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EFFECTS OF THE SHAPE AND SPEED ON SOIL RESISTANCE OF THE MOLE PLOW

by

Rustu Kasap

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of the requirements for the degree

of

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in

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Rustu Kasap

Rustu Kasap

NOTATION

A_b	Cross bearing area of the blade, in.^{2}
A_t	Cross bearing area of the torpedo, in.^{2}
ACR	Apparent cohesion ratio, dimensionless
B	Width of footing, in.
b	Thickness of the blade, in.
C	Cohesion of the soil based on effective stresses, lbs./in.^{2}
C'	Cohesion of the soil based on effective stresses on a continuous foundation, lbs./in.^{2}
C_1	Dynamic cohesion of the soil, lbs./in.^{2}
C_H, C_V	Horizontal and vertical component of the force on the torpedo at the distance Z_3 from the beam, lbs.
c	Distributed stress on the torpedo, lbs./in.^{2}
D	Diameter of the bearing area of the torpedo, in.
d	Distance from the soil surface to the center line of the torpedo, in.
d_f	Depth of footing below the soil surface, in.
F	Experimental total of the dynamic resistance acting on the mole plow, lbs.

NOTATION (Continued)

F_1	Theoretical resistance of the soil acting on the mole plow based on Polparsi (1970) equation.
F_b	Bearing resistance of the soil acting to the front of the blade and torpedo on the direction of movement, lbs.
F_f	Friction resistance of the soil acting on the side surfaces of the blade and torpedo in the direction of movement, lbs.
F_{static}	The theoretical static resistance of the soil against the mole plow, lbs.
$F_{dynamic}$	Theoretical dynamic resistance of the soil against the mole plow, lbs.
F^R	Resultant of the resistance of the soil acting on the mole plow, lbs.
F^H, F^V	Horizontal and vertical components of the resultant force F^R, lbs.
F_1^H	Horizontal force acting on the blade at bearing B, lbs.
F_2^H, F_2^V	Horizontal and vertical components of the force acting on the blade at hinge A, lbs.
F_5^V	Vertical force acting on the pushing beam, lbs.
F_6^H	Horizontal force required to push the mole plow through the soil, lbs.

NOTATION (Continued)

f	Factor for local shear failure varying between 2/3 for a stiff clay, to 1 for a soft clay, dimensionless
h_1	Depth of the blade under ground, in.
j	Distributed stress on the bob, lbs. /in.^{2}
K	Distributed stress on the blade of the mole plow, lbs. /in.^{2}
K_1	Bearing capacity reduction factor for the ellipsoidal bearing area of the torpedoes with different front angles, dimensionless
K_2	Ratio of the effective frictional area to the actual area, dimensionless
L	Beam length from the hitch to the blade, in.
ℓ	Resistance from hitch "0" to B_v, in.
ℓ_4	Distance from hinge A to F_4^V on upper member of the pushing beam, in.
ℓ_5	Distance from F_5^V to F_4^V on the upper member of the pushing beam, in.
N_c, N_γ, N_q	The bearing capacity factors, dimensionless
N_c', N_γ', N_q'	The bearing capacity factors for continuous foundation, dimensionless
P	Distributed stress of the ground on the beam, lbs.
P_H, P_V	Horizontal and vertical components of the force on the beam, lbs.
Q_b	Bearing resistance of the soil on the blade, lbs.

NOTATION (Continued)

Q_t	Bearing resistance of the soil on the front of the torpedo, lbs.
R_1, R_2	Reactions on the roller bearing support No. 1 and No. 2, lbs.
S_e	Total effective frictional area of the mole plow, in.^{2}
S_b, S_t	Gross frictional surface areas of the portion of the blade and torpedo of the mole plow moving in the soil, in.^{2}
S_s	Shaft resistance of the pile, lbs. /in.^{2}
T	Haulage tension, lbs.
U	Pore pressure in the soil, lbs. /in.^{2}
W	Weight of the mole plow, lbs.
w	Moisture content, percent
Z_1	Distance from the haulage tension T, to the hinge "0", in.
Z_2	Distance from the blade force K to the beam axis, in.
Z_3	Average depth of a mole channel, in.
γ	Unit weight of soil, lbs. /in.^{3}
ϕ	Angle of internal friction, degree
ϕ'	Angle of internal friction for continuous foundations, degree
$(\Delta q_s)_u$	Ultimate bearing capacity of long footing, lbs. /in.^{2}
$(\Delta q_s)_{ub}$	Ultimate bearing capacity of the soil for the blade, lbs. /in.^{2}

