0) GD<br>PU<br>THITE(6.102)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | E(INN) JUX(INN) JUY(INN<br>EAD WLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L) JUC(L) PHE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO SOO<br>RINT INPUT DATA                                        | AND HORIZONTAL TRAVEL<br>DARY CONDITIONS<br>INTS AND NO. OF ITERATE                                                                       | DISTANCE          |             | · · · · · · · · · · · · · · · · · · · |  |
| 4019<br>0021<br>0021<br>0023<br>0024<br>0025<br>0026<br>0029<br>0029<br>0020                                                                                                                                                                                             | DO 800 K=1.NB<br>NH=H6C(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO<br>1F(HOPC.EQ.D).(<br>DD 470 L=1.NOPC<br>READ(5.116) ID(<br>490 CONTINUE<br>110 READ(5.4) NOINC<br>490 IF(J1.NE.0) dD<br>pr<br>TRITE(6.102)<br>WRITE(6.2) (N.4)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | E(NN) JUX(NN) JUY(NN<br>EAD BLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L) JUC(L) PRE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO 500<br>RINT INPUT DATA<br>(CORD(N.W).PRI.2).                     | HEILINP)                                                                                                                                  | DISTANCE          | •           | <pre></pre>                           |  |
| 4010<br>6020<br>6021<br>9023<br>0024<br>6025<br>0026<br>6027<br>0026<br>6029<br>6030<br>6030                                                                                                                                                                             | DO 800 K=1.NB<br>NM=HBC(K1<br>800 READ(5.13) CODI<br>AT<br>READ(5.8) THD.1<br>AT<br>10 (HOPC.EQ.0).(<br>DO 400 L=1.NOPC<br>READ(5.118) ID(<br>490 CONTINUE<br>110 READ(5.4) NOTH<br>490 IF(11.NE.0) OD<br>PHITE(6.102)<br>WRITE(6.103)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | E(MN).UX(MN).UV(MN<br>EAD WLADE VELOCITY<br>VEL.BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L).JUC(L).PHE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO 500<br>RINT INPUT OATA<br>(CORD(N.H).PHI.2).                       | NAND HORIZONTAL TRAVEL<br>NARY CONDITIONS                                                                                                 | DISTANCE          |             |                                       |  |
| 6010<br>6020<br>6021<br>9022<br>0023<br>0024<br>6025<br>0026<br>6025<br>0026<br>6029<br>6030<br>6031<br>0032                                                                                                                                                             | DO 800 K=1.NB<br>NM=HM6C(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>400 L=1.NOMC<br>READ(5.4) NOINC<br>400 IF(J1.NE.0) GD<br>PI<br>= WITE(6.102)<br>WRITE(6.2) (N:<br>WRITE(6.3) (N:<br>WRITE(6. | E(NN) UX(NN) UV(NN<br>EAD WLADE VELOCITY<br>VEL.BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L).JBC(L).PNE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO SOO<br>RINT INPUT DATA<br>(CORD(N.M).PP1.2).                       | AND HORIZONTAL TRAVEL<br>ARV CONDITIONS<br>NTS AND NO. OF STERATE<br>RELINE?                                                              | DISTANCE<br>DNS 2 | •           |                                       |  |
| 4019<br>0020<br>0021<br>0023<br>0024<br>0025<br>0026<br>0029<br>0030<br>0031<br>0033                                                                                                                                                                                     | DO 800 K=1.NB<br>NH=H8C(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>READ(5.118) IOC<br>490 CONTINUE<br>110 READ(5.4) NOTH<br>490 IF(J1.NE.0) GD<br>PH<br>TRIFE(6.102)<br>WRITE(6.2) (N+1<br>WRITE(6.3) (N+1<br>PRIE(6.104)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | E(NN).UX(NN).UV(NN<br>EAD WLADE VELOCITY<br>VEL.BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C(L).JUC(L).PHE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO SOO<br>RINT INPUT DATA<br>(CORD(N.M).PH1.2).                            | HATCH), T(N), N=1, NE)                                                                                                                    | DISTANCE<br>045   | •           |                                       |  |
| 4019<br>4029<br>6021<br>9022<br>9023<br>0024<br>9025<br>9026<br>9029<br>6030<br>0032<br>0033<br>0034                                                                                                                                                                     | DO 800 K=1.NB<br>MM=MBC(K]<br>800 READ(5.13) CODI<br>AT<br>READ(5.8) THD.1<br>IF(MOPC.E0.0) (<br>DD 470 L=1.NOPM<br>READ(5.118) ID(<br>490 CONTINUE<br>II MEAD(5.4) NOIM<br>490 IF(J1.NE.0) dD<br>P<br>TRITE(6.102)<br>WRITE(6.2) (N.6<br>WRITE(6.2) (N.6<br>WRITE(6.104)<br>DO 900 K=1.NME                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | E(NN).UX(NN).UV(NN<br>EAD WLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L).JBC(L).PHE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO 500<br>RINT INPUT DATA<br>(CORD(N.M).PHI.2).                       | AND HORIZONTAL TRAVEL<br>NARY CONDITIONS<br>NTS AND ND. OF ITERATE<br>(1410, NP)                                                          | DISTANCE          | •           |                                       |  |
| 6010<br>6020<br>6021<br>9022<br>9023<br>0024<br>6025<br>0026<br>6027<br>0028<br>0029<br>0030<br>0031<br>0033<br>0034                                                                                                                                                     | DO 800 K=1.NB<br>NM=HBC(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>NETE(6.103) MOIN<br>WRITE(6.103)<br>WRITE(6.104)<br>DO 900 K=1.NB<br>MNHMC(K)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | E(MN).UX(MN).UV(MN<br>EAD WLADE VELOCITY<br>VEL.BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L).JUC(L).PHE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO 500<br>RINT INPUT OATA<br>(CORD(N.M).PHI.2).<br>(NOP(N.M).M=1.4).1 | AND HORIZONTAL TRAVEL<br>DARY CONDITIONS<br>INTS AND NO. OF ITERATE<br>MEL.NP)<br>HAT(N),T(N),N=1,NE)                                     | DISTANCE          | •           |                                       |  |
| 6010<br>6020<br>6021<br>9022<br>0023<br>0024<br>6025<br>0026<br>6025<br>0026<br>6027<br>6028<br>0029<br>6030<br>0031<br>0032<br>0035<br>0035                                                                                                                             | DO 800 K=1.NB<br>NM=H8C(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>READ(5.8) THO:<br>400 CONTINUE<br>HE<br>110 READ(5.4) NOING<br>400 IF(J1.NE.0) GD<br>PT<br>THITE(6.102)<br>WRITE(6.2) (N:<br>WRITE(6.103)<br>UN 900 K=1.NB<br>NN=NBC(K)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | E(NN).UX(NN).UV(NH<br>EAD WLADE VELOCITY<br>VEL.BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C(L).JUC(L).PHE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO SOO<br>RINT INPUT DATA<br>(CORD(N.H).PHI.2).<br>(NOP(N.H).HEI.4).I      | AND HORIZONTAL TRAVEL<br>ARV CONDITIONS<br>INTS AND NO. OF STERATE<br>(HELONP)                                                            | DISTANCE          |             |                                       |  |
| 4019<br>0021<br>0021<br>0023<br>0024<br>0025<br>0026<br>0029<br>0030<br>0031<br>0034<br>0035<br>0034                                                                                                                                                                     | DO 800 K=1.NB<br>NM=HBC(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>READ(5.118) IOC<br>490 CONTINUE<br>110 READ(5.4) NOTH<br>490 IF(J1.NE.0) GD<br>PL<br>TRIFE(6.102)<br>WRITE(6.103)<br>WRITE(6.3) (N-0<br>HRITE(6.104)<br>DO 900 K=1.NB<br>NN=NGC(K)<br>\$00 WHITE(6.11)NN.0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | E(NN) UX(NN) UV(NN<br>EAD BLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L) UBC(L) PRE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO 500<br>RINT INPUT DATA<br>(CORD(N.N) PRI.2).<br>(NOP(N.N) MRI.4).1 | AND HORIZONTAL TRAVEL<br>NARY CONDITIONS<br>(NTS AND ND. OF ITERATE)<br>(NAT(N),T(N),N=1,NE)                                              | DISTANCE          | •           |                                       |  |
| 0010         0021         0023         0024         0025         0020         0020         0020         0020         0020         0020         0020         0020         0020         0020         0021         0032         0033         0034         0035         0034 | DO 800 K=1.NB<br>MM=MBC(K]<br>800 READ(5.13) CODI<br>AT<br>READ(5.8) THD.1<br>AT<br>IF(MDPC.EQ.0).C<br>DO 490 L=1.NOM<br>READ(5.118) IDC<br>490 CONTINUE<br>II READ(5.4) NOIM<br>490 IF(J1.NE.0) GD<br>PU<br>TRITE(6.102)<br>WRITE(6.2) (N.6<br>WRITE(6.2) (N.6<br>WRITE(6.103)<br>WRITE(6.104)<br>DO 900 K=1.NB<br>HN=MBC(K)<br>900 WHITE(0.11)NN.6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | E(NN).UX(NN).UV(NN<br>EAD BLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BDUND<br>GO TO 110<br>C<br>C(L).JBC(L).PHE(L)<br>EAD NO. OF INCREME<br>TO 500<br>RIMT INPUT DATA<br>(CORD(N.M).PHI.2).<br>(NOP(N.M).HHI.2).              | AND HORIZONTAL TRAVEL<br>NARY CONDITIONS<br>(NTS AND ND. OF ITERATE)<br>(NET.NP)<br>(NAT(N),T(N),N=1,NE)                                  | DISTANCE          | •           |                                       |  |
| 0010         0021         0023         0024         0025         0026         0027         0028         0029         0030         0031         0034         0035         0036                                                                                            | DO 800 K=1.NB<br>NM=MBC(K]<br>800 READ(5.13) COOL<br>READ(5.13) COOL<br>READ(5.13) COOL<br>10 (NDPC.EQ.0).(<br>DO 470 L=1.NOPC<br>READ(5.11A) IOC<br>490 CONTINUE<br>110 READ(5.4) NOIN<br>490 CONTINUE<br>MRITE(6.102)<br>WRITE(6.103)<br>WRITE(6.104)<br>DO 900 K=1.NB<br>NN=NBC(K)<br>\$00 WRITE(6.11)NN.(                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | E(NN).UX(NN).UV(NN<br>EAD WLADE VELOCITY<br>VEL.BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L).JUC(L).PHE(L)<br>EAD NO. OF INCREME<br>C.NOITER<br>TO 500<br>RINT INPUT OATA<br>(CORD(N.H).PHI.2).<br>(NOP(N.N).H=1.4).1 | AND HORIZONTAL TRAVEL<br>DARY CONDITIONS<br>(NTS AND NO- OF ITERATE<br>(<br>N=1+NP)<br>(NAT(N),T(N)+N=1+NE)                               | DISTANCE          | •           |                                       |  |
| 0010         0021         0023         0024         0025         0026         0027         0028         0029         0031         0032         0033         0034         0035         0036                                                                               | DO 800 K=1.NB<br>NM=MBC(K]<br>800 READ(5.13) COOL<br>READ(5.8) THO.4<br>READ(5.8) THO.4<br>IF (MOPC.EG.0).(<br>DO 470 L=1.NOPC<br>READ(5.11A) IOC<br>490 CONTINUE<br>H<br>110 READ(5.4) NOINC<br>490 CONTINUE<br>H<br>110 READ(5.4) NOINC<br>490 IF(J1.NE.0) GD<br>P<br>WRITE(6.102)<br>WRITE(6.103)<br>WRITE(6.104)<br>DO 900 K=1.NB<br>NN=NBC(K)<br>900 WRITE(6.11)NN.(                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | E(NN) JUX(NN) JUY(NH<br>EAD WLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C(L) JUC(L) PHE(L)<br>EAD NO. OF INCREME<br>TO SOO<br>RINT INPUT OATA<br>(CORD(N.M) PHI.2).<br>(NOP(N.M) HHI.4).1                | AND HORIZONTAL TRAVEL<br>NARY CONDITIONS<br>(NTS AND NO. OF ITERATIONS<br>(NTS AND NO. OF ITERATION<br>(N. 1. NP)<br>(NAT(N).T(N).N=1.NE) | DISTANCE          | •           |                                       |  |
| 4019<br>0021<br>0021<br>0023<br>0024<br>0025<br>0029<br>0030<br>0031<br>0032<br>0034                                                                                                                                                                                     | DO 800 K=1.NB<br>MM=MBC(K]<br>800 READ(5.13) CODI<br>AT<br>READ(5.8) THD.1<br>IF (MOPC.EQ.0).C<br>DG 470 L=1.NOM<br>READ(5.116) ID<br>490 CONTINUE<br>II MEAD(5.4) NOIM<br>490 IF(J1.NE.0) dD<br>PI<br>TRIFE(6.102)<br>WRITE(6.103)<br>WRITE(6.104)<br>DO 900 K=1.NB<br>NN=NBC(K)<br>\$00 WHITE(6.11)NN.0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | E(NN) UX(NN) UV(NN<br>EAD BLADE VELOCITY<br>VEL-BANGLE<br>EAD PRESSURE BOUND<br>GO TO 110<br>C<br>C(L) UBC(L) PRE(L)<br>EAD NO. OF INCREME<br>TO 500<br>RINT INPUT DATA<br>(CORD(N.M) PRI.2).<br>(NOP(N.N) M=1.4).1             | AND HORIZONTAL TRAVEL<br>NARY CONDITIONS<br>(NTS AND NO. OF ITERATE)<br>(NAT(N),T(N),N=1,NE)                                              | DISTANCE          |             |                                       |  |


