GEOTECHNICAL RESEARCH CENTRE

SOIL DEFORMATION AND SLIP RELATIVE TO GROUSER SHAPE AND SPACING

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R.N. YONG, A.F. YOUSSEF and H. ELMAMLOUK

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R.N. Yong, A.F. Youssef and H. El-Mamlouk
Geotechnical Research Centre
McGill University
Montreal, Canada

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SUMMARY:

The development of soil deformation patterns and failure status behind grousers in the production of drawbar pull is examined in relation to grouser shape, size, and spacing (between grousers). The kinds of deformations, slip conditions, and patterns of soil displacement can be usefully examined to provide the input required for optimizing track performance.

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by

R. N. Yong[1] A. F. Youssef[2] and H. El-Mamlouk[3]

INTRODUCTION

In the development of mobility of tracked vehicles, the interaction between the vehicle and the ground is maintained through the track/grouser system which, together with the road wheels, sprockets, and associated suspension arrangement constitute the running gear of the tracked vehicle. By and large, except for the development of the space link track system as a concept and a viable track design, attention to the grousers (cleats) and their participation in the development of tractive forces in the running gear system has been minimal. The scarcity of rigorous rational theories for the assessment and evaluation of total track performance has in large measure contributed to the inadequate attention of grouser/track participation in the running gear system for production of tractive effort.

Two recent priority concerns have made it important to examine the grouser/track system in greater detail. These are:

(1) The requirement for protection of the surficial environment from excessive surface disturbance - especially in the more fragile environments, and

(2) The need for obtaining the greatest amount of usefu. work for the least expenditure of fuel energy.

In response to the first of these concerns, recent experiments such as those by Yong, Fattah and Youssef (1976) have examined the development of a passive track system where the grousers used have been designed so that their interaction with the terrain surface for production of traction is not in any way destructive. Arising from this and other previous studies, it is evident that the geometry and the spacing of grousers in a track system can immeasurably affect the performance of the tracked vehicle - with all else being maintained constant.

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[1]William Scott Professor of Civil Engineering and Applied Mechanics; Director, Geotechnical Research Centre, McGill University, Montreal, Canada.

[2]Research Associate, Geotechnical Research Centre, McGill University, Montreal, Canada.

[3]Graduate Research Assistant, Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Canada.

Since the interaction of the grouser/track system with the terrain is through the development of thrust in the soil interfaco region, it is apparent that there needs to be a proper appreciation of the kinds of deformation and shear patterns in the soil. The spaco link track concept advanced initially by Bekker (1960) was one of the earlier attempts in the rational examination of grouser/track performance, where the soil behaviour patterns behind a series of moving grousers are used to provide the design requirements for grouser spacings.

Whilst it may be reasonably assumed that the requirement for optimum production of thrust in a grouser/track system is such that the complete shear distortion region of the reacting (supporting) terrain needs to be developed, it is apparent that some optimum design spacing of grousers can be established in relation to grouser shape and size. A knowledge of the shear and deformation performance of the reacting terrain in the wake of grouser thrust can contribute to the development of optimum performance of a total grouser/track system.

This study is concerned with the problem posed by the second listed priority given in the preceding. It examines the performance of a multiple grouser system in relation to soil reaction in response to grouser thrust and attendant grouser spacings. Three types of grouser have been used where the spacing between the grousers has been varied. The track sections which contained the fullscale grousers have been shortened to provide for the glassbox experimental test series. By imposing the same experimental boundary condition to all the tests conducted (i.e. rigid track system), where both grouser and variable spaces have been introduced, it is possible to compare the various deformation patterns experienced by the grousers under thrust development. Correlations and comparisons between the necessary forces required to induce motion, and the developed thrusts and soil behaviour patterns, show the efficiency of the grouser system in relation to the spacings between grousers.

EXPERIMENTATION

To examine the effectiveness of grouser shape and spacing of grousers in the development of drawbar pull in a tracked vehicle, there are several levels of examination that can and should be implemented. These begin with the use of actual tracked vehicles as reported by Yong et al. (1976). There are however, some limitations with this type of field testing approach. These lie primarily in the area of isolation of parameters and their effects since full scale field trials are difficult to reproduce insofar as full boundary constraints and factors are concerned. To produce a more controlled system section belt or section track testing can be performed in the laboratory. These essentially involve the use of actual size grousers on small track systems. To progress one more step in the basic research direction, a representative set of grousers can be systematically studied. This can be further studied in terms of single grouser tests. The schematic diagram which shows the hierachy of sophistication or fundamental approach to the study of grousers and their role in a track system for production of tractive effort is given in Figure 1.

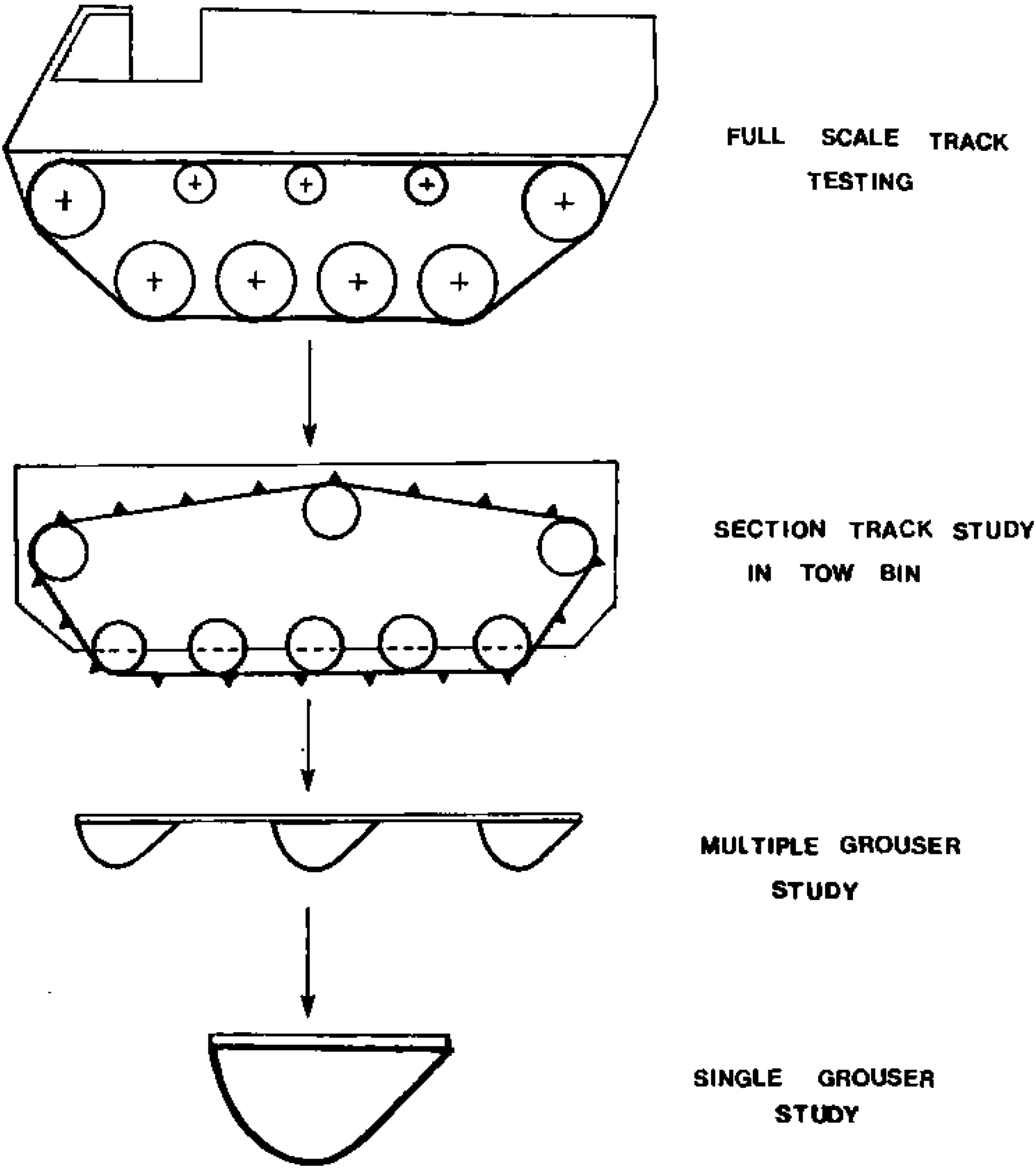


FIG. 1 LEVEL OF DETAIL IN TRACK/GROUSER STUDY

In this study, the method chosen for examination of the contribution of grousers and their spacing to the efficiency of a track was the multiple track system as identified in Figure 1. The three types of grousers used are shown in Figure 2. These are identified as standard, aggressive, and passive grousers and are identical in size and shape to the ones used in the field study reported by Yong et al. (1976).

The actual experimental technique used for production of the drawbar pull test consisted of forcing the multiple grouser element into the compacted clay contained in the soil bin with lucite side walls. The rigid top connecting plate in essence provided for a condition of extreme track rigidity. The use of the lucite side walls permitted visual appreciation of the soil distortion as grouser thrust is developed. With a superposed grid systems inscribed on the clay prior to the fixing of the lucite side walls, distortion of the clay behind the moving grousers can be easily observed. Single grouser tests were also performed to show and to isolate the effect of grouser geometry on the development of soil distortion. Figure 3 shows the test facility used for the multiple and single grouser experiments.

The soil used in the test box was a kaolinite clay, prepared at a moisture content of about 44 percent. At this water content, the soil was between 93 to 98 percent saturated - depending on the efficiency of compaction. By and large, the strength test results show a high degree of soil property reproducibility.

To record the history of motion or deformation of the soil arising from the thrust developed by the grouser, a series of photographs were taken during continuous motion of the grousers. With the record obtained from the photographs, the displacement patterns developed as the soil deformed during grouser movement in the multiple or single grouser test series provided a visual description of soil reaction in terms of velocity fields, strain rate distributions, and slip lines generated. Surficial measurements during the test series included the recording or the thrust developed by the multiple grousers. By comparing these to the single grouser tests, it is possible to isolate the influence of spacing and the effect of grouser geometry on the production of gross tractive effort.

TEST RESULTS AND DISCUSSION

With the experimental facilities shown in Figure 3, the thrusts developed by the multiple or single grouser systems are given in terms of horizontal forces, - since the grousers were constrained from moving upward during horizontal displacement - i.e. the grousers were only allowed to move in the horizontal direction. Figures 4, 5 and 6 show the relationships between the horizontal forces developed and grouser displacements. In these figures, comparisons are made between the multiple grouser system and the single grouser for the same grouser geometry.