NOTATION (Continued)

$(\Delta q_s)_{ut}$	Ultimate bearing capacity of the soil for the torpedoes, lbs. /in.^{2}
$(\Delta q_s)_{u_1}$	Bearing capacity of the soil in normally consolidated clay for round footing, lbs. /in.^{2}
α	Adhesion of the soil to the surface, lbs. /in.^{2}
σ	Total stress, lbs. /in.^{2}
$\bar{\sigma}$	Effective stress, lbs. /in.^{2}
δ	Angle of friction of the soil on the pile surface, degrees
ρ_b	Bulk density of the soil on dry weight basis, lbs. /in.^{3}

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ABSTRACT

Effects of the Shape and Speed on Soil Resistance

Of the Mole Plow

by

Rustu Kasap, Master of Science

Utah State University, 1971

Major Professor: Komain Unhanand
Department: Agricultural and Irrigation Engineering

The purpose of this study is to investigate the effects of shape and speed of the mole plow on soil resistance by means of a model. Two sets of mole plows were used in these experiments. The first set consisted of five different shapes of mole plows where one has only a blade and the other four have similar blades with torpedoes having different front angles. The second set was similar to the first set except the sides of each plow in the set were made thinner than the front edge to eliminate the friction resistance of the soil on the surface.

An equation for determination of the soil resistance on the plow was developed and expressed as a function of the mole plow shape, speed of the mole plow through the soil, and the physical properties of the soil.

The equation was verified by experiments for the case of a very slowly moving plow with a blunt leading edge. It was found that the theoretical resistance computed from the equation for a very slowly moving plow with a blunt front agreed satisfactorily with the experimental results.

The studies also indicated that by modifying the shape of the mole plow to minimize the frictional resistance on the surface, the power required to operate the plow may be reduced as much as 30 - 40 percent. Such modification can be done by reducing the thickness of the blade and, perhaps, reducing the diameter of the torpedoes of the portion behind the front edge.

(76 pages)

INTRODUCTION

Mole drains are merely unlined cylindrical channels formed in the soil by pulling a plug, bullet shape device or a ball through the soil at a depth of about 18 to 24 inches below the surface. Drains of this type are inexpensive but short lived. The main advantage is the relatively low initial cost in comparison with the tile drainage system. Other benefits from mole drainage include its subsoiling effect, which improves air circulation through the soil and breaks up hard pans; and its use as a subirrigation system, where the irrigation water is applied to the soil through mole channels.

There is ample evidence that carefully planned mole drainage systems operate efficiently and for long periods in clay where levels, contours and other factors are suitable.

The following factors influence efficiency and life of mole drains:

1. Structural stability of the subsoil
2. Soil moisture content at the time and after the moling
3. Amount and intensity of rainfall
4. Seasonal temperature variations
5. Depth of the mole drain
6. Diameter of the mole drain
7. Equipment and method of installation

8. Gradient of channel drains
9. Care of outlets
10. Irregularity of the ground surface
11. Length of the mole drain.

The Importance of the Problem

One of the major factors which govern the installation cost of a mole system is the power required to install the lines. This power requirement will determine whether the power unit available on the farm is adequate to perform the task or the work must be contracted.

Based on present knowledge, factors influencing the power required to draw a mole plow through the soil are:

1. Width of the blade
2. Length of the torpedo
3. Thickness of the blade
4. Diameter of the torpedo
5. Shape of the front end of the blade
6. Shape of the front end of the torpedo
7. Friction between the metal and the soil
8. Speed of the plow
9. Depth of the mole drain
10. Physical properties of the soil.

Previous studies reveal that there is a range of optimum soil moisture most suitable for moling for each soil. Therefore, for a certain soil at its optimum moling soil moisture content, the power requirement for moling is a function of the shape of the mole plow and the operating speed of the pulling tractor. Therefore, knowing the best shape for the mole plow and the optimum tractor speed are essential for the optimization of the power requirements for mole drain construction.

