Suggested Short Title

SIMILITUDE STUDIES OF POTATO

HARVESTER DIGGER

SIMILITUDE STUDIES OF POTATO HARVESTER DIGGER

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

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September 1971

ABSTRACT

The principles of dimensional analysis and similitude have been employed to study the process of digging root crops out of the ground. The digger blade selected for this study is currently being used successfully for harvesting potatoes in New Brunswick. The purpose of the study was to discern some of the problems involved in harvesting root crops.

A soil bin and its related equipment were built to carry out two and three dimensional studies. The relation of soil forces acting on the digger at different approach angles in sand and clay loam was investigated. Crop parameters such as the effect of density and shape were evaluated. The effects of velocity, volume of soil upheaval and potato elevation in relation to digger travel were appraised.

The results of the investigation have consolidated some previous findings such as the increase in tool approach angle causes increase in draft. A concise significant concept regarding the presence and importance of a harvest delineation plane has been discussed. A few diffuse areas for future research have been suggested.

ACKNOWLEDGMENTS

It is a pleasure for the author to express his deepest gratitude to Professor R. S. Broughton (former Chairman, Agricultural Engineering Department), in appreciation of his continual encouragement and inestimable inspiration throughout the course of his studies.

The author is deeply indebted to Dr. R.M. Halyk (Agricultural Engineering), for the suggestions, constructive criticisms, and for extra effort and time liberally given in supervising this undertaking.

Grateful appreciations are given to Messrs. J. Ogilvie (Chairman, Agricultural Engineering) and E. Norris (Agricultural Engineering) for their suggestions.

The assistance of Dr. B.P. Warkentin (Soil Science) was essential to the progress of this investigation. Special thanks are humbly recorded.

Unbounded and sincere thanks are due to Mr. S.S. Kim (Agricultural Engineering Ph.D. student) whose research interest invigorated this study. Working together the test facilities were designed and built.

Thanks are extended to Messrs. J. Webb, J. Beasley (Machine Shop), R. Nattress, R. Cassidy (Instrument Dept.), C. Lovegrove (Photography) and R. Alward (Brace Research Institute) for their valuable suggestions and assistance, and to R. Lake (Food Science).

Thanks are also extended to Mrs. O. Goldstein who was responsible for the drawings, and Mrs. M. Harvey who so ably typed the manuscript.

Last, but not least, the author would like to record particular thanks to the Canadian International Development Agency for their financial support and the Government of Trinidad and Tobago for study leave. Without their support, this undertaking would not have been possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

LIST OF SYMBOLS

a	distance from blade bevelled tip to the point the resultant force acts (Figure 20)
ac	acre
b	perpendicular distance from R to c on the digger (Figure 20)
c	centre of the digger cross-section
cm.	centimeter
D	draft
F	force
ft.	feet
g	acceleration of gravity
h	height of digger (Figure 20)
K	distance travelled by the blade
Kg	kilogram
L	characteristic length
l	length of tool
m	model
mm.	millimeter
n	distance moved by the potato or the buried object
P	resistance to penetration
p	prototype
R	resultant force
r	moment arm from centre of tool to transducer axis

r.p.m. revolutions per minute

S.G. specific gravity

T time

u volume of soil mold

V velocity

W weight

W_1 weight of container plus moist soil

W_2 weight of container plus oven-dried soil

W_c weight of container

w_a water content in percent

w width of tool

z depth of operation

Greek Symbols

π Buckingham Pi term

θ digger approach angle

β angle which R forms with the tool surface

ρ dry bulk density or bulk volume weight

n_λ scale factor

% percent

$^\circ$ degrees

I. INTRODUCTION

A. Importance of the Study

Tropical countries, and the West Indies is no exception, are very dependent on root crops as a source of starchy food; the sweet potato*, yam and cassava are the most significant, but many other root crops are of minor importance. The Irish potato is the major root crop grown for human consumption in the temperate regions, but it is also grown in some tropical regions where favourable conditions exist, usually at higher altitudes such as the central uplands of Jamaica.

Root crops, although forming a major part of the West Indian diet have characteristically been produced by peasants on small holdings (1). The dominance of peasant production with tools such as the fork, hoe and cutlass means that a large input of labour is required and this places early limits on the size of the farm that can be cultivated. In 1961 (47), farms under five acres in Jamaica produced 9,019 crop acres of sweet potato; farms between five acres and twenty-five acres in size produced 7,595 crop acres, whilst all farms over twenty-five acres produced only 1,071 crop acres. This

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* Appendix A.

is still the general trend with all other root crops in most islands; that is, the production is on small farms with large inputs of family labour. It has been estimated (1) that two to eight times more man hours are required for hand harvesting of root crops than for all other growing operations. Masefield (1963) reports that thirty-four percent of the crop production work is spent in harvesting. Yields also tend to be low. Yam yields vary from five to ten tons per acre and sweet potato, one to 6 tons/ac. In field experiments, 20 tons/ac and 13 tons/ac respectfully have been recorded (18).

Traditionally, West Indian agriculture has emphasized the production of export or cash crops and a five percent annual increase of sugar cane and cocoa production is hardly surprising. At the same time, the importation of food has increased at a rate of about eight percent per annum over the last ten years. There is evidence that the root crops have suffered a decline in production in many islands. For example, between 1942 and 1958, the per capita intake of roots, tubers and other starchy foods declined by 48 percent (47). In Trinidad, per capita consumption of yams, sweet potatoes, eddoes and tannias, has shown a marked downward trend from 1954 to 1963.

Population is increasing faster than food production; industrialization is very limited as the natural resources are scarce; capital and resources to pay for imported goods are also very limited; and, at the same time, foreign aid and recurrent grants are steadily decreasing. It is obvious, therefore, that food and vegetable production must be increased as a possible solution to these problems.

Labour demands associated with root crop harvesting must be resolved in order for root crops to become a reliable, cheap source of food supply. Spectacular reductions in labour requirements can be achieved by mechanization, and this also permits timeliness of operations. Small acreages do not encourage large foreign manufacturers to develop expensive harvesting equipment, and the number of machines needed is too small for mass production. Almost all the machinery used in the West Indies tends to be confined to sugar-cane and rice crops and these machines were built for temperate conditions. The machines meet soils which are harder, wetter and stickier than in temperate countries and soil resistances during ploughing of up to thirty pounds per square inch have been recorded (1).

Past attempts (4, 21) at mechanization of root crop harvest have been on a "trial and error" basis with some degree of success. Campbell (4) designed a reasonably successful share (Figure 15) for lifting sweet potatoes and aiding in yam harvesting. A sweet potato harvester developed for use in the United States on loose soils has been tested at the University of the West Indies (12). Many difficulties were encountered. There were heavy vine and soil build ups resulting in blockage at the digger level. The machine could not operate under heavy soil conditions; manoeuverability was insufficient and the turning radius too great for small fields.

Adaptations too, are at least a trial and error process which may prove to be expensive; also, power requirements may not be compatible with available sources. To increase total agricultural productivity, even in areas where rural underemployment is serious, selective mechanization of small holdings with simple power equipment is urgently needed. Techno-economic factors which prevail should not deter some degree of mechanization.

The situation in agriculturally developed countries, although not bad, has much room for improvement. In the U.S.A. potato harvesting equipment has continued to be refined and improved (5), however, not nearly enough attention has been devoted to the serious problem of damage occurring to the potato as a direct result of the harvest operation. Lilley and Smith's analysis (1969), of the operations of the conventional two row potato harvesters, shows approximately 50 percent of the crop to be damaged, and as a direct result 10 percent of the crop completely lost after storage. Kittridge (1969) reported 15 percent of the potato crop was damaged during harvesting so it did not meet U.S. No. 1 grade. O'Brien and Scheuerman (1968) investigated the mechanical harvesting and handling of sweet potatoes in California, using a modified trailed potato digger. Although detachment of the potatoes from its root and vine system needed urgent attention and tuber damage was considerable, the report is encouraging and suggests research oriented towards "Complete economical mechanization of the sweet potato". Zahara and Scheuerman (1969) found harvesting sweet potatoes with a simple combined digger-conveyor reduced labour requirements by 38 percent.

Potato production studies in New Brunswick (41) show substantial crop losses; 36.7 percent of the crop fell below Canada No.1 grade, and 50 percent of Canada No.1 grade tubers had some type of mechanical injury. Total field loss during harvesting was 2.4 percent. There is, therefore, urgent need to study more fully the harvest operations of root crops, not only to solve West Indian needs but also for more economical production through less damage for Canadian needs.

Contemporary mechanical harvesting of root crops consists primarily of cutting the soil together with the roots in a specialized manner, then effectively separating the product from the soil (15). It is a highly specialized tillage action and tools may be designed to permit cutting and lifting of the soil in a specified manner and also for the controlled application of force to the soil.

The prime performance characteristic is the percentage of the crop harvested without damage, but draft measurement is also necessary since usually a large amount of energy is required to move the tool through the soil. The most widely used method of energy transfer to the soil is to pull the tool through it. Reasonably fast and efficient machines have evolved to harvest Solanum tuberosum by this method. Satisfactory results have been obtained with trailed lifting shares which possess a certain degree of tuber gathering ability and can therefore tolerate a small amount of misalignment for sugar-beets, carrots and onions. Much however, is left to be desired in the development of harvesters for tropical root crops.

To develop suitable tools for harvesting root crops, basic knowledge of their morphology, physiology, cultivation and root distribution is essential, along with a thorough understanding of the mechanics of the tools and soil. This would allow control and prediction of the effects of harvesting through tool design and movement.

Most of the technological advances have evolved through trial and error methods in the field over a period of years. However, two other possible approaches would appear to be suitable., first, a theoretical analysis; and second, dimensional analysis and similitude. The situation suggests to the author that the latter approach can lead to a clearer understanding of the physical aspects of root crop harvesting in order to achieve effective mechanization. The objectives of this study have been formulated to achieve such an understanding of the problem.

B. Objectives of the Study

This study was undertaken to pursue the following objectives:

1. To study the soil parameters or characteristics which are pertinent to harvesting root crops.

2. To study the potato parameters that are important in harvesting and to trace the actual path of movement of potatoes as they are harvested.

3. To study draft and power requirements for harvester blades or diggers.

4. To investigate the effects of blade angle in the horizontal plane and the velocity of operation.

5. To make force predictions from the model to the prototype tools required for harvesting deep root crops.

C. Scope of the Study

The dimensional analysis and similitude approach was chosen for a number of reasons. The large number of unpredictable variables and the limited information available about those pertinent variables do not facilitate the formation of mathematical equations. The similitude approach was more convenient, effective and much cheaper than field tests.

The investigation included the design models of one successfully operating harvester digger to evaluate from analytical, visible and photographic data the five points listed above. Little success has been reported in the literature concerning soil strength investigations. Soil parameters evaluated in this study were bulk volume weight, resistance to penetration of a standard cone penetrometer and moisture content.

Use has been made of newly developed techniques as far as possible with necessary adaptations. Preliminary studies were carried out in a small glass sided box to determine which parameters are important in root crop harvesting.

II. LITERATURE REVIEW

Classical soil mechanics, developed within civil engineering, is the basis for soil-implement mechanics. The classical work of Coloumb (51), Rankine (51), Ohde (19) and others are well documented. Their theories considered mainly the static loading of soils. These theories have now been applied to the dynamic action of soils in studies on shearing and cutting actions. The first practical application was in the field of tillage, cultivation and earth-moving equipment around 1925 (8, 39).

Soehne (1956) was the first to use model ploughs in a soil bin to simulate the manner in which a plough share cuts through and breaks up soils. A complete theoretical analysis was reported.

Bockhop (1957) used the principles of similitude and analyzed a tillage-soil system, and finally made force predictions on prototype tools from the models. From then on, several specially equipped laboratories (8, 13), with indoor soil bins, were constructed and the principles of similitude were used for the purpose of making force and other predictions of the prototype from model studies (See references 6, 9, 22, 25, 27, 40, 50). Primarily, draft and its dependent functions were studied. Major difficulties were encountered in the following areas:

1) determining pertinent soil parameters and their measurements;

2) scaling of soil and tool parameters;

3) making measurements of soil forces on tools.

These are considered separately below:

1) Pertinent Soil Parameters and their Measurements.

Soil physical condition is described by many parameters such as strength in shear, friction and cohesion. Freitag et al (13) prepared a list of all soil parameters used to date in studies dealing with mechanical actions in soils. Definition of soil parameters that are meaningful and pertinent to harvesting requires that the exact role the soil plays in harvesting be well understood.

Prochazka (1964) found that the force required to extract sugar-beets from clay was greater than that for sand. Also, the extraction of the product was easier in wet soils than in hard dry soils. Wang (1966),working with a clay loam soil, found that all the energy versus moisture content curves had minimum values when the moisture content was close to 17 percent. The energy required was for deformation only. This suggests that 17 percent moisture content might be optimum for tillage operations.

Highly compacted soils as measured by bulk density required greater energy for rupture and cutting than loose low density soils (15, 30). Compacted sandy soils did not require as great a force to enable tool movement as did clay soils with equal moisture content. Clark and Liljedahl (7) indicated that generally soil density and thus also the degree of compaction changes with depth.

Many investigations (2, 27, 38) indicate soil adhesion to be small and thus it can be neglected. Cohesion can be used to reflect soil strength; however, resistance to cone penetration is a better indicator,according to Freitag (1967). The cone penetrometer was shown to provide a good estimate of the mechanical strength of soils in farm and military vehicle mobility and also in the cutting of soil (13, 14, 20, 57). The cone penetrometer is especially desirable since it is sensitive, simple to construct and operate, and versatile, as it can be used in the field as well as in the laboratory. The cone penetrometer permits a measure of soil consistency with depth (13), and allows comparison of one bin preparation with another.

The literature review then has indicated that soil type, bulk density, moisture content and resistance to penetration are important factors to consider in the present study.

2) Scaling Factors

Some workers (27, 40, 36) developed distorted model theory in their effort to scale soil and tool parameters, but the accuracy of the predictions from the model to prototype tools were not adequately consistent (9, 40, 27, 36). Others (16, 42, 22) prepared and used artificial soils, but in the design of practical machines this does not seem to be the proper approach.

Distortion effects (40) can be accounted for empirically by observing the trend of results obtained with models of a broad range of sizes working in the same soil under similar conditions. This method requires a great number of tests at low velocities to minimize time effects. Schafer (1968) however, did not indicate what velocities were sufficiently low. Many experimenters (31, 45, 49) have conclusively shown that increasing velocity increases draft. Since draft is of greatest practical significance in power cost, and because the trend in harvesting machinery is towards bigger, more powerful and speedier units, velocity was considered as an important variable.

Since it was impossible to scale the independent variables characterizing the physical properties of soils to suit both the model and the prototype separately, the same soil has often been used in both cases (45, 53). The preparation of the soil ensured that both prototype and the model operated in soils of similar physical properties. Compensated models, which are specially distorted models designed in such a manner that the soil scale effects are cancelled, have therefore been used.

3) Measurement of Tool Stresses

Clyde (1937) was probably the first to measure the pulling forces acting on tillage tools using hydraulic transducers. However, it was not until Cook (1951) developed the strain gauge ring type transducer that measurements of tool stresses became easier and more accurate. A complete description of the construction and analysis of the extended ring transducer was carried out by Siemens (1963). Generally, satisfactory performance of this system of tool stress measurement has been reported (15, 44).

A. Draft and Power Requirements of Tillage Tools

Draft of tillage tools is affected by a number of factors such as cutting depth, tool approach angle, width and friction, manner of tool movement, soil deformation and velocity, but the exact nature of the relationships have not been established.

The general trends of observations (45, 13, 30, 27, 44, 21, 15, 43) indicate that the critical angle for minimum draft on an inclined tool lies somewhere between 40 and 45 degrees to the horizontal. Draft appears to be insensitive to change in approach angle up to 45 degrees but increases rapidly thereafter.

Zelenin (15) developed mathematically the relation of draft and depth. He noted a parabolic relationship by the formula

$$P = Kh^n$$

where P = cutting force (draft) of a horizontal blade

K = coefficient of soil resistance

h = depth of operation

n = coefficient

He found that the value for n was approximately 1.35 based on a wide range of soil and moisture conditions. A series of experiments at the National Tillage Machinery Laboratory in Auburn, Alabama, found this exponent to vary with depth and soil type (38).

A number of tests have been conducted to relate tool orientation and draft force. Gill (1967) summarized the work done by numerous scientists who used different types of tillage or soil cutting tools and related draft requirements to velocity, tool depth to width ratio and angle of approach.

Generally, draft force increased with velocity and depth to width ratio. Draft was shown to be influenced to a greater extent by the lift angle than by the side angle. Parochazka (34) undertook investigations into the force and power relationships of fixed shares and lifting wheels of sugar beets under field conditions. He found the forces on lifting tools in work are of different origin and nature, mainly due to soil reaction acting continuously, and also to the reaction of the beet roots as they are being lifted.

Burkhardt et al (1970) have shown that an uprooting force of 2 to 4 pounds is required to detach roots of mature sweet potatoes from actively growing roots. No references could be found showing the relationships between uprooting forces and draft forces.

B. Force Relations Between Model and Prototype Tools

Many studies have been made with models in an effort to predict the performance and requirements of prototype tools. Bockhop (1957) used model concave discs to predict the draft of the prototype. Prediction error, however, was large in that it varied from 28 to 64 percent.

McLeod (1959) carried out distorted model studies on similar concave discs. His conclusion was that the distorted model system predicted the magnitude of soil force components on a concave disc with reasonable accuracy and reliability.

Osman (1964),using models of simple soil cutting blades in different soil types conducted tests at different angles of operation. He produced curves which enabled the ready calculation of cutting forces for a wide range of soils. These computed results were found to provide practical information concerning the design of prototype cutting blades. Reaves (1966), using model triangle chisels, reported that in general, model prediction of draft for the prototype was satisfactory for two soil types.

Schafer et al (40) found that the technique of distorted model theory can be used to accurately predict draft of bulldozer blades. They did not, however, state the degree of accuracy that could be obtained.

It appears that model studies with soil tools have been reasonably successful in predicting the force requirements of prototypes. The validity of model analysis depends on how closely the model operating environment simulates the prototype environment, and on the accuracy of the measuring and recording devices used.

C. Movement of the Harvested Product

Prapuolenis (1949) described techniques to evaluate the position and distribution of potatoes in the soil. This knowledge is essential to the design of diggers. Park (1949) designed a middle-buster type digger with special attachments to bring sweet potatoes to the top of the soil. West (1958) described many types of shares or diggers used in the United States and United Kingdom.

He advised that one had to determine the type most suitable and use that one. This advice implies trial and error which can be expensive. The rotating square section rod developed by the United States Department of Agriculture was considered as an improvement over the blade type share. However, this rod tends to bend in heavy soils. Discs with open grid-like centres have been tried but the cost of these is high (55).

Each type of digger design will affect the movement of the potato in a definite manner. The literature survey did not reveal any serious studies where the primary intentions were to determine the movement of the product. Parochazka made some assessment of root crop motion primarily to reduce damage and to achieve partial cleaning. Martini (15) studied the movement of soil caused by plows operating at variable speeds. He found the movement of soils differed considerably due to the influence of gravity and the direction of the forces applied by the plow.

Crowther and Gilfillan (1959) found that the general behaviour of potatoes and soil agreed with that to be expected from basic fluid flow considerations.

Most of the present research work in potato harvesting is concerned with the separating of stones and clods or the cleaning of the product. Sides (1967) prepared a progress report on this aspect of harvesting. Thus there is,apparently, little design information available for root crop diggers and no attempt appears to have been made to evaluate their action by similitude techniques.

III. DESIGN AND PROCEDURE

This study was undertaken to acquire basic information on the draft and resultant force acting on a potato digger due to tool geometry, soil parameters and other variables. Potato and soil movement were studied; relationships were evaluated and combined with model theory to predict prototype performance. A particular digger was selected primarily because of its reputed success in New Brunswick, and also because of its simplicity in construction and operation.

Some preliminary tests were conducted with model diggers in two soil types to ascertain what angles permit proper lift of potatoes from the soil. The pattern of soil fracture and volume of upheaval were also studied.

A. Design of the Experiment

The list of variables shown in Table 1 was considered pertinent in determining the forces acting on diggers. Dimensional analysis was carried out; model design conditions were determined; models were accordingly designed; instrumentation was selected and the experiment was conducted.

1. Dimensional Analysis and Similitude

Dimensional analysis makes possible the theory of models whereby scale test models can be used in experiments to predict the performance and to improve the design of large expensive equipment. The principle of similitude is applied to experiments with scale models. Langhaar (1965), Murphy (1950) and others have established procedures for similitude and dimensional analysis.

Table 1. Pertinent Variables for a Potato Harvester System.

Quantity	Symbol	Dimensions*
Digger		
Unspecified Length Characteristic height (w) length (l)	L	L
Approach Angle	θ	
Soil		
Bulk Volume Weight	ρ	FL^{-3}
Resistance to Penetration	P	FL^{-2}
Moisture Content	W_a	——
Other Variables		
Draft (horizontal component of pull)	D	F
Operational Depth of Digger	z	L
Acceleration of Gravity	g	LT^{-2}
Velocity	V	LT^{-1}

* Fundamental dimensions selected for this investigation were force (F), length (L), and time (T).