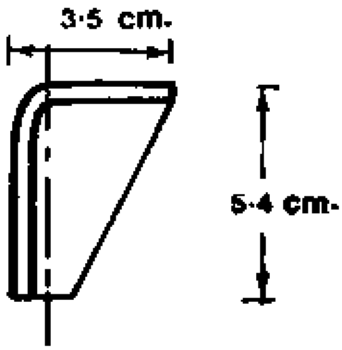
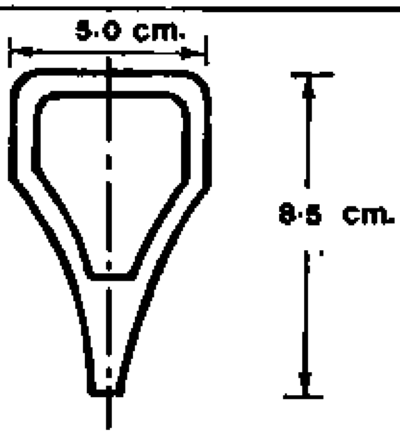
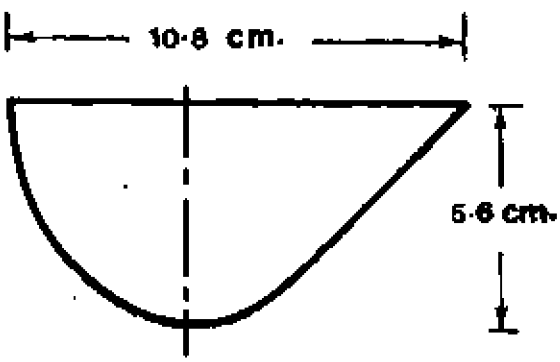
GROUSER GEOMETRY	DEFINITION
	STANDARD GROUSER
	AGGRESSIVE GROUSER
	PASSIVE GROUSER

FIG. 2 GROUSER DESCRIPTIONS AND DEFINITIONS

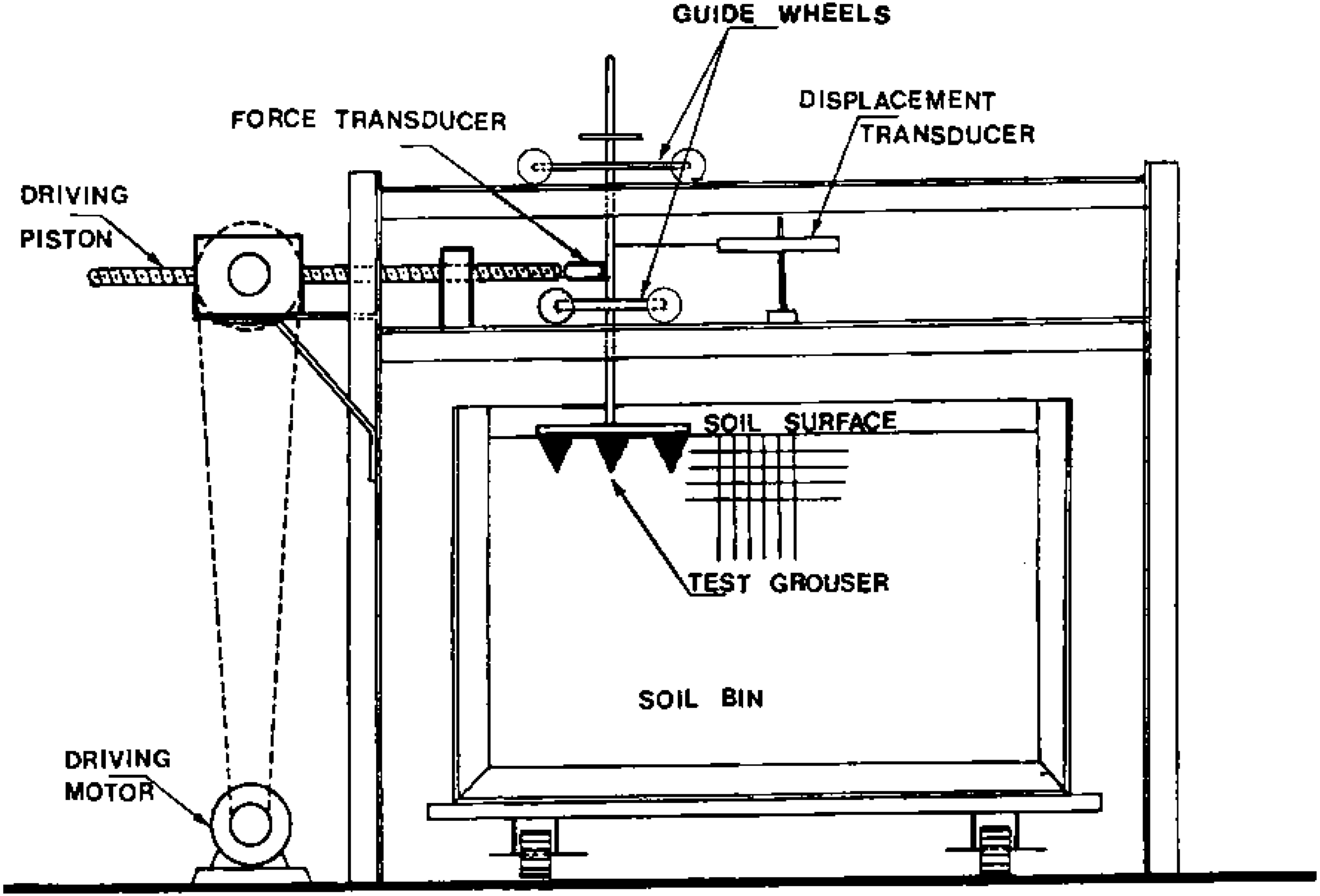


FIG. 3 SINGLE AND MULTIPLE GROUSER TEST FACILITY

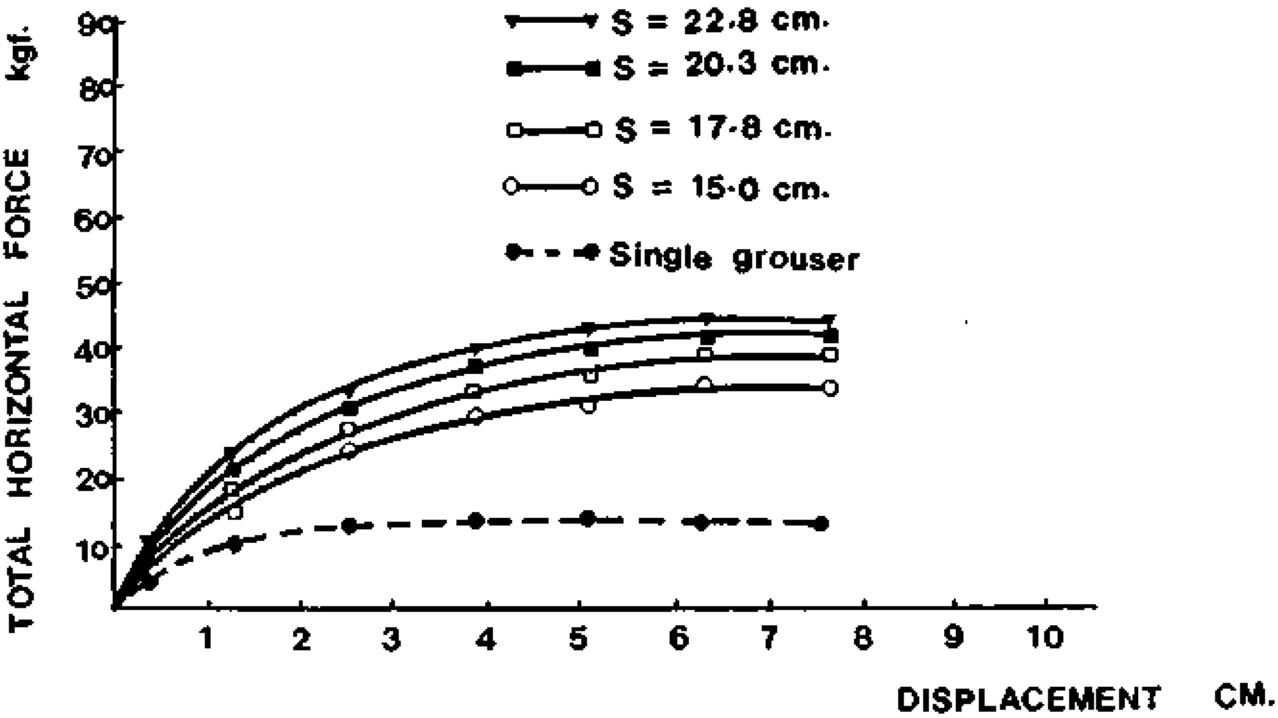


FIG. 4 HORIZONTAL FORCE-DISPLACEMENT RELATIONSHIPS FOR STANDARD MULTIPLE GROUSER WITH DIFFERENT SPACINGS.