Only a small amount of basic information is available on the mechanics of soil under the influence of mole plow equipment. Even though there are many investigations carried out concerning the performance of various shapes and types of tillage tools, only a few deal with the soil mechanics involved.

This study concerns the mechanics of the soil as a mole plow is drawn through it and whether it is possible to obtain an understanding of the soil failure process and find the analytical solution that would predict the soil resistance as a plow is moving through the soil. An experimental investigation by means of a model included the measurement of the force required to draw the plow. Different shapes of mole plows and moling speeds were used in the experiments. The result of the experimental investigation was compared with the theoretical predictions for certain cases. It is expected that the studies should yield information on the effects of the shape of the mole plow and moling speed on the power requirement.

Objectives

The primary objective of the study is to investigate the effect of the shape of the mole plow and the operating speed on the resistance of the soil by means of a model in the following manner:

1. To investigate the resistance of the soil for a different design of mole plow moving at a very slow speed through the soil.

2. To study the variation of the soil resistance with the speeds of the mole plow.

3. To investigate the possibilities of reducing power requirements for moling by modifying the shape of the torpedo and the blade.

Limitations

Due to the nature of the problem which involves a large number of variables, it is necessary to set limitations to eliminate some of the variables.

1. Only one type of soil was used throughout the experiments. The soil selected contained a large percentage of clay. This was because mole drains are mostly used for drainage of clay soil in which it is found to be more durable than in other soils.

2. The maximum speed of 0.10 mph was used in the experiment. The speed closest to that used in practice cannot be produced in a laboratory with the available equipment. At such speed, more sophisticated testing equipment costing several times the cost of the one available is required.

3. The soil moisture was limited to about 27 percent which was expected to be most suitable for moling as far as the shape and surface of the mole channel were concerned.

REVIEW OF LITERATURE

History of Mole Drainage

There are several indications that mole drains were used in England since 1796 (Weaver, 1964). According to Hudson and Hopewell (1950), the practice of moling dates from the beginning of the eighteenth century in England. They stated that farmers would place a piece of pipe horizontally into the soil 2 to 3 feet deep and pack clay around it, then punch holes in the clay. When the clay dried, the pipe would be pulled out, leaving a hole later known as a "mole". This method was also known as "plug draining". Rid (1956) stated that after the advantages of underdraining became apparent to English farmers, they conceived the idea of underdraining by machinery. Several plows were invented and patented in England, the objective of which was to make surface drains of a few inches depth only.

Klippart (1867) reported that the first account of a mole plow which had succeded was found in the "Repertory of Arts and Sciences," vol. 8, a serial London publication, which commenced about the year 1796. This was the first record which could be found of an implement or machine with which covered or underground drains were successfully made.

According to Harrison (1959), the first reported work with mole drainage in Florida was done in 1928 by Allison at Lake Harbor in the

Everglades mulch soils. Studies at the Everglades indicated that a 30-inch depth was most efficient for moling. Any lesser depth caused the moles to collapse by vertical pressures created when heavy farm equipment crossed them. Also, torpedoes with a diameter larger than 6 inches tended to make larger tunnels, but cave-ins were more likely to occur. A 6-inch diameter torpedo formed a mole tunnel approximately 4 inches in diameter. He also mentioned that spacing between mole tunnels varied from 5 to 10 feet. According to Harrison (1959), however, recent research indicated that moles spaced at 20 feet were just as efficient as those placed at 10 feet.

Hudson and Hopewell (1950) stressed the importance of maintaining a uniform grade when moles are pulled on slopes of less than about 1 in 30, but on steeper slopes they considered that a slight reduction in fall (as long as it is not lost entirely) over a short distance was of little consequence.

Bukavetskas (1966) showed a positive role of mole drainage to dry marshy low lands with peat layers not less than 0.8 inch deep, especially in addition to other drainage methods. The yield increased by 13 - 20 percent and capital investments were justified during 18 - 20 months.