| MONTRAN IV CLEVEL 21<br>MONTRAN IV CLEVEL 21<br>MONTANA IV CLEVEL 21                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | GDATAZ DATE = 73105 04/43/41<br>ATAZ<br>TITLE(LE).WP-WE-WEB-WEB-WLD-NMAT-WSEF.LE,MT0-MT5<br>CUM[2].CPM[2.10].MPT6(2.10).EC(50).GAM(50).<br>AMOC(2:10.50).MPT6(2.10).EC(50).GAM(50).<br>AMOC(2:10.50).MPT6(2.10).BEC(50).COMPRE(150)<br>AMOC(2:10.50).PMEEEEV(150).COMPRE(150)<br>AMOC(2:10.50).PMEEEEV(150).COMPRE(150)<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEV(150).<br>AMOC(2:10.50).PMEETEEEEV(150).<br>AMOC(2:10.50).PMEETEEEEV(150).<br>AMOC(2:10.50).PMEETEEEEEV(150).<br>AMOC(2:10.50).PMEETEEEEV(150).<br>AMOC(2:10.50).PMEETEEEEV(150).<br>AMOC(2:10.50).PMEETEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEE |                                       |   |
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| MONTRAM IV 6 LEVEL 21<br>COMPONYCONTINE 60<br>COMPONYCONTINE 60<br>COMPONYCO                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | GDATAZ DATE = 73195 84/43/41<br>ATAZ<br>TITLE(12).WP.ME.MOF.MCM.MLD.MMAT.MSEF.LI.MT4.MT5<br>CURI2).CPR12.10).MPT8(2.10).EG(50).GAM(50).<br>AMOC(2.10.50).PMESTR(55).PMEDEV(55).COMPRE(55)<br>MVAL(2).COP(2.10).AM12.10).GM(2.10)<br>DATA FOR MOMLINEAR MATERIAL PROPERTIES<br>THE IMPUT CURVE FOM EACH COMFINING PRESSUME IS<br>(SIGMAI-SIGMA3) VS EPSILONI<br>STADT BFADING MOM-LIMEAR IMPUT DATA                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 1000<br>74<br>1                       |   |
| evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel<br>evel | ATA<br>TITLE(L2).MP.ME.NB.NDF.NCN.NLD.NNAT.NSEF.LI.NT0.NT5<br>Curi2).CPR(2.10).MPTS(2.10).EG(90).CAM(50).<br>Auoc(22.10.50).MPTS(2.10).EG(90).CAMPE(150).<br>NVAL(2).CUP(2.10).MPTS(10).BN(2.10)<br>BATA FON MONLINEAR NATERIAL PROPERTIES<br>Int INPUT CURVE FON EACH CONFINING PRESSURE IS<br>(SIGMA1-SIGNA3) VS EPSILQNI DATA<br>STADT BFADING MON-LINEAR INPUT DATA                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                       |   |
| 1.400%, 400%, 400%, 400%, 400%, 70%<br>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | CURI2).CPRI2.10).MPTS(2.10).EG(50).GAM(50).<br>Audc(2.10.50).PRESTR(550).PREDEV(550).CDMPTE(550)<br>NVAL(2).CMPT2.10).AM(2.10).BM(2.10)<br>Data For Monlinear Material Propertes<br>Data For Monlinear Material Propertes<br>(sigmai-sigma) VS epsilon:<br>Star Frantus Mon-limear Imput Data                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | · · · · · · · · · · · · · · · · · · · |   |
| Common View Common                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | AMOCIZ-10.50).PRESTR(450).PREDEV(450).COMPRE(450)<br>NVAL(2).COPTZ-101.AM(Z-10).BREDEV(450).COMPRE(450)<br>Data For Monlinear Material Propertes<br>ata For Monlinear Material Propertes<br>(sigmal-sigmas) VS epsiloni<br>Stadt Brading Mon-linear Imput Data                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                       |   |
| C C C C C C C C C C C C C C C C C C C                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | DATA FOR MONLINEAR MATERIAL PROPERTIES<br>The Infut Curve for Each confining Pressure îs<br>(sigmai-sigma) vê epsiloni<br>Stadt Beading Mon-Linear Indui Data                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                       |   |
| C C C C C C C C C C C C C C C C C C C                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | THE IMPUT CURVE FOR EACH CONFINING PRESSURE IS<br>(Signal-Signa)) vs Epsilqni<br>Stadt Rfading Mum-Lingar Imput Data                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                       |   |
| C MRITE(4.44)<br>C MRITE(4.44)<br>C MRITE(4.44)<br>C MR.D(5.45) TR<br>MCU<br>MCU<br>MCU<br>MCU<br>MCU<br>MCU<br>MCU<br>MCU<br>MCU<br>MCU                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | STADT BETADING NON-LINEAR INPUT DATA                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | • •                                   |   |
| •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••           •••••         •••••         •••••         •••••                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                       |   |
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| 0007         0012010011           0007         001200151001           0007         00120015100           00012         304 MRTF6(6.452)           0012         304 MRTF6(6.452)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | HY IS THE MUMBER OF NOM, INEAR CURVES IMPUT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                       |   |
| 0000 MCURVENCUR(1)<br>0010 IF (NCURV) 30<br>0012 304 MRITE(6.452)<br>0012 410 510                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | HCURITY.ITT.MCHAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | × -                                   |   |
| 0011 304 BRITE(6.452)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 4 - 104 - 310                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                       |   |
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| 0114 READ(5,110) C<br>0115 READ(5,120) C                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | PA(1.44C).AXHUL1.AXHUL2.MPT3(1.4C)<br>HC.CPA(1.4C).MPT3(1.4C)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | ۵                                     |   |
| Cate Merants(1.MC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | F                                     |   |
| 0015                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | GAN(LP).LPs1.NPT)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                       |   |
| 929 90 330 LP-1.40                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | (                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                       |   |
| 0021 EYLLANC .LP) =E                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | -                                     |   |
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| • 8824 330 CONTINUE<br>• 825 3000 CUNTINUE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | •                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                       |   |
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| u u<br>*                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | INE INPUT VALUES FOR EACH NORMAL PRESSURE<br>Are hyperrollic coefficients a and b                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                       |   |
| PO20 IF(MMAT.EO.MC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | MAT1 60 TO 601                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                       |   |
| 0026 READ(5-100) (                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | NVAL(I) . 1 MML. MMAT)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | ÷                                     |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                       | , |
| 0031 NVALUE-NVALUE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                       |   |
| 0032 [FINVALUE )623                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | . 603.604 *                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                       |   |
| 0034 003 MILE(0.607)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                       |   |
| 0035 604 WRITE(6+607)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                       |   |
| 0036 0036 00 605 W#1.N<br>0037 READ(5.606) C                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | MALUE.<br>Martine.<br>Martine.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                       | - |
| 0036                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | NV . CMP(1, NV) . AM(1, NV) . BM(1, NV)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                       | - |
| 0037 005 CONTINUE<br>0040 000 CONTINUE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                       |   |
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|                    | SUUROUTINE STIFTE(N)                         |                         | •           |            |
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|                    | 11200).UV(200).IBC(10).JBC(10).P             | RE(10).T(450).KDEW.YDEW | -CEX(450)-  |            |
| •                  | 2044[450], PRCOHD(200.2)                     |                         |             |            |
| <b>4404</b>        | COMMON/STIFF/ESTIFM(12,12).A(3.              | 6).8(3,6),SK[400,80].AR | EA (450) .  |            |
|                    | 10(400)+H(6)+H(8)+WAND+D(400)+A              | P(406)                  |             |            |
|                    |                                              | d)+DKSIJ+DKNIJ+DKSII+DK | NLI         |            |
|                    | OFTERNING FLEMENT                            |                         | • .         |            |
| 4447               | 1=NOP(N+1)                                   | COMMECTIONS ,           |             | •          |
|                    | J=N0P(N,2)                                   |                         | ·           |            |
| 6603               | K=NOP <sup>7</sup> (N,3)                     | · • *                   |             | •          |
| 4010               | ORX(N)={CORD(1+1)+CORD(J+1)+COR              | D{K.1}}#8.333333        |             |            |
| 0011               | ORY(N)=[CORD(1+2)+CORD(J+2)+COR              | D(K.2)1+0.333333        |             | ***        |
| 5                  | SET UP LOCAL COORD                           | INATE SYSTEM            | · _ ·       | -          |
| 0013               | AK#CODO(K_1)=COBO(1_1);                      | 2                       |             | ,          |
| 0614               | 84#6080(4.2)#6080(1.2)                       |                         |             |            |
| 0015               | MK=CORD(x,2)-CORD(1,2)                       | •                       |             |            |
| 0616               | AREA(N)=(AJSHK-AKCHJ)/2.                     |                         |             |            |
| 9017.              | IF (ANEA(N) LE.Q.) GO TO 220                 |                         |             |            |
| . f 🐂              | FORM STRAIN DISP.                            | MATRIX                  |             |            |
| ÷ C                | AND SAVE ON TAPE                             | •                       |             | . 4        |
| 0618               | A(1,1)=8J-8K                                 |                         |             | •          |
| 6019               | At1.23=0.                                    |                         |             |            |
| <b>4</b> 920       | A(1+3)=8K                                    |                         | -           | `          |
| 0022 · · ·         | A[]_+}=D+<br>A[]_+]==R(                      |                         |             |            |
| 8023               | Att.6180.                                    |                         | ~           | •          |
| 8024               | A[2+1]#D.                                    |                         | ,           |            |
| 2200               | ALZ+2}=AK-AJ                                 | •                       |             | 3          |
| 0024 ·             | A(2+3)=0.                                    |                         |             | Ť          |
| 0027               | A { Z . 4 } =- AK                            |                         | -           |            |
|                    | A12.5)=0.                                    |                         |             | <u>گر</u>  |
| 0027               | M(2+6)#AJ                                    | ē.                      |             |            |
|                    | A(3)]}#AK#AJ<br>A17.9)580.000                |                         |             |            |
| 4432               | 4/3. 11=-AK                                  |                         |             |            |
| 803.4              | A[ 3.4 ) #AK                                 |                         |             | • ·        |
| 4L90               | A(3,5)=AJ                                    |                         |             | 2          |
| 0435               | A(3.6)=-P.J                                  | -                       |             | ,          |
| 0036               | WRITE(NTS) No(EA(I.J).J=1.6).[#              | 1.3)                    |             |            |
| - · C              | FORM STRESS STAIN                            | NATE EX                 |             | •          |
| -0837              | CONH=EE(N)/((1.+ENU)+(1ENU+2.)               | ) #AREA [N] ) .         | •           |            |
| 96.09<br>010       | ESTIFM(1+1)=COMM+(1-ENU)                     | -                       |             |            |
|                    | 507150(1 31-0                                | •                       |             |            |
| 8641               |                                              |                         |             |            |
| 0042               | ESTIFH(2,2)=ESTIFH(1,1)                      |                         | 1           |            |
| 0043               | ESTIF4(2.3)+0.                               |                         | 1           |            |
| 0044               | ESTIF 4(3,1)=0.                              |                         | {           |            |
| 0045               | £\$T1+#(3,2)=0.                              |                         | i.          |            |
|                    |                                              |                         | · · · /     |            |
|                    |                                              |                         |             |            |
|                    |                                              |                         | · J ·       | · <b>K</b> |
|                    |                                              | ~                       | -           |            |

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FORME 0ATE = 73195 04/43/41 PAGE 0001 - 12 FORMS STIFFNESS HATRIX COMMON/CONTR/TITLE(12) . NP . NE . NB . ND . NCH . NLD . NHAT . NSEF . LI . NT4 . NT5 GONNON/DATA/CURD(200.2).NOP(450.4).INAT(450).NOC(50).CODE(200).UX 1(200).UV(200). HC(10). JUC(10). PRE(10). T(450). XDEN. VDEN. DRX(450). COMION/ANAL/NOINC . SOUNT IN TEST IL TEST INI TER . HOI TER . VEL THO COMMON/STIFF/EST, FH(12.12). A(3.6).8(3.4). SK(400.80). AREA(450).

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SUBROUTINE FORME

2087(450).PRCORD(209-2)

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6665 1C(400).R(8).N(6).#8AND.D(400).AH(400) DIMENSION XET3.21 ..... INTEGER WEAND 9997 ZERO STIFFNESS MATRIX DO JOO N=1.NSZF 9908 0909 0010 DEN1=0.0 0011 DO JOO NAL. WBAND 0012 390 SK(N.H]=0. SCAN ELEMENTS C. 001.2 20 480 MM .... 1010 "INDPLN, J+CO. HOP(N+4)) "60 TO 100 0015 CALL STIFTICN) 60 10 101 ..... 0017 100 CALL STIFTE(N) 101 CONTINUE ..... RETURNS ESTIFH AS STIFFNESS MATRIX σ STORE ESTIFA IN SA FIRST ROVS LFINOPINESS.EGANOPINEASS GO TO 307 0819 6929 NENWA 1590 60 TO 308 \$922 307 NCN#3 -023-308 00 360 JJ-1.NCN 0924 NROVE = ( NOP ( N. JJ) - 1 ) =NOF 9025 IF (NRGs8) 360, 305, 305 305 DU 350 J=1.NDF .0024 .0027 NRCHB=NRCHB+1 0028 1=(JJ-1)+NDF+J THEN COLUMNS c 00330 KK=1+NCN 0029 0030 NCOLS=(NOP(N,KK)-1)+NOP 0031 00 320 K=1.NDF 0032 L = (KK-1) + K6633 NCOL = NCOL8 + K + I -NROW8 # c SKIP STORING IF BELOW BAND IF (NCUL ) 320. 320. 310 8034 1035 310 SK(NROBB.NCOL)=SK(NROWB.NCOL)+ESTIFA(I.L) 320 CONTINUE 0036 0037 330 CONTINUE 0038 350 CONTINUE 0039 360 CUNTINUE 400 CONTINUE 0040 C ADDITION OF CONCENTRED FORCES