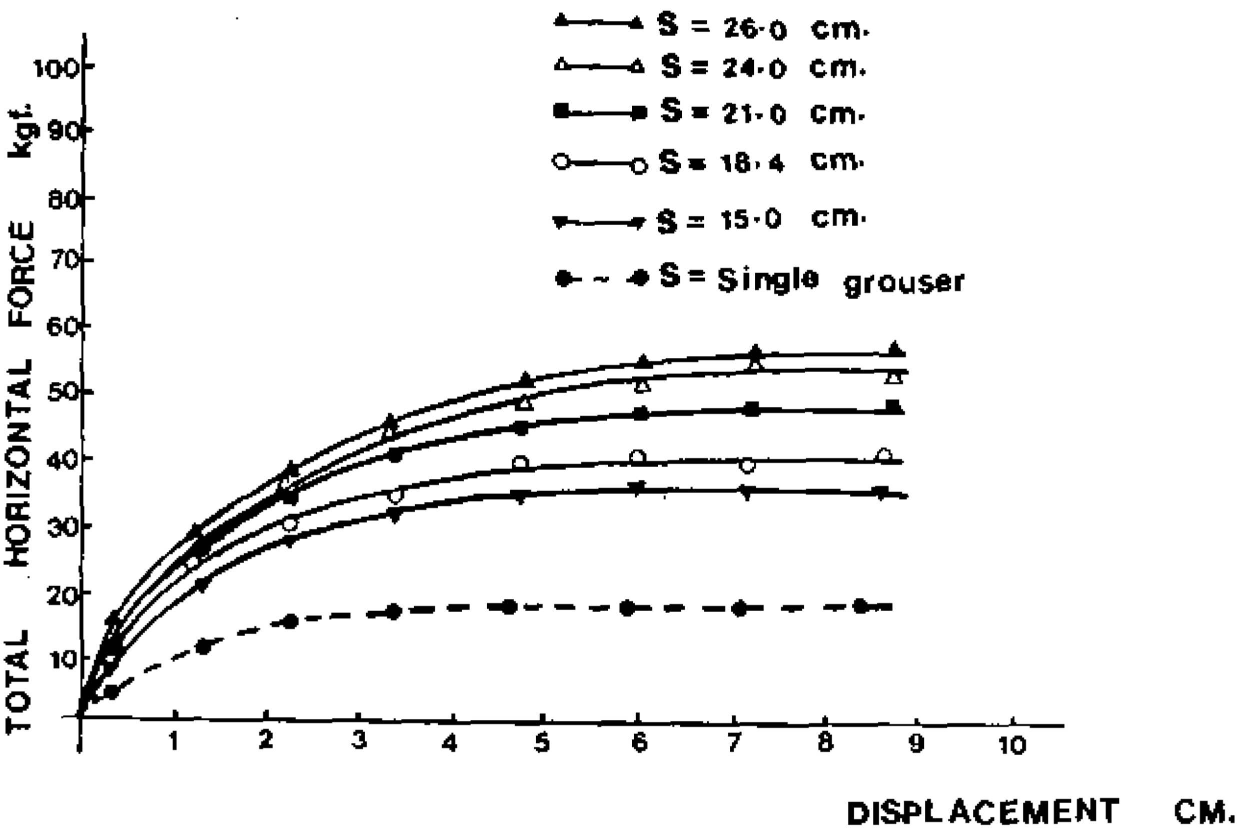


FIG. 5 HORIZONTAL FORCE-DISPLACEMENT RELATIONSHIPS FOR PASSIVE MULTIPLE GROUSER WITH DIFFERENT SPACINGS

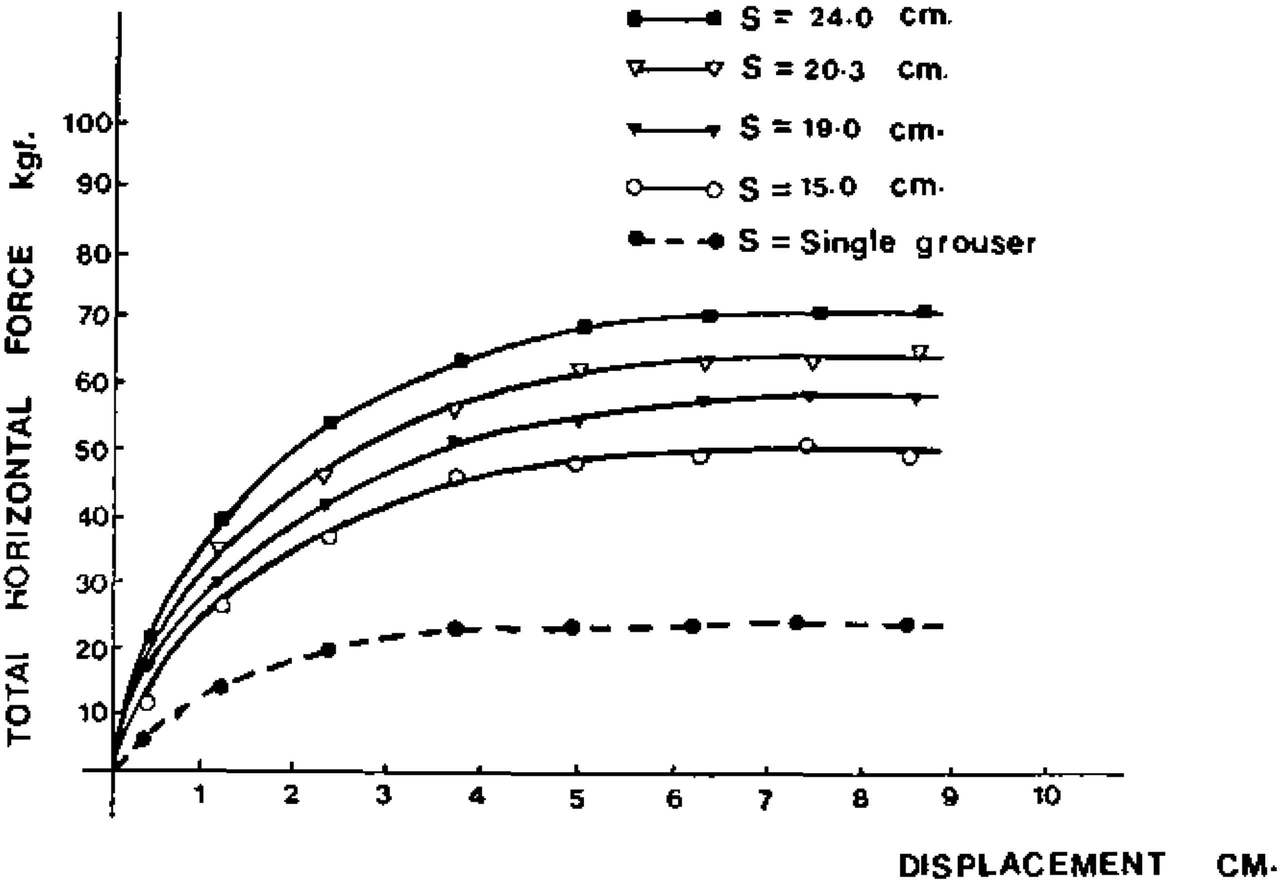


FIG. 6 HORIZONTAL FORCE-DISPLACEMENT RELATIONSHIPS FOR AGGRESSIVE MULTIPLE GROUSER WITH DIFFERENT SPACINGS

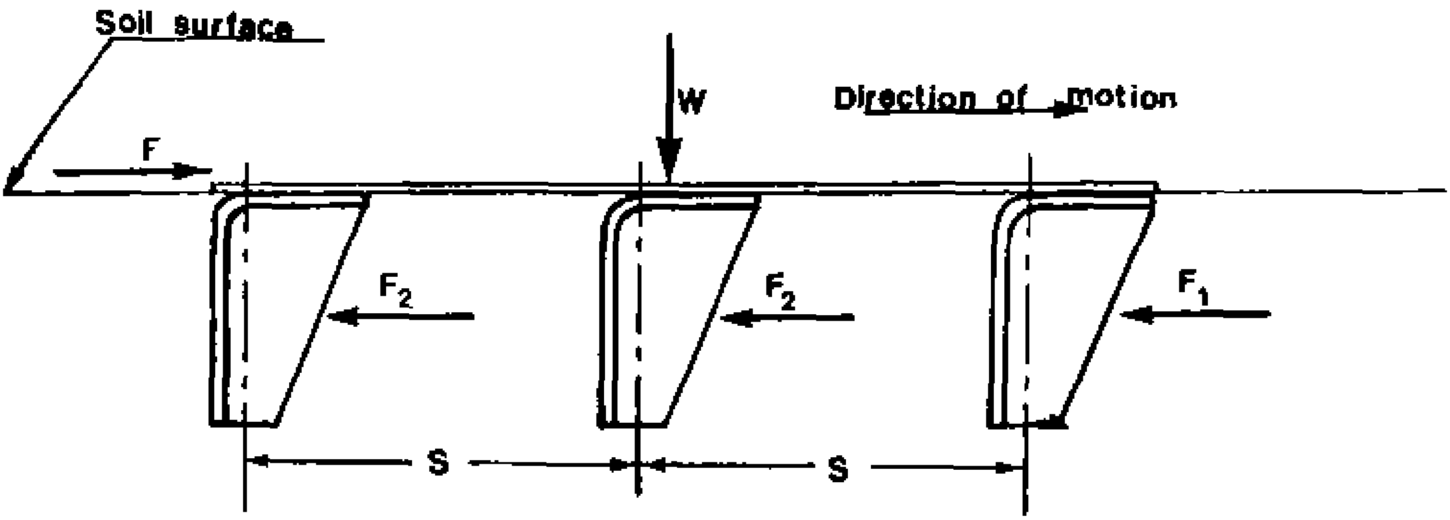
The multiple grouser test series consisted of three grousers with spacings given as shown in Figure 3. As can be expected, the total horizontal force developed by the multiple grousers is larger than that shown by the single grouser. It is however not a simple multiplication of three for the total force developed (i.e. three times the single grouser force) as might be expected because of the fact that the multiple grouser test series consisted of three grousers.

In the single grouser tests, the passive soil deformation zone established during grouser thrust can effectively be described in terms of the limit equilibrium Rankine Passive Zone with due account given to the constrained zone at the grouser interface - as described and analyzed by Yong and Sylvestre-Williams (1969). Using the length of this zone as the spacing requirement between adjacent grousers, one can establish a space link design criterion. As can be seen from the multiple grouser tests, the total force developed depends in large measure on the spacing between grousers. The larger the grouser spacing, the larger is the total horizontal force developed. This can at times be more than three times the total thrust developed by a single grouser, which indicates that the grouser spacings exceed the Rankine Passive Zone criterion, and that some augmentation of grouser action is achieved through active soil participation with the grousers to increase total track force. This will be evident in Figures 10, 11 and 13.

Because of the interference of one grouser on the development of the soil deformation on the adjacent grouser, analysis of multiple grouser effect can be quite complex. In order to reduce the test result to a common base, the method of evaluation shown in Figure 7 has been adopted. This includes consideration for the fact that the leading grouser has in effect an infinite soil extent in front of it during its travel - producing in effect the Rankine passive zone attributable to single grousers. The forces developed by the leading grouser are designated as F_1. Since the following grousers are in essence constrained by the leading grouser, the forces acting on the subsequent grousers in the multiple grousers are designated as F_2. The total existing force developed by the multiple grouser element, in this case consisting of three grousers, is given as the sum total of $F_1 + 2F_2$. The schematic diagram given in Figure 7 illustrates the total action.

Figure 8 demonstrates the effect of spacing on the total force developed. In this instance, the common base has been used as described in Figure 7 and the thrust developed on the intermediate grousers designated as F_2 is related to the spacing between grousers. As noted, the aggressive grouser system produces the largest force. However, one should also consider the grouser spacing associated with the maximum thrust developed by the grousers. The diagram shows that the horizontal force increases as the spacing between grousers increases. Presumably this should asymptote to a constant value where the maximum force developed can be obtained consistent with a maximum spacing for the grousers. It should be noted at this point however that the development of maximum thrust by the grouser system which might require excessive grouser spacing may not be consistent with the ride comfort required for operation of the vehicle.

By plotting the gradient of the force given in Figure 8, i.e. the maximum force per unit spacing, the diagram given in Figure 9 is obtained.



F_1 = Resisting force of the first grouser with infinite soil extent in front of it.

F_2 = Resisting force of the second or third grouser of the multiple grouser element.