Investigations had been conducted to find the durability of the unlined and plastic lined mole channels by Willardson (1961). The objective of this experiment was to determine the applicability of shallow lined and unlined mole drains to conditions found in a system in the poorly drained lands of Cache Valley. The unlined mole drains collapsed after one year and did not produce water at all. The plastic lined drains successfully survived 3 flooding cycles in addition to over winterings. In the area served by the plastic lined mole drains in the first period of flooding, the electrical conductivity of the soil was reduced from approximately 5 to approximately 0.8 millimhos per centimeter. Additional flooding during the season resulted in no further appreciable reduction in the salt content as the effluent from the mole drains had essentially the same conductivity as the water used for flooding.

Henderson, Lindt and Pearl (1954) reported that mole drains were used on the Sutter Basin for conventional subirrigation which consisted of controlling the water level in the soil by applying water to the moles. He indicated that the land was preirrigated by flooding. Aksenov (1965) described the positive effect of a deep (70 cm) mole plowing

of Chernozen soils for subirrigation on the reduction of evaporation of its moisture during the growing period.

According to Nicholson (1942) and Hudson and Hopewell (1950), mole drains were used quite successfully in Great Britain and New Zealand where the maximum life of the mole drains was as much as 10 to 15 years. The Soil Conservation Service, National Engineering Handbook (1958) stated that mole drainage had been used successfully in some parts of the world, especially in Great Britain, Western Europe, and New Zealand, because climatic conditions as well as the farm lands were suitable for this type of drainage. Mole draining was limited in the United States due partly to the lack of extensive farmland suited for mole drain construction, partly to the past high cost of adequate power equipment to install the drains, but largely due to the lack of understanding of their requirements and limitations which resulted in many past failures.

Power Requirements

There are several factors affecting the power requirement for operating the mole plow. Piper (1958) reported that under average

conditions a light mole plow with a 1/2-inch blade and a 2-inch plug at a depth of 8 inch can be drawn by a tractor of not less than 25 drawbar horsepower. The state of the surface soil affects the traction.

Mayo (1955) stated that for ease of operation a tracklaying tractor of the 30 to 40 horsepower class was required and was absolutely necessary on rolling country. Wheeled tractors fitted with steel grippers of 30 to 40 horsepower had completed the work using 2-1/2 inch mole torpedoes on a flat country.

Norum and Gray (1964) discussed that the pull required to install mole lines varies with the texture, moisture content and bulk density of the soil and depth of operation. They also expressed that the pull required to install lines to a depth of 2 feet in sandy loam and clay loam soils having moisture at field capacity may be in the order of magnitude of 10,000 pounds. It was generally accepted that the resultant force on a tillage implement pulled at a constant speed of operation was governed by the shearing strength of the soil and the adhesion of soil to metal. The shearing strength of a soil was dependent on its cohesive strength and angle of internal friction. In turn, such properties varied with the soil factors such as bulk density, clay content, and soil moisture content.

To obtain the pull requirements of the mole plow under different condition, Norum and Gray ran a series of tests in 3 different soil types: sandy loam; loam and a clay loam. In these tests the measured the pull by a simple beam type, strain gauge dynamometer coupled

between the power unit and the mole carrier. Visual reading of pull were observed during the time taken to install a line approximately 100 feet in length. These readings were then averaged to obtain a representative pull for a given soil at a given depth. In as much as the line of pull was nearly horizontal in the direction of travel, the pull observed can be taken equal to the draft. All lines were constructed at a speed of 1-1/2 mph. Then they applied the principles of dimensional analysis to the results of these tests. Dimensionless prediction equations expressing the relationship between pull, F, average depth of mole channel, Z_3, thickness of mole blade, b, bulk density of the soil, ρ_b. and the moisture content of the soil, w, were derived for each soil type are shown below:

Sandy loam: $F/Z_3^3 \rho_b = 35 - 0.25 w - 0.61 Z_3/b$ (1)

Loam: $F/Z_3^3 \rho_b = 81 - 0.53 w - 2.5 Z_3/b$ (2)

Clay loam: $F/Z_3^3 \rho_b = 92 - 1.1 w - 2.3 Z_3/b$ (3)

They found from the equations two interesting aspects regarding the interrelationship between pull and moisture content and depth of operation as follows:

1. A given increase in moisture content in the clay loam soil produced a larger decrease in pull than an equal change in moisture content of the sandy loam soil.

2. A given increase in depth of operation in the clay loam soil produced a greater increase in pull than an equal change in depth in sandy loam soil.