Since draft was the dependent variable, the general system relationship can be expressed as

$$D = f(V, g, z, \rho, P, l, w, \theta, W_a) \quad (1)$$

According to the principles of dimensional analysis, only a single one dimensional value from the above set can be considered because this describes the remaining variables. There are therefore eight variables with three basic dimensions. Five independent terms were formed by inspection after a study of the pertinent literature, and are as follows:

$$\pi_1 = \frac{D}{\rho z^3} \qquad \pi_2 = \frac{v^2}{gl}$$

$$\pi_3 = \frac{w}{l} \qquad \pi_4 = \frac{P}{\rho l}$$

$$\pi_5 = \theta$$

Independence is noted as only one variable is unique in each term, e.g. Draft appeared in only one term. The relationship can now be expressed as follows:

$$\frac{D}{\rho z^3} = f\left(\frac{v^2}{gl}, \frac{w}{l}, \frac{P}{\rho l}, \theta\right) \quad (2)$$

Identifying the π terms,

$\pi_1 = \frac{D}{\rho z^3}$ the draft term (Bockhop, McLeod)

$\pi_2 = \frac{v^2}{gl}$ the speed term (Froude's number)

$\pi_3 = \frac{w}{l}$ the height to length ratio term

$\pi_4 = \frac{P}{\rho l}$ the resistance to penetration term

$\pi_5 = \theta$ the angle of approach term

The model must have a quantitative value for each dependent π term numerically equal to the corresponding term in the prototype relationship. By equating π terms then, the design conditions of the model were determined. Take, for example, π_2,

$$\frac{V_m^2}{g_m l_m} = \frac{V_p^2}{g_p l_p}$$

or

$$\frac{V_m^2}{V_p^2} = \frac{l_m}{l_p}$$

$$\frac{V_m}{V_p} = \left[\frac{l_m}{l_p}\right]^{1/2} \qquad (3)$$

$$V_m = V_p \left[\frac{l_m}{l_p}\right]^{1/2}$$

where the subscript m is used to indicate the model and p the prototype. Both model and prototype were operated in the same gravitational field and design conditions involving the π_2 term were easily satisfied by operating the digger at its specified velocity. V_p was known and $\frac{l_m}{l_p}$ satisfied by design conditions discussed on page 21 . Design conditions for π_3 were satisfied in the construction of the tool.

By operating the model and the prototype at the same angle in similar soil, design conditions for π_5 were met. Keeping the soil moisture content equal for both model and prototype, further satisfied all design conditions. Agricultural soils were used in a controlled environment laboratory.

It was difficult to satisfy π_4 without distortion since ρ and P must be scaled. π_4 is controlled by soil properties and a numerical value for the distortion factor n_λ cannot be arbitrarily selected (53, 58). π_2 and π_3 terms have been scaled such that their respective similarities are equal to the ratio of their characteristic lengths. To continue this process with π_4,

$$\frac{P_m}{P_p} \quad \frac{\rho_p}{\rho_m} \qquad \text{should also be equal to} \qquad \frac{l_m}{l_p}$$

If P were the same in the model and prototype then ρ for the model must be scaled as

$$\rho_m = n_\lambda \rho_p$$

It is difficult to control ρ (soil density) and therefore, quite intricate to achieve scaling in this manner.

When P and ρ are different in the model and prototype, scaling both to equal the length scale ratio can easily be achieved. It is easy to vary P and as a result there is a diminutive alteration in ρ.

$$\frac{P_m}{\rho_m l_m} = \frac{P_p}{\rho_p l_p}$$

$$\frac{l_m}{l_p} = \frac{P_m}{P_p} \frac{\rho_p}{\rho_m} \tag{4a}$$

Let $$\frac{l_m}{l_p} = n_\lambda$$

Then $$n_\lambda = \frac{P_m}{P_p} \frac{\rho_p}{\rho_m} \tag{4b}$$

π_4 can be satisfied if the correct value of the right hand side of equation (4b) can be found.

Note that now from equation (3) we get,

$$V_m = V_p \left[n_\lambda\right]^{\frac{1}{2}} \tag{5}$$

Actual field data were used for values of P_p and ρ_p. These soils were transported to and prepared in the laboratory, and again P_m and ρ_m were measured. These values were substituted in equation (4b) and an estimate of n_λ was obtained.

There was then complete similarity between model and prototype, since π_2, π_3, π_4 and π_5 terms were all satisfied. Analytically then, it was feasible to undertake similitude studies of a potato harvester digger.

2. Equipment

For the experimental investigation, a laboratory soil bin and associated equipment to test the tools were designed and constructed.

Design Conditions

After an exhaustive study of existing literature on soil bin construction, the following considerations motivated the design.

1) Versatility - The equipment would be used for study and research on tillage and harvesting tools and also on traction devices of agricultural vehicles, i.e. flexibility to accomodate many areas of study was important enough to justify a relatively high cost of construction.

2) The desire to observe visually and to take photographs of the actions at the tool/soil interface led to a stationary tool and movable bin with a glass side. This design facilitated easy installation of leads from the dynamometer.

3) A rigid and strong bin to allow proper mixing, rolling and compacting of soil, and its ability to allow proper soil parameter measurements was necessary.

4) Operational velocities of the bin when projected should be similar to what might be encountered in the prototype situation.

5) Space and cost requirements: the design needed maximum space and power when compared to other designs.

6) The bin profile should be large enough so that the failure plane (48, 51) will intersect the soil surfaces. Since there is hardly any information on size relationship between tillage tool or traction device size and the soil bin, Harrison's (1961) recommendation of a bin width-to-depth ratio if 3:1 was considered as a minimum.

Construction Details

Soil bin. A soil bin, 3.6 meters long, .9 meters wide and .45 meters deep was constructed with 11 gauge steel sheets, and frame of angle iron and steel bars. Eight 15 cm. diameter iron wheels with frames were put on and the whole apparatus set on rigidly fixed, level rails. Two sets of side bearing were used to prevent the bin derailing.

The bin was powered hydraulically with a five horse power electric motor and associated actuators and controls (Figure 21). A hydraulic motor, chain and sprocket drives provided the link between the bin and power source. The bin filled with soil had maximum speed attainment of three miles per hour in six feet of acceleration.

Tool carrier. A system of vertically movable arms, set on two stationary upright posts over the bin, carried the tool bars on which were suspended the dynamometer and tool carrier. This carriage could be manually shifted across the bars and, also, by means of a screw threaded bar, it allowed accurate adjustment of the tool in the vertical direction. Thus the tool could be operated at any depth and set anywhere across the bin. Counterweights were used to balance the tool arms and to ensure no load was exerted by the tool arm and carriage on the diggers. A system of pulleys and cables connected the arm to the counterweights.

Soil processing unit. The processing of soil in the bin was achieved with a hydraulically powered, 35.5 cm. diameter rototiller;

a set of rubber compaction wheels, of 35.5 cm. diameter and 2.54 cm. width; a water filled, 30 U.S. gallon capacity roller; a flat plate for levelling or scraping; and a fork. These five components, assembled as one unit could be operated singly or in set pairs, to a depth of 30 cm. in the bin. The unit was then mounted on vertically movable arms over the bin. A hydraulic cylinder provided the power for raising the arm, and the components to be used were manually rotated into working position.

A water barrel, calibrated in gallons was installed above the bin to facilitate easy addition of measured volumes of water by spraying when processing the soil.

Controls. Complete control of the bin and the associated equipment was maintained at the operator's console. The bin and soil conditioning equipment controls (manual and electric) were installed on a table with a pannel board (Figure 16). Microswitches appropriately placed at either end of the track automatically switched off the electric drive motor,thereby allowing braking of the bin. As a safety measure, a spring and shock absorber system was installed at either end of the tracks to stop the bin,should the microswitches fail to be energized.

Cone penetrometer. A cone penetrometer was mounted above the soil bin and could be easily moved across its frame thus facilitating penetration at any point in the soil.

3. Selection and Description of Soils

Two agricultural soils from Macdonald College Farm were selected to represent soil types suitable for root crop growing. Both types were passed through a 6.4 mm. sieve to remove rocks and other debris. Complete mixing was carried out to ensure homogeneity. This meant the soil in the test bin was uniform vertically and laterally. This situation is seldom encountered in the field where soil is usually layered. Therefore, the soils used can be considered as a simple homogeneous media.

Table 2a. Mechanical Analyses of Soils by the Hydrometer Method.

Soil Type	Coarse Sand %	Fine Sand %	Silt %	Clay %
	2.0 - .2 mm.	0.2 - .02 mm.	0.02 - .002 mm.	0.002
Sandy loam	74.0	16.6	7.6	1.0
Clay loam	61.8	3.2	26.1	8.0

Table 2b. Mechanical Analyses of Soils by the Sieving Method.

Particle Size	Sandy Loam		Clay Loam	
mm.	%	Cumulative %	%	Cumulative %
0.074	0.1	.1	12	12.00
0.074	7.6	7.7	14	26.00
0.149	62.7	70.4	22.5	48.5
0.297	27.3	97.7	23.4	71.9
0.595	2.2	99.9	28.0	99.9
2.380	0.1	100.0	0.1	100.0

4. Soil Measurements*

Resistance to Penetration

A standard cone penetrometer designed and constructed by Kim (1969) was used to measure soil resistance to penetration. The force required to push the cone at a speed of 18.3 meters per minute into the working depth of the soil was indicated in pounds on an X - Y recorder.

Bulk Density and Moisture Content Determinations*

A core sampler, 50.8 mm. in diameter and 14 mm. wide was used to take a known volume of soil for bulk density and moisture content determinations. Sampling varied from two centimeters below the surface to the working depth of the tool.

5. Soil Processing

Each soil type required specific preparation techniques. Soil processing consisted of rototilling and/or forking. Water was added while tilling if required. Tilling was followed by light rolling using a smooth - surfaced water weighted garden roller or flat-shaped wheeled packer and compacting to the desired strength. The levelling blade operated simultaneously with the roller.

The speed of the bin and the total number of roller passes were varied to obtain the desired soil strength profile as uniform as possible to the depth at which the model digger operated when working at a depth greater than 10 cm. Processing was done in two layers. The surface of the first layer was scarified to obtain a

* See Appendix B for details.

bond with the next layer.

It should be noted that the field soil is normally thoroughly plowed to a depth of about 12 cm. Mounds are then made approximately 6 to 8 cm. high before potatoes are planted. Field soils, therefore, are comparatively loose for the growing depth of the potatoes.

6. Instrumentation

The tool was mounted on an electrical resistance strain gauge dynamometer. The dynamometer, an extended ring transducer type (Figure 20), was sensitive to vertical and horizontal forces and to moments. The outputs from the gauges were put through a four-conductor cable to a signal conditioner, amplifier and finally recorded on an oscillograph.

The bin speed was noted on an R.P.M. indicator with a tachometer generator. The output of the generator was amplified and recorded on the oscillograph. Bin displacement was measured with a potentiometer, the output amplified and recorded.

Two forces, one moment, bin velocity and displacement were the measurements taken and recorded (Figure 1). An X - Y plotter was used to record draft versus bin velocity.

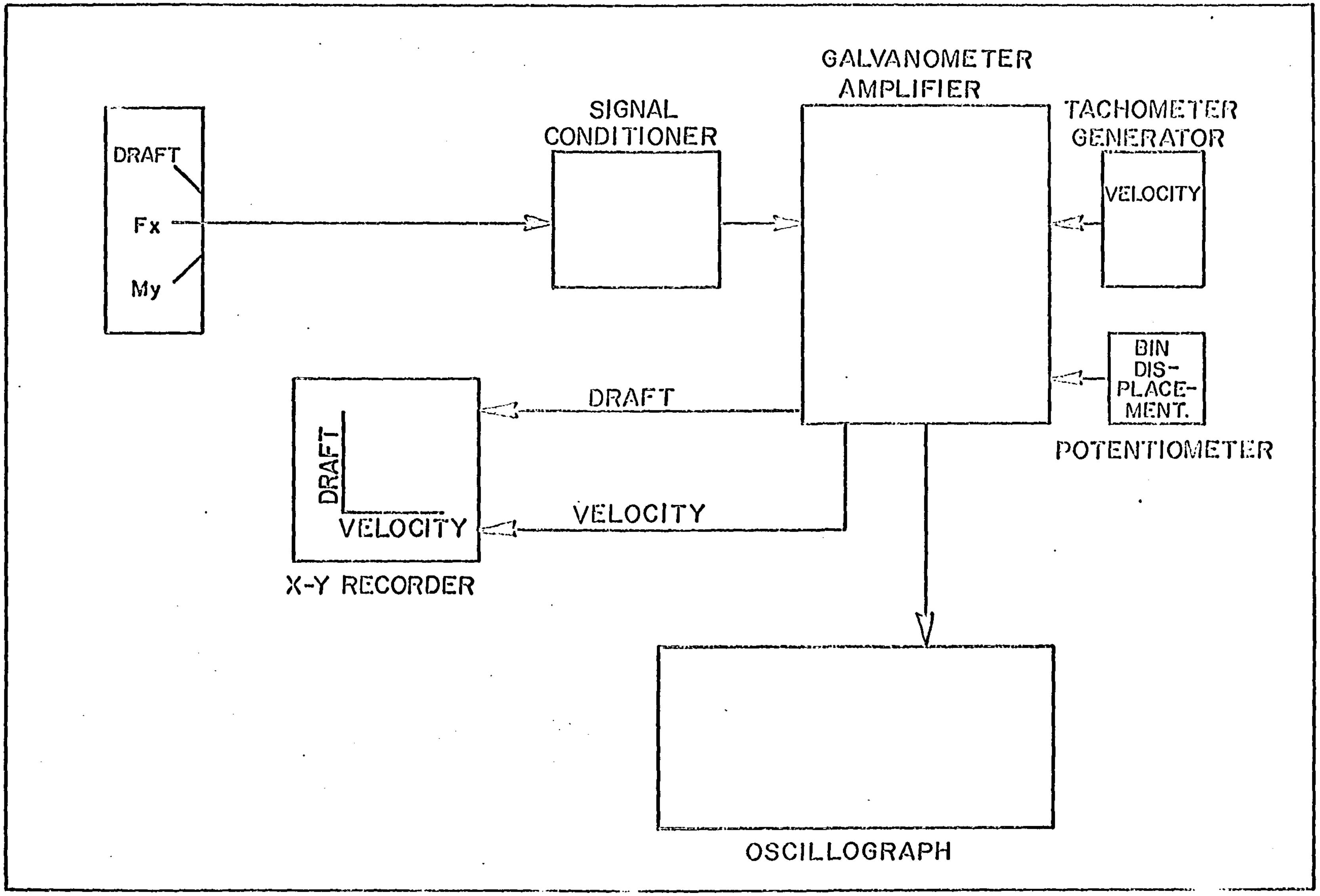


FIGURE 1. SCHEMATIC OF THE INSTRUMENTATION

PRELIMINARY STUDIES
SOIL BOX

OSCILLOGRAPH

AMPLIFIER

SIGNAL
CONDITIONERS

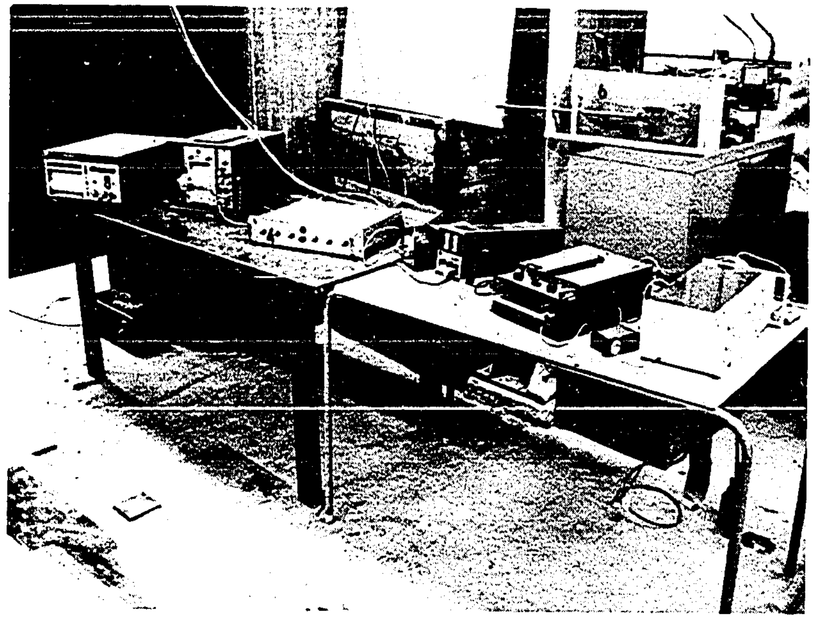


Figure 2. Instrumentation Layout.

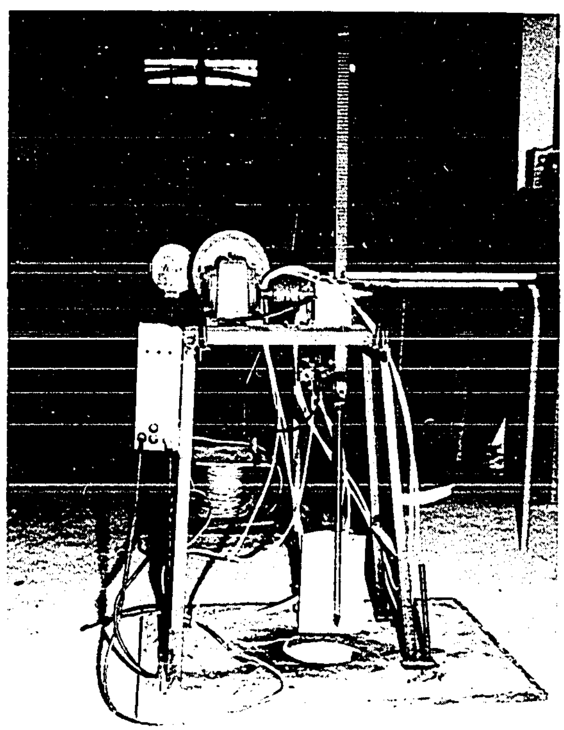


Figure 3. Cone Penetrometer.

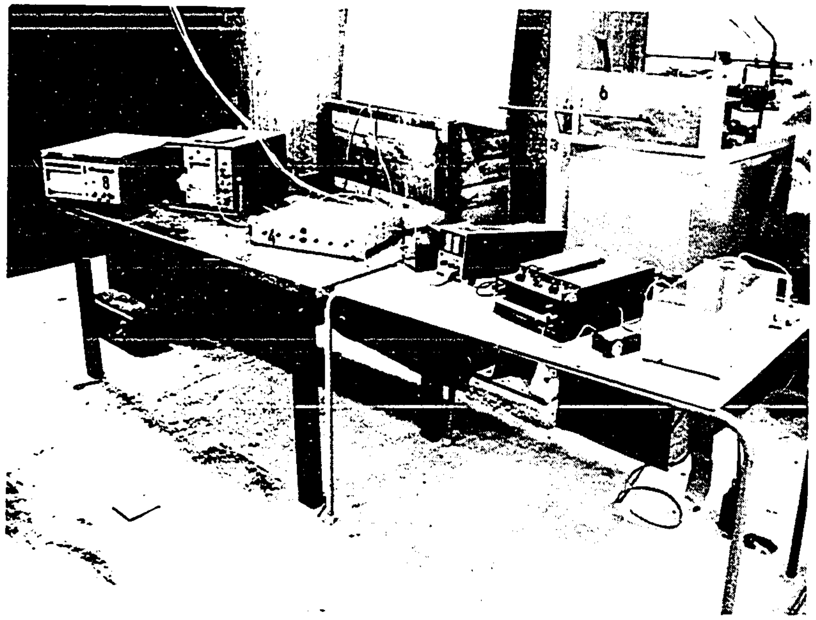


Figure 2. Instrumentation Layout.

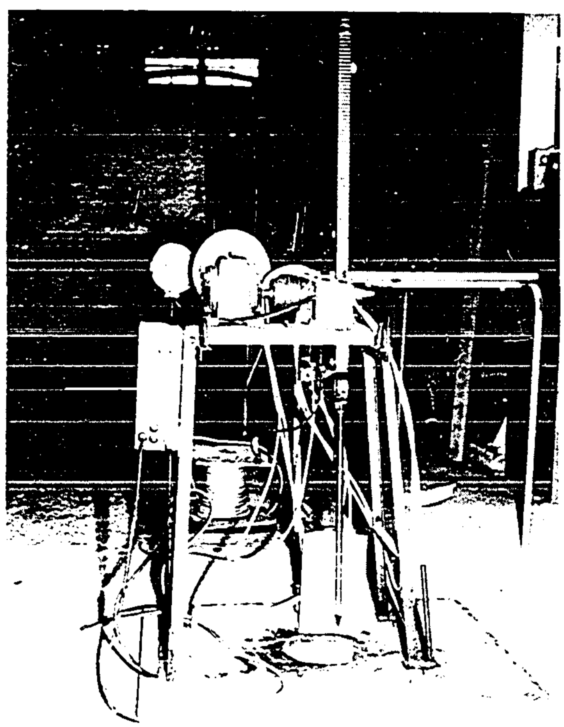


Figure 3. Cone Penetrometer.