F = Total resisting force of the multiple grouser element.
= $F_1 + 2F_2$

FIG. 7 LAY-OUT OF MULTIPLE GROUSER ELEMENT WITH THE FORCE COMPONENTS ACTING ON IT

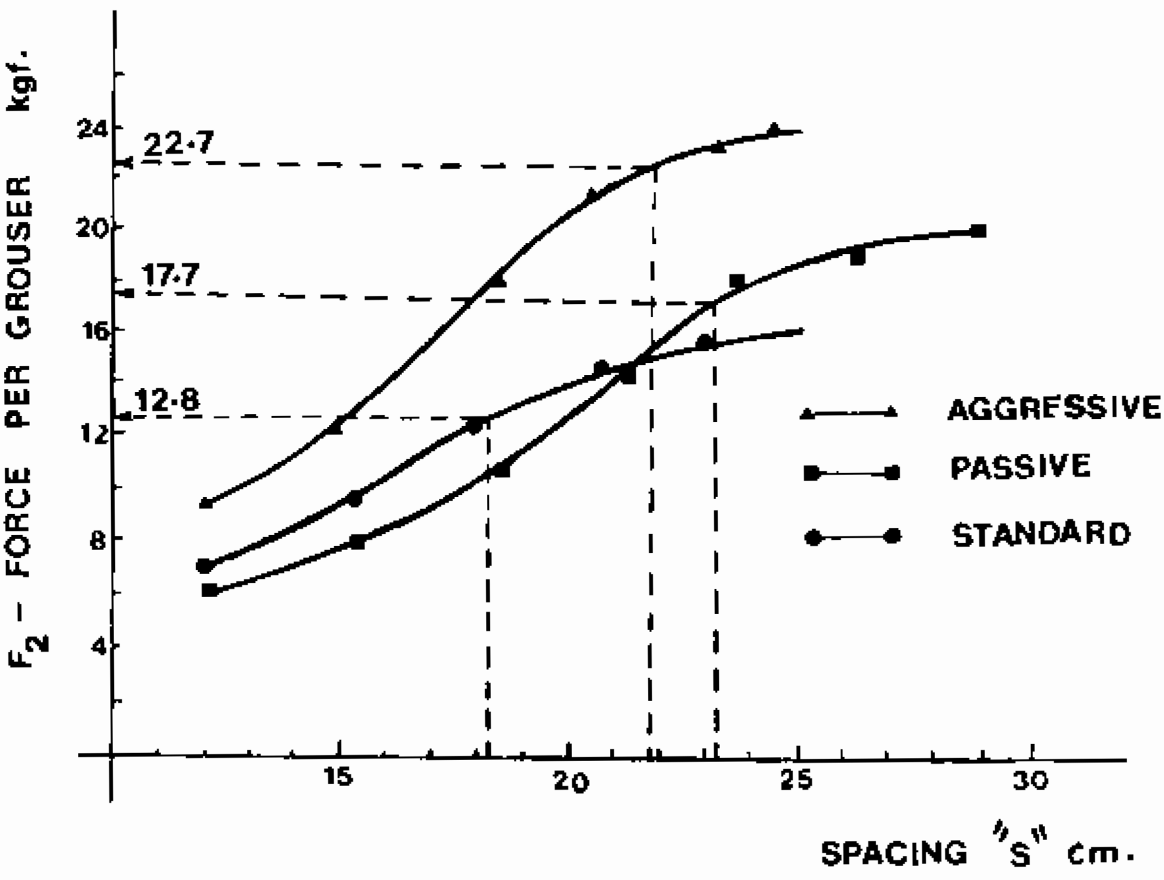


FIG. 8 RELATIONSHIPS BETWEEN HORIZONTAL FORCE PER GROUSER AND THE SPACING OF THE MULTIPLE GROUSER SYSTEM

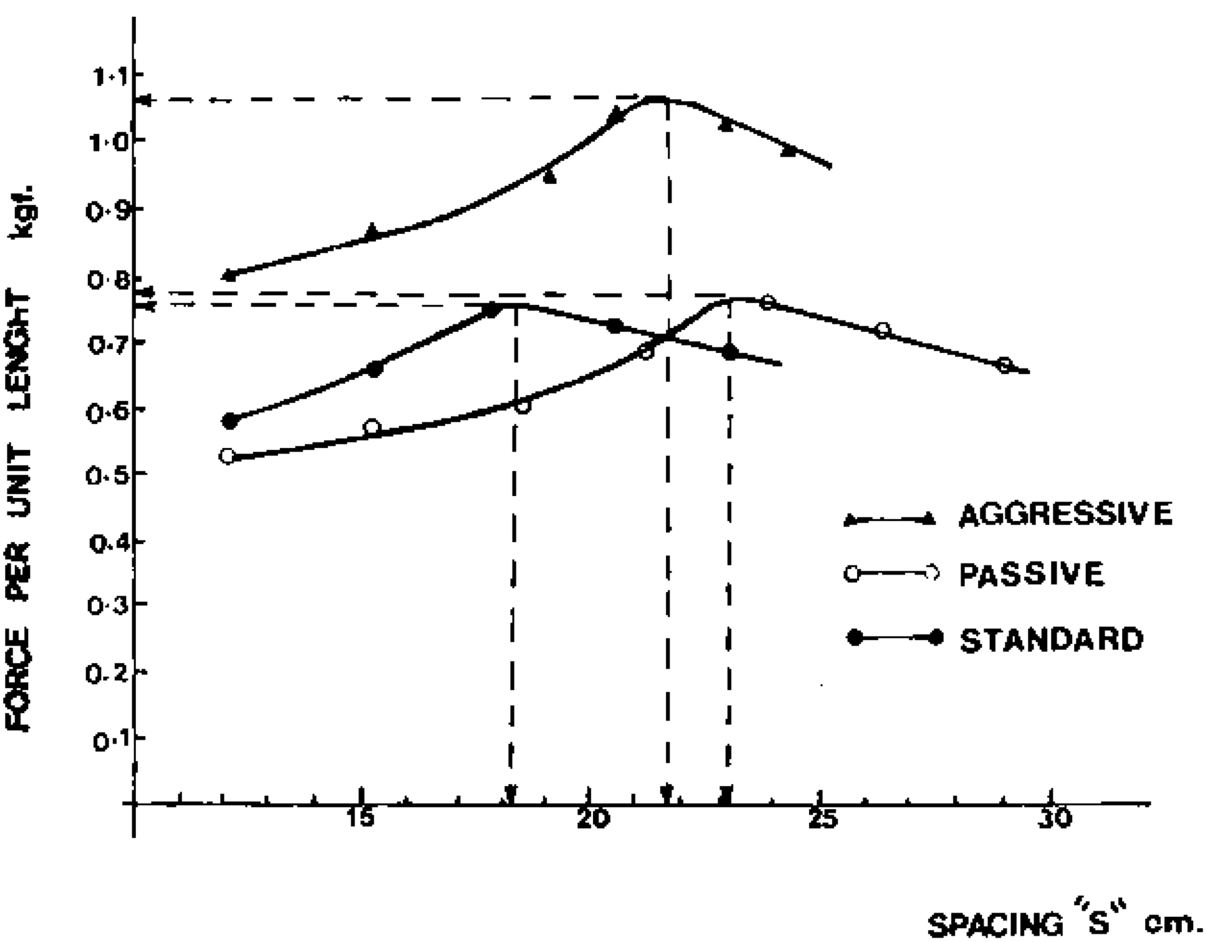


FIG. 9 MAXIMUM UNIT FORCE-SPACING RELATIONSHIPS FOR THE THREE GROUSER TYPES

As noted from the diagram, the spacing required for development of the maximum force per unit spacing is given as 18.2 cm for the standard grouser, 21.8 cm for aggressive grouser, and 23.2 cm for the passive grouser. These same spacings are superposed on Figure 8 to show their corresponding forces developed - i.e. 12.8 kg for the standard grouser, 17.7 kg for the passive grouser, and 22.7 kg for the aggressive grouser for the corresponding optimum grouser spacings as indicated in Figure 9. We note with interest that these forces, designated as optimum forces, are approximately equal to those forces developed by the single grousers of identical geometry. This indicates that when one utilizes grouser spacings in excess of those prescribed by the Rankine passive zone for single grousers, the rate of increase in thrust development decreases. This can be easily observed in Figure 8 where the maximum thrust is seen to develop at spacings in excess of the Rankine passive spacing.

Displacement and Velocity Distribution Patterns

To study the deformation behaviour of the soil in the face of a moving grouser, representative particle displacements at different locations were recorded at various time intervals during the test. As described previously, this was achieved with the aid of the grid network technique.

The deformation patterns of the nodal points obtained from the grid, are plotted in Figure 10 (a,b,c) for the standard, passive, and aggressive multiple grousers respectively after a total displacement of 4.0 c .

A significant difference between the soil particle displacement patterns is observed behind the first and second grousers of the multiple grouser system. Because of the unhindered soil zone, soil undergoes forward and upward deformation in front of the first grouser - typical of the Rankine passive performance of soil. In the case of the intermediate positioned grouser, the soil in the region between the front of that grouser and the back of the first one was found to move horizontally with approximately the same degree of grouser displacement. This was attributed to the upward restriction imposed by the horizontal connecting plate at the top of the grousers which prevented upward heave of the soil. This situation is not unlike that imposed by a very rigid track. These observations support the postulate that the intermediate grouser behaves considerably different from that of a single grouser due to the difference in boundary conditions, spacing and vertical movement restrictions.

As observed from the displacement patterns given in Figure 10, the soil contained between the grousers moved in concert with the grousers (horizontally) for the rigid track simulation - thus testifying to the grouser augmentation effect referred to previously in the discussion of results shown in Figure 8. The soil-grouser augmented phenomenon, which is further discussed in Figure 13, thus produces a track enhancement effect. It is apparent that if track rigidity is relaxed, i.e. if the track becomes more flexible, some upward movement of the soil contained between the grousers will occur. When this happens the initial enhancement of track performance obtained in the rigid track situation through coupling motion of soil and grouser, becomes diminished.

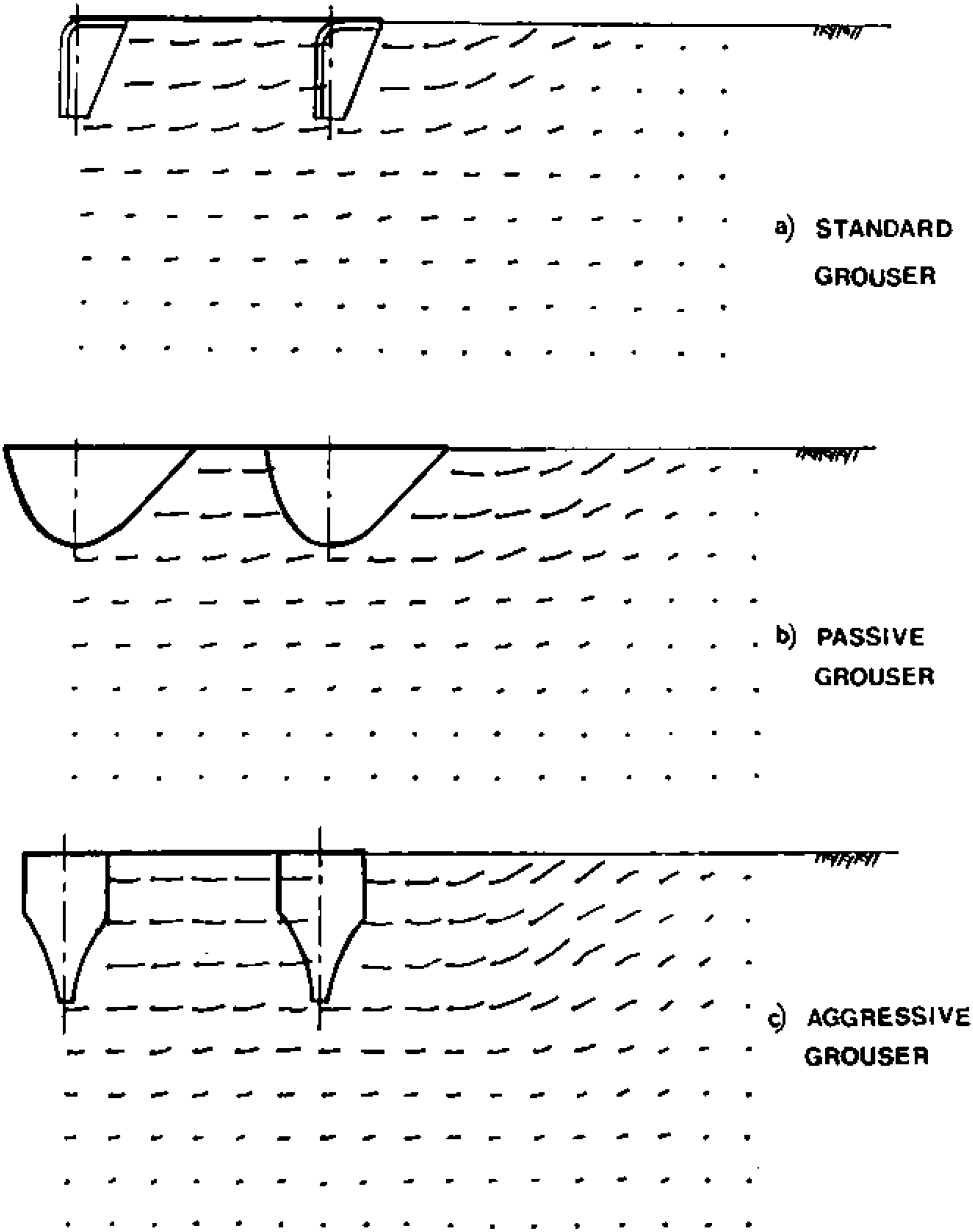


FIG. 10 DEFORMATION PATTERN OF NODAL POINTS AT GROUSER DISPLACEMENT OF 4.0 cm

The velocity components of the nodal points were calculated using the Cartesian coordinates within the Lagrangian space using the expression:

$$U = \frac{dx}{dt} \qquad V = \frac{dy}{dt}$$

where

U = instantaneous particle velocity in the X-direction

V = instantaneous particle velocity in the Y-direction

x, y = horizontal and vertical coordinate of the point at any instant of time as measured from a fixed given point

t = time

The results obtained for the vertical velocity components were negligibly small in view of the upper boundary constraint and also in view of coupled motion of soil and grousers in the horizontal direction. Hence, only the horizontal components of velocity need be shown. As an example, Figure 11 shows the horizontal component of the nodal point velocities for the passive grouser at two different values of its displacements. Similar diagrams can be obtained for the other grousers. From these iso-velocity contours, it is observed that the highest velocity occurs in the zone bounded by the grouser face and the upper connecting plate. It is also observed that no intersection of the contour lines occurred with the upper plate which indicates that the soil in the upper zone moves with the same velocity as the upper plate. A concentration of the velocity contour lines occurs at the grouser tip level for higher grouser displacements.

Figure 12a illustrates the variation of horizontal velocity with depth at mid-distance between the passive grousers (shown in Figure 11) for different grouser displacements. It is observed from this figure that the horizontal velocity decreases with increasing depth from the surface until a certain depth, identified as the affected depth, after which the soil ceases to move. This depth was found to increase with increasing horizontal grouser displacements. It can be noted from the same figure that the reduction of the horizontal velocity with depth occurs at different rates depending on the displacement of the grouser. At higher displacements, a sharp decrease of velocity occurs at approximately the same level of the grouser tips.

The main features of the above observations are the same for the other two types of grousers (standard and aggressive) as shown in Figure 12b, c, except for the magnitude of the affected depth below each grouser type.

Development of Failure Zones

The development of the failure zones as interpreted from soil-strain data for the multiple passive grouser system at different displacements of the grousers is shown in Figure 13. From shear tests performed on the kaolinite clay, it was established that failure occurred at about 15 percent strain.

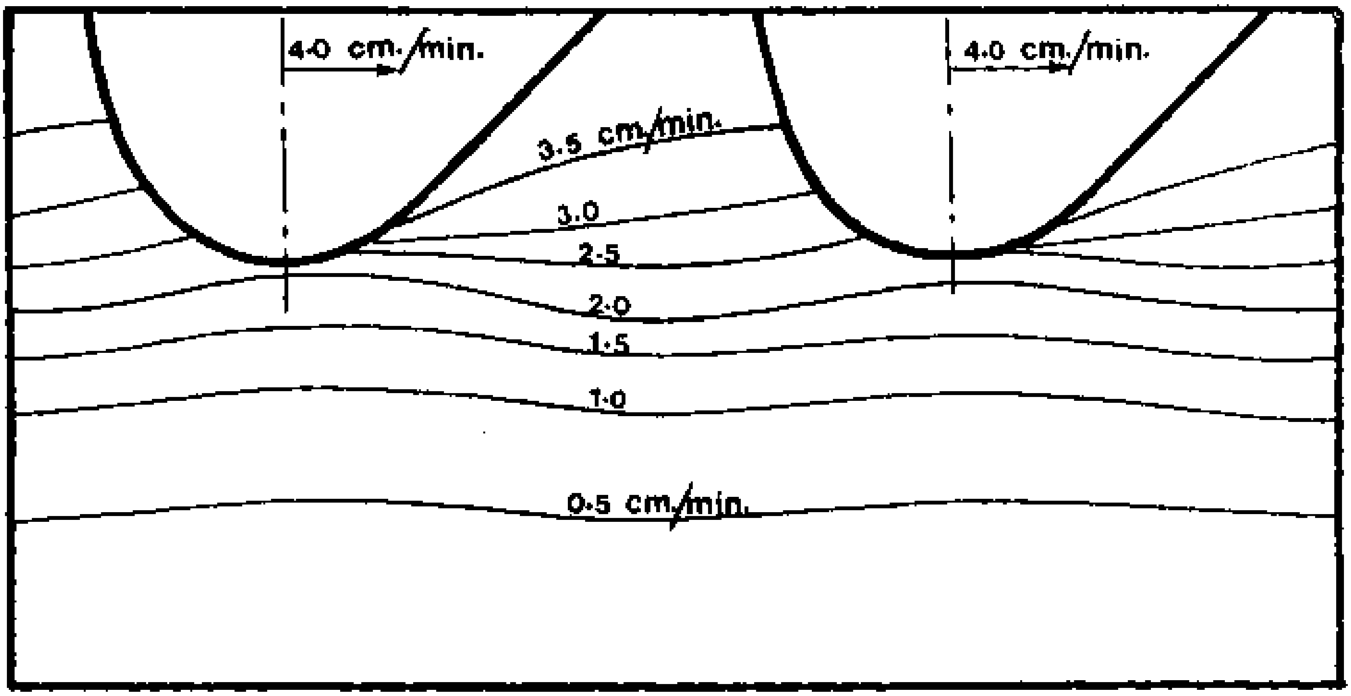


FIG. 11a HORIZONTAL VELOCITY DISTRIBUTION PATTERN FOR PASSIVE GROUSER
Grouser Displacement = 1.7 cm

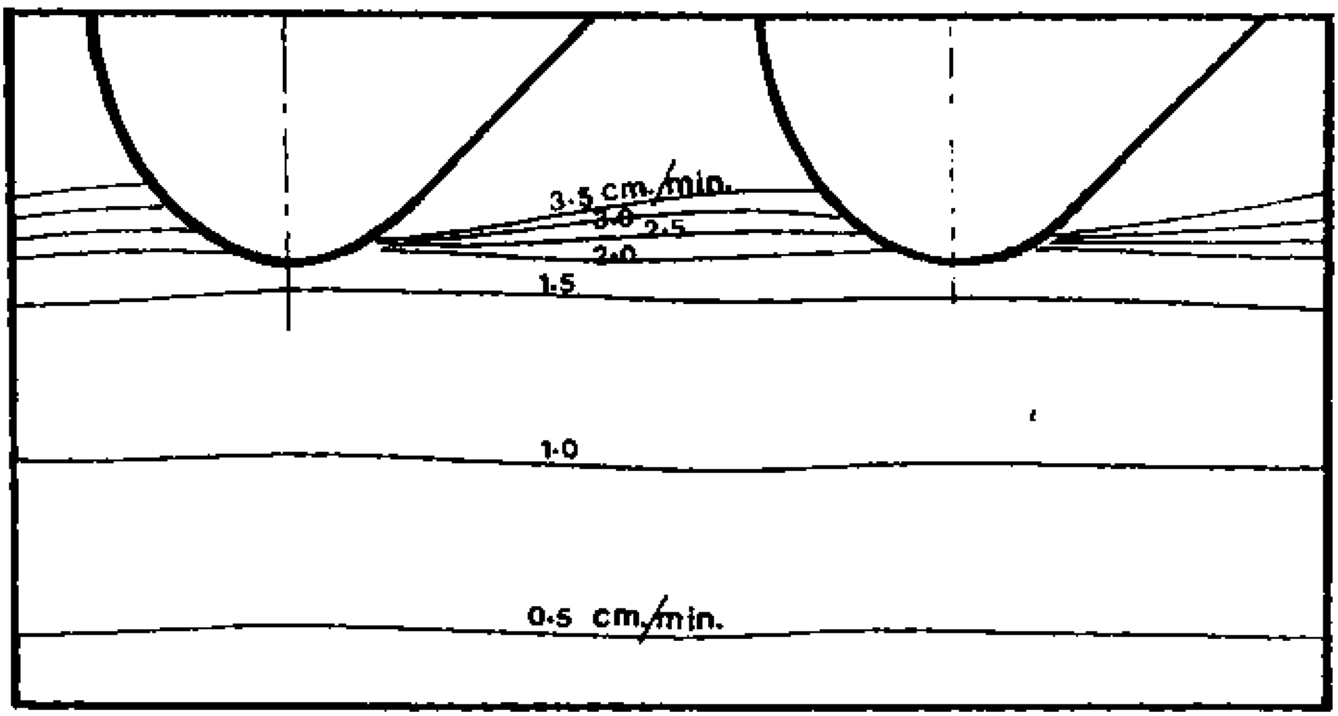


FIG. 11b HORIZONTAL VELOCITY DISTRIBUTION PATTERN FOR PASSIVE GROUSER
Grouser Displacement = 4.3 cm