The range in validity of their equations was limited to the test conditions, which were:

1. A speed of operation of approximately one and one-half mph,

2. Moisture content within the range of 15 to 25 percent for the sandy loam, 10 to 28 percent for the loam and 11 to 25 percent for the clay loam,

3. Ranges in depths of operation within 17 to 24 inches in the sandy loam, 16 to 22 inches in the loam and 16 to 21 inches in the clay loam,

4. A mole plow which was geometrically similar to the one used in all the tests.

These results were related to differences in the cohesive and adhesive properties of the different soils. According to Baver (1959), the cohesive force in a soil was a function of the number and thickness of the moisture films between soil particles. This force becomes larger as the number of films becomes greater and the thickness of the films becomes smaller. Baver reported that Johannsen found the force required to cause a metal wedge to penetrate clay briquettes increased rapidly with decreasing moisture content less than 25 percent. In fine sandy soils this force increased rapidly with decreasing moisture

content for moisture content less than 7 percent but only attained a maximum increase in resistance equal to approximately one-third of the maximum attained in the clay soil. With respect to resistance of adhesion in a soil, Nichols (1931) found that draft increased linearly with the colloid content in the soil.

Schwab (1947) stated that track-type tractors or cable winches were suitable for pulling in mole drains. The power requirements varied from about 30 to 70 horsepower for depths of 2 and 3 feet, respectively, depending on tractor speed, soil moisture, soil type, and size of the mole channel.

Hudson, Hopewell, Bowler and Cross (1962) expressed that the factors which determine the size of the tractor to carry out the mole drainage work were so variable that they hesitated to approach this subject. They stated that the results of draft measurements of a mole plow at Massey College serve to emphasize the importance of soil moisture conditions. In August, when the subsoil was moist, the average pull was 2,100 pounds, which is well within the range of a wheel tractor in the 18 - 20 drawbar horsepower class. By October, the clay was still moleable, but considerably drier than in August, and surface conditions were ideal. At that time average pull required was about 4,000 pounds. A crawler tractor in the 21 - 25 drawbar horsepower class in good condition would have carried out this work because of the lower gear ratio generally available in this type of machine. By

November, the clay had dried still further and a pull of 6,500 pounds was recorded, at which point a 40 drawbar horsepower tractor stalled.

Hudson, Hopewell, Bowler and Cross also indicated that in heavier soils the power required would be increased but not so greatly if the subsoil was wet. Reports from farmers suggested that the draft was increased considerably when these soils started to dry out.

Childs (1942) described the elements of mole plow as shown in Figure 1. It consisted of a steel beam hauled by a force applied at the forward end and carrying a blade and torpedo at the rear end. The elements of a mole plow and the forces acting on it as shown in Figure 1 are:

T is the haulage tension, lbs.

P is the distribution stress on the blade of the mole plow, lbs. /in.^{2}

K is the distributed stress on the blade of the mole plow, lbs. /in.^{2}

c is the distributed stress on the torpedo, lbs. /in.^{2}

j is the distributed stress on the bob, lbs. /in.^{2}

When the mole plow was moved through the soil, frictional resistance acted between steel and metal as a function of the velocity of travel. There was also shear stress parallel to the line of intersection of the steel and a surface parallel to the ground and passing through the point at which the stress was being considered. Because of the symmetry, the resultant of the lateral components of these distributed forces was zero.