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MOF. MCN. MLD. MMAT. MSZF. LT<br>"Go. 4 ). I MAT (1450). MBC (150). COD<br>. MPE (10). T (1450). MBC (150). COD<br>. LTEST. MITER. MOITER. VEL. THD<br>. LTEST. MITER. MOITER. VEL. THD<br>. A (1400)<br>. A (1400). A (1400). A (1400)<br>. COMPA<br>. MTS (1450). P (150). P (1500)<br>. MTS (1410). P (150). COMPA<br>. MTS (1410). P (150). COMPA<br>. MTS (1410). P (150). COMPA<br>. MTS (1410). P (11. D (150).<br>. MTS (1410). P (11. D (150).<br>. MTS (15. M). J (150).<br>. MTS (15. M). MCREMENT A<br>. MTS (15. T (150).<br>. MTS (150). T (150).<br>. MTS (150). T (150).<br>. MTS (150). T (150).<br>. MTS (150). T (150).<br>. 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SK(400.80).AREA<br>AR(400)<br>TOI450.4).STRT0(450.3).SHAK<br>(450).FRIN(0450.1).POIST0(2)<br>(4).PSTRT0(450).FRIN(150)<br>AF(150).PRED(1450).COMP)<br>AF(150).PRED(1450).COMP)<br>AF(150).PRED(1450).COMP)<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(1450).COMP<br>AF(150).PRED(150).PRED(1450).COMP<br>AF(150).PRED(150).PRED(1450).COMP<br>AF(150).PRED(150).PRED(1450).COMP<br>AF(150).PRED(1450).PRED(1450).COMP<br>AF(150).PRED(150).PRED(1450).COMP<br>AF(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(150).PRED(1 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       | COMMONASTRES/01510(2.200).510<br>SPENTO(2000/04510(2.200).510<br>COMMONASTRES/01510(2.200).501<br>EV(2:10.50).6010(32<br>COMMUNELAS/E.ENU.EE(50).601.60<br>EV(2:10.50).6010(32<br>EV(2:10.0110,011)<br>EV(2:10.0110,0110,0110,010<br>EV(2:10.0110,0110,0110,010,01<br>EV(2:100,0110,0110,0110,010,01<br>EV(2:100,0110,010,010,010,010,01<br>EV(2:100,0110,010,010,010,010,00<br>EV(2:100,000,0110,010,010,010,00<br>EV(2:100,000,000,0110,00,010,00<br>EV(2:100,000,000,0110,00,010,00<br>EV(2:100,000,000,0110,00,010,00<br>EV(2:100,000,000,0110,00,010,00<br>EV(2:100,000,000,0110,00,000,010,00<br>EV(2:100,000,000,0110,00,000,010,00<br>EV(2:100,000,000,0110,00,000,000,000,000,00<br>EV(2:100,000,000,000,000,000,000,000,00<br>EV(2:100,000,000,000,000,000,000,000,000,000                                                                                                                                                                                                                                            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57<br/>D RENISTINU DIS (2, 10, 50), 57<br/>E OULUVALENCE (515, 5.0)<br/>F ME SIND MT3<br/>ME SIND MT3<br/>M</td> <td>HISS2-110, EGG 20.10, CAN 201<br/>ESTR(450), PREDEV(450), CAN 201<br/>450), DKS1J, DKN1J, DKS11, DKN1<br/>415<br/>MJS 200, TO EACH INCREMENT A<br/>M15 200, TO EACH INCREMENT A</td> <td></td> <td>•</td> <td>•</td> <td>2</td> |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   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    | 167(2:10.50).6A40C(2:10.50).FC       169     167(2:10.50).6C       11     152(2:10.50).6C       12     1015(2:20)       13     1015(2:20)       14     1015(2:20)       15     1015(2:20)       16     1015(2:20)       17     1015(2:20)       18     1015(2:20)       19     1015(2:20)       11     1015(2:10)       12     117(117       13     117(117       14     117(117       15     117(117       16     117(117       17     1015(2:1)       17     1015(2:1)       18     10004       19     1015(2:1)       11     1015(2:1)       11     1015(2:1)       12     1015(2:1)       13     1015(2:1)       14     1015(2:1)       15     1015(2:1)       16     1015(2:1)       17     1015(2:1)       18     1015(2:1)       19     1015(2:1)       11     1015(2:1)       12     1015(2:1)       13     1015(2:1)       14     1015(2:1)       15     1015(2:1)       16     1015(2:1)       17     10                                                                                                                 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| <pre>entremotions.col<br/>infloctures<br/>feeling units<br/>feeling un</pre>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           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| <pre>comparamentors.co<br/>interest values<br/>interest values<br/>interes</pre>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       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<td>•</td> <td></td> <td>2</td>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | MTS<br>MOF[:4w1.MP]<br>MTS OUE TO EACH IMCREMENT A<br>ED TO THOSE EXISTING BEFOME                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        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| 881       001370(1,410-01370(1,41)-01370(1,410)-01370(1,410)-0131(1,410)         882       61270(1,410-01370(1,410)-0131(1,410)         883       61270(1,410-01370(1,410)-0132(1,410)         884       61270(1,410-01370(1,410)-0132(1,410)         884       61270(1,410-01370(1,410)-0132(1,410)         884       61270(1,410)-01370(1,410)-013-0130         884       174(4172-4472-4017770)-01320(1,410)-013-0130         884       174(4172-4472-4017770)-01320(1,410)-013-0130         884       174(4172-412-0130-0130)-01320         884       174(4017-0130-0130-0130)-01310         884       174(4017-0130-0130-01120)-01310         884       174(4011-010-0100-01120)-01310         884       174(4011-010-0100-01120)-01310         884       174(4011-010-0100-01120)-01310         884       174(4011-010-0100-01120)-01310         884       174(4011-010-0100-01120)-01310         884       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  84       17401126.0.01110.0.01510.0.01         84       17401126.0.01110.0.0110.0.0110.0.01         84       17401126.0.01110.0.0110.0.010000         84       20010000000000000000000000000000000000                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 81     01370(1,40)=01370(1,40)       82     01370(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=01370(1,40)       84     0130(1,40)=0130(1,40)       84     0130(1,40)=0130(1,40)       84     0200 MC=1.04       84     0200 MC=1.04       84     0200 MC=1.04       84     0200 MC=1.14       84                                                                                                                                                                                                                                                                                                                                                                      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       26         02 501 141           27         04 602 J=1.2           26         05 01570(J,M)=015(J,M)           27         04 602 J=1.2           26         05 01570(J,M)=015(J,M)           27         05 01571                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   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G0 T0 903<br>29 MHTECA.ME.MOJTER) G0 T0 903<br>20 MHTECA.ME.MOJTER) G0 T0 703<br>20 MHTECA.ME.MEN<br>20 MHTECA.MEN<br>20 MHTECA.MEN<br>20 MHTECA.MEN<br>20 MHTECA.MEN                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       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| 88       01570(j.m)=01570(j.m)=01510(j.m)=01510(j.m)         88       maiffe(a.112)         17(41756+05.112)       017051 40 10         88       maiffe(a.112)         171(1175       (a.101570(j.m)-j.m), mil.me)         88       maiffe(a.112)         111       (a.101570(j.m)-j.m), mil.me)         112       (a.101570(j.m)-j.m), mil.me)         113       (a.101570(j.m), j.m), mil.me)         114       (a.101570(j.m), j.m), mil.me)         115       (a.101570(j.m), j.m), mil.me)         115       (a.101570(j.m), j.m), mil.me)         115       (a.101570(j.m), j.m), mil.me)         115       (a.101570(j.m), mil.me)         115       (a.10150(j.m), mil.me)         115       (a.10111)         115       (a.10111)         115       (a.10111)         115       (a.10111)         115       (a.11111)         115       (a.11111)         115       (a.11111)         115       (a.11111)         115       (a.11111)         115       (a.11111)         115       (a.111111)         115       (a.111111)         115       (a.11111111) <td< td=""><td><pre>B 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DisTo(J.Wiedistro(J.WiedistJ.W)<br/>A DisTo(J.Wiedistro(J.WiedistJ.W)<br/>A Districtance wolfteth GO TO 903<br/>A Districtance clarker porces<br/>A Districtance</pre></td><td>15 652 DISTO(J.#)=#015TO(J.#)=DIS(J.<br/>16 [f(NITER.ME.WOITER) 60 TO 903<br/>27 MEITE(A.112)</td><td></td><td></td><td></td><td></td><td></td></td<>                                                                                                         | <pre>B 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| 1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1       1                                                      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| 13       0.3 CONTINUE       C.ALCULATE ELEWENT FORCHS         13       C       D0 200 HC=1.ME         13       FALCULATE ELEWENT STRAINS         13       FALCULATE ELEWENT STRAINS         14       C       D0 200 HC=1.ME         15       FRADUNES N.(LAITE ELEWENT STRAINS         15       FRADUNES N.(LAITE ELEWENT STRAINS         15       FRADUNES N.(LAITE STRAINS         15       FRADUNES N.(LAITE STRAINS         15       FRADUNES N.(LAITE STRAINS         15       FRADUNES N.(LAITE).J.J.F.1.0).151.3)         15       FRADUNES N.(LAITE).J.J.F.1.0)         15       FRADUNES N.(LAITE).J.J.F.1.0).151.13)         15       FRADUNES N.(LAITE).J.J.F.1.0)         16       FRADUNES N.(LAITE).J.J.F.1.0).151.13)         17       FLADE N.J.F.1.0)         18       FLADE N.F.1.0)         19       FLADE N.F.1.0)         19                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 13       •0.3 CONTINUE       CALCULATE ELEMENT FORCER         13       EALCULATE ELEMENT FORCER         13       EALCULATE ELEMENT FORCER         13       EALCULATE ELEMENT FORCER         13       EALCULATE ELEMENT FORCER         14       D0 200 MC-1.08         13       EALCULATE ELEMENT FORCER         14       D0 200 MC-1.08         13       EALCULATE ELEMENT FORCER         14       D0 200 MC-1.08         15       D0 260 [=1.3]         14       D0 260 [=1.3]         15       FOURDER         16       D0 260 [=1.3]         17       D0 260 [=1.3]         18       D0 260 [=1.3]         19       D0 260 [=1.3]         200 240 J = 1.00F       EALOURER         200 240 J = 1.00F       EALOURER         200 240 J = 1.40F       EALOURER         200 240 J = 4.40F       EALOURER                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        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     19       PANOP         10       PANOP         11       PANOP         12       PANOP         13       PANOP         14       PANOP         15       PANOP<                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           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     315       EalCollate Elewent Stating         314       EalCollate Elewent Stating         315       EalCollate Elewent Stating         314       EalCollate Elewent Stating         315       EalCollate Stating         314       EalCollate Nucleation         315       EalCollate Nucleation         315       EalCollate Nucleation         315       EalCollate Nucleation         315       EalCollate Nucleation         316       EalCollate Nucleation         317       EalCollate Nucleation         318       EalCollate Nucleation         319       EalCollate Nucleation         311       EalCollate Nucleation         312       EalCollate Nucleation         313       EalCollate Nucleation         314       EalCollate Nucleation         315       EalCollate Nucleation         316       EalCollate Nucleation         317       EalCollate Nucleation         318       EalCollate Nucleation         319       EalCollate Nucleation         311       EalCollate Nucleation         320       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           | P 963 CONTINUE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              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| 31     00 200 MC=1.ME       31     1 F(MOP(MT-3).ME.MODF(MC.41) GO TO 200       32     READ(YTS) N.((A(1.J).J=1.0).[=1.3)       33     WEMOP(N.1)       34     D0 260 151.3       35     VENOP(N.1)       36     D0 260 151.3       37     VENOP(N.1)       38     VENOP(N.1)       39     VENOP(N.1)       31     VENOP(N.1)       32     VENOP(N.1)       33     VENOP(N.1)       34     Z       35     VENOP(N.1)       36     O       37     VENOP(N.1)       38     Z       39     VENOP       30     Z       31     VENOP       32     VENOP       33     VENOP       34     Z       35     VENOP       36     CONTINUE       37     VENOP       38     Z       39     CONTINUE                                                                                                                                                                                                                                                                                                                                                  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1=1.3<br>N=NOP(N,1)<br>P=NOP(N,1)<br>P=NOP(N,1)<br>P=NOP(N,1)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2)<br>P=D(2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 18       D0 200 HC=1.WE         11       1F(MOP(WC.3).WE.MOD(MC.41) G0 TO 200         11       READ(MTS) N.((A(1)).J=1.0).[=1.3]         115       D0 260 [=1.3]         115       D0 260 [=1.3]         115       D0 260 [=1.3]         115       D0 200 [=1.3]         115       D0 260 [=1.3]         115       D0 200 [=1.3]         115       D0 200 [=1.3]         115       D0 200 [=1.3]         115       D0 200 [=1.3]         116       D0 200 [=1.3]         117       E(1-1)*D=1         118       D1         119       D1         110       D1         111       D1         112       D1         113       D1         114       D1         115       D1         118       D1         119       D1         119       D1         110       D1         111       D1         112       D1         113       D1         114       EX         115       L         115       L         114       L                                                                                                                                                                                                                                                                                                                                                          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| 31     17 (MOP(W.J).WE.MOP(MC.A)) GO TO 200       324     READ(MTE) N.((6(1.J).JMI.0).101.3)       314     READ(MTE) N.((6(1.J).JMI.0).101.3)       315     NO 200 151.3       316     NO 200 151.3       317     NO 200 151.3       318     NO 200 151.3       319     NO 200 151.3       310     NO 200 151.3       311     NO 200 151.3       312     NO 200 151.3       313     NO 200 151.3       314     NO 200 151.3       315     NO 200 151.3       316     NO 200 151.3       317     NO 200 151.3       318     NO 200 151.3       319     NO 200 151.3                                                                                                                                                                                                                                                                                                                                                                                                                                                                     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113       No 200 [a1.3]         114       D0 200 [a1.3]         115       D1 200         111       D1 200         111       D1 200         111       D1 200         112       D1 200         113       D1 200         114       No 110         115       No 110         115       No 110         115       No 110         114       No 110         115       No 110         115       No 110                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             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N.((A(1.J).JMI.6).[A1.3)         115       D0 200 [31.3]         116       N.((A(1.J).JMI.6).[A1.3))         116       D0 200 [31.3]         116       N.((A(1.J).JMI.6).[A1.3))         116       D0 200 [31.3]         116       N.((A(1.J).JMI.6).[A1.3])         116       N.((A(1.J).JMI.6).[A1.3])         117       N.((A(1.J).A.1.6))         118       N.(A.1.1.8)         119       N.(A.1.1.8)         110       N.(A.1.1.8)         111       N.(A.1.1.8)         112       N.(A.1.1.8)         113       N.(A.1.1.8)         114       N.(A.1.1.8)         115       N.(A.1.1.8)         118       N.(A.1.1.8)         119       N.(A.1.1.8)         111       N.(A.1.1.8)         112       N.(A.1.1.8)         113       N.(A.1.1.8)         114       N.(A.1.1.8)         115       N.(A.1.1.8)         118       N.(A.1.1.8)         119       N.(A.1.1.8)         119       N.(A.1.1.8)         119       N.(A.1.1.8)         119                                                                                      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| 333     READ(MIC) N.((S([]).JM(.0).[S1.3])       334     PO 260 [S1.3]       335     PWOP(N.[1])       336     PWOP(N.[1])       336     PMOP(N.[1])       337     PMOP (N.[1])       338     PWOP(N.[1])       339     PWOP(N.[1])       331     PWOP (N.[1])       332     PWOP (N.[1])       331     PWOP (N.[1])       332     PWOP (N.[1])       333     PWOP (N.[1])       341     PU POP       353     PU POP       354     PU POP       354     PU POP       355     PU POP       354     PU POP       355     PU POP       354     PU POP       355     PU POP       355 <td>313       READ(MIC) N.((S([]).JMI.6).[=1.3])         314       DO 200(151)         315       DO 200(151)         316       N*((A([]).JMI.6).[=1.3])         315       VENUP(N.[])         316       N*((A([]).JMI.6).[=1.3])         317       VENUP(N.[])         318       VENUP(N.[])         319       If(M.EQ.0)G(170 260         310       If(M.EQ.0)G(170 260         311       If(M.EQ.0)G(170 260         312       DO 200 1 1 200      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                                                                                                                                                                                                                                                                                                        | 313       READ(MIC) N.((S([]).JMI.6).[=1.3])         314       DO 200(151)         315       DO 200(151)         316       N*((A([]).JMI.6).[=1.3])         315       VENUP(N.[])         316       N*((A([]).JMI.6).[=1.3])         317       VENUP(N.[])         318       VENUP(N.[])         319       If(M.EQ.0)G(170 260         310       If(M.EQ.0)G(170 260         311       If(M.EQ.0)G(170 260         312       DO 200 1 1 200         313       If(M.EQ.0)G(170 260         314       DO 200 1 1 200         315       If(M.EQ.0)G(170 260         316       DO 200 1 1 200         317       DO 200 1 1 200         318       If(M.EQ.0)G(170 260         319       If(M.EQ.0)G(170 10 260         320       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213       I/A = K + NUF                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  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| 13.4     0.0 260 [=1.3]       13.5     1.0 00 260 [=1.3]       13.6     1.1 0.0 10 260       14.6     1.1 0.0 10 260       15.6     1.1 0.0 10 260       14.6     1.1 0.0 10 260       15.7     1.1 0.0 10 10 260       15.6     1.1 0.0 10 10 260       15.6     1.1 0.0 10 10 10 10 10 10 10 10 10 10 10 10 10                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       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136     11.1       137     11.1       138     11.1       139     11.1       131     11.1       131     11.1       132     11.1       133     11.1       134     11.1       135     11.1       131     11.1       132     11.1       133     11.1       134     11.1       135     11.1       131     13.1       132     13.1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 12 1 READ(NIA) N. ((B(I.J). Jat. 6).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 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| 15     W=NOP(N,1)       15     IF(M=E0.01GQ TO 260       15     N = 1.00F       15     0 = 1.00F       10     2.0 = 1.00F       11     2.0 = 1.00F       12     1.1 = 015(1.01)       13     2.0 = 015(1.01)       14     1.0 = 015(1.01)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              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       11       2.1 * 0.1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                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1) *MOF         14       K = (1 - 1) *MOF         15       0 0 240 J #1.MOF         15       240 R(1J) = DIS(J.M)         16       240 R(1J) = DIS(J.M)         17       10 K + NUF         18       10 K + NUF                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          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| No         IF(M.EQ.015q TO 200           13         K = (1 - 1)*MOF           14         L1 = 1, K           13         L1 = 1, K           14         L1 = 1, K           15         240 E(11) = DIS(1, M)           14         240 E(11) = DIS(1, M)           15         240 E(11) = DIS(1, M)           16         1.4 K                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           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MOF       15     2 + 1 + MOF       16     2 + 0 + 1 + MOF       17     2 + 0 + 1 + 1 + MOF       18     2 + 0 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        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| 37     K = (1 - 1) + MOF       136     00 240 J = 1. MOF       13     1 - K       14     1 - K       15     240 RF(1) = DIS(J.M)       11     240 COVTINE       12     1 - K       13     20 COVTINE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          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| 39     1.1 ± 1 + K       30     240 f(1) ± 1 + K       31     240 f(1) ± DIS(1.M)       31     240 COVTIME       32     1.4 ± + MUF                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    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|--------------|-----------|-------------------------------------------------------------------------|--------------|--------------|---------------------------------------|----|
|              | •         |                                                                         | ·            |              |                                       |    |
| 0043         | -         | DO 500 [=]                                                              |              |              |                                       |    |
|              | 24        | 5 FUNCE(N.1]=0.                                                         |              |              |                                       |    |
|              |           |                                                                         | •            | ۰.           | Ċ                                     | •  |
| 0046         |           |                                                                         | 2            | •            |                                       |    |
|              |           | - DU JUU J E JOIN<br>                                                   | • • •        | ,            | ,                                     |    |
| 9848         | •         | · SIR(N:[]=SIR(N:[]=(A(])) · A(]=)) · · · · · · · · · · · · · · · · · · | ,,           |              |                                       |    |
|              | 3         |                                                                         | F(M. 91)     |              |                                       |    |
| 0050         | · 4       | 200021014J#FUNGEIN14J7ENG*IFUNCEIN11J7FUNC                              | ETHOR / June |              | , , , , , , , , , , , , , , , , , , , |    |
|              |           | TALCHEATE DOINCIDAL STUFESES                                            | <b>\</b>     |              |                                       |    |
| ٢            | رع        |                                                                         |              |              |                                       | •  |
|              | ¥         |                                                                         | \ '          | . :          |                                       |    |
|              |           | TELNOPIN-11-NE-MORIN-A11 60 10 660                                      | - \          | •            | •                                     |    |
| 0083         |           | K = FORCE(N, 1) + FORCE(N, 2) 1/2.                                      | ° 47         |              |                                       | 1  |
| 3955         | <b>۔</b>  | 0#\$98711(FORCE(N.2)-FORCE(N.1))/2.)**2+ FO                             | ACE(N.3)++2) |              |                                       | •) |
| 0056         |           | 54 X+G+0                                                                |              |              |                                       |    |
|              | •         | Shina G-Q                                                               |              |              | · •                                   |    |
| 9954         |           | IF (FORCE(N.2), EQ.SHIN)GO TO 700                                       |              | •            |                                       |    |
| -0059        |           | ANG=57.29578+ATAN(PORCE(N.3)/(FORCE(N.2)-S                              | 41433        |              |                                       |    |
| 8060         |           | 60 TO 210                                                               |              |              | 1                                     |    |
| 8861         | · · · · · |                                                                         | 3            |              | i                                     |    |
| 8042         | · · · 2   | CONTINUE                                                                |              |              | ,                                     |    |
| 0063         |           | DE CONTINUE                                                             |              |              | . +                                   |    |
|              |           | CALCULATE PRINCIPAL STRAINS                                             |              |              | 4                                     |    |
|              | · č       | AND DIRECTIONS                                                          | I            | s /          | /                                     |    |
| 0464         | 42        | DO BOO NEL.NE                                                           | 1            | 4 <u>-</u> C | 1                                     | •  |
|              | 4 z C     | [F(NOP(N.3).NE.NOP(N.4)) 60 TO 800 -                                    |              | , -          |                                       |    |
| 0066         | ,         | E=(STQ(N,1)+\$TR(N,2))/2.                                               | ł            |              |                                       |    |
| 0067         |           | F=SQR1(((STR(N.2)-STR(N.1))/2.)++2+(STR(N.                              | 37/2-)++2)   |              |                                       |    |
|              |           | LMAX=E+F                                                                |              |              |                                       |    |
| 0069         |           | ENINEE-F                                                                |              |              | -                                     |    |
|              | ,         | F(STR(N.2).EQ.EP(N) GO TO 900                                           |              |              | •                                     | •  |
|              |           | EANG=57.29578+ATAN((STR(N.3)/2.)/(STR(N.2)                              |              |              |                                       |    |
| 0072 °       |           | - 60 TO 220                                                             |              | •            | 5                                     |    |
| 8073         | • •       | BO EANG=90.                                                             |              |              |                                       |    |
| 4074         | 2         | LO CONTRINE                                                             |              |              | e                                     |    |
| 2560         |           | DO CONTINUE                                                             |              |              |                                       |    |
|              | ► C       | EUMULATIVE STRESSES AND STRAT                                           | MS .         |              | x                                     |    |
| 2076         |           | IF(NITER-NE-1) GO TO BOZ                                                |              |              |                                       |    |
| 0477         | •         | DO SOL N=1-NE                                                           |              |              | •                                     |    |
| 8078         | r.        | IF(HUP(N.J).NE.NOP(N.AF) GO TO BOL                                      |              |              | ş                                     |    |
| 8879         |           | DO 240 [=1+3                                                            |              | 3            |                                       |    |
|              |           | PSTRTU(N, I)=STRTU(N+I) '                                               |              | •            |                                       |    |
| <b>***</b> 1 | 2         | 90 STRID(N.1)=STRID(N.1)+STR(N.1)                                       |              |              |                                       |    |
| 0082         | -         | DO 304 [#1.4_                                                           |              |              |                                       |    |
| 0043 -       | . •       | PSIGTO(N,1)=SIGTO(N+1)                                                  |              |              | x                                     |    |
| 0084         | . 3       | 04 SIGTU(N+I)=SIGTO(N,I)+FORCE(N+I)                                     |              |              |                                       |    |
| 0085         | 8         | DI CONTINUE                                                             |              | 6            |                                       |    |
| 0086         |           | GC TO 806 .                                                             |              | •            |                                       |    |
| <b>9027</b>  | · · 🕷     | 02,00 807 N=1,NC                                                        |              |              |                                       |    |
| 8 Q.B.K      |           | IF(NOP(N,3);NE.NOP(N,4)) GO TO 807                                      |              |              |                                       |    |
| 9689         |           | 60 A01 I=1,3                                                            |              | ~            |                                       |    |
| 9090         |           | 03 STRTO(N.1)=PSTRTO(N.1)+STR(N.1)                                      |              |              |                                       |    |
|              | -         | 00 605 TELA .                                                           |              |              |                                       |    |
| 0091         |           |                                                                         |              |              |                                       |    |