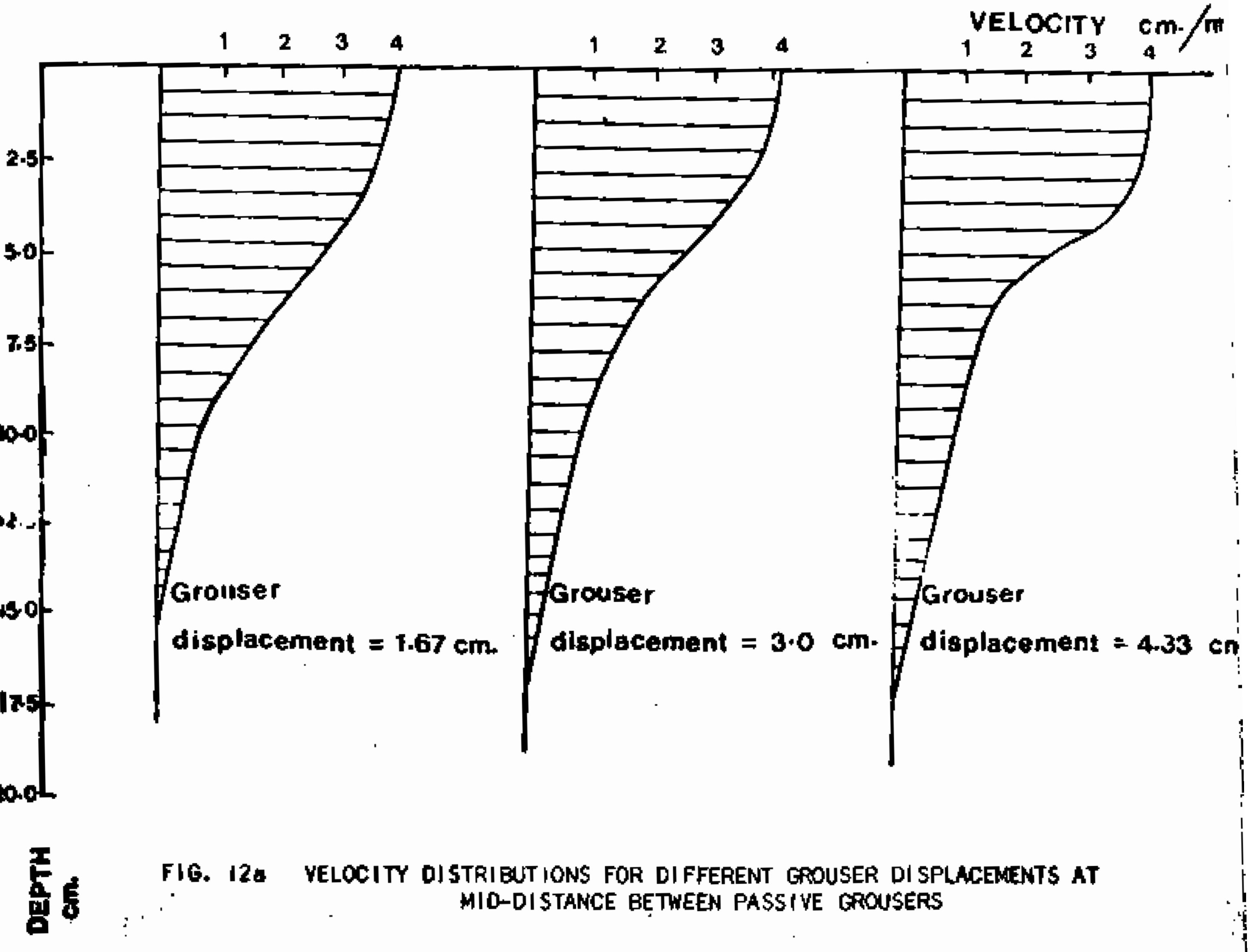


FIG. 12a VELOCITY DISTRIBUTIONS FOR DIFFERENT GROUSER DISPLACEMENTS AT MID-DISTANCE BETWEEN PASSIVE GROUSERS

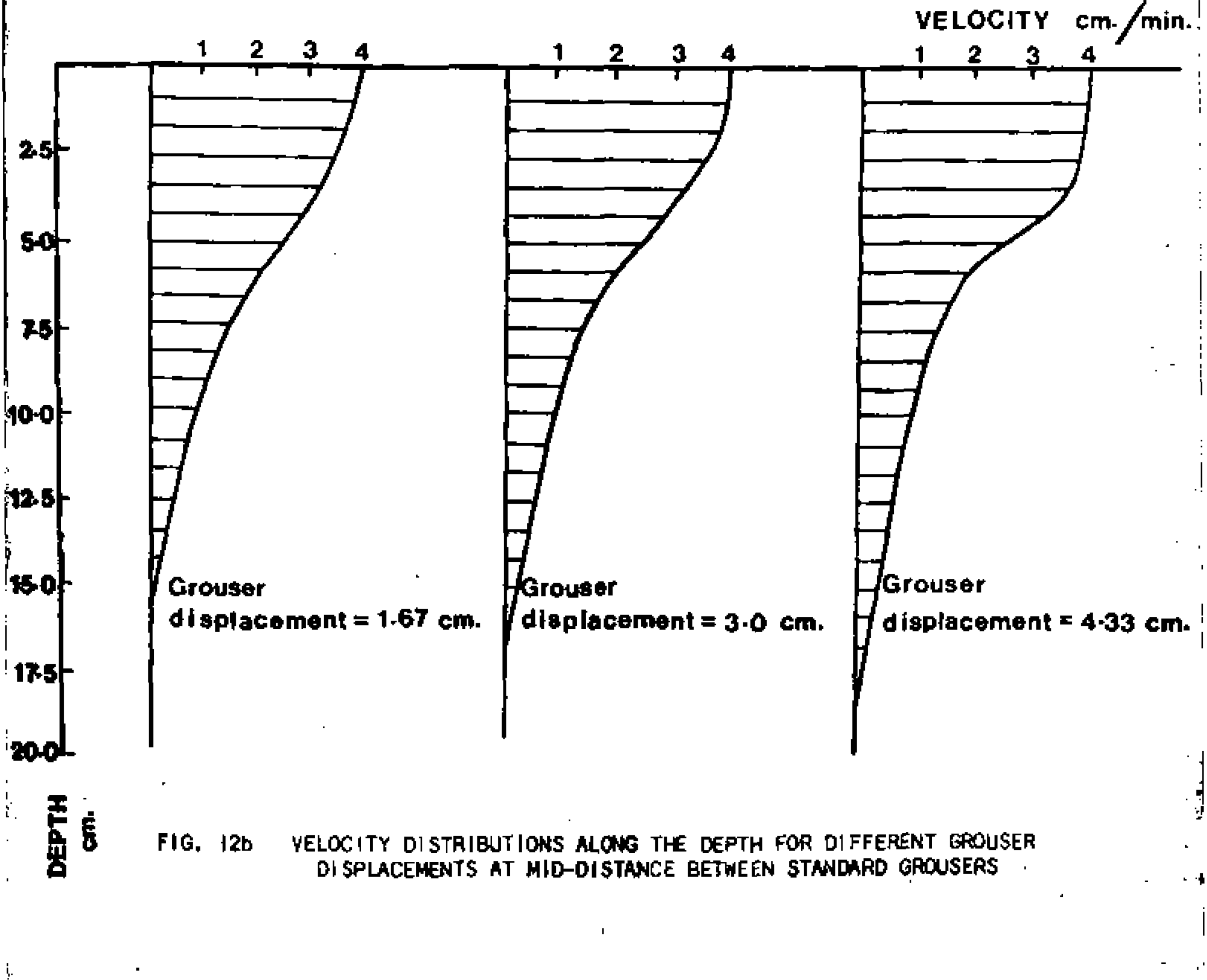


FIG. 12b VELOCITY DISTRIBUTIONS ALONG THE DEPTH FOR DIFFERENT GROUSER DISPLACEMENTS AT MID-DISTANCE BETWEEN STANDARD GROUSERS

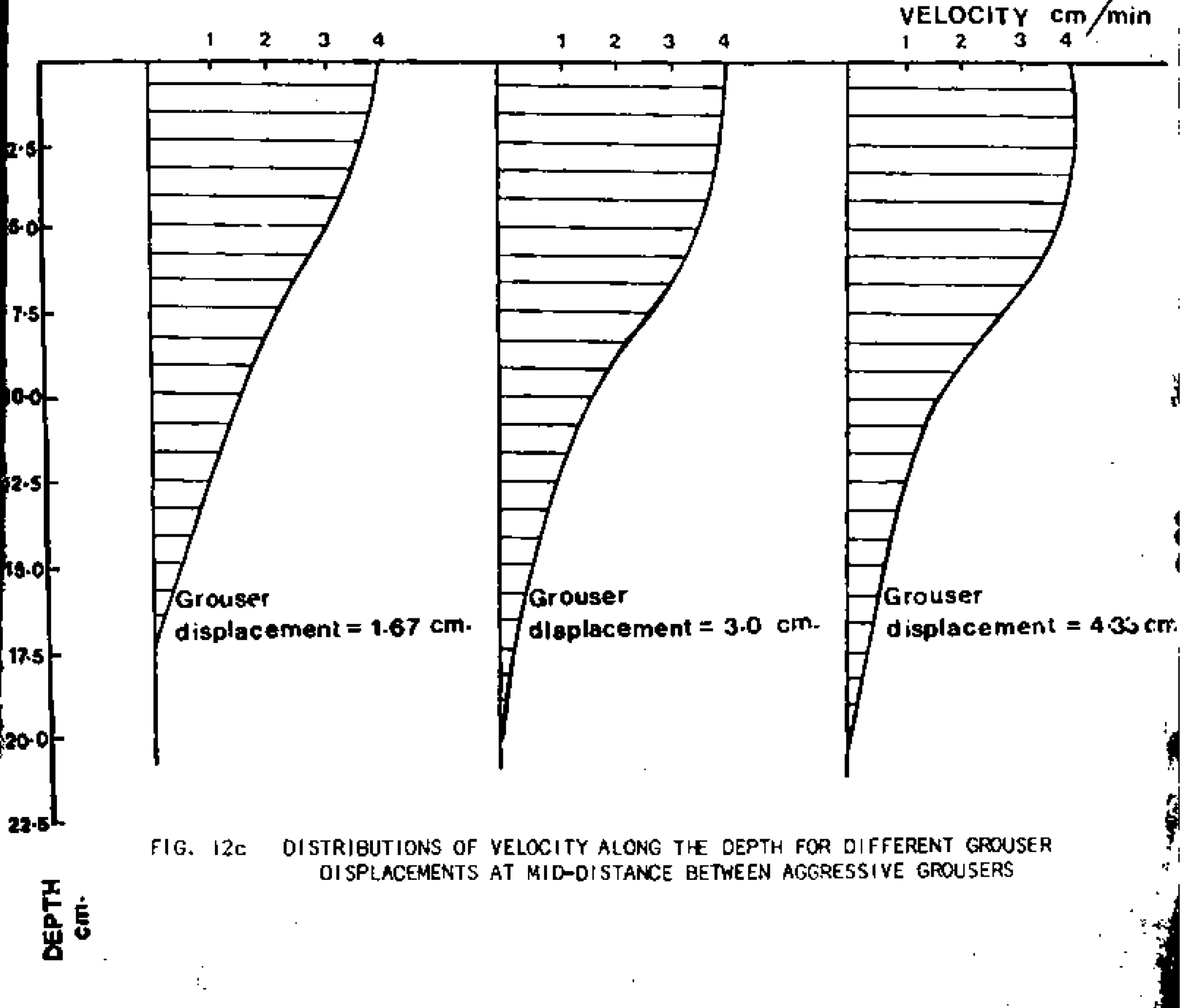
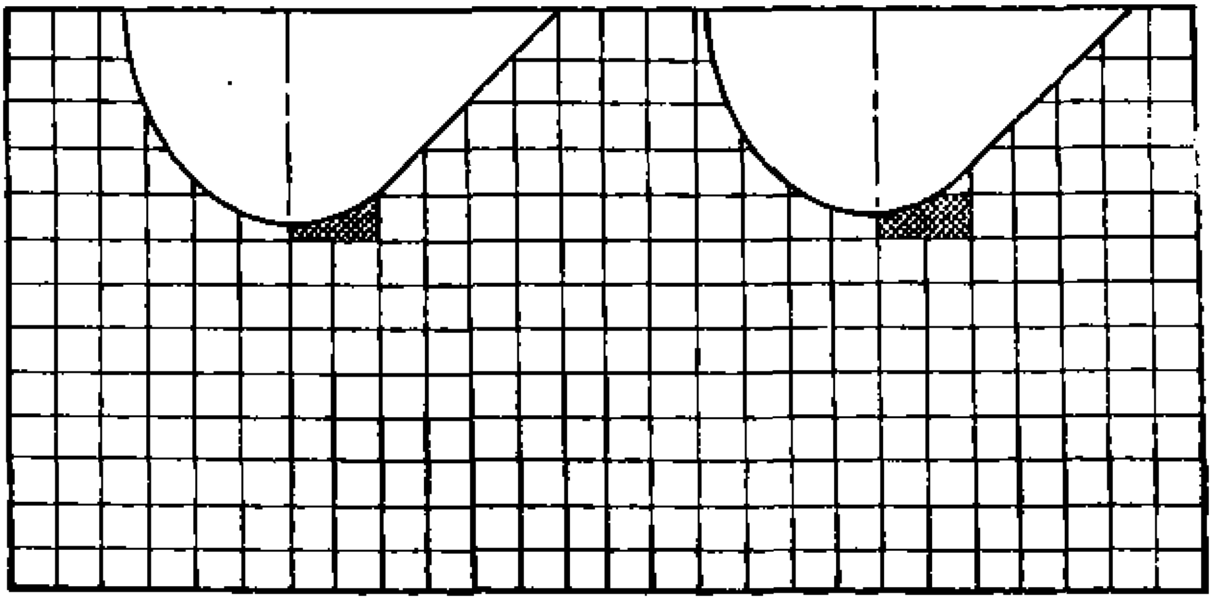
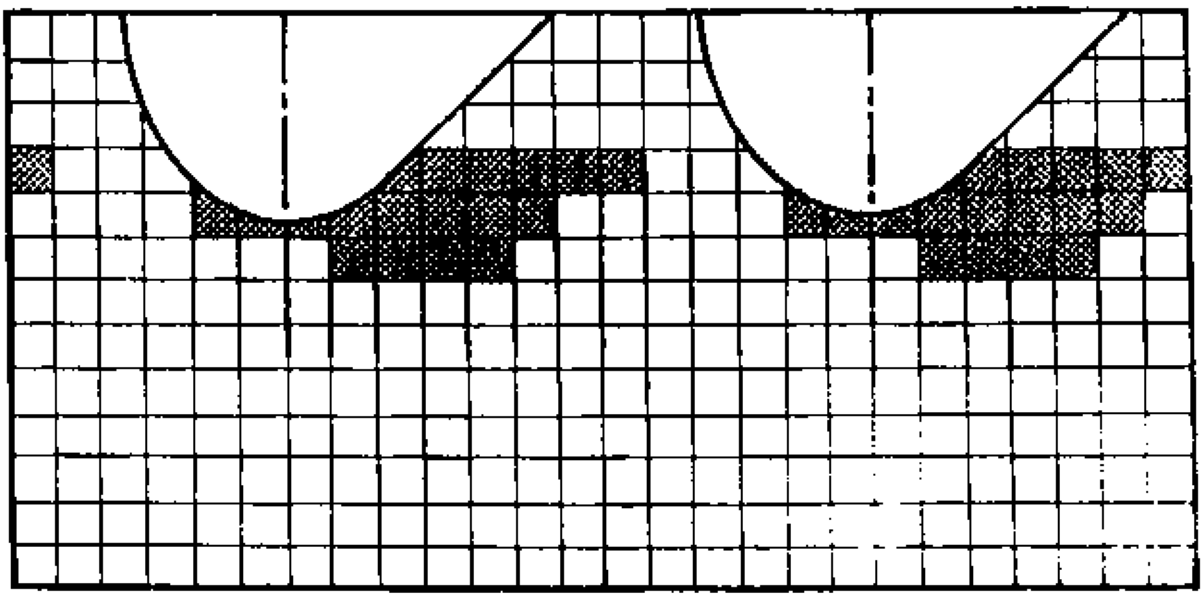