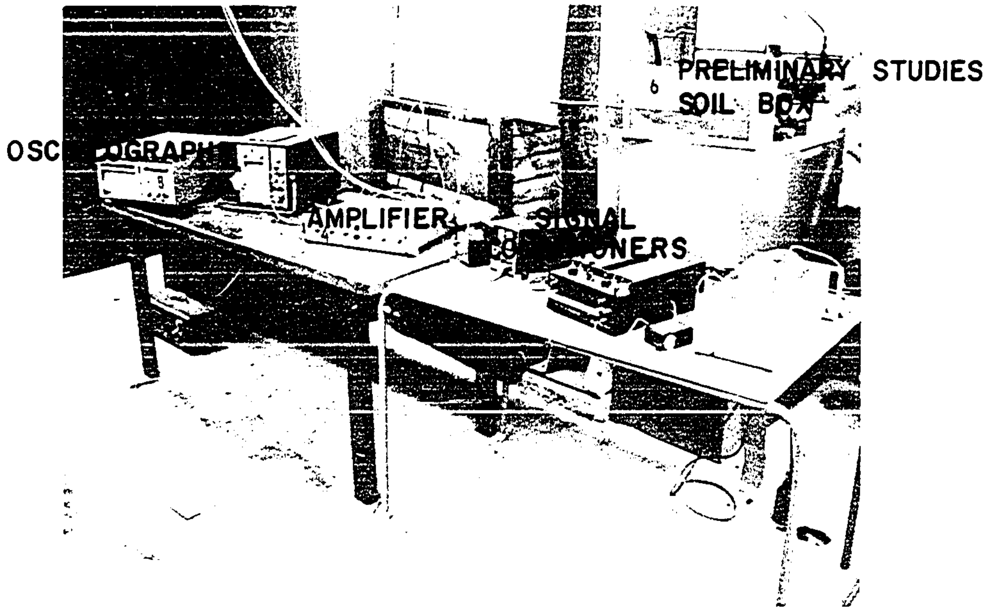
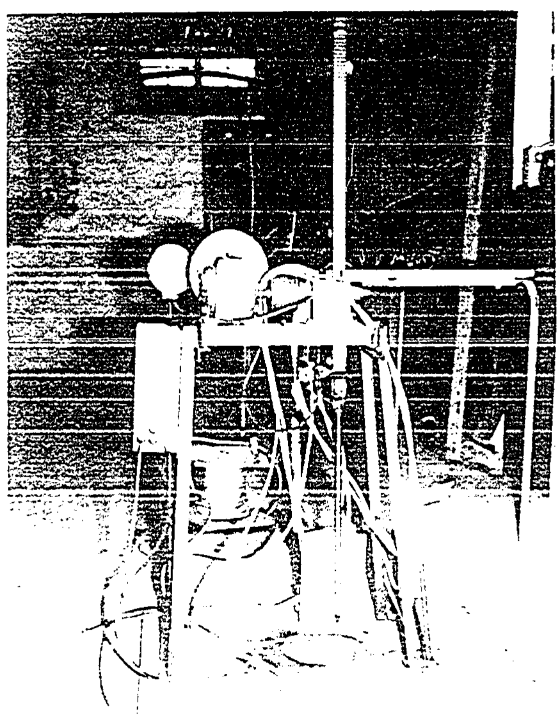


Figure [illegible]. Instrumentation Layout.



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B. Experimental Procedure

1. Preliminary Investigation

A small glass sided box (Figure 22) was constructed to carry out preliminary investigations to determine which parameters are important in root crop harvesting. Two soil types; a sand, and a clay loam were used at various moisture contents. One blade design, a flat plate 5 cm. wide by 7.6 cm. long, with the leading edge bevelled on the upper surface at a 45 degree angle was used.

The blade was moved forward, along the glass side, sufficiently slowly so that a quasi-static condition prevailed. It was 2.54 cm. into the soil, and approach angles from 15 to 60 degrees, in 5 degree increments were tried. Movement of the tool within the soil created stress fields within the medium. Particularly interesting was the failure surface because lifting of buried objects occurred when these objects were located within the failure surface.

It was noted that movements of the buried objects were purely translational and occurred when they were entirely within the failed surface. When the objects (Figure 22 A1) were located in the region delineating the stress field above the failure surface from the granular medium below it, only then did the probability of rotation exist.

The term failure surface does not adequately describe the phenomenon which was observed. It was felt that the term "harvest delineation plane", if used, would more appropriately describe the fact that a buried object having a small density difference between itself and the soil, would move towards the surface of the soil; those objects below this plane would not move to the surface (Figure 22 B). Thus the harvest delineation plane defines the region where harvest with a moving (translating) tool can occur.

Since the efficiency of harvesting in terms of useful soil movement is important, the volume of soil upheaval was also measured. This volume was calculated by drawing the boundary of the soil moved against the glass side on clear plastic material held against the glass. The area of this drawing was determined and multiplied by the blade width. It was found that tool approach angles, operational depth, soil moisture and soil type affected the volume of soil disturbed by the tool. Small angles caused the disturbed soil mass to be elongated and the volume smaller. The volume of soil moved by the tool in dry sand was greatest when the approach angle was between 30 and 45 degrees. Cohesion of wet sand caused the volume of soil moved to increase with increasing approach angle. Working with clay loam, it was noted that the volumes moved were less dependent on moisture. Above 30 degrees, the volume of soil moved was adequate for harvesting. The greater the approach angle and operational depth the greater the volume of soil moved by the blade.

A study was made of the movement of pieces of potato (S.G. 1.12), balsa wood (S.G. 0.22), cedar wood (S.G. 0.44 - o.47), aluminum (S.G. 2.4) and iron slugs (S.G. 7.2) in relation to soil movement.

Round, rectangular, flat and oblong shapes were tried.

Results of this buried object movement studies are shown in Tables 3a and 3b , and in Figure 4 . Figure 4 shows a dimensionless plot of angle versus the ratio of object distance to digger distance travelled in centimeters before the object reached the soil surface. What is desirable is a low ratio which means that the blade moved a short distance before the object came to the surface. High ratio means that both blade and object moved a great distance before the object reached the surface, which is undesirable. From the figure, therefore, the blade operated at approach angles of 20 to 45 degrees seemed most suitable. However, the low approach angle of 20 degrees allowed the object to come into contact with the blade and this can cause product damage. For this reason, 20 degree approach angled blade was not used, but further testing in this range is necessary. The curves of the graphs suggest that small diggers perform better than larger ones for shallow buried objects at low approach angles. This advantage is lost with angles over 50 degrees.

Diggers must also be adjusted at least one centimeter below the object. This allowed the object to be located within the harvestable region, thereby ensuring its movement within adequate soil mass. It is not necessary for the tool to come in contact with the buried object for the product to be removed from the soil. Only at large approach angles, that is, greater than 70 degrees, and small angles of 20 degrees, did the object tend to come in contact with the tool.

Results - Preliminary Studies.

Measurement* data of the relative movement of a digger and buried potato and balsa pieces (equal size) travelled before the pieces reached the soil surface.

Digger Size - 5.08 cm. wide by 10.16 cm. long, upper leading edge bevelled at 45 degrees.

Operational Depth - constant at 3.8 cm.

Placement of Object - the lowest point of the object 2.54 cm. deep in the soil and always 5.0 cm. preceeding the blade leading edge.

Table 3a

Blade Angle	Distance moved in cm.					
	Blade (K)	Potato (n)	$\frac{n}{K}$	Blade (K)	Balsa(n)	$\frac{n}{K}$
20	22.8	7.6	.27	22.8	7.6	.27
30	20.3	6.2	.30	21	6.5	.31
40	17	7.0	.41	18	7.6	.42
45	18	10	.55	18	9.5	.52
50	20.8	12.2	.59	21	12.0	.57
60	24	16.4	.67	24	15.5	.63
70	26.6	21.3	.82	29	20.0	.69
80	33	28.5	.86	34	28.0	.82

* Average of two tests.

Continuation of Preliminary Results

Digger Size - 5 cm. x 5 cm.

Operational Depth - as before

Placement of Object - as before

Table 3b

Blade Angle	Distance moved in cm.					
	Blade	Potato	$\frac{n}{K}$	Blade	Balsa	$\frac{n}{K}$
30*	15.24	3.8	.25	12.7	5.08	.4
40	15.24	3.54	.24	12.7	3.8	.3
45	15.24	3.2	.21	13.7	7.6	.55
50	15.24	8.5	.56	15.24	8.2	.54
60	15.24	9.0	.59	15.24	8.5	.56
70	15.24	10.16	.67	15.24	9.5	.62
80	18.0	14.0	.77	17.5	14.0	.81
90	21.5	16.5	.75	23.5	16.5	.8

* Depth of operation 3.2 cm.
All average of two tests.

The density of the object affected its motion out of the soil. Balsa wood, cedar wood and potato pieces were translated within the soil mass (density 1.7 - 2.3), at approximately the same rate as the soil particles. The path upward seemed to depend on the approach angle, soil moisture, soil type and the depth that the object was

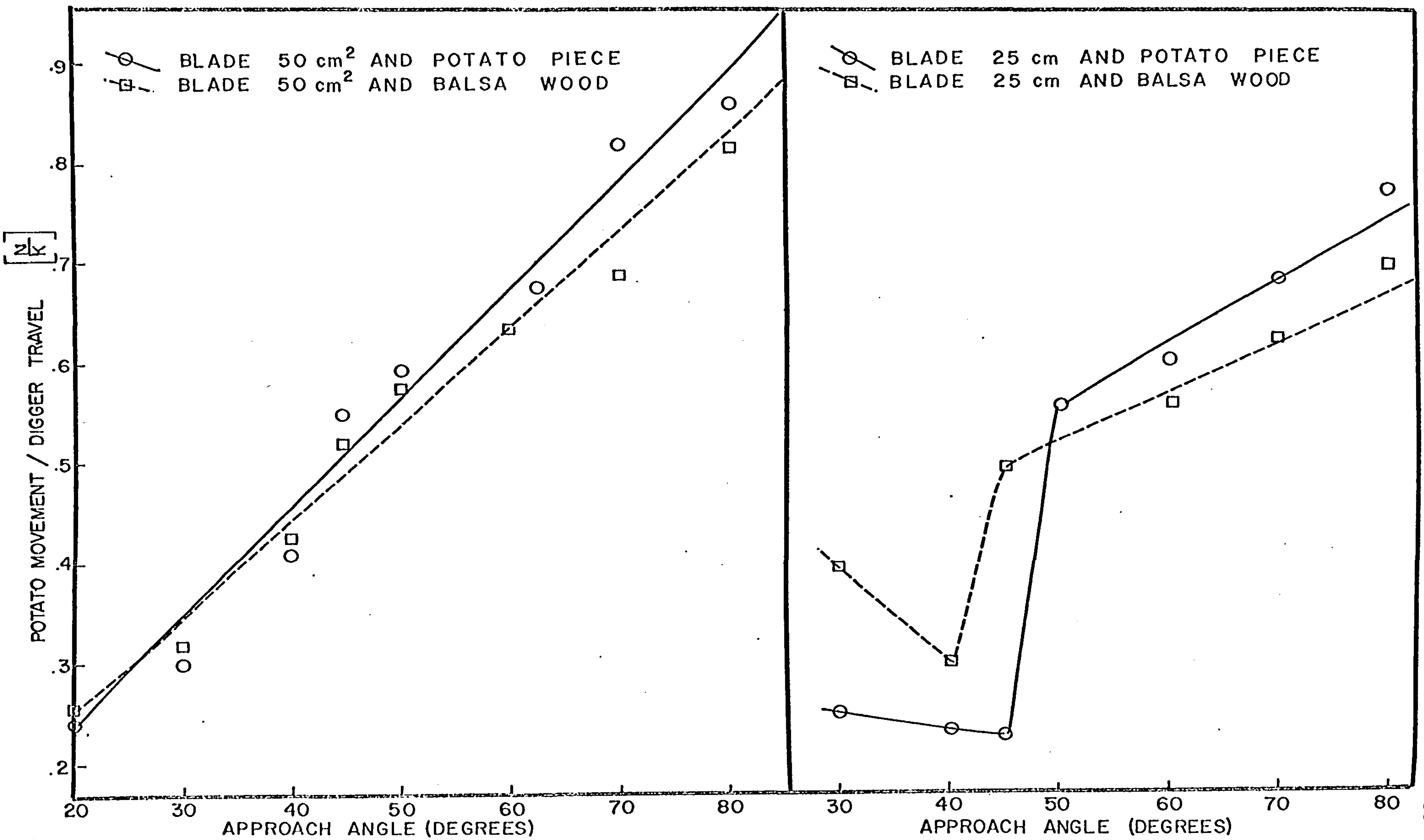


FIGURE 4. RELATION BETWEEN POTATO MOVEMENT/ DIGGER TRAVEL RATIO AND APPROACH ANGLE DIMENSIONLESS PLOT

buried. Aluminum pieces reached the surface but required a longer travel distance than potatoes or wood. Round iron slugs moved downwards. All tests for the effect of density were carried out at an approach angle of 40 degrees. When the density of the object was less than that of the soil, the path of motion of the object approximated that of the harvest delineation plane.

It was also found that the distance from the blade tip to the soil surface ruptured by the harvest delineation plane was related to the operational depth and approach angle of the tool. The exact nature of this relationship was not investigated.

2. Experimental Plan

Field data of the condition of the two chosen soil types, sand and clay loam, were taken on three separate occasions throughout the experiment. Potatoes were grown on the clay loam soil. The penetration resistance of the soils was measured by using the same penetrometer that was used in the soil bin. In addition, soil samples were taken and tested for moisture content and bulk density. These results are presented in Table 11.

These soils were brought into the laboratory and placed into the bin. Scaled round potatoes were buried approximately 15 cm. apart and 1 cm. above the operational depth of the tool. Potato damage studies (12) show that the weight of potatoes harvested without injury averages 125 grams. The average size of round potatoes weighing 125 grams was 7.5 cm. in diameter. This length characteristic was the basis for scaling potatoes in the model studies. The soils were then prepared to simulate the conditions encountered in the potato plot with respect to penetration resistance, moisture content and bulk density.

The average penetrometer readings over the working depth of the model were compared to the average penetrometer reading over the working depth of the prototype. Calculations of the distortion factor n_λ were made using equation (4), i.e.

$$n_\lambda = \frac{P_m}{P_p} \quad \frac{\rho_p}{\rho_m}$$

Relaxing the maintenance of rigid soil property specifications one can vary n_λ . This enables substantial savings in time and effort due to the reduced number of models that have to be made, and in the number of tests that have to be performed before meaningful results can be obtained.

In the soil bin, resistance to penetration (P_m) and to a diminutive extent bulk density (ρ_m), can be controlled by the weight and number of roller passes. This method was used to get values of n_λ close to two models that were used.

Operational velocity was calculated from equation (5), i.e.

$$V_m = V_p \left[n_\lambda\right]^{\frac{1}{2}}$$

Two models and the prototype were tested at three approach angles, namely 30, 37 and 45 degrees to the horizontal for all tools.

Tool models were 0.5 and 0.7 of the prototype.

Operational depths were determined according to

$$Z_m = Z_p \cdot n_\lambda$$

where Z_p and n_λ are known.

3. Design of Model Diggers

The original prototype digger was 50.8 cm. long, 22.86 cm. wide and made of 1.59 cm. thick T_1, Type A alloy steel, with a leading cutting edge of 2.54 cm. at 45 degrees (Figure 14). It was felt that if models were to be larger than 0.8 of the prototype, then it was better to use the prototype itself. Three models were made geometrically similar to the prototype. They were as follows:

Table 4

Model Number	Scale Factor	Length(l) cm.	Height(w) cm.	Thickness cm.	Leading Edge	
					Length cm.	Angle°
1	0.5	25.4	11.43	0.79	1.27	45
2	0.75	38.7	17.2	1.19	1.91	45
Prototype	--	50.8	22.86	1.59	2.54	45

Making the models involved simply cutting flat T_1, Type A alloy steel plates of desired thickness to the appropriate length and width. Tool surface roughness, and hence internal frictional angle, can be neglected since the surfaces of the models were highly polished. The edges of all tools were lined with teflon (Figure 16) to facilitate two dimensional studies near the glass side of the bin. When the value of n_λ was found the blade closest to that value was used in the test.

4. Operating Procedure

The bin speed was calibrated whilst the tool was set in the soil at the working depth. This was done by means of a hydraulic servo valve and noted with the aid of a tachometer generator, both on the r.p.m. indicator, and an oscillograph.

The bin was put in starting position and the tool set into the soil. The bin was accelerated to the desired speed within a distance of approximately .9 meters (3 feet), then at steady speed the testing distance of 1.83 meters (6 feet) was covered. The tool bar was then mechanically raised (Figure 19) within the remaining 60 cm. before the end of the bin was reached. An automatic microswitch cut off the current to the electric drive motor and the bin decelerated to a stop. Data acquisition was only from the 1.83 meters testing area.

5. Two Dimensional Studies

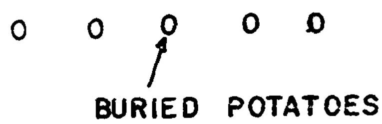
Two dimensional studies were carried out primarily to check and to study further, conclusions made in the preliminary studies.

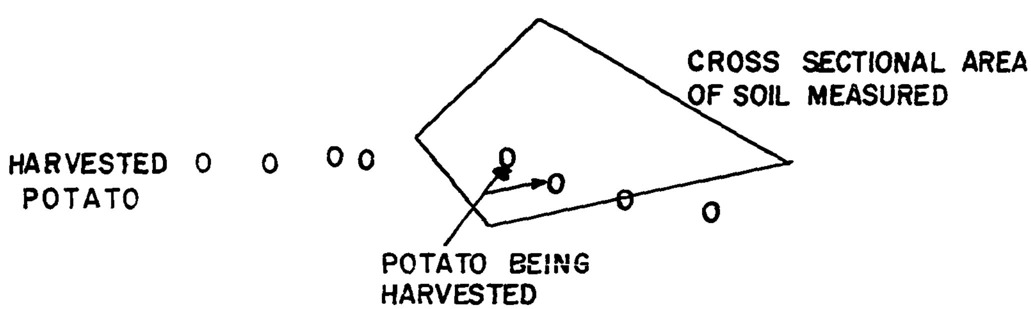
Potatoes were buried approximately 7.5 cm. in the soil as shown in Figure 5, touching the glass of the bin. The prototype blade, in clay loam soil type only was operated at approach angles of 30, 40 and 50 degrees, at one m.p.h. and 10 cm. deep. The teflon-lined edge lightly rubbed against the glass during operation. These tests were duplicated; that is, six tests were performed.

In each test the potatoes were easily harvested. The potatoes were carried with the soil mass and never came in contact with the digger (Figure 6). Measurements of the soil volume showed that the greater the approach angle, the larger the volume of soil that was carried. This was reflected also by the larger draft force required to operate the larger approach-angle blade. However, there seemed to be no apparent advantage of this greater volume over that moved by the blade operated at 30 degrees.

The potatoes fell over the top edge of the blade at an almost constant rate to the soil surface. There was no bruising or damage, except for the few potatoes that were placed directly in the path of the leading edge of the digger. Movement of the potatoes was purely translational.

The length of the harvest delineation plane was affected by changes in approach angle. Working at 6 cm. in sand, the prototype produced a harvest delineation plane averaging 33 cm. long, from the bevelled edge to the soil surface. At 37^{o} and 45^{o}, it was 30 cm. and 26 cm. respectively. The importance of this is that buried


BURIED POTATOES


CROSS SECTIONAL AREA
OF SOIL MEASURED
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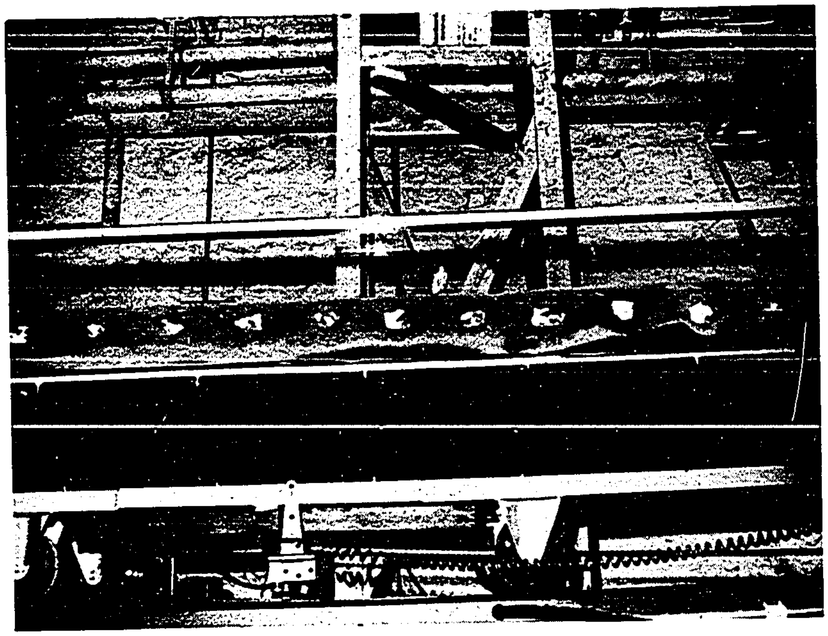


Figure 5. Soil Bin with Potatoes Buried in the Soil along the Glass Side.