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|                                                 | SuperOUTINE REAC(J.4.4)<br>COMMONTINE REAC(J.4.4)<br>COMMONNARTA/CONDIZO0.2).N<br>COMMONNATIF/CST[10].JUC<br>COMMONST[F/CST[10].JUC<br>COMPLATIF/CST[10].JUC<br>COMPLATIF/CST[10].JUC<br>COMPLATIF/CST[10].JUC<br>COMPLATIF/CST[10].JUC<br>COMPLATIF/CST[10].JUC<br>COMPLATIF/CST[10].JUC<br>COMPLATIF/CST[10].JUC<br>DIFFERER MANDIN.J]<br>INTECER MANDIN.J]<br>INTECER MANDIN.J]<br>JIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]<br>LIZZAUDIN.J]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                                                                                                                                                                                                                                                                                                             | 28-6.1.414.415<br>1. CODE (2.07) . UX<br>DEN.OFY ( 450) .<br>. AREA( 450) . |                                       | • • • •                               |
|                                                 | - THOPE AND TAY CONDICEDES 2) - M<br>COMMON DATA/CONDICEDES 2) - M<br>COMPONSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(12,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMPUNSTIFF/CETIFH(13,18<br>COMP                                                                                                                                                                                                                                                                                                                                                                                                                | COP(450.4). [MAT(450).490(150<br>(10).992(15).7(000.40)<br>(400).AR(3.6).40.40.40.40<br>(400).AR(400).40)<br>(400).AR(400).40<br>(400).40.40.40.40.40.40<br>(400).40.40.40.40.40<br>(400).40.40.40.40.40.40<br>(400).40.40.40.40.40.40.40<br>(400).40.40.40.40.40.40.40.40<br>(400).40.40.40.40.40.40.40.40.40.40.40.40.40. |                                                                             |                                       | · · · · · · · · · · · · · · · · · · · |
|                                                 | COMMONDATA/CONDICO0.2).<br>COMMONDATA/CONDICO0.2).<br>DBY(149).PMCCOND(200.2)<br>DBY(149).PMCCOND(201.2).<br>COMPONSTFF/C2T[FH(12.12<br>COMPONSTFF/C2T[FH(12.12<br>COMPONSTFF/C2T[FH(12.12<br>DIMENSION U(C)<br>DIMENSION U(C)<br>DIMENSION U(C)<br>DIMENSION U(C)<br>DIMENSION U(C)<br>DIMENSION U(C)<br>DIMENSION<br>CALF STOPTON 2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T27000(N,2)-1<br>L2T270000(N,2)-1<br>L2T270000(N,2)-1<br>L2T270000(N,2)-1<br>L2T270000(N,2)-1<br>L2T2700000(N,2)-1<br>L2T2700000(N,2)-1<br>L2T2700000000000000000000000000000000000                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 000(450.4).41450).7(450).400(50<br>(10).4413.4).413.413.413.413.40.400<br>(400).441.400.400<br>(400).441.400<br>51199455 Matrix For Eleve<br>6070 504                                                                                                                                                                       | 0CODE (2007CV<br>DEN.ORX(450).<br>AREA(450).                                |                                       | · · · ·                               |
|                                                 | COPY(440), PMCCOND(200.2)<br>COPMPLASTIF/C3TIF/(3.12<br>COPMPLASTIF/C3TIF/(3.12<br>C10001-01<br>D10001001<br>D10001001<br>D10001001<br>C4LL STIF/2001<br>J1=20000100, 1)<br>L222000100, 2)<br>L222000100, 2)<br>L2220000000, 2)<br>L2220000000, 2)<br>L222000000000000, 2)<br>L2220000000000000000000000000000000000                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 1).413.4).41(3.6).40(3.00.40)<br>400).41.400<br>51177655 MATRIX FOR ELENE<br>60 10 504                                                                                                                                                                                                                                      |                                                                             | · · · · · · · · · · · · · · · · · · · | · · · ·                               |
|                                                 | CCOMPUSTINATION (0). 0000000000000000000000000000000000                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 11.413.4).81.40.801.400.400<br>4001.481.400.401<br>5010 504<br>81                                                                                                                                                                                                                                                           | - VIII                                                                      | ,<br>,<br>,                           | ,<br>,                                |
|                                                 | DIMENSION U(4)<br>INTEGER FILAND<br>IF(MOP(N.3). MEDCALCULATE<br>F(MOP(N.3). MEDCALCULATE<br>CALL ST)FT2(N)<br>JI22004(N.3). MEDCALCULATE<br>JI22004(N.3). SOUTH<br>L22004(N.3). SOUTH<br>L2004(N.3).                                                                                                                                                                                                                                     | STEPPEESS MATRIX FOR ELEME                                                                                                                                                                                                                                                                                                  | 2                                                                           |                                       |                                       |
|                                                 | If (MOP(N, 3) - ME CAL CUL ATE<br>If (MOP(N, 3) - ME - MOP(N, 4))<br>CALL 37 IF 72 (N)<br>J = 24 MOP(N, 1) - 1<br>J = 24 MOP(N, 2) - 1<br>J = 24 MOP(N, 2) - 1<br>L =                                                                                                                                                                                                                                                                                                                                                                                     | GOTO SOA MATRIA FOR ELEN                                                                                                                                                                                                                                                                                                    | 2 L                                                                         | ;<br>;<br>;                           |                                       |
| L                                               | If (MOP(N.3).AL-MOP(N.4))<br>I=2000F(N.1)-1<br>J=2000F(N.1)-1<br>J=2000F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F(N.2)-1<br>L=200F                                                                                                                                                                                                                                                                                              | 60 10 20<br>1                                                                                                                                                                                                                                                                                                               |                                                                             |                                       |                                       |
| 0 0 0 T N 7 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 | JI=2000101.1)-1<br>JI=2000101.1)-1<br>JI=2000101.1)-1<br>KI=2000101.2)-1<br>LI=2000101.3)-1<br>LI=2000101.3)-1<br>LI=2001011.3)<br>U(1)=C(11)<br>U(2)=C(11)<br>U(2)=C(11)<br>U(2)=C(11)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)=C(12)<br>U(2)<br>U(2)=C(12)<br>U(2)<br>U(2)<br>U(2)<br>U(2)<br>U(2)<br>U(2)<br>U(2)<br>U(                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                             |                                                                             |                                       | ·                                     |
|                                                 | 11-20-00-01-01-01-01-01-01-01-01-01-01-01-01                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                                                                                                                             |                                                                             |                                       | ¢                                     |
|                                                 | KI=2000F(N_2)-1<br>KI=2000F(N_2)<br>LIT2000F(N_3)-1<br>LIT200F(N_3)-1<br>U(1)5C(J1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U(1)5C(K1)<br>U                                                                                                                                                                                                                          | •                                                                                                                                                                                                                                                                                                                           |                                                                             | ,<br>,<br>,                           | ¢                                     |
|                                                 | LisephoP(N.3)-/<br>LisephoP(N.3)-/<br>U(1)=C(J1)<br>U(1)=C(J1)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U(2)=C(J2)<br>U |                                                                                                                                                                                                                                                                                                                             | *                                                                           |                                       |                                       |
|                                                 | Landbauern)<br>urr:necr<br>urr:necr<br>urr:necr                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                             |                                                                             |                                       | ;                                     |
| 2                                               | U(1)=C(J)<br>U(2)=C(J2)<br>U(3)=C(K)<br>U(3)=C(K)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                                                             |                                                                             |                                       | ,                                     |
|                                                 | (1))-C(K))                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                                                             |                                                                             | ,                                     |                                       |
|                                                 | U(4)=C(K2)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                                                             |                                                                             |                                       | _                                     |
|                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                             |                                                                             | 1                                     |                                       |
| - 100<br>- 100                                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                             | ,                                                                           |                                       |                                       |
| 1200                                            | If (CODE (H) . ME. 1. ) 60 TO S                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                             |                                                                             |                                       |                                       |
| 4622                                            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | -                                                                                                                                                                                                                                                                                                                           |                                                                             |                                       | -                                     |
|                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | ٩                                                                                                                                                                                                                                                                                                                           |                                                                             | •                                     |                                       |
| 0025 0<br>8636 426 4                            | DO 425 Leis6<br>Sumstantententi, 14400 J                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                                                                                                             |                                                                             | ,<br>,                                |                                       |
| 4000                                            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | ĩ                                                                                                                                                                                                                                                                                                                           | _                                                                           | -                                     |                                       |
| 0020 . 501 1                                    | 60 70 503<br>1510005141.60.2.1 60 70 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                             | •                                                                           |                                       | a <b>*</b>                            |
| 0010                                            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | ţ                                                                                                                                                                                                                                                                                                                           | -                                                                           | ¢                                     |                                       |
|                                                 | K###NOP(N.J)-1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                                             |                                                                             |                                       | -                                     |
|                                                 | 00 426 L=1.6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                                                                                                                             |                                                                             | •                                     | _                                     |
| 0034                                            | 50#=\$UM+E3TIFM(1°L}+U(L)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                             |                                                                             |                                       |                                       |
|                                                 | ak (kj=ak (kj+5up<br>1#29j                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | •                                                                                                                                                                                                                                                                                                                           | ,                                                                           |                                       | •                                     |
| X                                               | K=20MOP(N.J)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                                                                                                                             |                                                                             | ş                                     | •                                     |
|                                                 | SCH=0.0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                                                                                                                                             | •                                                                           |                                       | <i>\\$</i> 7                          |
|                                                 | SUMESUM+ESTIFM(1.L)+U(L)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | -                                                                                                                                                                                                                                                                                                                           |                                                                             |                                       | -                                     |
| C 0041                                          | AR (K)=Ak(K)+5UM                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                                             |                                                                             | •                                     | •                                     |
|                                                 | CONTINUE<br>GO TO 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                                                                             | _                                                                           | n.                                    |                                       |
| 0444 , 504 C                                    | CALL STIFTI (N)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                             | •                                                                           | D ,                                   | ر<br>م                                |
| 8045<br>8046                                    | []=24MOP(N,]]-]<br>[2=34MOP(N,])-]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                                                                                                                                                                                                                                                                                                             | •                                                                           |                                       |                                       |
|                                                 | 1=54MD6(N,2)-1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | •                                                                                                                                                                                                                                                                                                                           |                                                                             | .,                                    |                                       |
|                                                 | J2=24NDD(N,2)<br>X1=24NDD(N,11)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                             |                                                                             | T                                     | •                                     |
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| 9692 (                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |     |                    | COMON/CC       | MTH/TITL        | .E[12].NP.NE                 | • NB • NEX* •                          | NCH. NLDANHAT INSEP                    | LI.NT4.NT5       | •   | 1         | - ,  | • |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    | 1 sNOPC sNC    | AT              |                              |                                        |                                        |                  |     | /         |      |   |
| 19993                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |     |                    | COMMON/24      | TAZORO          | 500 · 21 · HOP (             | 430.4141                               | #A1(430],NBC(30]                       | CODE (296) .UX   | •   |           |      | - |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    | 1(200).UV!     | 20013 [BC       | 5(10).JBC(10                 | 1. PRE(10                              | ) . T { 4 50 } . XDEN . YDE            | [N. DRX (450) .  |     | 1         | •    |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    | 208114503      | PREGROFT        | 236 . 2 )                    |                                        |                                        |                  | •   |           | · .  | 1 |
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| 4443                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    |                | 1 P P / E 3 F 1 |                              | 13.81.01                               | 7+0), <i>2m(400</i> +00)+1             | WEA14301+        |     |           |      |   |
| in the second                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    |                |                 |                              | 510/454                                |                                        |                  |     |           | -    |   |
| Contraction of the local division of the loc |     | •                  |                |                 | ULCIGUU)   3 [               | 01014300                               |                                        |                  | ,   |           |      |   |
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| 4041                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 5   |                    |                | STORIZOU        | ABA1. FDE121                 | A501.061                               | 1454) -CSIMPO -CSIM                    |                  |     | •         | ,    |   |
| 6468                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    | COMMONS        | 1147/1144       |                              | A (450)                                |                                        | DENEASA1.50      | · , |           |      |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    | 142.21.014     | 50.21.00        | A45.21.V/A4                  | 3.21.478                               | 1450.21.0VI450.81                      | -CAVE(450-3).    |     | •         |      |   |
| • •                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |     | -                  | 30001AEA 4     |                 |                              |                                        | ······································ |                  | '   |           |      |   |
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| , and a r                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |     | _ <u>}</u> `       | · CONTACCE     | 06.01           |                              | C00001                                 |                                        |                  | -   |           | -    |   |
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| 0010                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | -   |                    |                | 11-0000         |                              |                                        | •                                      |                  | ,   |           |      |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    | PROUNDING      |                 |                              |                                        |                                        |                  |     | •         |      |   |
| 0013                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | - 1 |                    |                |                 |                              |                                        | *                                      |                  |     |           |      |   |
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|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     | . *                | ****           |                 |                              |                                        | CONTRACT S                             | 0                |     |           |      |   |
| 0017                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    |                |                 |                              |                                        |                                        |                  | •   | •         |      |   |
| 0019                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | •   | ີ່ຈ                | DO 200 Na      |                 |                              |                                        |                                        | -                |     |           | 1    |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    | OK(N)+D1       | (1.8)           |                              |                                        |                                        |                  |     |           |      |   |
| 4421                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    | OVINIACT       | 12-ML           | •                            | •                                      |                                        |                  |     |           |      | , |
| 0.622                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |     |                    | W# f M 1 =0 24 | NIZT            |                              | ,                                      |                                        |                  |     |           |      |   |
| 6623                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    | TYCN J=DT      | NIZTT           |                              |                                        |                                        |                  |     |           |      |   |
| 8824                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 5   | م <sup>ين</sup> بر | DO-CONTINUE    |                 |                              |                                        | 4                                      |                  |     |           |      |   |
| 8625                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     | م م                | ##1 TE 16.1    | 1               |                              |                                        |                                        |                  |     |           |      |   |
| 0424                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     | <i>,</i>           |                | ) (NuPRC        | CORD ( N. 1 ) . PM           | COMD (N.Z                              | CORD(N.L).CORD                         | NSZZOVX(N).      |     | , ,       |      |   |
| ~                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |     |                    | LVYINJINE      | (INP)           | •                            |                                        |                                        |                  |     |           |      |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | r   | c                  |                | COM             | PUTATION OF                  | STRAIN R                               | ATES AND DIRECTIC                      | ON OF PRINCIPAL  |     |           |      |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     | C                  |                | STR4            | AIN RATE IN                  | CONTINUU                               | H ELEMENTS                             |                  |     |           |      |   |
| 0027                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    | 00 300 NI      | P.NE            |                              |                                        | •                                      |                  |     |           | •    |   |
| 028                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |     |                    | LF (NOP(N      | 3) •NE•N        | DP(N,4)) GO                  | 10,300                                 |                                        |                  |     |           |      |   |
| 0429                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | `   |                    | EPSX(N)=       | ST#EN.E32       | /11 1                        | •                                      | · ·                                    | ,                |     |           |      |   |
| 0030 °                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |     |                    | EPSY(N)=       | 5TR(N+2)/       | /11 5 1 9 .                  | •                                      |                                        |                  |     |           |      |   |
| 6031                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    | GANKY (N )     | STR(N=3         | )/TT `                       | -                                      | •                                      |                  |     | •         |      |   |
| 00Ĵ2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    | E+tEPSX()      | 1)+EPSY()       | 1))/2.                       | ,                                      |                                        |                  | •   |           | •    |   |
| 0033                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    | FESORTIL       | EPSY(N)-        | -EPSX(N))/2.                 | 3++2+14A                               | MXY{N]/2.}++2)                         |                  |     |           |      |   |
| 0034                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     | 1                  | EPSIIIN)=      | E+F             |                              | i                                      |                                        |                  |     |           | 1    |   |
| 0035                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    | EPS12(N):      | -F -            |                              | 1                                      |                                        |                  |     |           |      |   |
| 80.36                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |     |                    | IF(EPSY(A      | 1).EQ.EP        | SIR(N)) GO T                 | 1 101                                  | -                                      |                  |     |           |      |   |
| 0937                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | ·   | . '                | PSI(NJ=5)      | .29578+4        | TAN ( (GAMXY (               | M1/2.1/C                               | EPSY(N)-EPS12(N)                       | • •              |     |           | •    |   |
| 0039                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                    | GO TO 300      |                 | ,                            | 1                                      |                                        |                  |     |           |      |   |
| 8039                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     | . 3                | 01 P51(N)+90   | .0              | · •                          | 1                                      |                                        |                  |     |           |      |   |
| 0400                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     | 3                  | DO CONTINUS    |                 | •                            | 1                                      |                                        |                  |     |           |      |   |
| · ·                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | -   |                    | •              | 1               |                              | 1                                      | r                                      | •                |     |           |      |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    |                | ÷.              | 52.5                         | /                                      |                                        |                  | • 1 | \$        |      |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    |                |                 | اهو)                         | 1                                      | • 1                                    |                  |     |           | -    |   |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                    |                | (;,             | •                            |                                        |                                        | •                | 9   |           |      |   |