FIG. 12c DISTRIBUTIONS OF VELOCITY ALONG THE DEPTH FOR DIFFERENT GROUSER DISPLACEMENTS AT MID-DISTANCE BETWEEN AGGRESSIVE GROUSERS



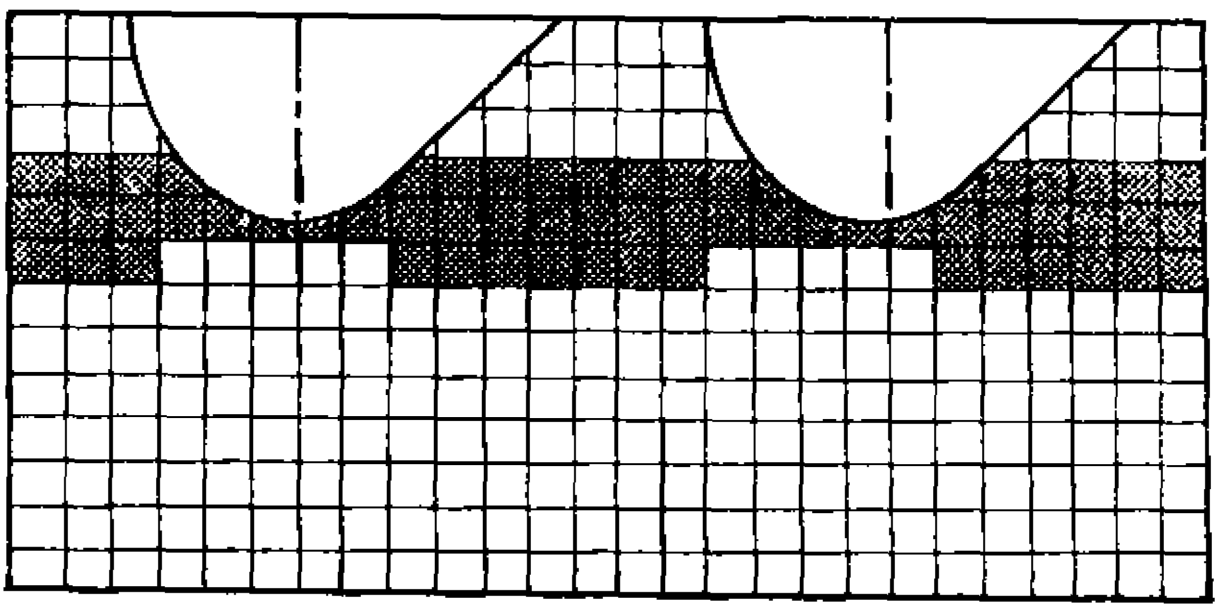
a) GROUSER DISPLACEMENT = 2.67 cm.

FIG. 13 DEVELOPMENT OF FAILURE ZONE FOR PASSIVE GROUSER-CLAY SYSTEM



b) **GROUSER DISPLACEMENT = 4·0 cm.**

FIG. 13 DEVELOPMENT OF FAILURE ZONE FOR PASSIVE GROUSER-CLAY SYSTEM



c) GROUSER DISPLACEMENT = 4.67 cm.

FIG. 13 DEVELOPMENT OF FAILURE ZONE FOR PASSIVE GROUSER-CLAY SYSTEM

It is this strain criterion which dictates when failure occurs in the soil mass. Using this strain criterion, interpretation of the soil displacement data (with time) under grouser thrust showed that failure in the soil started at the region adjacent to the curved toe front of the passive grouser, and propagated both horizontally and vertically as grouser displacement increased. At higher grouser displacements (4.67 cm), the failure zone was found to cover the whole zone in front of the grouser toe and to occupy the entire distance between the grouser tips. It is noted that the failure zones were located only at or near the grouser tip levels and that no failure occurred near the soil surface. This supports the contention that the upper plate which simulates a rigid track, forces the soil below it to move horizontally as a dead zone with minimal distortion inside the region between the grousers. In effect, this provides for augmentation of grouser thrust, i.e. the soil assists the grouser in development of greater thrust through an increase in the effective size of the grouser. This can be visualized if one considers the "dead" zone of the soil between grousers as an integral part of the grouser system. It is possible to have an extension of the track system further into the ground. Note however that when the track becomes less rigid the distortion in the region between the grousers becomes larger. This will reduce thrust enhancement for the same grouser spacing.

Slip Surfaces

To study the spacing effect on the deformation behaviour of the soil beneath a grouser, the grid line deformations were observed at different time intervals for different spacings between grousers. These observations allowed one to locate the position of the slip surfaces as given in Figure 14 for the case of the multiple passive grouser system. Similar diagrams can be obtained for the other grousers and for other spacings, as for example in Figure 15 - for the case of the multiple aggressive grouser system. In Figures 14 and 15 the slip lines for three different spacings are drawn at different time intervals corresponding to successive advances of the grouser elements through the soil. It is observed that the shape and direction of the slip surfaces advance depending on the spacing available between the two successive grousers. For the case of minimum spacing as shown in Figures 14a and 15a, the first slip is somewhat horizontal with a slight inclination indicating that at small spacings, little shear distortion occurs in the soil region between grousers. As the spacing increases, the first slip takes more of an upward curvature and some shear or distortion of soil occurs through the zone above the grouser tips. This curvature is seen to decrease after a certain limit spacing because of the previously mentioned restriction imposed by the upper connecting plate.

The slip zone, defined as the zone bounding the successive slip lines due to the grouser advance through soil, is shown on the same figure. This zone is very limited in the vertical direction for the case of very small spacing, which again indicates that the shear distortion of the soil mass between grousers is small. For a large spacing between grousers, it is noted that the slip zone occupies a considerable part of the region between grousers and its width is enlarged, indicating that the shear distortion occurring in the failed soil mass (with the increase of input energy) is dissipated in that region.