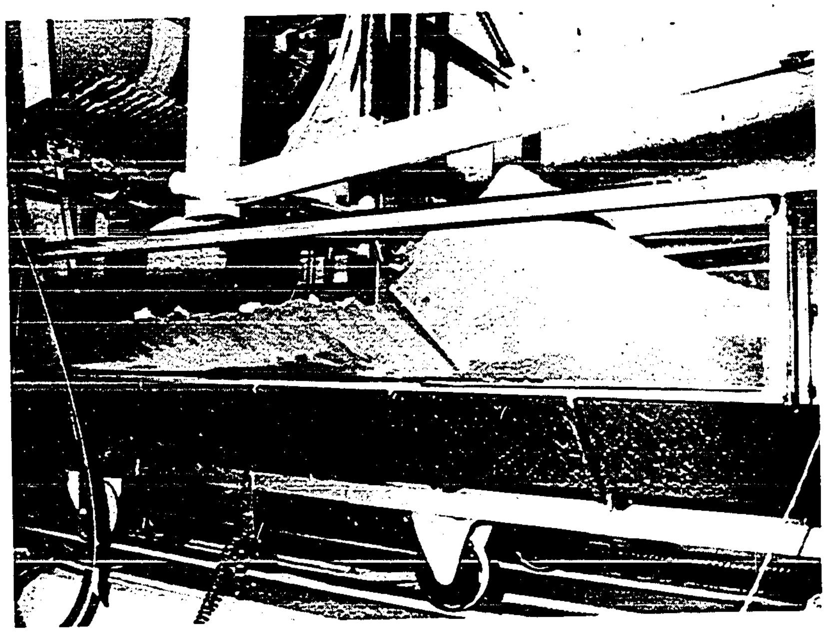


Figure 6. 2-Dimensional Harvest Study.

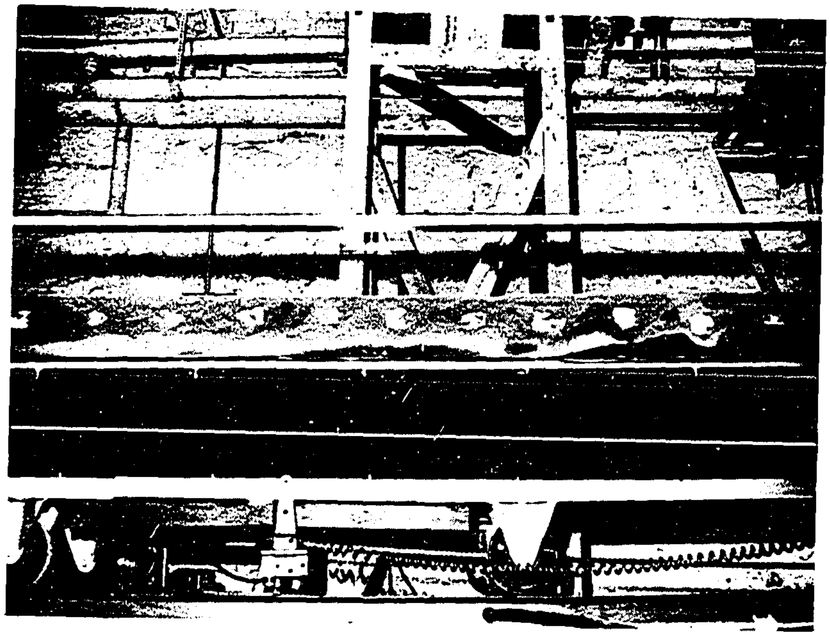


Figure 5. Soil Bin with Potatoes Buried in the Soil along the Glass Side.

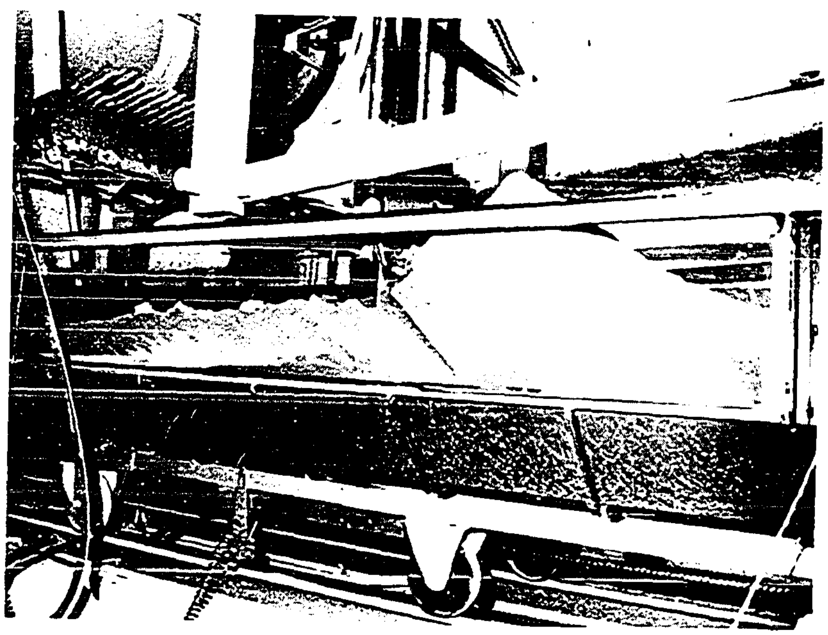


Figure 6. 2-Dimensional Harvest Study.

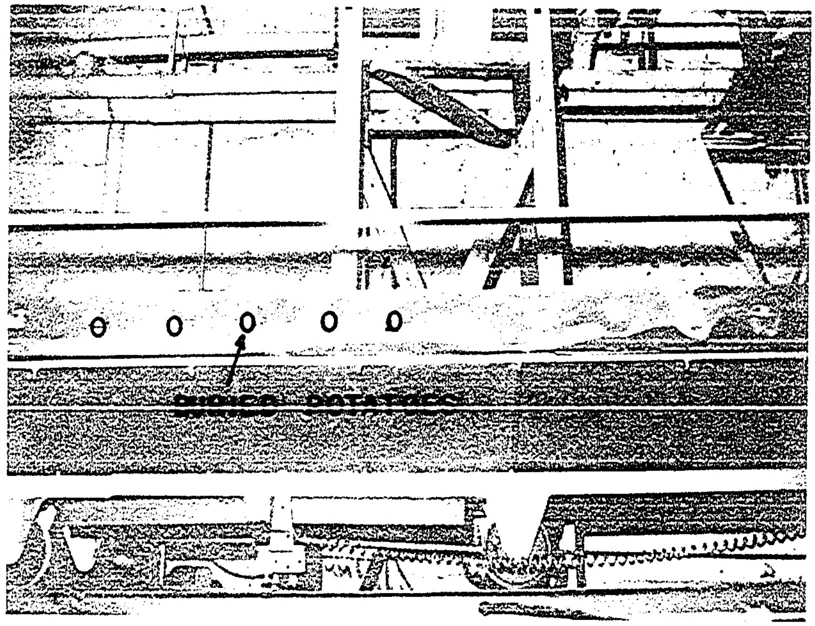
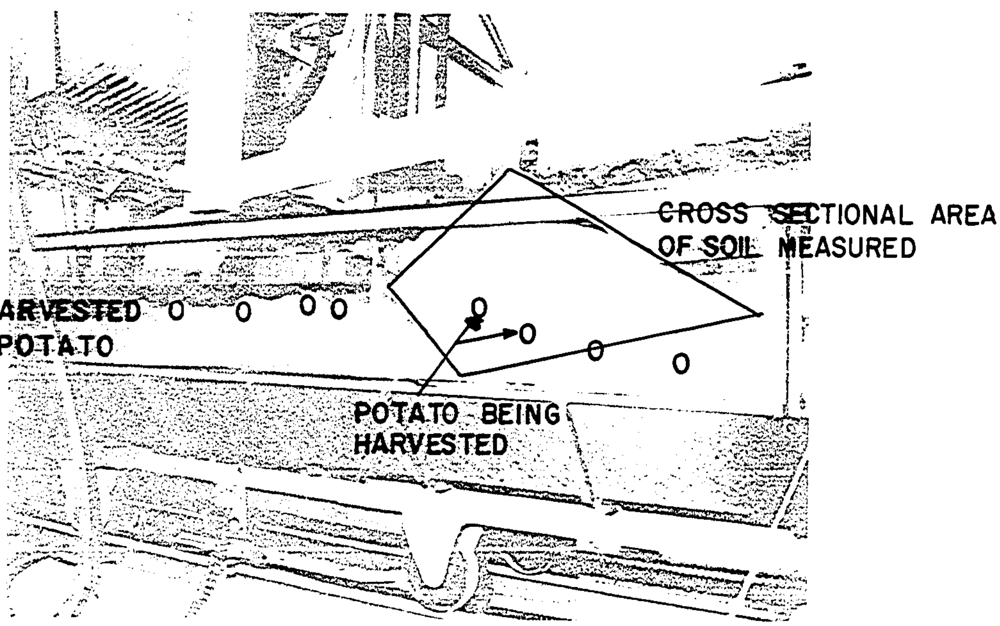


Figure 5. Soil Bin with Potatoes Buried in the Soil along the Glass Side.



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potatoes will be disturbed or loosened from their resting position earlier, and therefore be susceptible to harvest an instant earlier when diggers are set at an approach angle of 30 degrees rather than at 37 or 45 degrees. However, the relative importance of deeper harvest has also to be weighted against this, if the digger blade length is a limiting factor.

6. Draft Studies

Draft studies using model diggers of 0.5, 0.75 and 1 times full scale were conducted to determine the effects of scaling. The model design allowed operation through a wide range of approach angles (0^o to 90^o from the horizontal), speeds (0 to 4.8 km/hr) and depths (0 to 30 cm.).

The tests were conducted in the centre of the soil bin in order to minimize edge effects of the bin sides. Sand and clay loam soils were used. The soil was rototilled and watered. It was covered with a plastic sheet and left for two days to equilibrate. After this period, it was levelled and rolled and soil samples were taken for moisture content and bulk density determinations. If satisfactory, a test was performed; if not, the process was repeated until the desirable conditions were obtained.

Results are presented on the following pages.

IV. DATA COLLECTION AND RESULTS

Table 5. Soil and Tool Operating Conditions

Test No.	SOIL CONDITIONS: Cone Penetration Kg/cm^2 Field	Cone Penetration Kg/cm^2 Lab	Bulk Density gm/cm^3 Field	Bulk Density gm/cm^3 Lab	Moisture Content % Field	Moisture Content % Lab	TOOL OPERATIONAL CONDITIONS: Scaled Model Desired n_λ	Scale Actually Used	Desired Speed m.p.h.	Actual Speed m.p.h.	Angle degrees	Depth of Operation cm.
S1	3.30	3.10	1.80	1.76	16.7	15.4	1.08	1.00	1.00	0.96	30	12
S2	3.30	3.37	1.80	1.90	16.7	14.8	0.97	1.00	1.00	1.05	38	12
S3	3.30	2.80	1.80	1.74	16.7	16.5	0.96	1.00	1.00	1.00	44	12
S4	2.10	1.68	1.78	1.80	17.1	17.2	0.80	0.75	0.87	0.88	31	9
S5	2.10	1.58	1.78	1.68	17.1	16.3	0.78	0.75	0.87	0.85	37	9
S6	2.10	1.40	1.78	1.66	17.1	15.5	0.71	0.75	0.87	0.89	45	9
S7	1.40	0.98	1.75	1.69	15.8	17.4	0.72	0.50	0.71	0.69	30	6
S8	1.40	0.91	1.75	1.61	15.8	16.7	0.70	0.50	0.71	0.72	36	6
S9	1.40	0.85	1.75	1.65	15.8	15.8	0.64	0.50	0.71	0.68	45	6

Table 5. (Continued) Soil and Tool Operating Conditions

Test No.	SOIL CONDITIONS: Cone Penetration Kg/cm^2 Field	Lab	Bulk Density gm/cm^3 Field	Lab	Moisture Content % Field	Lab	TOOL OPERATIONAL CONDITIONS: Scaled Model Desired n_λ	Scale Actually Used	Desired Speed m.p.h.	Actual Speed m.p.h.	Angle degrees	Depth of Operation cm.
CL 1	4.30	3.70	1.92	1.67	16.8	18.8	1.05	1.00	1.00	1.01	31	12
CL 2	4.30	4.10	1.92	1.70	16.8	19.0	1.09	1.00	1.00	0.99	37	12
CL 3	4.30	3.60	1.92	1.71	16.8	17.5	0.95	1.00	1.00	1.02	45	12
CL 4	2.80	1.80	1.80	1.68	17.4	18.0	0.70	0.75	0.87	0.85	29	9
CL 5	2.80	1.90	1.80	1.67	17.4	16.4	0.77	0.75	0.87	0.89	37	9
CL 6	2.80	2.00	1.80	1.65	17.4	20.5	0.80	0.75	0.87	0.85	45	9
CL 7	1.70	1.20	1.72	1.65	19.2	19.4	0.69	0.50	0.71	0.71	30	6
CL 8	1.70	1.10	1.72	1.68	19.2	17.1	0.64	0.50	0.71	0.72	37	6
CL 9	1.70	1.20	1.72	1.69	19.2	16.7	0.72	0.50	0.71	0.69	44	6

Table 6a. Results of Tests in Sand (S) Soil Type

Test No.	Draft (KG)	Vertical Force (KG)	Moment (KG - cm.) About Horizon Axis	Moment (KG - cm.) About Blade Centre
S1	78.0	- 22.70	1,427	110.7
S2	82.1	- 16.00	1,721	166.9
S3	92.9	- 25.40	1,896	72.2
S4	57.6	14.50	437	35.4
S5	58.9	22.70	435	81.6
S6	68.0	20.50	601	57.1
S7	43.1	15.00	345	14.1
S8	44.5	13.60	428	38.2
S9	50.0	18.20	449	46.7

Table 6b. Results of Tests in Clay Loam (CL) Soil Type

Test No.	Draft (KG)	Vertical Force (KG)	Moment (KG - cm.) About Horizon Axis	Moment (KG - cm.) About Blade Centre
CL 1	90.0	- 20.4	1,389	177.8
CL 2	91.7	- 14.5	1,510	162.0
CL 3	103.0	- 23.1	1,780	191.4
CL 4	67.2	8.2	679	33.5
CL 5	75.8	9.1	766	30.5
CL 6	79.3	15.8	864	81.7
CL 7	52.1	11.3	442	43.1
CL 8	54.9	16.3	576	36.3
CL 9	59.8	21.4	760	48.5

V. ANALYSIS AND DISCUSSION

A. Draft Prediction

Draft of the model tools used was found to predict the prototype draft to a reasonable degree of accuracy. Table 7 shows that the draft of model tools with scale factor .75, range between 0.75 and 0.82 (0 to 9% error) of the prototype, and to range between 0.58 and 0.60 (16 to 20% error) for the .5 scale models for all the approach angles used in clay loam soil type.

The table also shows that prediction of prototype draft is easier when working with sand. For the .75 scale model, draft ranges between 0.72 and .74 (4% error) of the prototype and for the .5 scale model, it varies from 0.54 to 0.55 (8 to 10% error) of the prototype.

Since a 0.5 scale was used when in fact soil conditions specified the scale factor (n_λ) be 0.6, this undoubtedly was a source of prediction error.

Payne (1952) found draft to vary with soil density in agricultural soils. Density varies about $\pm$ 15% and its contribution to draft variation was about 10%. In these tests density varied with the number of roller passes, and the prototype was used in denser soils, thus suggesting a further source of prediction error. It is felt that prediction inconsistencies could be attributed to the

Table 7. Draft of Model Tools.

Model Size	Nominal Approach Angle	Soil Type	Draft (KG)	Draft Ratio
1	30	Sand	78.0	$\frac{78}{78} = 1.00$
3/4	30	"	57.6	$\frac{57.6}{78} = 0.74$
1/2	30	"	43.1	$\frac{43.1}{78} = 0.55$
1	37	"	82.1	$\frac{82.1}{82.1} = 1.00$
3/4	37	"	58.9	$\frac{58.9}{82.1} = 0.72$
1/2	37	"	44.5	$\frac{44.5}{82.1} = 0.54$
1	45	"	92.9	$\frac{92.9}{92.9} = 1.00$
3/4	45	"	68.0	$\frac{68}{92.9} = 0.73$
1/2	45	"	50.0	$\frac{50}{92.9} = 0.54$
1	30	Clay Loam	90.0	$\frac{90}{90} = 1.00$
3/4	30	"	67.5	$\frac{67.5}{90} = 0.75$
1/2	30	"	52.3	$\frac{52.3}{90} = 0.58$
1	37	"	92.8	$\frac{92.8}{92.8} = 1.00$
3/4	37	"	76.1	$\frac{76.1}{92.8} = 0.82$
1/2	37	"	55.2	$\frac{55.2}{92.8} = 0.60$
1	45	"	103.0	$\frac{103}{103} = 1.00$
3/4	45	"	79.5	$\frac{79.5}{103} = 0.77$
1/2	45	"	60.0	$\frac{60}{103} = 0.58$

scaling of depth, since at greater depth soil conditions, especially density, are vastly different.

B. Draft

Draft increased with an increase in the approach angle of the diggers (Figure 7). The increase in draft from 30 to 37 degrees was generally less than that from 37 to 45^{o} as noted by the gradient of the curves.

In order to understand the reason for increased draft due to approach angle further, two-dimensional studies (P.39) were conducted. Using the prototype tool and the .75 scale model at one depth but varying the angles, the area of the soil moved against the glass side of the bin was measured (Figure 6). The results are presented in Table 8 and Figure 8.

These studies showed that considerably more soil was moved at the largest angle. While more soil was moved at 37 than at 30 degrees, the increase was about six times less than from 37 to 45 degrees. The increased volume of soil moved, therefore, was the reason for greater draft at greater approach angles.

The effect of soil type can be seen by comparing the curves on each side of Figure 7. Draft requirements were consistently higher in the clay loam.

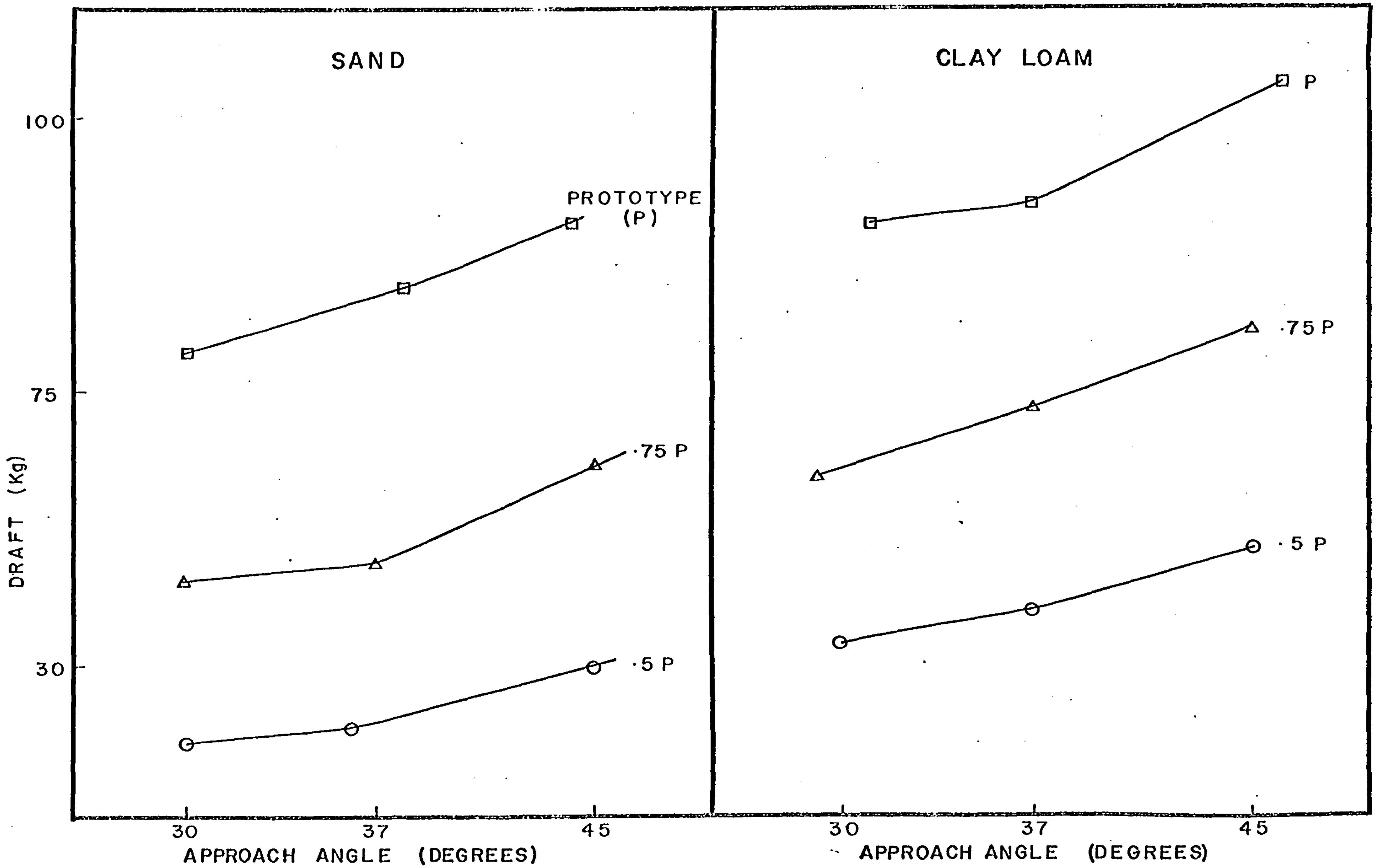

FIGURE 7. RELATION BETWEEN APPROACH ANGLE AND DRAFT

Table 8. Results of 2-Dimensional Studies to Measure Cross Sectional Area of Sandy Soil Moved by Diggers.