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|                | A C FEAS   | AVER                                   | DATE = 73195              | 04/43/41    | , PASE OVER |                                       |
|----------------|------------|----------------------------------------|---------------------------|-------------|-------------|---------------------------------------|
| 0039           | 644        | DD 600 J#1.4                           |                           |             | •           |                                       |
| 0840           |            | SFORCE(L.J)#SFORCE(L.J)/NOEL           | · _                       | -           |             | •                                     |
|                |            | \$516TO(L.J)#541670(L.J)/NOEL          |                           |             |             | ~                                     |
| 3843           |            | 00 664 Jul - 3                         |                           |             |             |                                       |
|                |            | SETEL - 11-557921 - 11/MOF1            | •                         |             |             |                                       |
|                | 4.0        |                                        | × -                       |             |             |                                       |
| 9944           | ¢v.        |                                        | ```````                   | *           |             |                                       |
| 0043 .         | -          |                                        | ,                         |             | -           |                                       |
|                |            | SEPSTIL FEETSTIL FROEL                 | × × ×                     |             |             |                                       |
| 0947           | -          | 344PXT(L)=344XT(L)/MCL                 |                           |             |             |                                       |
|                | s          | CALCULATE PRINCIPAL VI                 | ALUES AND DIRECTIONS      |             |             |                                       |
| 894#           | <u>~</u> ' | CALL PRINCL, SFORCE, AVSNAX, AVSHIN, A | VANGI                     |             | `           | ,                                     |
| ê047 -         | <u>,</u>   | CALL PRINCLISSIGIO, AVTHELAVTHN, AVT   | ANG)                      | `           |             | -                                     |
| 0050           |            | CALL PHINEL.SSTR.AVSHX.AVSHN.AVSAN     | 6)                        |             |             | 0                                     |
| 0051           | ,          | CALL PRIN(L, SSTRTD, AVSTHX, AVSTHN, A | VSTAN)                    |             | •           | · · · `                               |
| 0052           |            | E={SEPSX(L]+SEPSY(L))/2.               |                           |             |             | · · · · · · · · · · · · · · · · · · · |
| 0053           |            | F#SORT(((SEPSY(L)-SEPSX(L))/2.)**2     | +(5GAMXY(L)/2.)++2)       |             |             |                                       |
| 8054           |            | AVP\$11(L)=E+F                         |                           |             | 1           |                                       |
| 8055           |            | AVD\$1211 1#F-F                        |                           | *           | •           |                                       |
|                |            |                                        | -                         |             | 4           |                                       |
| 0030           |            |                                        |                           |             |             |                                       |
| 0021           |            | AAb21461+21+524218+414ME(204HEA(61))   | 2+)/(\$2#37(L)-AVP312(L)) | ) <b>)</b>  |             |                                       |
| 8058           | •          | GO TU JOB                              |                           |             |             |                                       |
| 0457           | 30         | / AVPS1(L)=90.0                        |                           | ``          |             |                                       |
| 9048 .         |            | I CONTINUE                             | 1                         | *           |             |                                       |
| - <b>806</b> 1 | 10         | CONTENUE                               |                           |             |             |                                       |
| 2              | C          | WRITE CALCULATED VALUE                 | ES                        |             |             |                                       |
| 0067           | · ·        | WB(TF(6.10))                           |                           | ت           |             |                                       |
| 0063           | •          |                                        | ISPORCELL                 | MAXEL 1     |             |                                       |
|                | ſ          | TAMENTALL A AMANGEL 1.4 -4 -MEL        |                           |             |             |                                       |
|                |            | 1ATB#14(5)+ATA#6(5)+5-1+##             | · .                       |             |             |                                       |
| 0004           |            |                                        |                           |             | •           | ĩ                                     |
| 0493           |            | WHITELDOIDSHILGCOWDILGJJGJ#1.67.1      | 391M/F01101101044944/f    |             |             |                                       |
|                |            | IAVSHN(L)+AVSANG(L)+L=}+NP)            |                           |             |             | 1                                     |
| 8066           | `          | WR1 FE(6.114)                          |                           |             | •           |                                       |
| 0067           |            | WRITC(6.306)                           |                           |             |             |                                       |
| 8968           |            |                                        | {\$\${GTO{L.[].]=1.4}.AVT | MX(L).      |             |                                       |
|                |            | 1AVTHN(L)+AVTANG(L)+L=1+NP)            |                           | ÷           |             |                                       |
| 0489           |            | WRITE(0.115)                           |                           |             | •           | -                                     |
| 8870           |            | "HRITE(6-202)                          | •                         |             |             |                                       |
| 0071           |            | WRITE (6.103) (L. (COMD(L.Jt.J.1.2).() | \$\$7#TO(L.1),1=1.3).AVST | MX(L).      |             | •                                     |
|                |            | LAWSTONIE LAWSTANEL LAL BL. MP1        |                           |             |             |                                       |
|                |            |                                        |                           | с.          |             |                                       |
| 44/2           |            | ENTIFICATION C                         | •                         |             |             |                                       |
| 8073           | •          | MM1FE(0+3)                             | <b>New West</b>           |             |             |                                       |
| 8974           |            | WRTIC(6.104)[L.SEPSX(L).SEPSY(L).S     | SAMAT(L).AVPSEL(L).AVPS   | [21].       |             |                                       |
|                |            | IAVPSI(L1.L+1.NP)                      | 1                         |             |             |                                       |
| 0075           | - 10       | E FORMATCILISS, TABLE 6 - INCREMENT    | STRESS AND STRAIN*//      |             | -           | 3                                     |
|                |            | 15X-ISTRESS INCREMENTIN                | 1                         | س - به      |             | -                                     |
|                |            | 1" NODE X Y X-STRESS                   | Y-STRESS XY-              | -STRESS     |             | •                                     |
| 1              |            | 2 Z-STRESS MAX-STRESS                  | HIN-STHESS ANGLE"         |             |             |                                       |
| 0874 1         | <b>9 n</b> | FORMATE ST. STRAIN INCREMENTIN         |                           |             |             |                                       |
| ,              |            |                                        | X-STRAIN V-STR            | ATM T       | • •         | •                                     |
|                | •          | A THUR A T                             |                           |             |             | • `                                   |
|                | •          |                                        |                           |             |             | <b>F</b>                              |
| -4474 )        | 30         | D FURMALLYDY SAFTABLE 7 - TOTAL STW    | ESS AND STRAIN //         |             |             |                                       |
|                |            | IT NUCE X Y X-STRESS                   | T-STRESS XY-              | - 3 I ME 33 |             |                                       |
| •              |            | 2 Z-STRESS MAX-STRESS                  | MIN-STRESS ANGLET         |             |             |                                       |
|                | •          | •                                      |                           |             |             |                                       |
|                |            | 5 FORMAT(///+1x+'TOTAL STRAINS')       |                           | •           |             |                                       |
| 0078<br>•      | . 11       | 5 FORMAT(///.1x."TOTAL STRÀINS")       |                           | •           |             |                                       |
| 0078           | . 11       | 5 FORMAT(///.1x."TOTAL STRAINS")       | 7                         | •           | · ,         |                                       |