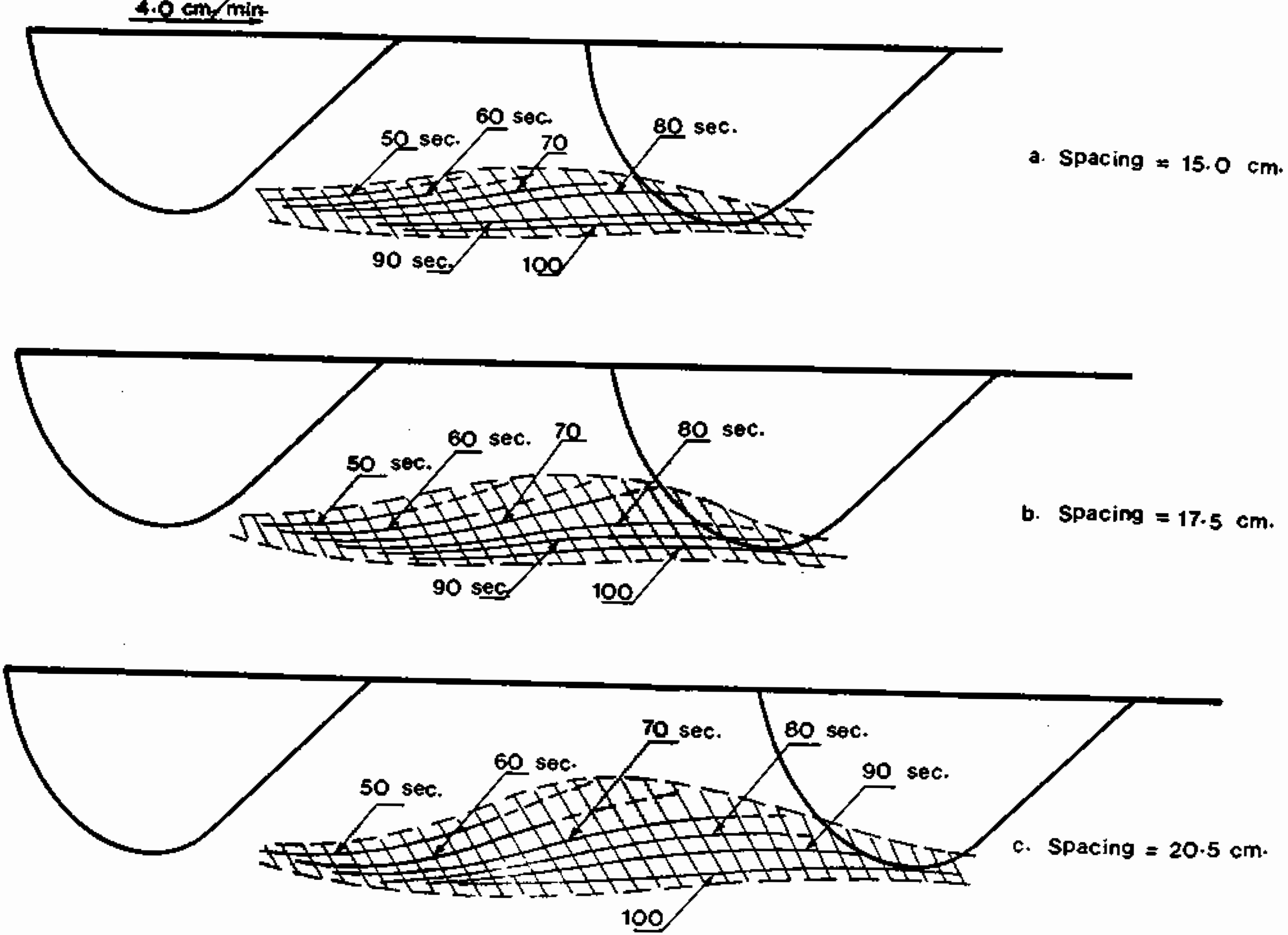


FIG. 14 SLIP LINES AT DIFFERENT TIME INTERVALS FOR 3 DIFFERENT SPACINGS OF PASSIVE GROUSER

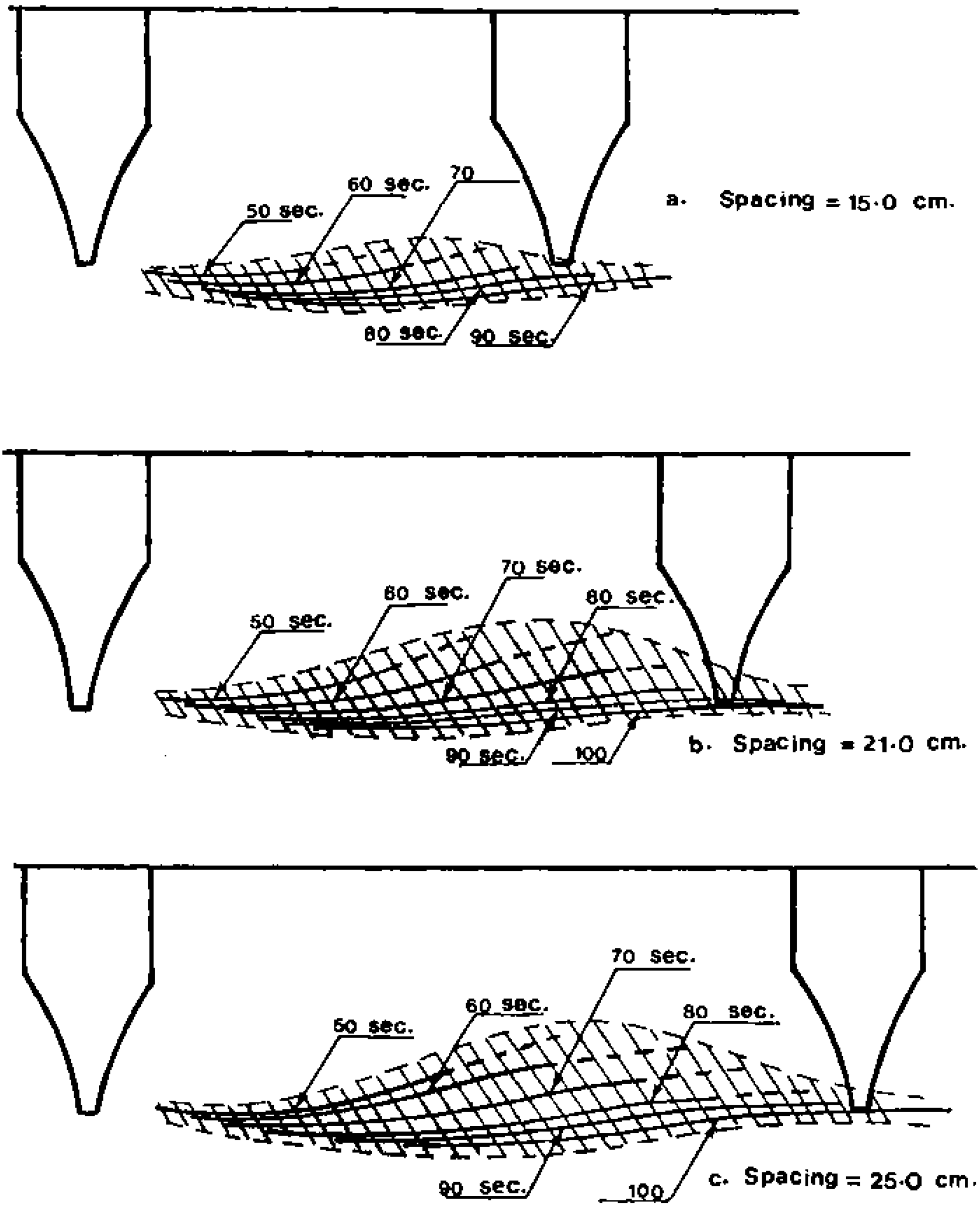


FIG. 15 SLIP LINES AT DIFFERENT TIME INTERVALS FOR 3 DIFFERENT SPACINGS OF AGGRESSIVE GROUSER

SUMMARY AND CONCLUSIONS

Since the presentation of the spaced link track concept by Bekker (1960) (Figure 16) where grouser spacings were dictated by the development of the Rankine Passive Zone in the face of the moving grouser, little has been done to provide actual detailed information on soil performance and behaviour in the face of moving grousers of various shapes and spacings. The theories that emanate from the development of passive shear zones in soils are similar to those that dictate optimum performance in view of maximum pressure developed because of the passive laterial pressures, and are consistent with limit equilibrium principles. However, in grouser-track considerations, the results of this present study indicate that the situation can be more complex. This is undoubtedly due to the upper constraint provided by the degree of rigidity or flexibility of the track, as demonstrated by the rigid plate (which simulates a rigid track) in the multiple grouser tests. The greater the flexibility of the mounting plate, the less is the development of the rigid zones as shown in the previous results. Such is the situation which occurs in more flexible tracks - as demonstrated in the companion study on track section (Yong, El-Mamlouk and Youssef, 1977).

The maximum thrust developed in the multiple grouser systems, as shown by the test results, occurs in situations where the grouser spacings are far in excess of the requirements imposed by the development of passive zones in the soil. In part, whilst this might be attributed directly to the rigid top constraint provided by the plate, it is reasoned that the combined soil-grouser motion producing the augmented grouser-action contributes to enhancement of track performance. However, there are other considerations which enter into the picture at this time, such as shape of the grouser and its aspect ratio. It is noted that whilst the soil performance in the face of the loading grouser can be approximated in terms of limit equilibrium behaviour such as that analyzed by Yong and Sylvestre-Williams (1969), the soil contained between the grousers does not obey limit equilibrium performance.

Whilst the results indicate that maximum drawbar pull for a rigid track can be obtained through a large spacing of the grousers, this will not be consistent with ride comfort since large spacings provide for irregularity in continuous ground contact. This produces, in effect, a bumpy ride in the track vehicle. The considerations that must be evaluated relate to (a) track rigidity, (b) grouser shape and size, and (c) spacing of the grousers in view of (a) and (b). The inter-relationships between all three are indeed obvious and complex - as indicated by the performance of the soil in the face of the leading grouser and also of the soil contained between the grousers. The rate of increase of thrust for the multiple grouser system in view of variation in grouser spacing is seen to be a useful indicator of track efficiency.

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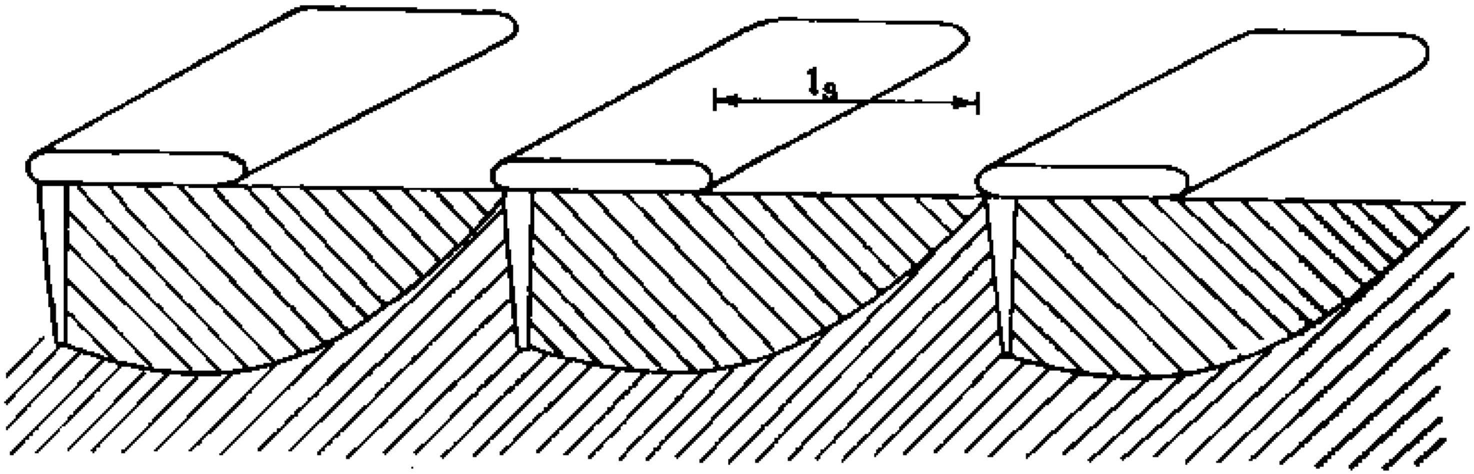

FIG. 16 DEEP FAILURE UNDER SPACED TRACK (After Bekker, 1960)

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