Angle (degrees)	Scale	Cross Sectional Area* of Soil Moved (cm^2)	Draft (KG) recorded from 3-Dim.
30	1.00	180	78.0
37	1.00	193	82.1
45	1.00	263	92.9
30	0.75	123	57.6
37	0.75	139	58.9
45	0.75	167	68.0

* Each value is the average of three measurements.

C. Resultant and Vertical Force

Working depth was scaled in proportion to model size, that is, the .5 scale model worked at half the depth of the prototype. The results of these tests yielded the information on Table 9 and Figure 9.

The scatter of the data suggests that there is confounding of depth with cone index readings and it may have been more appropriate to work the various models at selected depths, but time did not permit these series of experiments to be conducted. However, for the prototype, the resultant force acted primarily around the

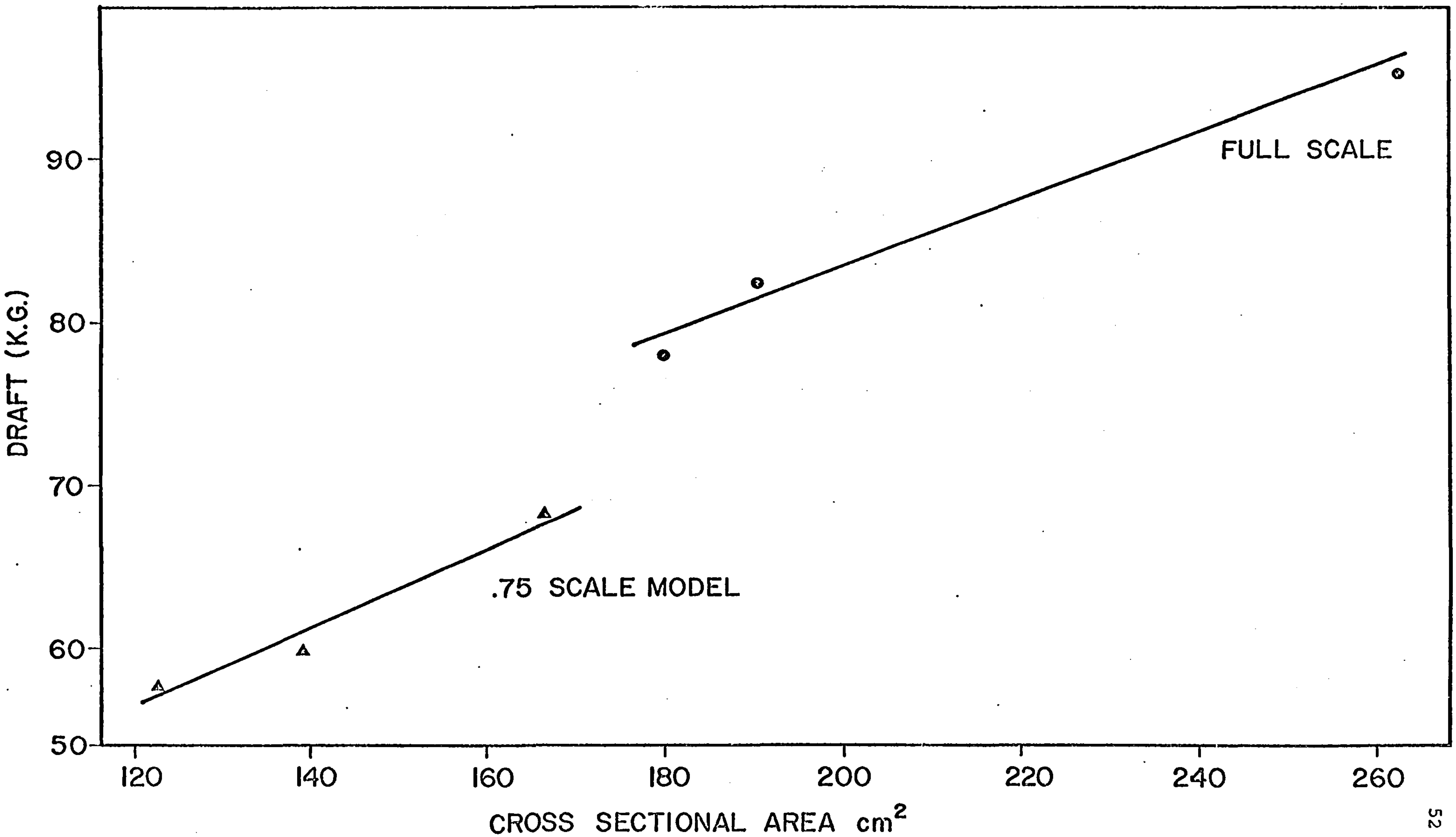

Figure 8. Relation between Draft and Soil Cross Sectional Area.

Table 9. Resultant Force Reaction Data

Depth (cm.)	Scale Factor	Angle (degrees)	Soil Type	a/w*	Resultant Reaction Angle β* (degrees)
6	0.50	30	Sand	$\frac{3.5}{11} = .38$	16
9	0.75	30	"	$\frac{9.5}{17} = .56$	20
12	1.00	30	"	$\frac{11}{22} = .50$	54
6	0.50	37	"	$\frac{3.7}{11} = .34$	21
9	0.75	37	"	$\frac{5.3}{17} = .31$	19
12	1.00	37	"	$\frac{8.8}{22} = .40$	52
6	0.50	45	"	$\frac{3.6}{11} = .32$	29
9	0.75	45	"	$\frac{7.5}{17} = .44$	27
12	1.00	45	"	$\frac{10.5}{22} = .47$	64
6	0.50	30	Clay Loam	$\frac{4.5}{11} = .41$	20
9	0.75	30	"	$\frac{9.5}{17} = .56$	26
12	1.00	30	"	$\frac{14}{22} = .63$	46
6	0.50	37	"	$\frac{3.0}{11} = .27$	21
9	0.75	37	"	$\frac{9.0}{17} = .52$	32
12	1.00	37	"	$\frac{11.5}{22} = .52$	53
6	0.50	45	"	$\frac{4.5}{11} = .41$	28
9	0.75	45	"	$\frac{7.0}{17} = .41$	31
12	1.00	45	"	$\frac{13.5}{22} = .61$	61

* Figure 20 and Appendix C for sample calculation.

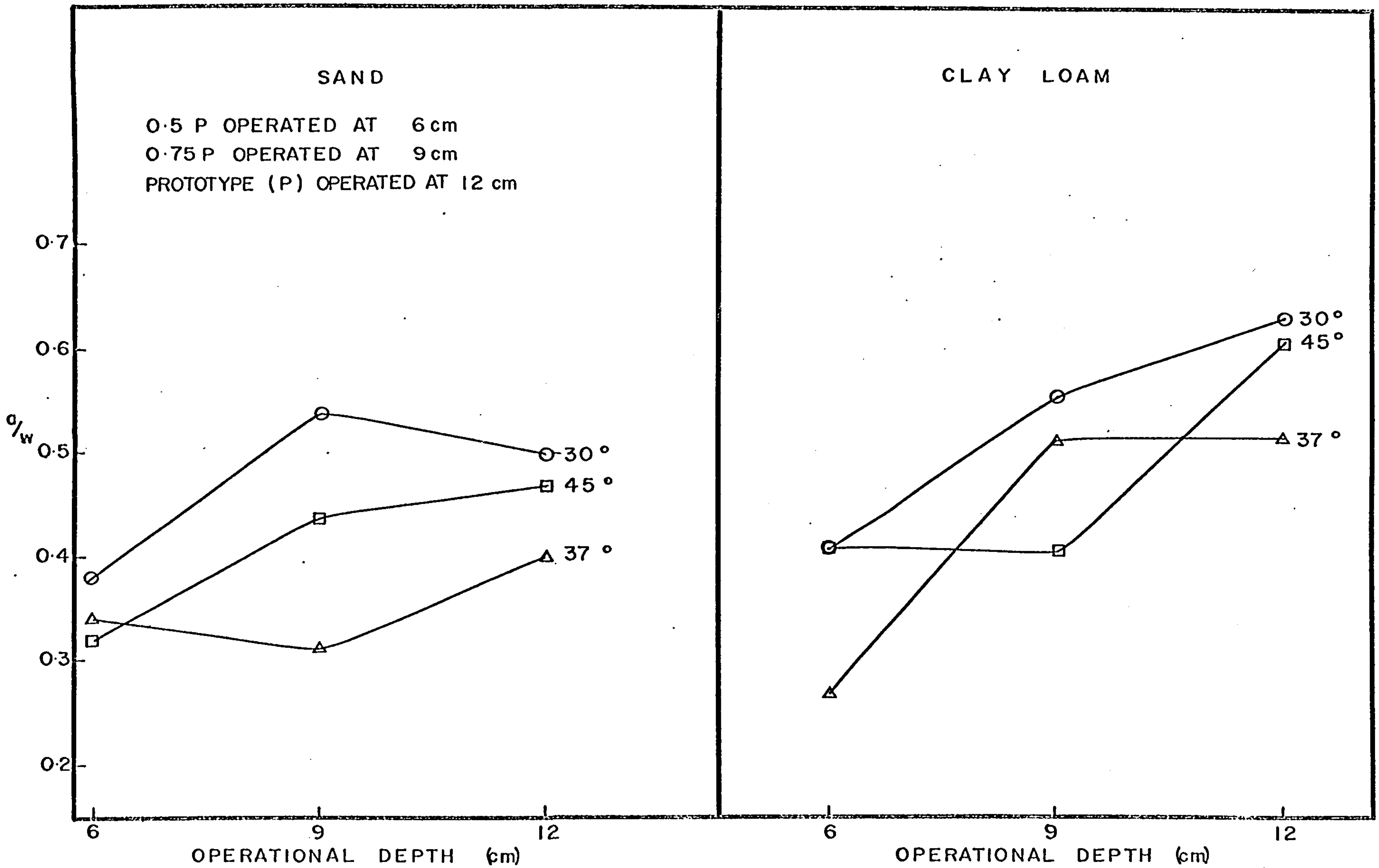

FIGURE 9. RELATION BETWEEN OPERATIONAL DEPTH AND a/w

middle portion of the blade. The angle (β) that the resultant formed with the blade surface was consistently greater for the prototype than that for the models.

The direction and magnitude of the resultant force are important factors in determining tool penetration and the volume of soil disturbed by the digger. For the prototype the direction was downwards with β being greater than 50 degrees. The resultant aided penetration of the tool into the soil. For the models the resultant did not appear to have any great effect on penetration.

The vertical force acted upwards for the models but downwards for the prototype. The effect of approach angle on the direction of the vertical force could not be ascertained from these tests.

D. Velocity

A number of tests were performed specifically to study the effect of increasing velocity on draft. The .5 scale model was operated at constant depth in dry sand at four different speeds. The angle was then changed and the tests repeated. The results are shown in Figure 10.

The effect of increasing tool velocity was to increase the draft on the tool. For a speed increase of 50%, the draft increased 35% when the approach angle was 30 degrees, and speed range was from .35 to 1.35 m.p.h. Since the bin was not being accelerated during the recording period the increased force could not be attributed to

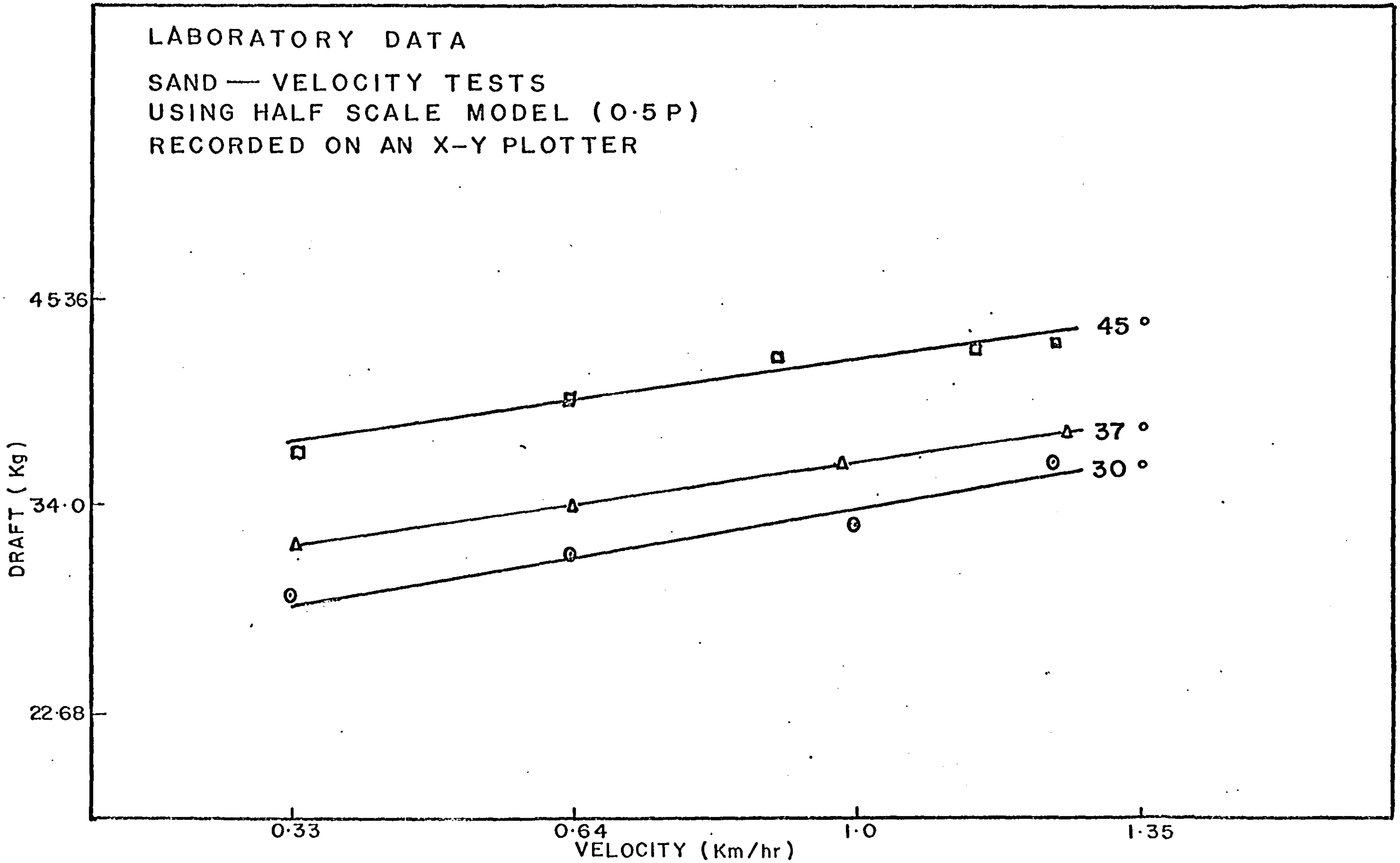

FIGURE 10. RELATION BETWEEN DRAFT AND SPEED

acceleration. It may be due to some unknown soil parameter. These velocity effects suggest that excessive harvesting speed with the digger tested is to be discouraged if power costs are high.

E. Effect of Approach Angle on Moment Acting about the Tool Centroid

The Moment acting on the digger was measured about the transducer horizontal axis. Corrections were made and the moment about the centroid of the cross-sectional area of the digger was found. Table 10 and Figure 11 show the effect of approach angle on the moment about the centroidal axis.

No satisfactory conclusions can be drawn from the data collected. There may be some inter-play or change of the role of the forces creating either increased draft or less moment or vice-versa. Comparing Figure 7 with Figure 11 for sand, the draft at 45° of all the diggers is high while the turning moment is low. Conversely at 37° the moment is high while the draft seem relatively cogent. This argument breaks down when clay loam soil is considered. Here both series of curves follow the same pattern suggesting both moment and draft go up or down simultaneously. The observations made may depend on soil type but further testing designed to prove this is necessary.

In harvesting root crops under field conditions the digger must overcome forces due to the presence of roots. Weaver (1935) has demonstrated the binding influence and increase in soil resistance to erosion due to plant roots. Draft therefore, would be

Table 10 Effect of Approach Angle on Moment

Approach Angle(°)	Corrected Moment about Centre of Blade	Scale (n_λ)	Depth (cm.)	Soil Type
30	14.1	.50	6	Sand
37	38.2	"	"	"
45	46.7	"	"	"
30	35.4	.75	9	"
37	81.6	"	"	"
45	57.1	"	"	"
30	110.7	1.00	12	"
37	166.9	"	"	"
45	72.2	"	"	"
30	43.1	.50	6	Clay Loam
37	36.3	"	"	"
45	48.5	"	"	"
30	33.5	.75	9	"
37	30.8	"	"	"
45	81.7	"	"	"
30	177.8	1.00	12	"
37	162.0	"	"	"
45	191.4	"	"	"

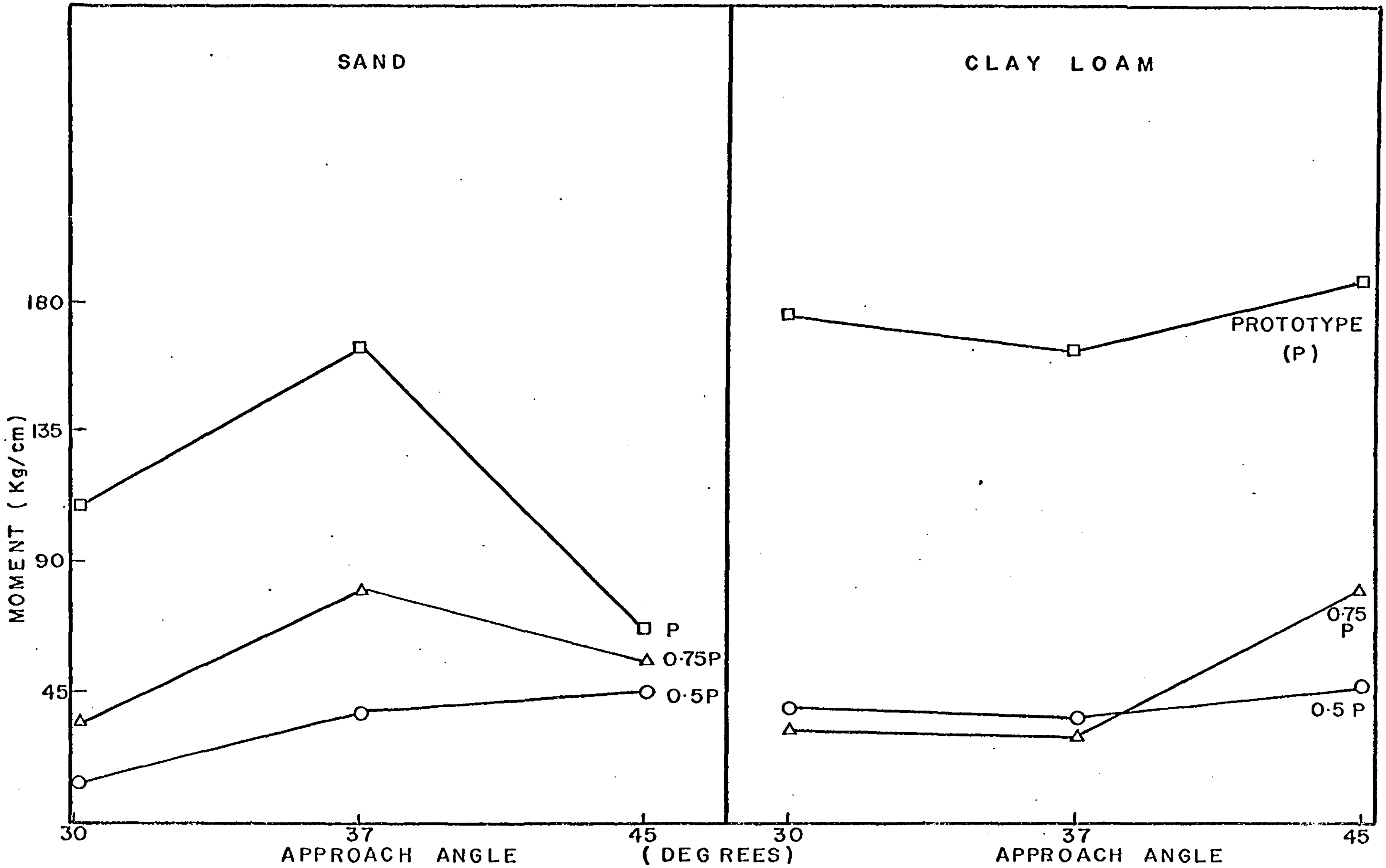

FIGURE 11. RELATION BETWEEN APPROACH ANGLE AND MOMENT ABOUT THE CENTROIDAL AXIS OF THE BLADE

increased as a direct result of the presence of roots.