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|--------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|--------------------------------------|-------------|---------------------------------------|
|                                                                                                                                                              | c                                                                                                                    | INTERPOLA                                                                                                                                                                                      | TE FOR STRESS D                                        | IFFERENCE VALUE                      | 5           | • •                                   |
|                                                                                                                                                              | č                                                                                                                    | CORRESPON                                                                                                                                                                                      | DING TO EPSILON                                        | 1                                    |             |                                       |
| 6834                                                                                                                                                         | 350                                                                                                                  | DENON=GANOC(L.NC.LP)-G                                                                                                                                                                         | AMOC( LANCALM-1)                                       | •                                    |             |                                       |
| 06.19                                                                                                                                                        |                                                                                                                      | FLWEN= (GANOCI   .NC.LP)-                                                                                                                                                                      | PRSTTOJ+(EY(L.N                                        | C.LP-1)-ET(I.NC.L                    | <b>0</b> )7 | × ,                                   |
| -                                                                                                                                                            |                                                                                                                      | THRETROPS IT .NC BLAFUN                                                                                                                                                                        | FRIDEMOM                                               |                                      | · • •       |                                       |
|                                                                                                                                                              | ~                                                                                                                    |                                                                                                                                                                                                | NE ETDERC_CTOÀI                                        | N CURVE IS STREM                     | ,           |                                       |
|                                                                                                                                                              | ς,                                                                                                                   |                                                                                                                                                                                                | 4 '<br>1 '                                             | A CONVE IS GIVEN                     |             |                                       |
| 4441                                                                                                                                                         |                                                                                                                      | IF (MC URV - [] 3396 3006 30                                                                                                                                                                   | 5                                                      |                                      |             |                                       |
| 1042 P                                                                                                                                                       | 334                                                                                                                  |                                                                                                                                                                                                | ANA CARDEN                                             | •                                    | <u>ر</u>    |                                       |
|                                                                                                                                                              | 432                                                                                                                  | FURNATION TO ACT                                                                                                                                                                               |                                                        | -                                    | •           |                                       |
| 8044                                                                                                                                                         | 360                                                                                                                  | EE (N) TAUS (TUPS TH-PHEDE                                                                                                                                                                     | *(#11/#03(P45))                                        | 0-PHESIM(M))                         |             |                                       |
| 0842                                                                                                                                                         |                                                                                                                      | IP(NITER-NE-NOITER) GO                                                                                                                                                                         | 10 392                                                 |                                      | •           |                                       |
| 8846                                                                                                                                                         |                                                                                                                      | PRESTR(N)=PRSTIC                                                                                                                                                                               |                                                        |                                      |             | •                                     |
| -0047 .                                                                                                                                                      |                                                                                                                      | PRESEV(N)=TOPSTR                                                                                                                                                                               |                                                        |                                      | •           |                                       |
| 8048                                                                                                                                                         | · .                                                                                                                  | "GO TO 392 -                                                                                                                                                                                   |                                                        | 1                                    |             |                                       |
|                                                                                                                                                              | c 4                                                                                                                  | IF HORE T                                                                                                                                                                                      | HAN ONE STRESS-                                        | STRAIN CURVE IS G                    | IVEN        | ,                                     |
| 8049                                                                                                                                                         | 365                                                                                                                  | {F(ABS(CONPRE(N))-0.0)                                                                                                                                                                         | 375.370.375                                            | ÷                                    |             |                                       |
| 0050                                                                                                                                                         | 375                                                                                                                  | IF (ABS(CONPRE(N))-CPR(                                                                                                                                                                        | [.NC]) 380.370.                                        | 385                                  |             |                                       |
| 0051                                                                                                                                                         | 380                                                                                                                  | HC=HC-1                                                                                                                                                                                        |                                                        |                                      | -           |                                       |
| 0452                                                                                                                                                         |                                                                                                                      | BOTSTR=TUPSTR                                                                                                                                                                                  |                                                        |                                      |             |                                       |
| 8053                                                                                                                                                         |                                                                                                                      | 60 10 125                                                                                                                                                                                      |                                                        |                                      |             |                                       |
| 8864                                                                                                                                                         | 178                                                                                                                  | ELANIANS I TOPE TO-DESDE                                                                                                                                                                       |                                                        | 0-005570(11))                        | •           | `                                     |
|                                                                                                                                                              | 310                                                                                                                  | CENTI-AUSTIONSIN PREVE                                                                                                                                                                         | V(W////AD3(F43))                                       | Q-PRESIR(N) /                        |             |                                       |
| 6002                                                                                                                                                         |                                                                                                                      | IF CHITER NE NOITERT GO                                                                                                                                                                        | 10 342                                                 |                                      |             |                                       |
| 0020                                                                                                                                                         |                                                                                                                      | PRESININ                                                                                                                                                                                       |                                                        |                                      |             | •                                     |
|                                                                                                                                                              |                                                                                                                      | PREDEV(N)=TOPSTH                                                                                                                                                                               |                                                        | -                                    |             |                                       |
|                                                                                                                                                              |                                                                                                                      |                                                                                                                                                                                                |                                                        |                                      |             |                                       |
| 0024                                                                                                                                                         | 20.0                                                                                                                 | STRAE EFIDESTRATASICUR                                                                                                                                                                         | PRE(WIJ-CPRII,                                         | C))/{CPR(1.MC+1)-                    | CPR([;NC])# |                                       |
| -                                                                                                                                                            |                                                                                                                      | L(BOTSTR-TOPSTR)                                                                                                                                                                               |                                                        |                                      |             |                                       |
| 8050                                                                                                                                                         |                                                                                                                      | EE (w) #ABS (STWNEW+PWEDE)                                                                                                                                                                     | V(N))/A85(PR\$T1                                       | D-PRES PR(N))                        |             |                                       |
|                                                                                                                                                              |                                                                                                                      |                                                                                                                                                                                                |                                                        |                                      |             |                                       |
| 0061                                                                                                                                                         |                                                                                                                      | IF (NITER.NC.NOITER) GO                                                                                                                                                                        | TO 392                                                 |                                      |             | •                                     |
| 0061<br>8062                                                                                                                                                 |                                                                                                                      | IF (NITER.NC.NOITER) CO<br>PRESTR(N)=PRSTTO                                                                                                                                                    | TO 392                                                 |                                      |             | •                                     |
| 0061<br>8062<br>8063                                                                                                                                         |                                                                                                                      | IF (NJ TER.NC.NOITER) GO<br>PRESTR(NJ=PRSTTO<br>PREDEY(N)=STRNEY                                                                                                                               | TO 392<br>,                                            |                                      |             | •                                     |
| 0061<br>8062<br>8063<br>0064                                                                                                                                 | 392                                                                                                                  | IF (NITER.NC.NOITER) GO<br>PRESTR(NI=PRSTTO<br>PREDEY(NI=STRNEY<br>CONTINUE                                                                                                                    | TO 392                                                 |                                      |             | ۰<br>-                                |
| 0061<br>8062<br>8063<br>0064<br>6065                                                                                                                         | <b>,</b> 348                                                                                                         | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRSTTO<br>PREDEY(N)=STRNET<br>CONTINUE<br>RETURN                                                                                                          | 10 392                                                 |                                      |             |                                       |
| 0061<br>5062<br>5063<br>0064<br>6065                                                                                                                         | <b>,</b> 398                                                                                                         | IF (NITER_NC.NOITER) CO<br>PRESTR(N)=PRSTTO<br>PREDEY(N)=STRNE¥<br>CONTINUE<br>RETURN<br>END                                                                                                   | TO 392                                                 |                                      |             | •                                     |
| 0061<br>8062<br>8063<br>8065<br>8065                                                                                                                         | <b>.</b> 398                                                                                                         | IF (NITER.NC.NOITER) CO<br>PRESTR(N)=PRSTTO<br>PREDEY(N)=STRNE¥<br>CONTINUE<br>RETURN<br>END                                                                                                   | TO 392                                                 |                                      |             | · · ·                                 |
| 0061<br>8062<br>8063<br>8064<br>8065<br>8866<br>40211045 IN                                                                                                  | <b>. 392</b>                                                                                                         | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRESTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT9 ID_EBCDIC.SOURCE.N                                                                         | TO 392<br>OLIST.NODECK.LO                              |                                      |             | • • •                                 |
| 0041<br>9062<br>9063<br>9065<br>9065<br>9066<br>*QPTIONS IN<br>+QPTIONS IN                                                                                   | <b>.</b><br><b>.</b><br><b>.</b><br><b>.</b><br><b>.</b><br><b>.</b><br><b>.</b><br><b>.</b><br><b>.</b><br><b>.</b> | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRSTTO<br>PREDEY(N)=STRNEY<br>CONTINUE<br>RETURN<br>END<br>CT+ ID.EECDIC.SOURCE.N<br>CT+ NAME THOMLIN .L                                                  | TO 392<br>OLIST.NODECK.LO<br>INECNT =                  | ' -<br>NAD • NONAP<br>56             |             | •<br>•                                |
| 0061<br>9062<br>9063<br>9064<br>9065<br>9066<br>9066<br>9066<br>9071045 IN<br>9071045 IN                                                                     | 392<br>EFFE<br>EFFE                                                                                                  | IF (NITER.NC.NOITER) CO<br>PRESTR(N)=PRSTTO<br>PREDEY(N)=STRNEY<br>CONTINUE<br>RETURN<br>END<br>CT ID_EBCDIC.SOURCE.N<br>CT ID_EBCDIC.SOURCE.N<br>CT NAME TATENTS .                            | TO 392<br>OLISTINODECKILO<br>INCONT =                  | -<br>IAD - NONAP<br>56<br>127 = 2308 | ·           | •<br>•                                |
| 0061<br>8062<br>8063<br>8065<br>8065<br>8066<br>*OPTIONS IN<br>*OPTIONS IN<br>*STATISTICS                                                                    | 392<br>EFFE<br>EFFE                                                                                                  | IF (NITER.NC.NOITER) CO<br>PRESTR(N)=PRSTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT ID.EBCDIC.SOURCE.N<br>CT NAME MONLIN L<br>SOURCE STATEMENTS =<br>DISCONSTICE (SUSSAIC)       | DLIST.NODECK.LD<br>INECNT =<br>66.PROGRAM 1            | AD - NOMAP<br>56<br>12E = 2308       |             |                                       |
| 0061<br>9062<br>9063<br>9064<br>9065<br>9066<br>*QPTIONS IN<br>*STATISTICS<br>*STATISTICS                                                                    | 392<br>EFFE<br>EFFE<br>8 10                                                                                          | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRSTTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT+ ID_EBCDIC.SOURCE.N<br>CT+ NAME THOMLIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED  | TO 392<br>OLIST, NODECK.LO<br>INCONT =<br>66.PROGRAM 1 | NAD - NOMAP<br>56<br>12E = 2308      | -<br>-      | •<br>•                                |
| 0061<br>9062<br>9063<br>9064<br>9065<br>9066<br>*QPTIONS IN<br>*QPTIONS IN<br>*STATISTICS<br>*STATISTICS                                                     | 392<br>EFFE<br>EFFE<br>+ NO                                                                                          | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRSTTO<br>PREDEY(N)=STRNEY<br>CONTINUE<br>RETURN<br>END<br>CT+ ID.EBCDIC.SOURCE.N<br>CT+ NAME MONLIN . L<br>BOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED  | TO 392<br>OLIST:NODECK.LO<br>INCONT =<br>66:PROGRAM 1  |                                      | -<br>-      |                                       |
| 0041<br>8002<br>8003<br>8004<br>8065<br>8066<br>8066<br>8066<br>80710M5 IN<br>80710M5 IN<br>857471571C3                                                      | 392<br>EFFE<br>EFFE<br>6 10                                                                                          | IF (NITER.NC.NOITER) GO<br>PREDEY (N)=PRSTO<br>PREDEY (N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT4 ID_EBCDIC.SOURCE.N<br>CT4 NAME MONLIN L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED   | TO 392<br>OLIST.NODECK.LO<br>INECNT =<br>66.PROGRAM 1  |                                      | -           | • • • • • • • • • • • • • • • • • • • |
| 0041<br>9063<br>9063<br>9064<br>9065<br>9066<br>*Options in<br>*Options in<br>*Statistics<br>*Statistics                                                     | 392<br>EFFE<br>6<br>6<br>10<br>10                                                                                    | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRESTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT+ ID_EBCDIC.SOURCE.N<br>CT+ NAME THDNLIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED  | TO 392<br>OLIST.NODECK.LO<br>INEGNT =<br>66.PROGRAM 1  |                                      | -<br>Le     |                                       |
| 0061<br>9062<br>9063<br>9064<br>0065<br>9066<br>*00710M5 IN<br>*00710M5 IN<br>*STATISTICS<br>*STATISTICS                                                     | 392<br>5 EFFE<br>6 5<br>10 NO                                                                                        | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRSTTO<br>PREDEY(N)=STRNEY<br>CONTINUE<br>RETURN<br>END<br>CT+ ID.EEICDIC.SOURCE.N<br>CT+ NAME THOMLIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED | TO 392<br>OLIST, HODECK.LO<br>INCONT =<br>66.PROGRAM 1 | AD. NONAP<br>56<br>12E = 2308        | -           | •<br>•<br>•                           |
| 0041<br>8002<br>8003<br>8004<br>8065<br>8066<br>*0PTIONS IN<br>*0PTIONS IN<br>*STATISTICS<br>*STATISTICS                                                     | 392<br>EFFE<br>EFFE<br>6 10                                                                                          | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRSTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT4 ID_EBCDIC.SOURCE.N<br>CT4 NAME MONLIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED    | TO 392<br>OLIST.NODECK.LO<br>INECNT =<br>66.PROGRAM 1  | AD. NOMAP<br>56<br>12E = 2308        | -           | • • •<br>•<br>•                       |
| 0061<br>9062<br>9063<br>9064<br>9065<br>9066<br>40PTIONS IN<br>•QPTIONS IN<br>•STATISTICS<br>•STATISTICS                                                     | 392<br>EFFE<br>EFFE<br>0 0                                                                                           | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRESTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT+ ID.EBCDIC.SOURCE.N<br>CT+ NAME "NDMLIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED  | DLIST.NODECK.LD<br>INECNT =<br>66.PROGRAM 1            | NAD. NOMAP<br>56<br>12E = 2308       | -<br>Le     | •<br>•<br>•                           |
| 0061<br>8062<br>8063<br>8066<br>8066<br>40PTIONS IN<br>+QPTIONS IN<br>+STATISTICS<br>+STATISTICS                                                             | 392<br>EFFE<br>EFFC<br>* NO                                                                                          | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRSTTO<br>PREDEY(N)=STRNEY<br>CONTINUE<br>RETURN<br>END<br>CT+ ID.EBCDIC.SOURCE.N<br>CT+ NAME TIDNLIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED  | TO 392<br>OLIST, NODECK.LO<br>INECNT =<br>66.PROGRAM 1 | AD. NONAP<br>56<br>12E = 2308        | -           |                                       |
| 0041<br>8002<br>8003<br>8004<br>8065<br>8066<br>8066<br>8066<br>80710M5 IN<br>80710M5 IN<br>857471571C3                                                      | 392<br>EFFE<br>EFFE<br>* NO                                                                                          | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRSTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT4 ID.EBCDIC.SOURCE.N<br>CT4 NAME PROMLIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED   | TO 392<br>OLIST.NODECK.LO<br>INCONT =<br>66.PROGRAM 1  | AD. NONAP<br>56<br>12E = 2308        | -<br>K      |                                       |
| 0041<br>9062<br>9063<br>9064<br>0065<br>0066<br>40PTIONS IN<br>+QPTIONS IN<br>+STATISTICS<br>+STATISTICS                                                     | 392<br>EFFE<br>6<br>10<br>10<br>10<br>10                                                                             | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRESTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT+ ID.EBCDIC.SOURCE.N<br>CT+ NAME "NDMLIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED  | DLIST.NODECK.LO<br>INECNT =<br>66.PROGRAM 1            | NAD., NOMAP<br>56<br>12E = 2308      | -<br>Le     |                                       |
| 0061<br>9062<br>9063<br>9066<br>9066<br>40PTIONS IN<br>+STATISTICS<br>+STATISTICS                                                                            | 392<br>6 EFFE<br>6 EFF<br>6 NO                                                                                       | IF (NITER.NC.NOITER) GO<br>PRESTR(NJ=PRSTTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT+ ID.EBCDIC.SOURCE.N<br>CT+ NAME THOMLIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED  | TO 392<br>OLIST, NODECK.LO<br>INEGNT =<br>66.PROGRAM 1 | AD. NONAP<br>56<br>12E = 2308        | -           | •<br>•<br>•                           |
| 0061<br>8062<br>8063<br>8064<br>8065<br>8066<br>*OPTIONS IN<br>*OPTIONS IN<br>*STATISTICS<br>*STATISTICS                                                     | 392<br>EFFE<br>EFFE<br>* NO                                                                                          | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRSTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT4 ID.EBCDIC.SOURCE.N<br>CT4 NAME MONLIN .L<br>BOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED    | TO 392<br>OLIST.NODECK.LO<br>INCONT =<br>66.PROGRAM 1  | AD. NONAP<br>56<br>12E = 2308        | -           |                                       |
| 0041<br>9062<br>9063<br>9064<br>9065<br>9066<br>9066<br>9066<br>9066<br>9065<br>9066<br>9065<br>9066<br>9065<br>9066<br>9065<br>9066<br>9065<br>9066<br>9066 | 392<br>EFFE<br>EFFE<br>* NO                                                                                          | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRESTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT+ ID.EBCDIC.SOURCE.N<br>CT+ NAME TADALIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED  | TO 392<br>OLIST.NODECK.LO<br>INECNT =<br>66.PROGRAM 1  | NAD., NOMAP<br>56<br>12E = 2308      | -<br>(*     | · · · · · · · · · · · · · · · · · · · |
| 0041<br>9062<br>9063<br>9064<br>9065<br>9066<br>40PTIONS IN<br>+STATISTICS<br>+STATISTICS                                                                    | 392<br>EFFE<br>EFFE<br>6 NO                                                                                          | IF (NITER.NC.NOITER) GO<br>PRESTR(N)=PRESTO<br>PREDEY(N)=STRNEW<br>CONTINUE<br>RETURN<br>END<br>CT+ ID.EBCDIC.SOURCE.N<br>CT+ NAME TADALIN .L<br>SOURCE STATEMENTS =<br>DIAGNOSTICS GENERATED  | TO 392<br>OLIST, NODECK.LO<br>INCONT =<br>66.PROGRAM 1 | AD. NONAP<br>56<br>12E = 2308        | -           |                                       |