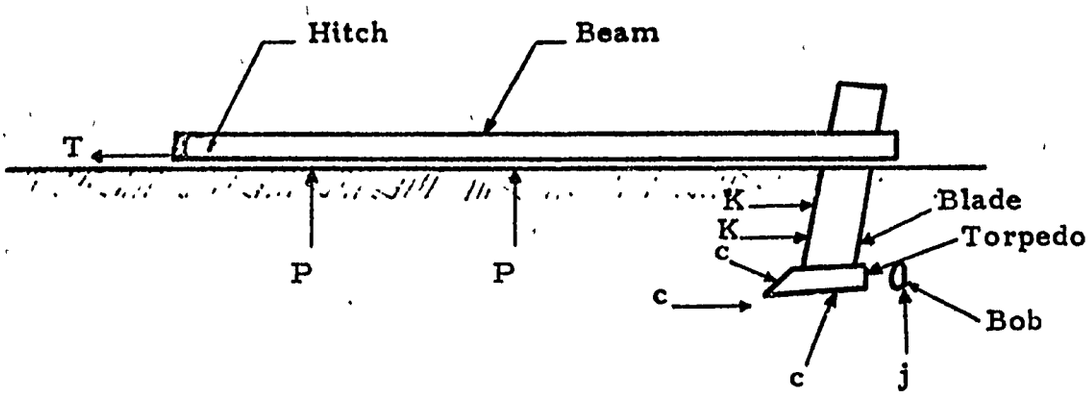


Figure 1. Diagrammatic sketch showing the elements of the mole plow. (Taken from Childs, E. C., 1942. The Mechanics of Mole Draining, Eng. Jour. Exp. Agr. 10, 169-181 p.)

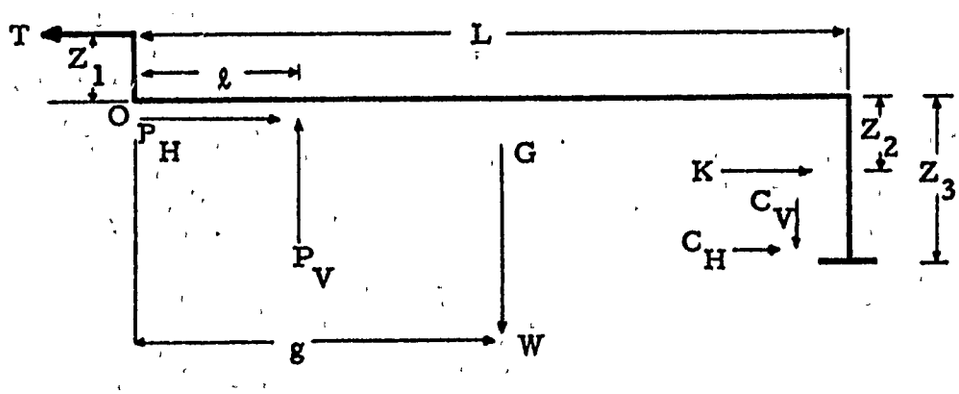


Figure 2. The force diagram for the mole plow. (Taken from Childs, E. C., 1942. The Mechanics of Mole Draining, Eng. Jour. Exp. Agr. 10, 169-181 p.)

In considering the equilibrium of the mole plow, the mole plow was assumed to move through the soil at a constant speed. The blade was set perpendicular to the direction of motion which was considered horizontal. All the distributed forces may be replaced by their corresponding resultants acting at each point, and the resultants could be substituted by their components parallel and perpendicular to the direction of motion. Figure 2 shows the force diagram for the mole plow treated in this way.

T is the tension having no vertical component; acting at the distance Z_1 from the hitch O, lbs.

K is the resistance blade force with no vertical component acting at the depth Z_2 from the beam, lbs.

P_V and P_H are the vertical and horizontal components, of the force on the beam

C_H and C_V are the horizontal and vertical components of the force on the torpedo at the distance Z_3 from the beam, lbs.

W is the weight of the mole plow acting at the center of gravity G which is at a distance g, behind the hitch O, lbs.

Z_3 is the average depth of mole channel, and the mole plow is to be considered working steadily at this depth, in.

ℓ is the length from hitch "C" to P_V, lbs.

L is the beam length from hitch to blade, in.

The conditions for static equillibrium were that the algebraic sums of the horizontal forces, the vertical forces, and the moments about any point were zero. Childs developed three equations based on the conditions for static equilibrium as shown below.

$$T = P_H + K + C_H \tag{4}$$

$$P_V = W + C_v \tag{5}$$

$$\ell P_V + Z_2 K + Z_3 C_H + Z_1 T = gW + L C_v \tag{6}$$

Childs also expressed that the measurements on the individual parts of the mole plow were not easily obtained, with the exception of the tension T. The draw-bar pull required to haul a mole plow in clay soil, at the depth of 24 inches and 3.5 inches in diameter channel was about 5,000 - 6,000 pounds. This draw-bar was less for shallow and small size of work and may be about 10,000 pounds for a mole channel 3-1/2 or 4 inch diameter drawn at a depth of 30 inches in dryish clay soil. He also took an average value of 6,000 pounds for a mole channel 3.5 inch diameter at the depth of 24 inches. Then he neglected friction between the beam and the ground in comparison with the great forces opposed to the blade and torpedo, and from Equation (4) obtained

$$K + C_H = 6000 \text{ lbs.} \tag{7}$$

The negligence of P_V was only justifiable for rough calculations. It was not intended to give the impression that this force was invariably

negligible. Hudson and Hopewell (1950) cited evidence to show that the necessary increase in haulage tension T when P_H was permitted may be sufficient to cause the mole plow to lift.