At harvest time sweet potatoes have actively growing roots while other potato species have partially decaying roots. Beets have deep tap roots while onions have shallow roots. How these different root systems and conditions affect harvest are important pieces of information in designing diggers for the various crops. Withered haulms and other debris on the soil surface are other significant factors affecting tool movement through the soil. Both roots and surface materials can also influence vertical forces and turning moment about the tool centroidal axis in an as yet unpredictable manner.

Simulation of these conditions in the laboratory would obviously be laborious and difficult, if not impossible. However, recognizing these short-comings and limitations, it is felt that some comprehension of the problems present and vital information regarding the science of harvesting root crops have been procured.

VI. SUMMARY AND CONCLUSIONS

A. Summary

The principles of similitude have been utilized by numerous scientists to predict the forces on prototype tillage tools after measuring the forces acting on models. With few exceptions, it was concluded that the principles of similitude were effectively used to evaluate the soil variables in tillage studies, and to determine the effect of soil and tool variables upon the resultant forces on tillage tools. This study was undertaken in an attempt to utilize the techniques of similitude for studying whether draft forces on a potato digger could be predicted from a model; to observe the actual digging operation as the angles were varied; and also to study the movement of the potatoes as they were harvested.

Photographic data was collected to assist in understanding the potato movement out of the ground.

A movable soil bin with stationary tool bar was designed and constructed and instrumentation was installed. Bin velocity, displacement, tool operational depth, vertical and horizontal (draft) forces, and the moment about the horizontal axis were measured and recorded.

Two soil types were used and uniformity tests, by mean bulk volume weight and mean resistance to penetration, were made.

B. Conclusions

1. The experiments revealed that a harvest delineation plane precedes the movement of a digger blade. This delineation plane determines whether or not a root crop will be properly harvested.

Soil character

2. Soil type affects draft and moment about the centroidal axis of the blade. Under the conditions specified draft requirements were consistently higher in the clay loam soil type.

Potato character specific gravity

3a. The specific gravity of the root crop is important to its harvest. Less dense materials are more easily harvested in a given soil medium.

Shape

3b. Shape of the root crop does not appear to be important. Translation and rotation of various shaped buried objects did not appear to be affected by their shapes during harvest.

Movement

4. A low potato movement/digger travel ratio is required for an efficient harvest. Low ratios are associated with short translation distance of the potato before it reaches the soil surface, thus preventing a potato build up in front of the digger.

Draft

5. Draft and moment about the centroidal axis of the blade increased with velocity, depth of operation, steepness of the approach angle and size of the digger. However, draft seemed to be directly related to the cross - sectional area of the soil moved by the digger.

Vertical force also increased due to increases in speed but to a lesser degree than draft and moment. Its direction changed with digger size and operational depth. Generally, the resultant force acted between the lower half and quarter of the blade surface.

Velocity

6. Draft of the .5 scale model was directly proportional to speed in the range of .35 to 1.35 m.p.h.

Digger approach angle

7. Greater approach angles increased draft, vertical force, moment and length of the harvest delineation plane. It appears that a 30 degree approach angle is best for root crop harvesting from the standpoint of power requirement and movement of the potatoes.

Prediction error

8. The experimental results indicated that prototype draft can be predicted from the draft of model diggers. Maximum predicted errors for the .5 scale models ranged between 16 and 20 percent of the corresponding prototype values. For the .75 scale models the highest error was 9 percent. These prediction errors are acceptable

in soil dynamics research (53).

Similitude technique

9. Similitude techniques, when properly used, can effectively predict the forces acting on harvesting tools. However, it is necessary to have adequate and accurate field data before applying such techniques. The effect of relaxing soil property specifications in the laboratory affects primarily the use of small models.

An understanding of the nature and magnitude of some problems present in the process of digging root crops out of the ground has been gained. It manifested itself primarily in the observation that a harvest delineation plane precedes the motion of a root crop harvesting tool. Reference to such a phenomenon could not be found in the literature.

VII. FUTURE RECOMMENDATIONS

Reference to future studies has been made in the course of the discussion, but there are other areas of investigation which are important in understanding the process of harvesting.

1) The existence of a harvest delineation plane as noted from the 2 dimensional studies, indicates that a 3 dimensional inquiry be made in order to define the harvest delineation surface.

2) Studies in soil mechanics that would explain the reason for increased draft due to increased velocity would remove many of the doubts that now persist regarding this phenomenon.

3) Theoretical studies which treat the soil as a fluid with potatoes moving through this medium should be carried out. The knowledge gained from hydro-dynamics and aerodynamics can be of immense value.

4) What constitutes a damaged potato and how to evaluate the damage on a numerical basis due to the digging operation would be a useful exercise. Botanical and physical characteristics, such as the degree of attachment to the plant and roots at harvest, need investigating. The distribution of the tubers within the ridge should be established for each crop.

5) Further study should be conducted to determine the soil properties pertinent to harvesting; and to specify those parameters which are responsible for "soil-type" effects.

6) It is desirable to determine exactly how the resultant force affects digger penetration when the tool operates with approach angles from 30 to 37 degrees for different tool sizes. A clear understanding of how the resultant force affects movement of the tubers is essential to the design of diggers.

7) The method of data collection and evaluation can be improved with the use of an analog computer and X-Y plotter. These instruments reduce the time required for data reduction and provide quick answers. Errors could be detected promptly and repetition of any discrepancies could be avoided.

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APPENDICES

APPENDIX A

The term "root crop" will be used to denote a crop grown specifically for the use of its underground organ irrespective of its morphology. Many underground organs are root swellings, e.g. radish, turnip, beet and carrot; but far more important are the stem modifications usually classified as rhizomes, tubers, bulbs and corms. A list of the important root crops grown in the West Indies follows:

Major Root Crops of the West Indies

Botanical Name	Common Name	Native to
MAJOR		
1) Manihot esculenta Crantz or m. utillissima Pohl	Cassava, manioc tapioca, yuca	Tropical America
2) Ipomoea batatas Lam	Sweet potato	New World
3) Dioscorea spp. (contain several hundred species) most important: alata L. D. Cayenensis Lam D. rotundata Poir	Yam	Africa
4) Solanum tuberosum L	Irish potato	Andean Highlands
MINOR		
5) Maranta arundinacea L.	Arrow root	
6) Calathea alloiua	Topee Tambou	
7) Colocasia esculenta L.	Dasheen and Eddoes	East Africa
8) Xanthosoma	Tannia	

APPENDIX B

Procedure for Determining:

A. Moisture Content and Bulk Volume Density

Field moisture content was determined at four depths, 5, 10, 15 and 20 cm. A 50 mm. diameter, 20 mm. high core sampler was used to take soil samples both in the field and in the laboratory. After the first sample was taken, the top soil was removed in a manner not to disturb the 5-10 cm. layer where another sample was taken. This process was continued until the fourth sample was taken between 15-20 cm. Two other locations were found and similar samples taken. Metal cans were used as sample containers.

The samples were weighed, oven dried at 105^{o}C for 12 hours, and reweighed again. The formulae used for calculating moisture content and bulk volume density respectively are:

1) $$w_a = \frac{w_1 - w_2}{w_2 - w_c}$$

2) $$\rho = \frac{w_1}{u(1 + w_a)}$$

in which w_a = water content (%)
w_1 = weight of container plus moist soil
w_2 = weight of container plus oven-dried soil
w_c = weight of container
u = volume of the mold
ρ = dry bulk density

B. Soil Resistance to Penetration

A standard cone penetrometer was used to measure soil resistance to penetration. It was made of a stainless steel rod, 1.59 cm. in diameter, the cone itself having an included angle of 30 degrees and a cross sectional base area of 1.27 square centimeters. During operation a constant speed of penetration of 18.3 meters per minute was used both for field and laboratory testing.

Four penetrometer readings were taken at random on and around the potato mounds. The four readings were them combined to obtain an average force versus depth curve. Three average curves were produced, one on each of the three days that soil samples were taken for moisture content and dry bulk density analysis.

The force readings were divided by the cross sectional area of the base of the cone. This gave a cone index. The three curves of the cone index versus depth were drawn on one graph (Figure 12, 13) one for each soil type. The curves were used to obtain the soil resistance data that was necessary in preparing soils in the laboratory.

The cone index showed little variation in the force required to penetrate the top eight centimeters of the soil, as the plot had been previously plowed. At about the plow depth which varied from 12 to 20 cm., the resistance to penetration increased rapidly with depth.

Typical cone index versus depth curves of laboratory prepared soil is shown in Figure 14.

Table 11. Field Soil Data.

Sample No.		Depth cm.	Weight: Solid + Water gm.	Weight: After Drying gm.	Moisture Content %	Bulk Density gm/cm^3
1st day	A	5	64	54	15.6	1.66
	B	10	67	56	16.6	1.74
	C	15	71	60	15.5	1.85
	D	20	81	64	21.0	2.10
2nd day	A	5	68	57	16.2	1.77
	B	10	72	60	16.7	1.87
	C	15	80	68	15.0	2.04
	D	20	75	64	14.7	1.95
3rd day	A	5	70	59	15.7	1.82
	B	10	67	55	17.9	1.74
	C	15	78	65	16.7	2.10
	D	20	80	70	14.3	2.40

A, B, C, and D are averages of three samples.

	5 cm.	10 cm.	15 cm.	20 cm.
Average Moisture Content %	15.80	7.06	16.60	16.50
Average Bulk Density gm/cm^3	1.75	1.78	1.99	2.72

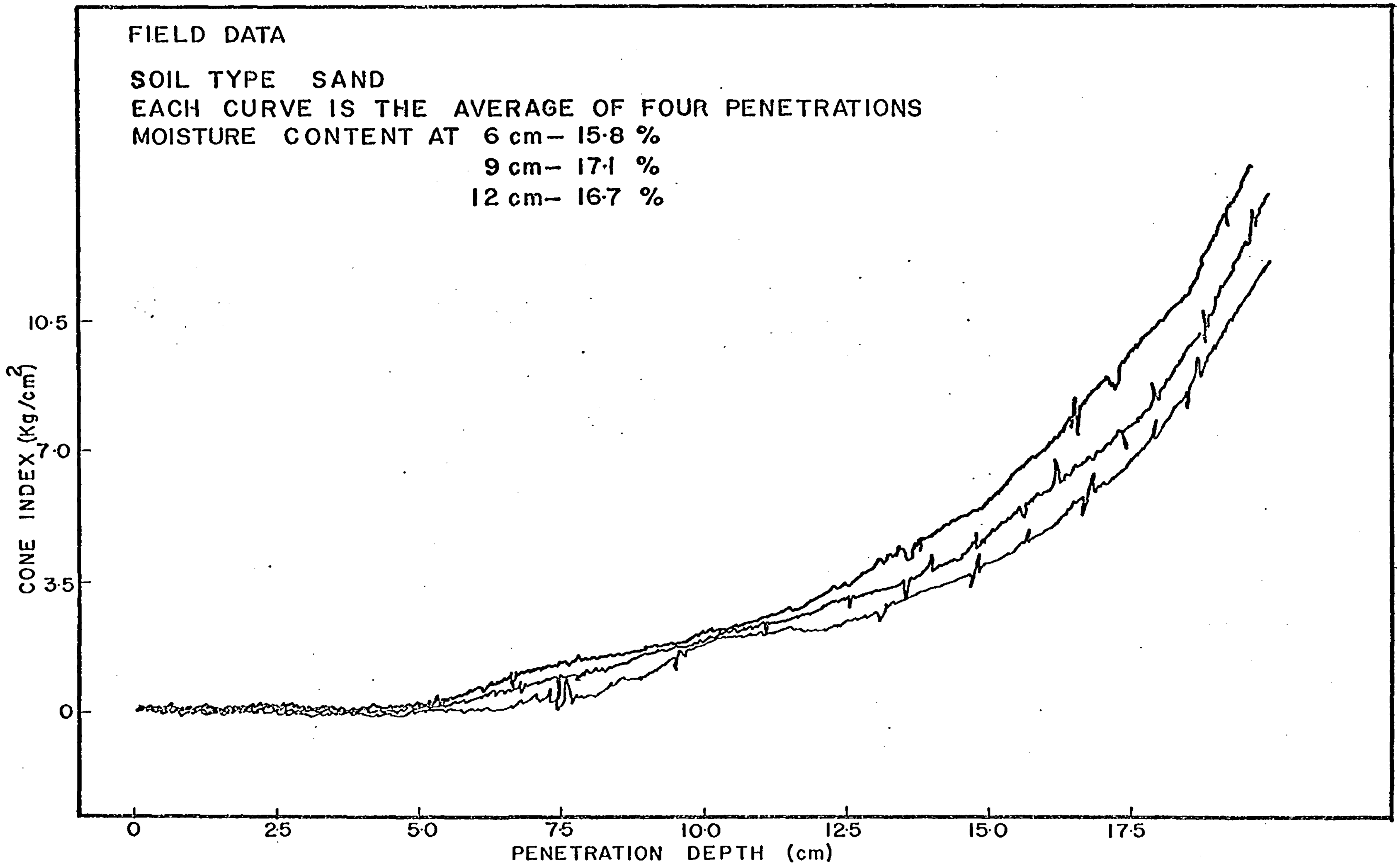


FIGURE 12. RELATION BETWEEN CONE INDEX AND PENETRATION DEPTH.

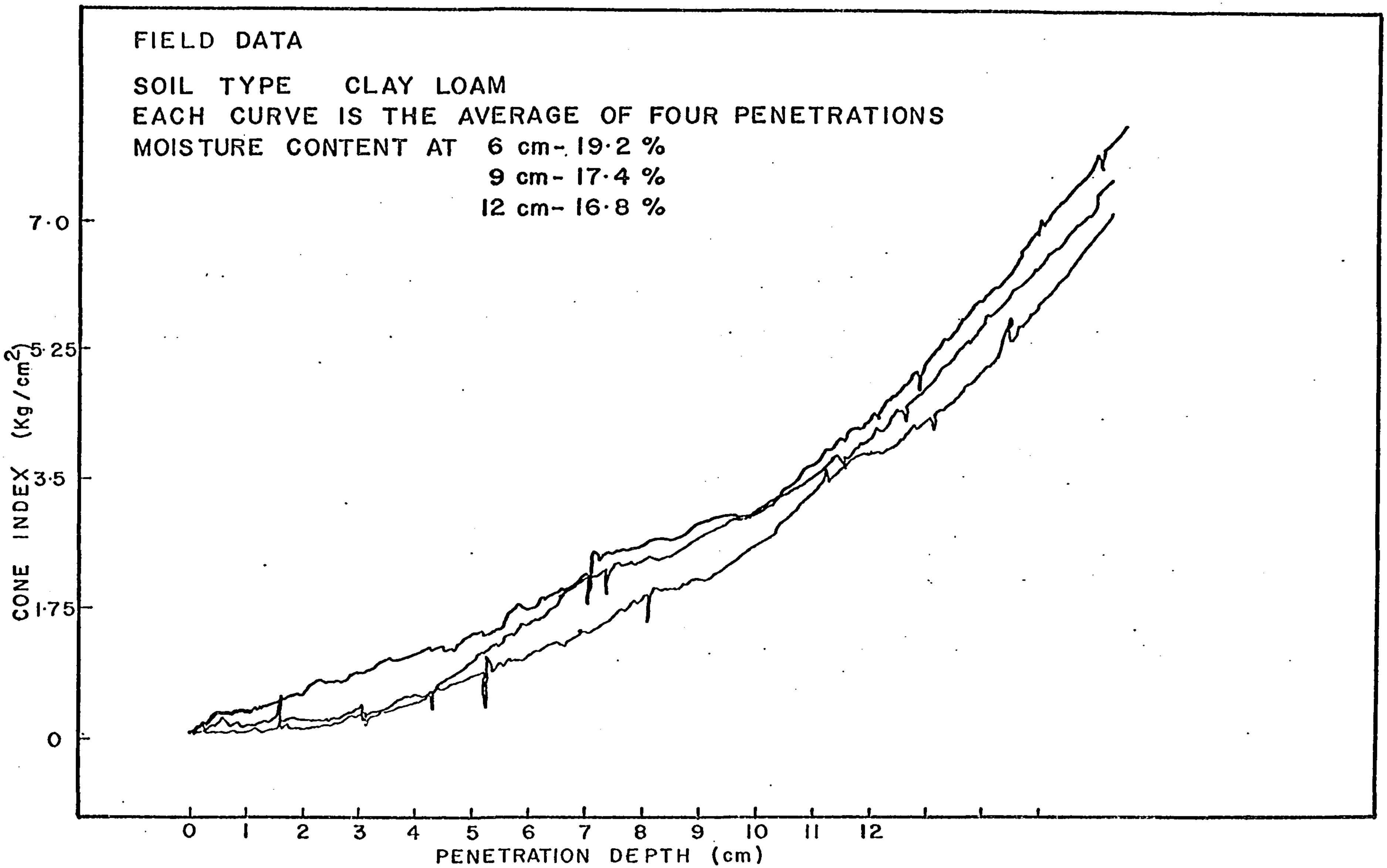


FIGURE 13. RELATION BETWEEN CONE INDEX AND PENETRATION DEPTH

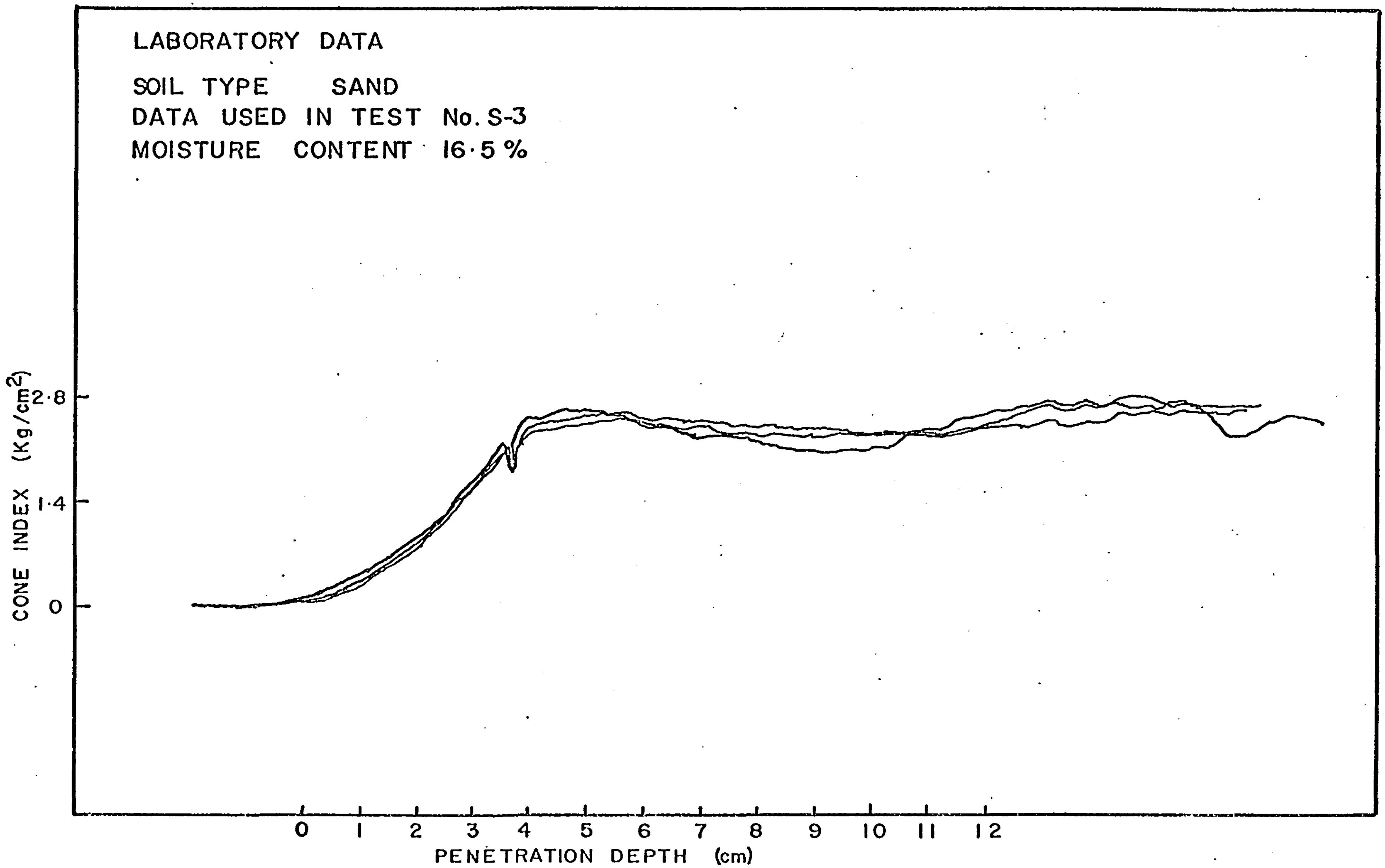


FIGURE 14. RELATION BETWEEN CONE INDEX AND PENETRATION DEPTH IN SAND LABORATORY PREPARATION

APPENDIX C

Sample Calculation of Moment (M_y) and Resultant Force (R)

The transducer was tested on an Instron testing machine to determine if the output of the gauges was a linear function of load. After this proved to be the case the transducer was set in its working position and connected to an oscillograph. Loads were applied to the tool and the lines of deflection recorded on the oscillograph chart were adjusted so that the light trace on the chart was a linear function of load.