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PORTRAN IV & LEVEL- 21 JNONLN 04TE = 73195. PAGE 0001 04/43/43 9001 SUBRUUTINE JHONLING COPMON/DATA/COND(200.2).NOP(450.4).14AT(450).NOC(50).CODE(200).UX 9002 1(200) .UV(200) . 10(10) . JOC(10) . PRE(10) . T(450) . XDEN . YDEN . DRX(450) . 2084(450).PRCORD(200.2) COMUNIJOINT/TELESABBOLE 8.8 24214503. ANG(450). DKS(450). DKH(450). 80 6663 1(2.2).#1450.2).P(450.2).V(450.2).AVP(450.2).CV(450.2).CAVP(450.2). 2PCV(453+2}+PCAVP(450+2)+81(8+8) COMMON/ JNUNL/WVAL(2).CNP(2.10).AH(2.10).UH(2.10) 8004 JOINT NONLINEAR ANALYSIS JHONLEN IS A ROUTENE THAT INTERPOLATES FOR SHEAR STIFFNESS HODULUS FHOM HYPERBOLIC STRESS-STRAIN CURVES DETERMINE TWO ADJOINING NORMAL PRESSURE DEPENDENT CURVES DEPENDING ON THE NORMAL PRESSURE ON THE ELEMENT 0005 L=IMAT(N) 0006 WYALLE-NYAL []] IF (NYALUE-11 359.300.310 8087 .... 389 WRITE(6.452) 0009 452 FORMAT(SX, 'ERROR IN NVALUE CARD') 300 TOWM=1./BH(1.1) ..... 0011 1F(CAVP(N.1)-TQUE) 350.350.355 0012 355 CONTINUE 001 Ĵ DKS(N)=0.5' ..... 60 TO 392. 0015 350 NV=1 0016 DK\${N]=[{:-ABS(CAVP[N,:])+BH([.1])+2]/AH([.1) 0017 GO TO 392 310 DO 340 NV-LINVALUE 0018 0012 IF(GHP([.NV)-CAVP(N.2)) 340,325,325 0020 348 CONTINUE c INTERPOLATE FOR A AND & VALUES CORRESPONDING TO NORMAL PRESSURE - LINEAR INTERPOLATION C 0021 325 AH1=AH(1.HV)-(AH11.HV)-AH(1.HV-1))+(CNP(1.HV)-CAVP(N.2))/ 11CNP(1.NY)-CNP(1.NY-1)) 0082 BH1=BH11+NV)-(BH11+NV)-BH(1+NV-L)J+(CNP(1+NV)-CAVP(N+2))/ MSCHINDEN 1(CMP(1,NV)-CNP(1,NV-1)) 8823 T04#41./6H1 0024 IF(CAVP(N.1)-TOWR) 360.360.365 ..... 365 CONTINUE 1026 DKS(N)=0.5 0127 60 TU 392 ..... 360 DKS(N)=([1.-ABS(CAVP[N.13]+8H1)++2]/AH1 0029 .. 392 CONTINUE 0030 RETURN 1100 / END ~ ~~~ SOPTIONS IN EFFECTS ID. EBCDIC. SOURCE. NOLIST. NODECK.LDAD. NOMAP +OPTIONS IN EFFECT+ NAME - JNONLN . LINECHT -56 \*STATISTICS\* SOURCE STATEMENTS . 31 .PROGRAM SIZE 1490 STATISTICS. NO DEAGNOSTICS GENERATED +STATISTICS+ NO DIAGNOSTICS THIS STEP 2

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| ORTHAN EV Q  | Level 21                      | MAIN                                     | DATE = 73191                   | 00/03/13          | PAGE 0002 | <u> </u> |
|--------------|-------------------------------|------------------------------------------|--------------------------------|-------------------|-----------|----------|
| 0049         | 25 EnEal                      |                                          | 4                              |                   |           |          |
| . /          | c                             | `                                        |                                |                   |           |          |
| 9916         | DO 28 IC-1.1                  | 0                                        | $\gamma$                       |                   |           |          |
| 0047         | 90 20 JC+1,1                  |                                          | ۲-<br>۲-                       | •                 |           |          |
|              | CL,JL,JIJATY US >             | )=={COAT(JC-1)=0.5+Y                     | (1,1,1)                        |                   | • 3       |          |
| 0050         | 00 290 K=1,4                  |                                          |                                | ·                 | •         |          |
| 0051         | 200 00 210 JC=1+1             | 12                                       |                                | •                 |           |          |
| 8041         | 201 80 210 10-1-0             | •                                        |                                |                   |           |          |
| 0054         | IC1=IC+1                      | •                                        | 1                              |                   | ,         | •        |
| 0055         | DI=XXALIC, JC                 | JS1-XX(IC.JC.JS)                         | (-                             |                   |           | •        |
| 0056<br>0057 | 02=XXA11C1+J                  | G.JS}-XXIIC1.JC.JS}                      | -XXA(1C,JC;JS)+XX(1C,JC,       | 1151              | *         |          |
| 0058         | 1F(03-0.) 20                  | ,J37************************************ |                                |                   |           |          |
| 8059         | 202 04=0.                     | ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~   | ł.                             | _                 |           |          |
| 0040         | 68 10 204                     |                                          | •                              | -3                | _         |          |
| 0061         | 203 04=(XX(IC,JC,             | ,JS1)-XX([C+JC+JS)),                     |                                |                   |           |          |
| 8063         | Di=XX(IC).JC                  | 2.JS}-#X(1C.JC2.JS)                      | 57-XXAEIC+JC2+JS1+XXIIC,       | ,JCZ+J\$)         |           |          |
| 0064         | IF(07-0.) 200                 | 6,205,206                                |                                | •                 |           |          |
| 0065         | 205 67=0.                     | • •                                      | 1                              |                   |           |          |
|              | 60 10 207                     |                                          | 1                              |                   |           |          |
| 1066         | 207 D8=YY(1C.JC2              | J\$}+%Y{{C+JC+J5}}                       |                                |                   | •         |          |
| 0069         | 17(08-0.) 20                  | 1,208,209                                |                                |                   |           |          |
| 0070         | 208 D9-0.                     | •                                        | /                              |                   |           |          |
| 0071         | 60 TO 210                     | . 1513-99825-85.4811                     |                                | 16 N              |           |          |
| 0073         | SIG XXA(IC.JC.JS              | L)=XX{{C,JC,JS1}+01                      | -02+04+(05+07-02+04)+04        |                   |           |          |
| Ser.         | C                             |                                          |                                |                   |           |          |
| 9074<br>Note | 220 D0 229 JC=1+1             | 12                                       |                                |                   |           |          |
| 8076         | - JUZ JUZ<br>DO 229 [C+1-1    | •                                        |                                | -                 |           |          |
| 0877         | IC1=IC+1                      | •                                        | /                              |                   |           |          |
| 1074         | DI=YYA(IC,JC)                 | JS)-YY(1C,JC,JS)                         |                                |                   |           |          |
|              | 02=TTALIC+JC2<br>DieVTLIC+JC2 | 2,JS1-7711C,JC2,JS)-<br>.181-77116       | -TTA(IC+JC+JS}+YY(IC+JC        | (JS) <sub>1</sub> |           |          |
| 1961         | IF(03+0.) 22                  | 2.221.222                                | /                              |                   |           |          |
| 082          | 221 D4=0.                     | · · · · · · · · · · · · · · · · · · ·    | 1                              |                   |           | -        |
| POUS<br>Doba | 50 TO 223                     | 1011_WV/10 NO 1011                       |                                |                   |           | 2        |
| 0085         | 223 05=YYA(1C1.)              | (2.JS)-YY(1C1.JC2.J                      | 5)-YÝAFTCI - JC - JS)+YY ( IC) | 1.102.151         |           |          |
| 0086         | D4=YY(IC1, JC                 | 2, JS)-YY(1C1, JC, JS)                   |                                | <b></b>           |           |          |
| 0087         | IF(06-0.) 22                  | 5,224,225                                | í.                             |                   |           |          |
|              | GQ TO 226                     | -                                        | 11.                            |                   |           |          |
| 0090         | 225 07= tyy11C. JC.           | .((2L.JL.JI)YY-(12L                      | /06                            |                   |           | ę •      |
| 091          | 226 DE=XX(IC1.JC              | 121-31 1XX-12L, JL                       |                                |                   |           |          |
| 1972<br>1993 | IF(08-0.) 220                 | ,227,228                                 | 1                              | ••                |           | -        |
| 094          | 60 TO 229                     |                                          | · /                            |                   |           |          |
| 015          | 228 09-1XX11C, JC             | JS1)-XX(1C,JC,JS))/                      | 108                            |                   |           |          |
| 296          | 224 YYA11C, JC, JS1           | ]=YY(IC+JC+JS1)+D14                      | 02+04+105+07-02+041+09         |                   |           |          |
|              | -                             | ·                                        | /                              |                   | _         | · • •    |
|              | -                             | 1                                        | 1                              | •                 | -         |          |
|              | •                             |                                          | 1                              | -                 |           |          |

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1F(JS-1) 308,304,308

307 FORMAT(100, "IMAGE", 12, 1-1, 121

309 FORMAT(1H1;\*1HAGE\*,12,\*-\*,12//)

DX(1,JC,JS)=XXA (1,JC,JS)-XXA (1,JC,JS)

306 WRITE(6,307) JS,JS1

308 WRITE(6,309) JS,JS1

GO TO 312

312 DO 311 JC=1-14

CG 313 1=1.10

| 0004 = 73191 00/03/13 |                                  | =1,101,107(1,12,123,1=1,10)<br>=1,101,17(1,12,15,151,10) | .10f8.3/1H _11%, DY.,3%,10f8.3)<br>.10f8.3/1H ,11%, VY.,3%,10f8.3)                          | D DIRECTION OF PRINCIPAL STRAIN RATE | IRECTION OF PRINCIPAL STRAIN RATE")                 | M: .10%, • YW• ,17%, • EPSX• ,10%, • EPSY• ,15                                                    | ₩0\$₩\$ 04-14,58%,04-14,17%,04-44,18%,0<br>₩00140 | N°,18%,°YN°,17%°ERSX°,16%,4EPSY°,15<br>H ,94%°→→°,18%,⊶→°,17%°-→→°,16%,6            | X, ****                                                         |                              | JC.JS))/[XXA ([].JC.JS)-XXA (].JC.JS<br>\/[XXA ([].JC].JS)-XXA (].JC[.JS))<br>JC.JS})/(YYA [].JC].ZS)-YYA (].JC.JS | N(1474 (11.4C1.4S)-474 (11.4C.4S))<br>.uc.4S9)/1474 (1.4G1.4S)-474 (1.4C.<br>S%)/1474 (11.4C1.4S)-474 (11.4C.4S) | XA (11.JC.JS)-XXA (1.JC.JS))+(VY(11.<br>JG[.JS)-XXA (1.JC].JS))]<br>5)(VA"(11.JC].JS)-XXA (11.JC.JS))/4 | \$) + + + + + + + + + + + + + + + + + + + | 0 T0 [331                                                                |                                                                           |            |
|-----------------------|----------------------------------|----------------------------------------------------------|---------------------------------------------------------------------------------------------|--------------------------------------|-----------------------------------------------------|---------------------------------------------------------------------------------------------------|---------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------|------------------------------|--------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|-------------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------|------------|
| VEL 21 RASH           | UR((, JC, JS)=TTA ((, JC, JS))TT | ######################################                   | 315 FORMAT(1) . 'ROM', [3,5%,'DX',3%<br>310 FORMAT(1) .'ROM', [3,5%,'UX',3%<br>311 CONTIMUE | COMPUTATION OF STRAIM RATES AN       | WRITE(4.320)<br>320 FORMAT(1)41. STRAIN RATES AND D | DU 390 J351.9<br>16(J5-1) 323,921,323<br>321 Multe(6,322)J5<br>322 Formatt140,°5ET°,12,/14 ,94,°1 | 17.04. ***********************************        | 223 MRITE(6, 324) JS<br>323 MRITE(6, 324) JS<br>324 FORMAT(1241, 527, 12,/14, 94,'1 | 925 451-454, '', 15%, '', 11<br>925 451-45+1<br>80 330 46-1, 13 | JCI=JC+1<br>WITTE(6+326) JCI | EPST=0.50+(UK(I1.JC.JS)-UK(I.<br>1)+(UX(I1.JC.JS)-UX(I.JC.JS)<br>EPST=0.50+(VY(1.JC)-JS)-VY(I.                     | 1))+(YY(1,4C(1,4S)-YY(1,4C,4S)<br>EPSXY=0.29+((UX(4,4C1,4S)-UX(1<br>145))+(UX(11,4C1,4S)-UX(11,4C,4              | ++{Vff1,3C,3S9-Vf1,3C,3S)/fx<br>+JC1,3S1-VV1,JC1,3S1)/fxxA {1<br>XM=fxxA ^f1,JC,4S)+xxA ^(1,JC1,2       | *.<br>YH=[YYA II-JC-JS]+YYA II-JCI-       | F/(485(EPSX-EPSY).(E.0.0001)<br>F=2.eEPSY/(EPSX-EPSY)<br>P31=0.544144(F) | PSI=(PSI=340.)/{2.53.14159]<br>60 18 332<br>331 [F(EPSXY-0.0) 334,335,336 | 335 PSI=0. |