Experiments with a model gave the ratio $K/C_H = 2.0$ for a shallow work. Combining this value and Equation (7) yielded:

$$K = 4,000 \text{ lbs.} \tag{8}$$

and

$$C_H \quad 2,000 \text{ lbs.} \tag{9}$$

Childs calculated C_v from Equation (6) by substituting the appropriate values of various terms and found $C_v = 500$ pounds. Childs expressed that it appeared to be possible to design a very light implement to work at a depth as great as 30 inches. In such a case, with a maximum tension of 10,000 pounds, a beam of 1 square inch cross section would be adequate, and therefore the breaking of the beam owing to the tensile stress exceeding the ultimate strength may be ignored. The strength of the beam and the blade was required chiefly to withstand the bending moments where the beam attached to the blade.

Polparsi (1970) developed an equation for the power requirement to operate a mole plow at a very small speed as follows:

$$F_1 = A_b(C N_c + \frac{\gamma}{2} b N_\gamma + \frac{\gamma}{2} h_1 N_q) + A_t(C N_c + 0.9 \frac{\gamma}{2} D N_\gamma + \gamma d N_q) + K_2 (S_b + S_t) C \tag{10}$$

in which

F_1 is the theoretical resistance of soil acting on the mole plow based on Polparsi (1970) equation, lbs.

A_b is the bearing area of the blade, in.^{2}

A_t is the bearing area of torpedo, in.^{2}

C is the cohesion of soil based on effective stresses, lbs. /in.^{2}

N_c, N_γ and Nq are the bearing capacity factors, dimensionless

γ is the unit weight of soil, lbs. /in.^{3}

b is the thickness of the blade, in.

h_1 is depth of blade under ground, in.

D is the diameter of torpedo, in.

d is the distance from the soil surface to center line of torpedo, in.

K_2 is the ratio of the effective frictional area to the actual area, dimensionless

S_b is the actual frictional area of the blade of the mole plow moving in the soil, in.^{2}

S_t is the actual frictional area of the torpedo of the mole plow moving in the soil, in.^{2}

The theoretical force required to operate the mole plow, assuming $K_2 = 1.0$, was found to be approximately 25 percent larger than the value obtained experimentally. Polparsi stated that the variation

of both theoretical and experimental resisting forces with moisture content was small in the range of excessively dry and wet soil. This variation was large in the range of moisture content suitable for the mole channel construction.

Moling Speed

According to Rowe and Barnes (1959) it has long been evident that the horizontal force increased as the plow speed was increased. High speed operation was desirable because it offered a means of increasing the output of machines without adding much to the weight of tractors or machines. They also stated that numerous tests of tillage implements had shown an increase in draft of from 25 to 80 percent when operating speed was doubled from 3 to 6 mph. This was of considerable interest to agricultural engineers, since one of the major methods of increasing the capacity of farm machinery was through higher operating speeds. The draft increase associated with speed was therefore a major factor limiting the speeds at which it was feasible to use mole plows.

Norum and Gray (1964) conducted experiments on mole drains and limited the speed of operation to approximately one and one-half mph.

Hudson, Hopewell, Bowler and Cross (1962) stated that good mole drainage work should be carried out at a slow and steady speed. The faster the torpedo of the mole plow traveled through the clay, the

more likely it was to tear the walls of the drain. They also mentioned that there was a danger where a powerful tractor was used to haul the mole plow to carry out the work at too great a speed. They quoted an instance in which a few drains drawn at a speed of 3-1/2 to 4 mph were of very little use after only 2 years. An experiment to determine the effect of speed of pulling was done in conjunction with the direction of pulling. Outflows over a similar period indicated no significant difference between drains pulled at just under 1 mph and at 3 mph.