M_y was recorded as a force and it was necessary to find the moment arm and to calculate the moment about the transducer axis. The moment arm (r) was found graphically by drawing the mounted tool (E) and transducer (B) as shown in Figure 20. r was measured through X perpendicular to F.

The chart reading of M_y was multiplied by r and thus the calculated moment found. The resultant force acting on the tool was calculated graphically to find both magnitude and direction.

The corrected or true length of the moment arm (S) was then found.

$$S = \frac{\text{Calculated Moment}}{\text{Resultant Force}}$$

The exact position where the resultant force (R) acted on the tool could then be located graphically since S is perpendicular to R. R times the perpendicular distance to the centre of the tool (b) gives the moment about the centroidal axis of the tool.

Test No.	Chart Record of M_y (Kg)	Calculated M_y (Kg cm.)	Resultant R(Kg)	S (cm.)	a (cm.)	b (cm.)	a/w	b x R (Kg cm.)
S7		345	46.1	7.5	3.0	.33	3/17 =.17	14.1

a is the distance from the tool bevelled tip to the point where the resultant force acts (Figure 20)

w is the width of the blade

a/w gives a dimensionless ratio which is used to compare the relative position of the resultant force in different size blades.

APPENDIX D. Glossary

Digger- (blade, tool)-a device which is used for the removal of root crops from the soil. It is used as a shovel which runs beneath the potato, and lifts the tubers and plants out of the ground.

Prototype- refers to the digger which is in use in the field and for which predictions are to be made.

Model - "a device which is so related to a physical system that observations on the model may be used to predict accurately the performance of the physical system in the desired respect" (Murphy, 1950). It is a small scale replica of the prototype.

Pi terms (π) - a Pi term denoted by π is an independent, dimensionless quantity formed by two or more variables influencing the system.

Design Conditions- each dimension and each operating condition of the model should be a replica of the prototype. If for the prototype $\pi_1 = f(\pi_2, \pi_3)$, then for the model, $\pi_{1m} = f(\pi_{2m}, \pi_{3m})$ and the design conditions require that $\pi_2 = \pi_{2m}$

$\pi_3 = \pi_{3m}$

Distortion factor - if a design condition cannot be satisfied such that $\pi_{2m} \neq \pi_2$

but $\pi_{2m} \cdot n_\lambda = \pi_2$

then n_λ is defined as a distortion factor and has a value from 0 to 1. If the model and prototype are geometrically similar, then

$\pi_{2m} = \pi_2$ and $\pi_{3m} = \pi_3$

Transducer -a device for translating a force signal into a strain signal.

Dynamometer - an instrument used for measuring the soil force and turning moment exerted on the digger.

$\frac{\text{Potato movement}}{\text{Digger travel}}$ - this ratio defines the relative movement of a digger and tuber during harvest. Measurement is made of the horizontal distance travelled by the blade and the tuber, from the instant the blade begins to move until the potato falls over the digger to the soil surface.

Harvest delineation plane - a surface demarcating the zone within which potatoes in the soil can be harvested.

SOIL
PROCESSING
EQUIPMENT

CONE PENETROMETER

TEFLON LINED BLADES

SOIL BIN

X-Y RECORDER

Figure 15. Simple Digger to Aid in Harvesting Root Crops Designed by L.G. Campbell.

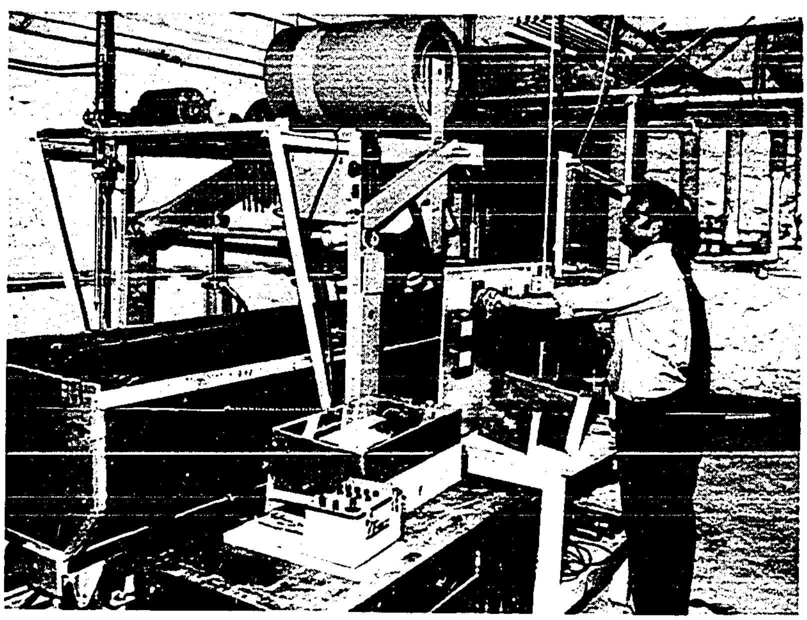


Figure 16. Sideview of the Soil Bin and Related Equipment.

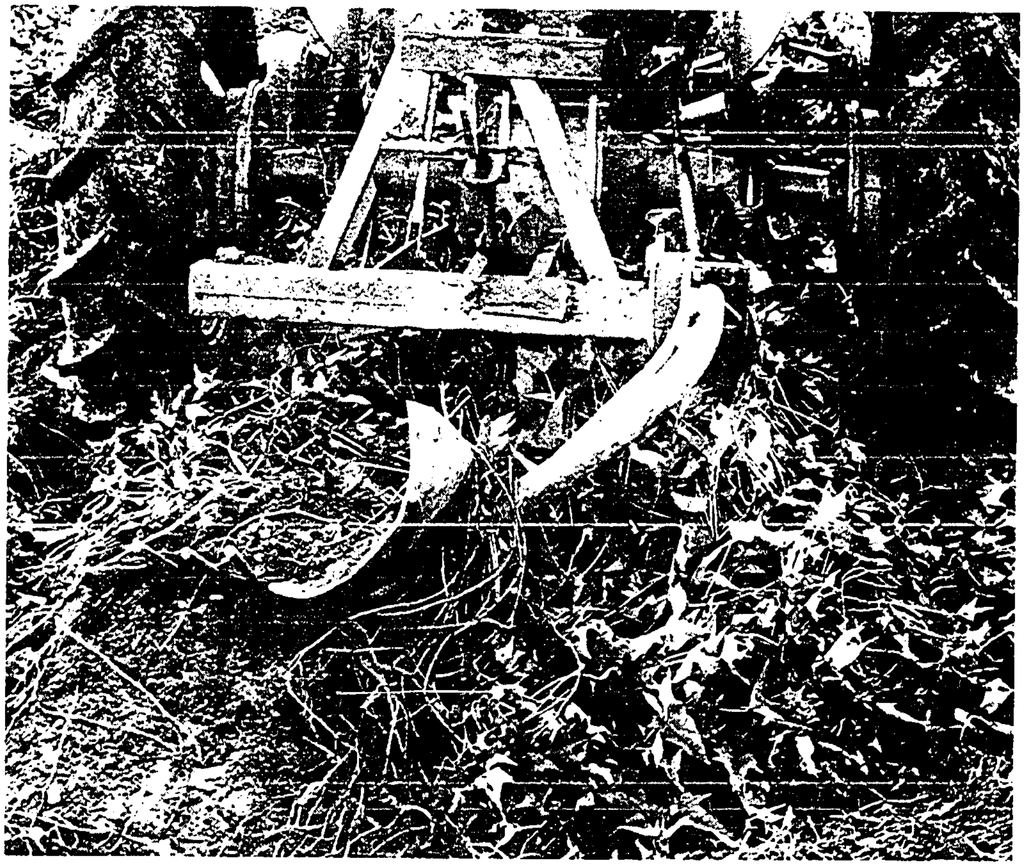


Figure 15. Simple Digger to Aid in Harvesting Root Crops Designed by L.G. Campbell.

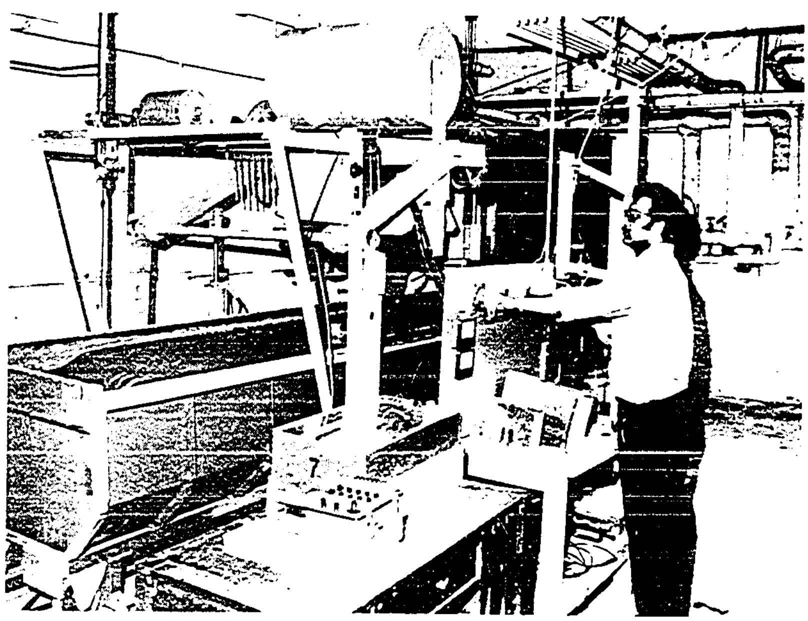
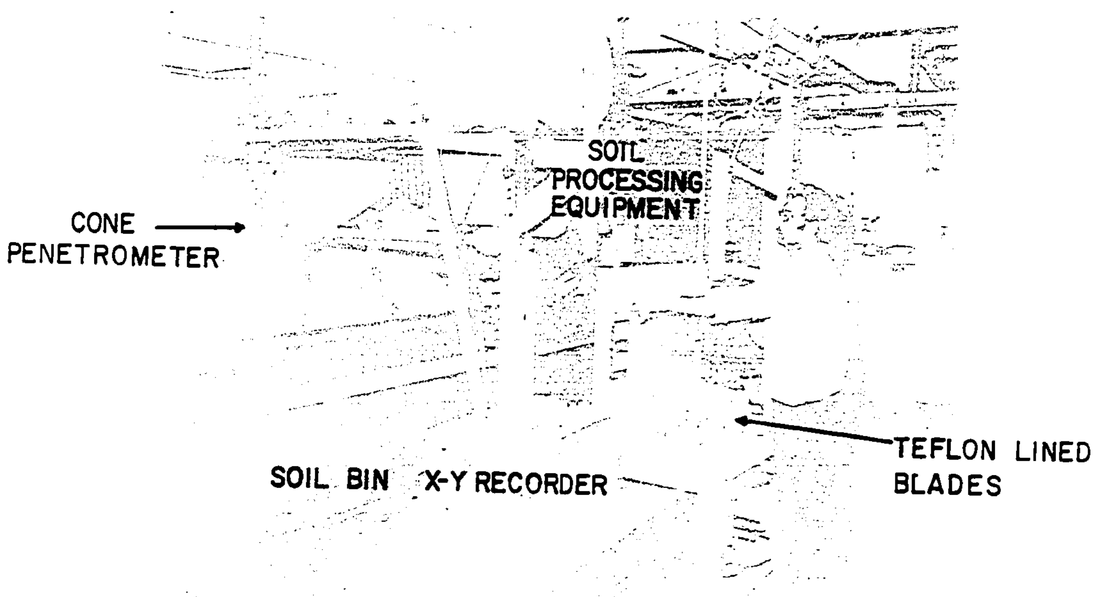


Figure 16. Sideview of the Soil Bin and Related Equipment.



SOIL
PROCESSING
EQUIPMENT
CONE
PENETROMETER
TEFLON LINED
BLADES
SOIL BIN
X-Y RECORDER

GARDEN ROLLER

FORK

CULTIVATOR

LIFTING →
CYLINDER

SOIL BIN

DISPLACEMENT
POTENTIOMETER

TRANSDUCER

DIGGER

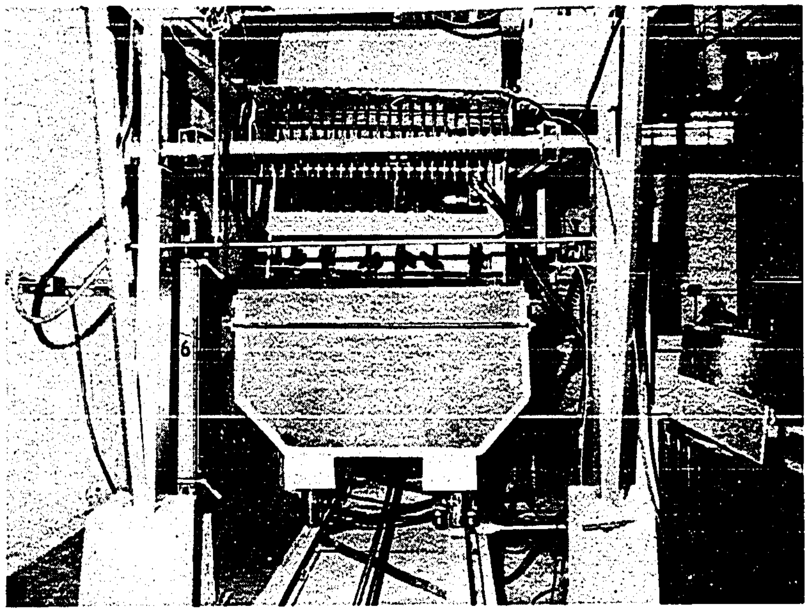


Figure 17. Front View of the Soil Bin and Related Equipment.

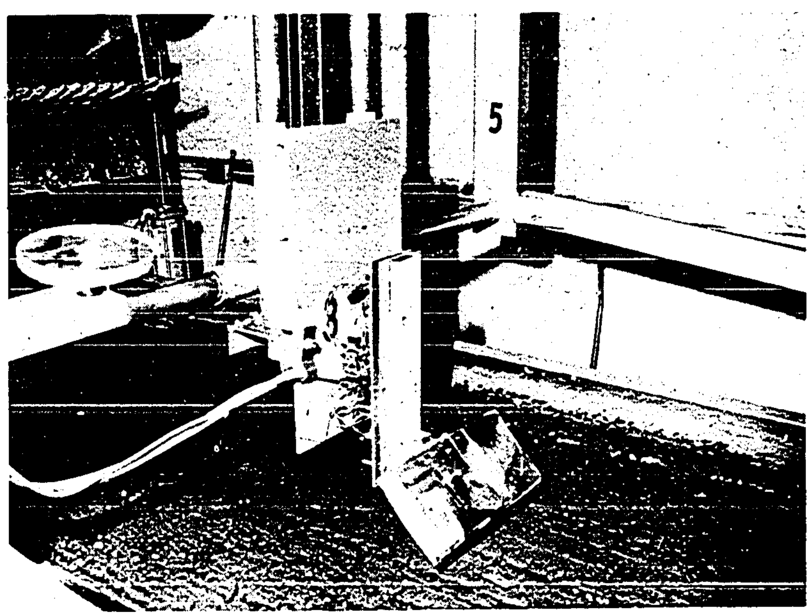


Figure 18. Half Size Model Digger Mounted on the Tool Carrier and Dynamometer.

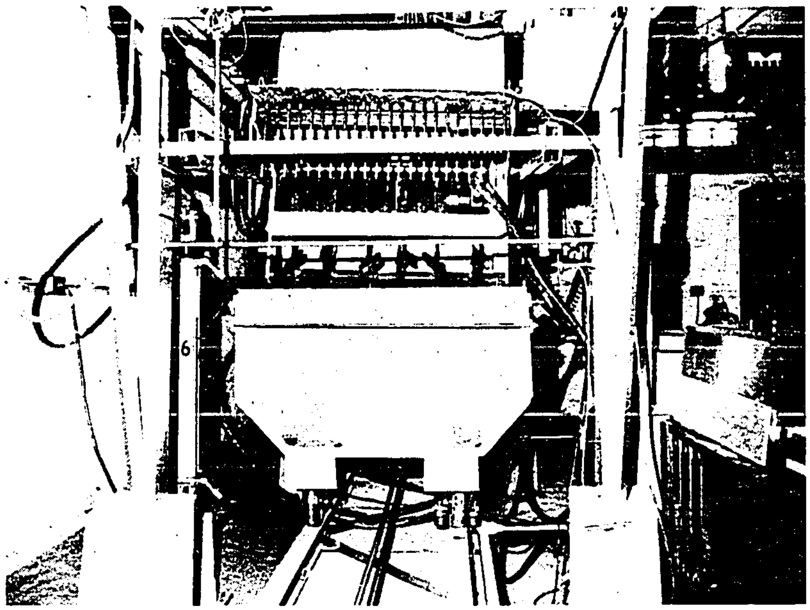


Figure 17. Front View of the Soil Bin and Related Equipment.

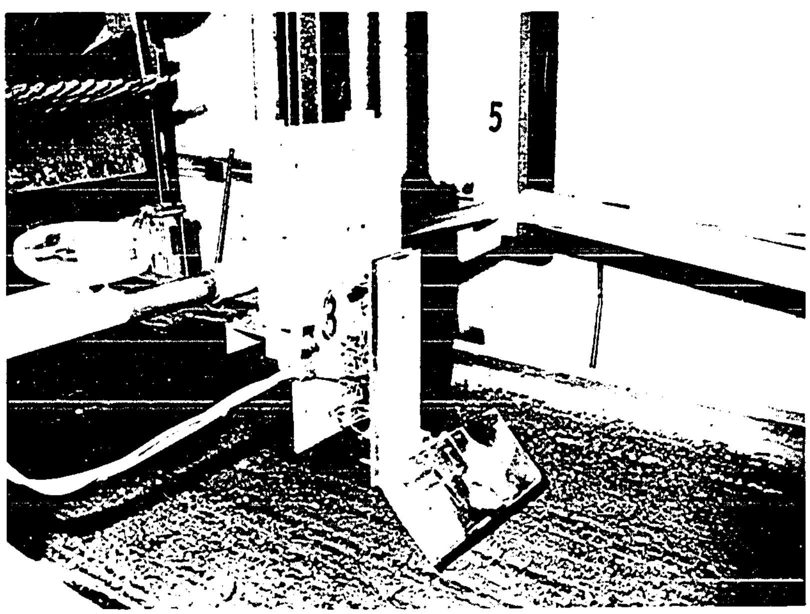


Figure 18. Half Size Model Digger Mounted on the Tool Carrier and Dynamometer.

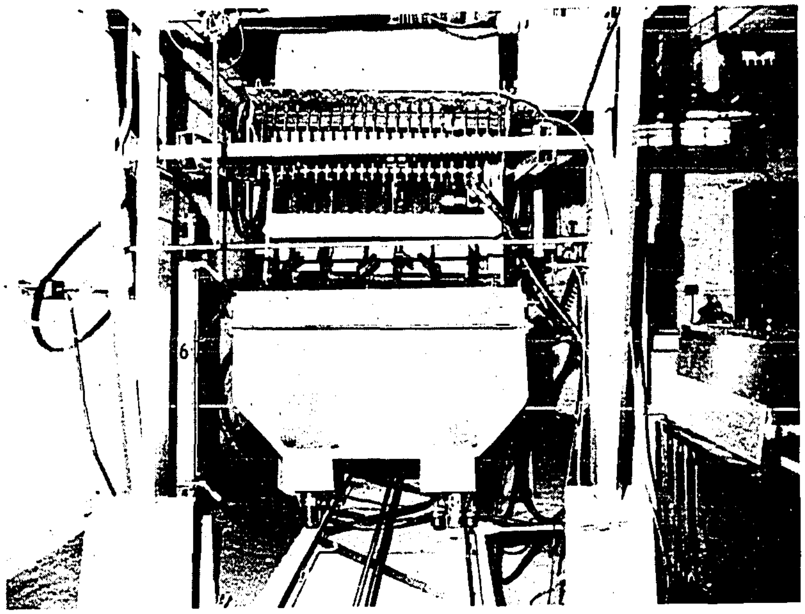


Figure 17. Front View of the Soil Bin and Related Equipment.