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|--------------|--------------|---------------|----------------------------------------|--------------------------|-------------|-----------|
|              | e '          |               | · . /                                  | · ·                      |             |           |
| 0196         | 332          | RK=1.         |                                        |                          | -           |           |
| 0181         |              | -IZ=TABSTEPS  | x}++2.+ABS(EPSY)++2.;                  | /2.+{ABS(EPSXY)++2.}     |             |           |
| 0182         |              | 13-1A051EPS   | X)++2.+AB\$(EP\$Y)++2.                 | 2.*(ABS(EPSXY)++2.))     |             | •         |
| 0143         |              | ESTREL, JC.   | 15}=\$0RT{0.66667}+\$0R                | F([3)                    | 1           |           |
| 0164         |              | PO(1.JC. 361  | #2.##K#SQRT(121                        |                          | •           |           |
| 0185         |              | WRITE(6, 328  | I) XN, YN, EPSX, EPSY, EP              | SXV+PSI+PD(I+JC+JS) Q    |             |           |
| 0186         | 320          | FURNATIIN .   | ,F14.3,5F20.3,F16.3}                   | ,                        |             |           |
| <b>9147</b>  | 330          | CONTINUE      |                                        | ζtr.                     |             |           |
| -            | 5            | AREA COMPUT   |                                        | <i>F</i>                 | -           |           |
| T            | č w          |               |                                        |                          |             |           |
| 0188         | •            |               |                                        |                          |             |           |
| 0189         | 630          | FORMAT(1H).   | 10%. MEAN AREAS'                       |                          |             | С         |
| 0196         |              | DG 402 JC=1   | .13                                    | 3                        |             |           |
| 0191 -       |              | .DO 401 1=1.  | • • · · · ·                            |                          |             |           |
| 0192         | <b>K</b>     | DO 400 JS=1   | 4,5                                    |                          |             | •         |
| 0193         |              | AREA(1, JC, J | /5)=[ABS[[XXA [[,JC+1                  | ,JS)-XXA (1,JC,JS))*(YYA | [[+1,JC+1,  | •         |
|              |              | 1351-444 (1,  | JC, JS) }-{XXA { [+1, JC               | +1,JS)-XXA (1,JC,JS))+(Y | YA 11,JC+1, |           |
|              | · · ·        | 135)-YYA (1,  | ,JC,JS)))+ABS[[XXA &[                  | +1,JC,JS)-XXA [1,JC,JS)) | *TYYA [1+1, |           |
|              |              | TIC+1"121-AJ  | VA (1,JC,JS))-(XXA (1)                 | +1,JC+1,JS}-XXA (1,JC,JS | ))=[YYA (]+ |           |
|              |              | P JC. JS1-11  | FA (1+,4G),453133772+                  |                          |             |           |
| Q174         | 900          | DO DA IE-1    |                                        | -                        |             |           |
| 0194         | 464          | ABEANT. M.    | . #\$1=[AB#A[F.M'. }\$]AA              | REALT. IC. ISALLY/2.     |             | v         |
| 0147         | 401          | CONTINUE      | •••···                                 |                          |             |           |
| 0198         |              | ElsPOD(JC.4   | . 1                                    |                          |             |           |
| 0199         | 5            | IFIKI-NE-1    | KI-0                                   | • •                      |             | ,         |
| 0200         |              | WRITEI6,605   | 5)KI,JC                                |                          |             | r (       |
| 0201         | 605          | FORMAT (//1)  | L.*RON*.[3]                            |                          |             |           |
| 0202         |              | DO 606 I=1.   |                                        |                          |             |           |
| 0203         | 606          | WRITE 6,607   | 7) [AREAH[[,JC,JS],JS=                 | 1.4)                     |             |           |
| 0204         | 607          | FURMAT()H     | ,4F10.4)                               |                          |             | <u>,</u>  |
| 4207         | • <b>9</b> 2 | CUNTINUE      | •                                      |                          |             |           |
|              | ž            | COMPLETATION  |                                        |                          |             |           |
|              | č            | CONFUTATION   | -                                      | Er unnat i un            |             |           |
| 0206         | •            | WRITE(6.514   | • •                                    |                          |             | •         |
| .0207        | 514          | FORMATILHI    | TOTAL POWER OF DEFO                    | RMATION*}                |             |           |
| 0208         |              | DG 623 JC-1   | 1,13                                   |                          |             |           |
| 0209         |              | DO 612 I=1,   | , 9                                    |                          |             |           |
| 0210         |              | DO 622 JS=1   | 1,4                                    | ٠,                       |             |           |
| 0211         |              | PDAII, JC, J  | S)=PO(T, JGq JS)+AREAN(                | I+JC+JS}                 |             | $\sim$    |
| 0212         | 422          | CONTENUE      |                                        |                          |             |           |
| - 0213       |              | KJ##00(JC,4   |                                        |                          |             |           |
| 9214-        |              | 17 [KJ/ME+1]  | / KJ70<br>8184.10                      |                          |             |           |
| 0214         | 404          | ##1121##600   | • ************************************ | ~                        |             |           |
| -0217        |              | CO 409 1=1    | ************                           |                          |             |           |
| 0218         | 601          | WRITE(6.41    | . [=2L. (2L.JC.JC.) (0)                | 41                       |             |           |
| 0219         | 610          | FORMATILN     | .4F10.4)                               | •                        |             |           |
| 0220         | 623          | CONTINUE      |                                        | 3                        |             |           |
| 0221' '      |              | 00 62 JS=1    | , 4                                    | ι.                       |             | •         |
| 0222 /       | •            | 00 41 JC-1    | •13                                    | 3                        |             | ۲<br>۲    |
|              | ,            | •             |                                        | ,                        |             | ¢ •       |

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|              | S LEVEL | <b>41</b>       | PAIN                         | DATE = 73191                           | 00/03/13       | PAGE 0006   |               |
|--------------|---------|-----------------|------------------------------|----------------------------------------|----------------|-------------|---------------|
| 0223         | -       | POT(JC-JS)=0    |                              |                                        |                |             |               |
| 0224 -       |         | 00 41 1=1.9     |                              |                                        |                |             |               |
| 0225         | 61.     | POTIJC.JSI=     | PDT(JC.JS)+PDA(I.JC.JS       | 1                                      | •              |             |               |
| 8224         |         | PCT0(JS)=0.0    |                              |                                        |                |             |               |
| 9227         |         | 00 43 JC=1.1    | 13                           | - I                                    | *              | ç           |               |
| 0228         | 63      | POTO(JS)-POT    | (JS)+POT(JC-JS)              |                                        | •              |             | 5- <b>4</b> - |
| 0229         | 62      | CONTINUE        |                              | •                                      | •              | •           |               |
| 0230         |         |                 | (POTOLIS).JSm1.A1            |                                        |                |             |               |
| 8711         |         | STRNAT (1NO.)   |                              | 14858 A1                               |                | 1           |               |
| 4533         |         | LOWING LTIAN.   | . INCREMENTAL ENERGIES.      | 14kI0.41                               |                |             |               |
| A723         | n.      | 161-5           |                              |                                        |                |             | •             |
| 0234         | -       | 15782           | •                            |                                        |                |             |               |
| 0235         |         | 153=4           | •                            |                                        |                |             |               |
| 8234         |         | 00 K3K M-1.     |                              |                                        |                |             |               |
| A111         |         | DD 223 30-11    |                              |                                        | 9              |             |               |
| 0231         |         | 04 363 L=1+1    |                              |                                        |                |             |               |
| VZ 34        | 243     | PUIUICI,JCI     | ={ 11/3. } = (PDA(1, JC, JS) | **.*PDA(1,JC,JS1)*Z.                   | +PDA(1,JC,JSZ  |             |               |
|              |         | 174.4FUATI+J    | 86,35313                     |                                        | -              | -           |               |
| 0237         |         | DU- 318 .K-1    | 13                           |                                        |                | 5 <b>•</b>  |               |
| 9249         |         | KK=NOD1JC+4     |                              |                                        |                |             |               |
| 0241 .       |         | IF (KK'HE-1)    | KK=0                         | •                                      |                |             |               |
| #Z42         |         | WRITE(6,521)    | F KK, JC                     |                                        | Ł              |             | V             |
| C243         | 521     | FORMAT ( // 11, | , *ROV*, [3]                 | ,                                      | •              |             |               |
| 0244         | 523     | DD 518 I=1,9    |                              | ٥                                      |                |             |               |
| 0243         |         | WR1TE(4,526)    | ) 1,POTOT(1,JC)              | r                                      |                | •           | •             |
| 0246         | 524     | FORMATIIN .     | POINT . 13-F20.3)            |                                        | 1              |             |               |
|              | ۲.      | COMPLITATION    | OF EFFECTIVE STRAINS         | AT EXH.YN)                             |                |             |               |
| 0247         | -       | WRITE14.4001    |                              |                                        | ·              |             |               |
| 0248         | 400     | FORMATICHIA     | FEFECTIVE STRAINSTI          |                                        |                |             |               |
| 0249         |         | JS=1            |                              |                                        |                |             |               |
| 0250         |         | 152.2           |                              | •                                      |                |             |               |
| 6261         |         | 163-3           | <b>`</b> ``                  |                                        |                |             |               |
| A383         | -       | 184-4           |                              | • -                                    |                |             |               |
| 8763         |         | 107 403 Mar     |                              |                                        |                |             |               |
| 4677<br>8961 | ~       | DC 402 JC=1     | 13                           |                                        |                |             |               |
| 4344         | 463     | 444 1-191       |                              |                                        |                |             | ٥             |
| ¥6.33        |         |                 | //                           | 4.+E3IXI1+JC+J\$Z1#Z.                  | +E3TR( I+JC+J5 |             |               |
|              | /       | 277467231811    | (+JC,J34))                   |                                        |                |             |               |
| 8270         |         | DO 403 JC#1,    | .13                          |                                        |                |             |               |
| 7 (38        | 403     | NRIJE16,404]    | JC.(EST(1.JC),1+1.9)         |                                        | ,              |             |               |
| リビンテ         | 404     | FURNATIIN .!    | ROW + [3,9F10.5]             | -                                      |                |             |               |
|              |         | DC 1006 J=1,    | 13                           |                                        |                |             | 0             |
| 0420         | :       | E3TT{J}=0.0     | •                            |                                        | •              |             |               |
| 6241         |         | DG 1005 1=1,    | <b>,</b> ♥`                  |                                        |                |             |               |
| 9262 .       | 1005    | ESTT(J)=ESTT    | [(J)+EST(1+J)                | •                                      |                | <del></del> |               |
| 6450         | 1006    | CONTINUE        |                              |                                        |                | -           |               |
| 0244         |         | SUM=0.0         |                              | •                                      |                |             |               |
| 0265         |         | 00 1008 J=1.    | .13                          |                                        |                |             |               |
| 8266         | 1008    | SUM=SUM+ESTT    | r(1) -                       |                                        |                | ٢           |               |
| 0247         |         | WRITE16.1001    | 12.1F(_fet.(L)1123) (1       | 8                                      |                |             |               |
| 0248         | 1007    | FORMATI 1HO.4   | AX. SIM OF FEFETTME          |                                        | 140.615 61     |             |               |
| 0269         | 314     | CONTINUE        | THE AND DE STEWILTE          | ************************************** | 1101112421     |             |               |
| 0270         |         | STOP            |                              | -                                      |                |             |               |
| 8271         |         | SWD             |                              |                                        | ~              |             |               |
|              |         | Eut             |                              |                                        |                |             |               |

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## B.2 LISTING OF PROGRAM "25"

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| 072                 | •     | 69 TO 700C                                                   | •            |        |       |       |                  | •          |                | •    | <i>*</i> • , |          |
| 623                 | C     |                                                              |              | -      |       | •     |                  |            |                |      |              |          |
| 055                 | 61130 | THE DISCO?                                                   | •            |        |       |       |                  |            |                |      | `            | ·        |
| 055                 |       | LD" THERIN                                                   |              |        |       |       | •                |            |                |      | •            |          |
| 044                 | •     | SPE DELCIO                                                   |              |        |       |       |                  | •          | •<br>c         |      |              |          |
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| 066<br>047          | · C   | TE ( MOT 1584(171) 00 TO 2000                                |              |        |       |       |                  |            |                | •    | ۰.           |          |
| 055                 | 2100  | CALL: NEGTYF(IP, 24, 24HNCP=0, FINI=:<br>Y=IREPLY(IR, 10, 1) | l, sto##2, B | ACK=3} | -     | • . • | ۰ <sup>°</sup> • |            |                |      | `            |          |
| C43                 |       | 00 TQ (2110, 2100, 2100, FFFF), I                            | 4            | 4      | •     | ~     |                  | •          |                |      |              |          |
| 0170                | 2110  | 19 (1° EU 07° GU 73 7000<br>19 (1° EO 1) 60 70 9330          |              |        | t.    |       |                  |            |                |      | ۰ 🛩          |          |
| 071                 |       | 15 (4, 86 2) - 60 TO 0500                                    |              | -      | •     |       |                  |            | •              |      |              | -        |
| 072                 | ~     | IF (). NE. 3) 62 76 2100                                     | -            |        |       |       |                  |            |                | ,    |              | •        |
| 074                 | 2200  | CALL NEGTYPAIP, 7, THENTER 1)                                |              |        | · ,   |       |                  | ·          | •              |      |              |          |
| 275                 |       | ID-IREPLY(IR. 10. I)                                         |              | C      | • -   |       |                  | •          | °              |      |              |          |
| 076<br>077          | 2210  | IF((ID, LT 1), CR. (ID GT, 194)) 69                          | 70 2200      | •      | -     |       |                  | -          | •              |      |              |          |
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| 070<br>6 <b>9</b> 0 | 2220  | SALL MIGTYF(IP.7.7HENTER J)<br>JD=IREFLY(IR.10.1)            |              | e      |       |       |                  |            |                | v    |              |          |
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| ç₽4                 |       | 1D-1D-2                                                      | -            |        | •     | r     |                  |            |                |      |              |          |
| 097<br>091          |       | IF(ID GT C) 60 TO 1200                                       |              |        | -     |       | ,                | A '        |                |      |              | 1        |
| C#7                 |       | ₩ <b>₩</b> ₩₩                                                |              |        |       |       | 1 • .            | <b>`</b>   |                |      |              | 1        |
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| CF1                 |       | IF(ID LE 176) 00 TO 3050                                     |              | •      |       |       |                  |            |                | •    | ,            | -        |
| 092<br>Ast          |       |                                                              | ι            |        |       | •     |                  |            |                |      |              | · 1      |
| 4+4                 | 3030  | IF (.D LE. 3) 00 TO 3150 "                                   | <i>ن</i> و   |        | 1     |       |                  |            |                |      |              | $\smile$ |
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| 697                 | 6,    |                                                              |              |        |       |       |                  | -          |                |      |              | · ·      |
| 024                 | 3100  | CALL SCAR(SCAR, RES)                                         | ,            |        | ,     |       |                  |            |                |      |              |          |
| 597<br>166          |       | VW(ID, 20)=525(1)<br>VA(ID=1) = 01=525(7)                    |              |        |       |       |                  |            |                |      |              |          |
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## B.3 LISTING OF PROGRAM "TAPE 25"

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| TAL IN T                                                             | LEVEL 21                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | AEGOAC .                                                                  | PATE = 731                             | F1        | 11/43/22 | PAGE 0 | 100 |   |   |
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| . 10                                                                 | PUNCTION ASCEAD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | ( M )                                                                     |                                        |           |          |        |     |   |   |
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| \$532 <b>5</b> 23                                                    | C [F(N] ].2.2<br>1 N°G41<br>1 N°G41<br>80 TO 3<br>2 N°C40<br>480V230<br>3 M17-M/L17<br>3 M17-M/L17                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                           | `````````````````````````````````````` | \$        | · ,      | •      | v   | a |   |
|                                                                      | C [= 1.4 2 4 M O C 41]<br>Ja (( MD) (41 7 + 04 1<br>Ja ( J 4 6 7 + 0 1 J 4<br>Ja ( J 4 9 + 2 4 + M O 4<br>Ja ( J 4 9 + 2 4 + M O 4<br>Ja ( J 4 9 + 2 4 + M O 4<br>Ja ( J 4 9 + 2 4 + M O 4<br>C 41 1 3 M O 4<br>C 41 1 3 M O 4<br>C 41 2 4 A C 4<br>C 41 2 4 A C 4<br>C 4 2 A C 4<br>C 4 A C | •3.4)<br>•32!eL26).426<br>•3<br>14.(17) •1.420<br>14.(17) •1.420          |                                        | · ·       |          |        |     | X |   |
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