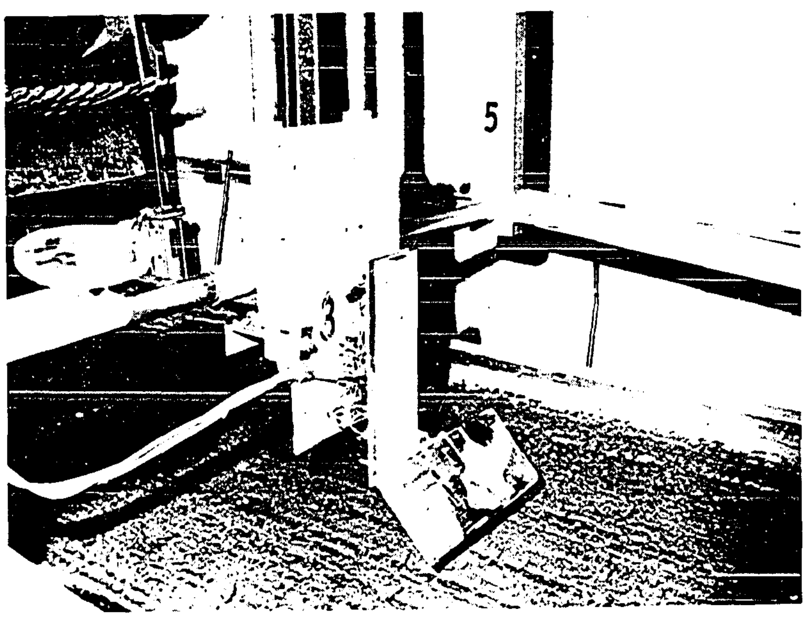
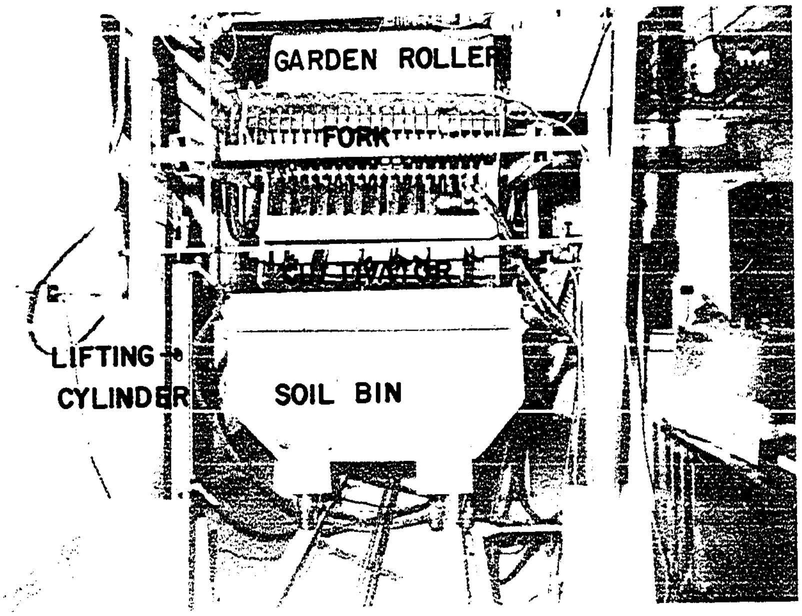
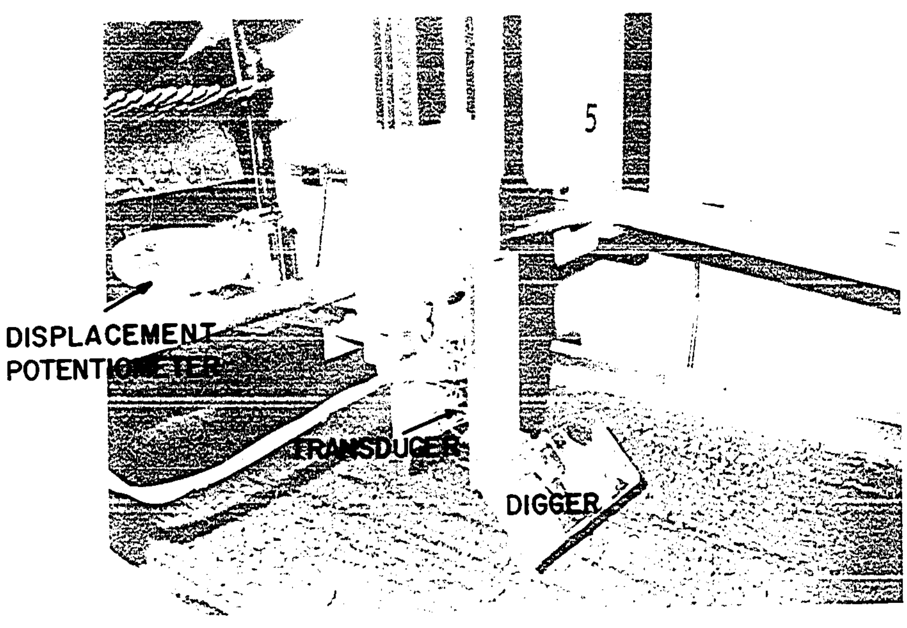


Figure 18. Half Size Model Digger Mounted on the Tool Carrier and Dynamometer.



[illegible] Equipment.



Half Size Model Digger Mounted on the Tool Carrier [illegible]

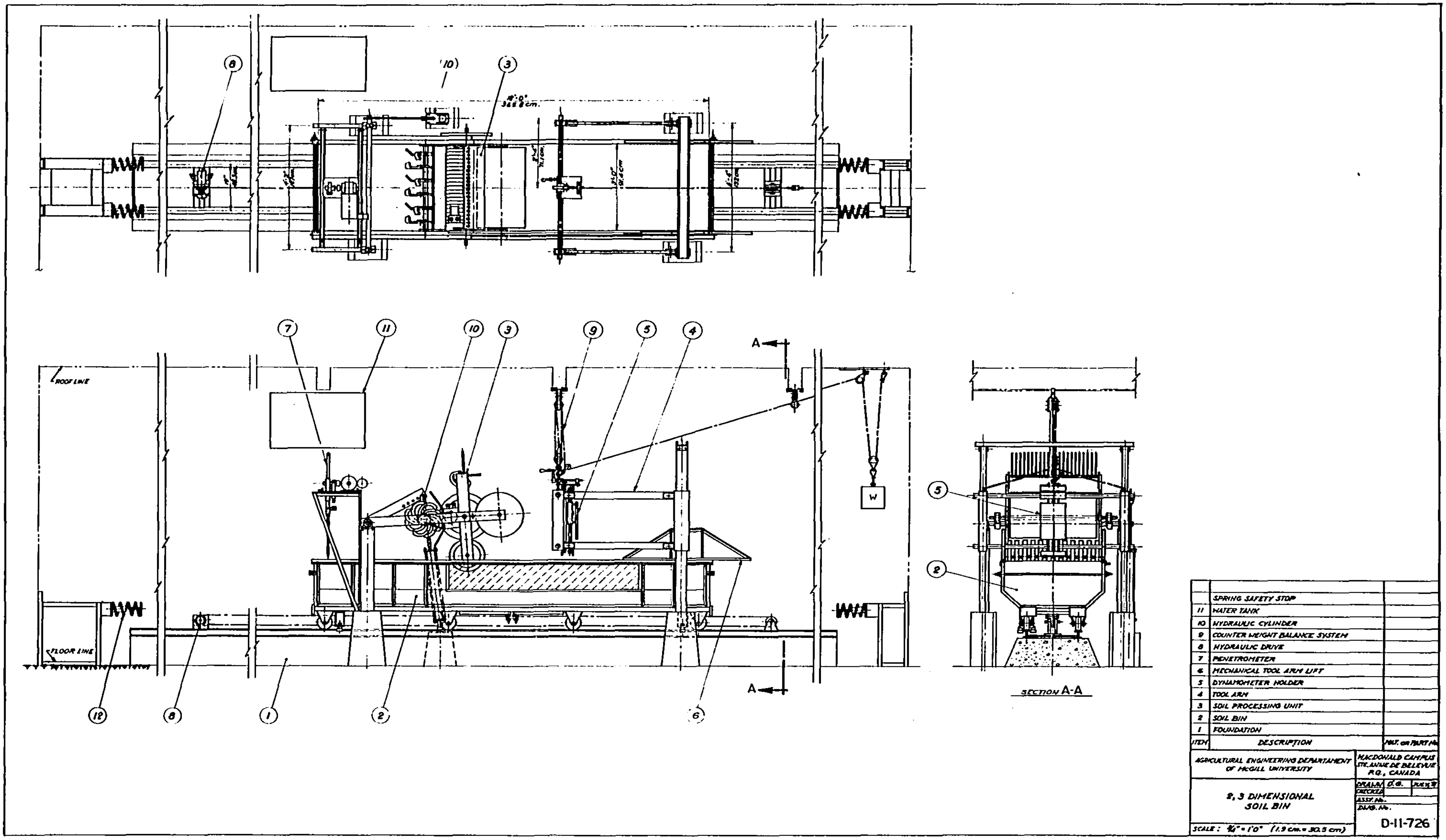


Figure 19. Overall View of 2 - 3 Dimensional Soil Bin.

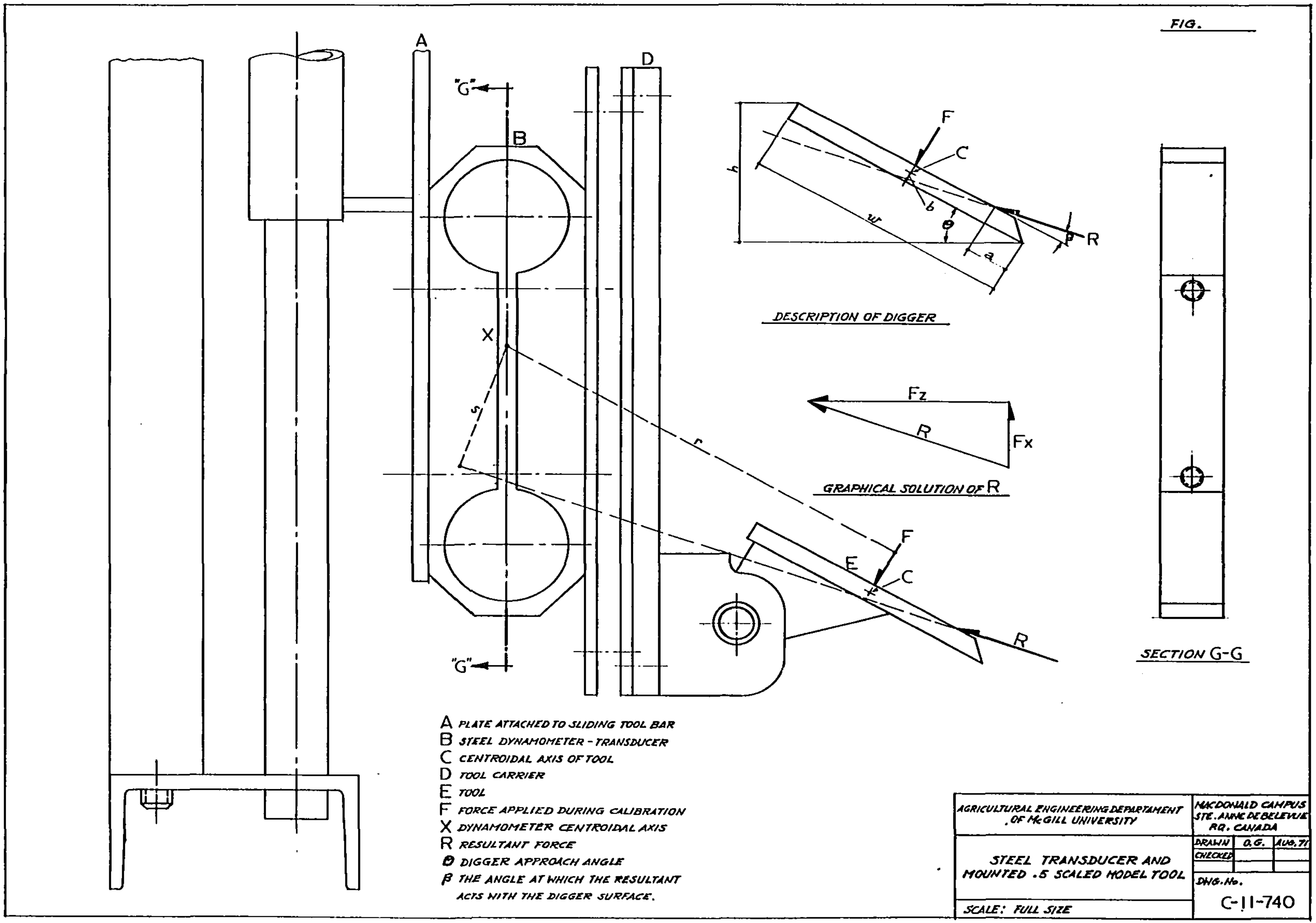


Figure 20. Steel Transducer and Mounted .5 Scaled Tool.

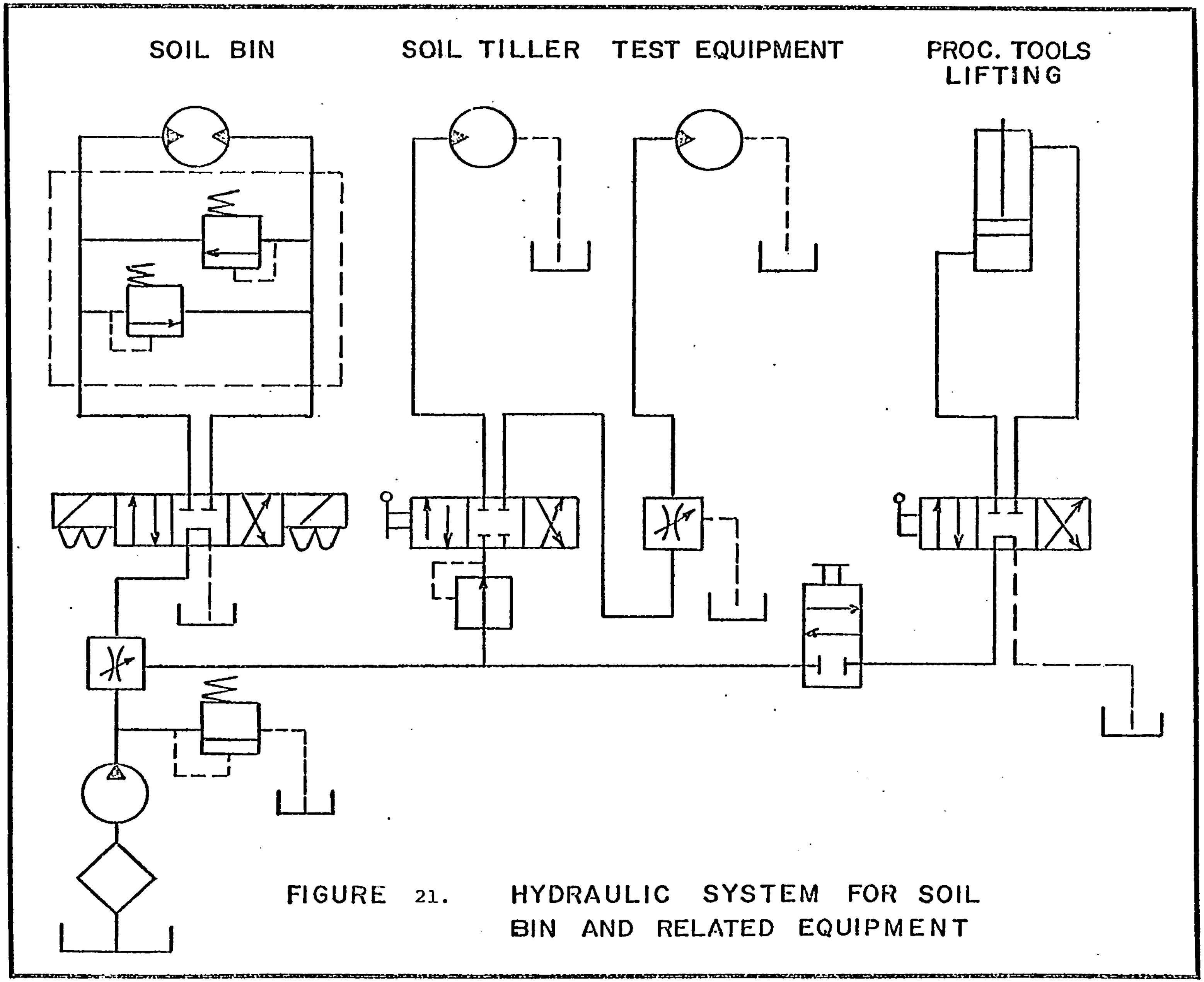


FIGURE 21. HYDRAULIC SYSTEM FOR SOIL BIN AND RELATED EQUIPMENT

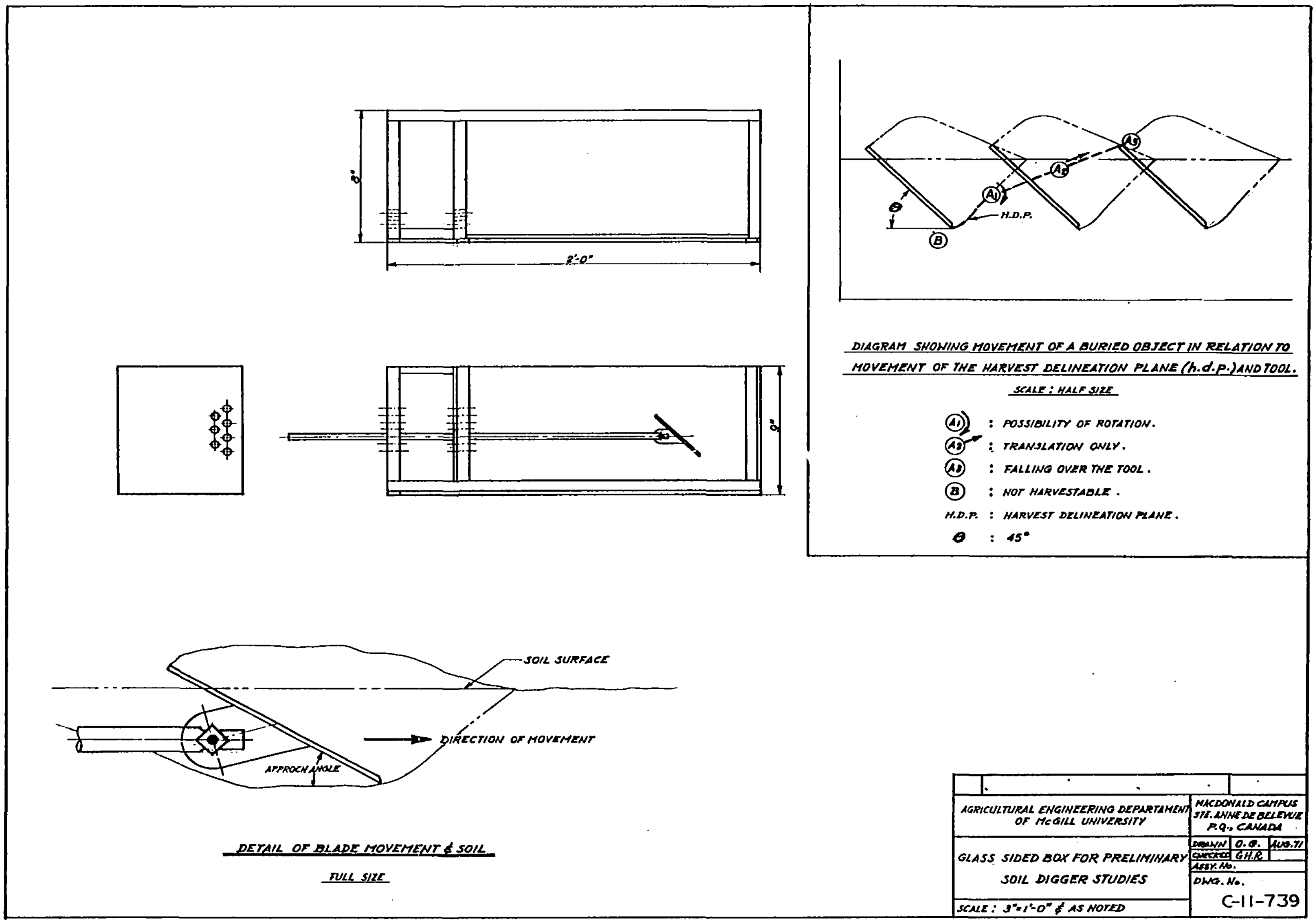


Figure 22. Glass Sided Box.