Mole Plow Design

Mayo (1955) stated that the general construction of mole plows was similar. As long as any adjustment for depth, the throwing of the plow out of the ground and letting it in were easily accomplished, and draft was not so excessive as to require unusually powerful tractors. The three points that matter in its construction were the thickness of the blade, the size of the plug, and the method of attaching the plug to the torpedo. He described that it was not recommended to use a blade greater than 1/2 inch in thickness, as tests had shown that earlier breakdown of mole channels occurred with the layer blade, because it weakened the top of the channel at the junction of the slit and the channel.

Henderson, et al. (1954), indicated that the moles were formed torpedoes ranging in diameter of 3-1/2 inches to 6 inches, with the

4 and 5 inch sizes the most common.

Piper (1958) recommended that a blade no more than 1/2 inch thick should be used to prevent breakdown of the drain at the point where the slit and channel joined. For the plug size it was preferable to have a steady flow of water in a mole drain rather than the large volume of water that a 4-inch to 6-inch mole could carry. Smaller drains were stronger and as they carried much less water they lasted longer, other conditions being equal. He recommended plugs having a diameter of 1-1/2 inches to 3 inches.

Harrison (1959) reported that moling in the Everglades mulch soils was done with torpedo of bullet shape, 6 inches in diameter, fixed in a galvanized pipe 24 inches in length. The blade thickness was 1 inch.

Childs (1942) used in his experiments the blade strip made of steel, 9 inch wide and 0.75 inch thick and about 3 feet long, bolted and wedged in the beam in a position approximately perpendicular to the latter. It was sharpened at the leading edge, and carried the torpedo at the lower end. The torpedo was a cylindrical bullet of steel which was from 2 to 3-1/2 inches in diameter, and was fixed rigidly to the blade. The nose of the torpedo was tapered off from the top to the bottom, so that in profile it was seen to be chisel-shaped. The torpedo was followed by a freely trailing bob, plug or expander

consisting of a short length of cylindrical steel bar slightly greater in diameter than the torpedo, tapering symmetrically at the fore end.

Cooper (1965) estimated that 80 percent of the draft on a mole plow came from the mole as its leading edge came into contact with undisturbed soil and made the initial break and lifted the soil the blade touched. The nose of a new mole had been cut off at a predetermined angle from the round section bar of which it was made. Apart from this slice, the remainder was round. The same mole plow, after having done much work, was found to have the corners practically worn off where once there was a flat cutaway nose. In all cases the nose of the mole was to be cut off at an angle of 30° or thereabouts, with the flat cut on top. He also gave the following measurements as a guide:

A mole 2 inch dia. and 8 inch long was enough to work 18 inch deep

A mole 3 inch dia. and 2 ft. long was enough to work 2 ft. deep

A mole 4-1/2 inch dia. and 3 ft. long was enough to work 2 ft. 9 inch deep

A mole 5-1/2 inch dia. and 3 ft. 6 inch long was enough to work 3 ft. 6 inch deep.

The above stated measurements had been obtained by a process of trial and error over a period of years. He also stated that, in all cases, the torpedo should be set parallel to the ground surface, as any dipping of the nose was quite unnecessary and would only call for more power at the draw-bar. If it became necessary to dip the nose

of the mole to obtain more penetration, it indicated that the mole had worn out excessively and needed replacement.

Cooper also summarized the requirements of a good mole plow as follows: it should be capable of producing 3-1/2 inch hole, clean and round at a depth of 26 inches. To do this the mole must be set perfectly parallel with the beam above and as this was the only part that held the machine in the ground at all, the minimum diameter of the torpedo must be 3 inches with a length not less than 2 feet, 3 inch, preferable several inches longer.

This should be followed by an expander, attached to the rear of the mole by a bar or chain which should be of sufficient size to seal the cut made by the blade, leaving a hole of the desired size. It should not be necessary to pitch the angle of the blade and mole to make it sit down tight, as this practice only left a ragged hole and created too much ground disturbance immediately above, with a consequent weakening of the roof of the mole.

In determining the length of the beam, it should be remembered that over 90 percent of the draft came from the mole which should be approximately 2 feet deep. This meant that the main resistance was 2 feet below the line of draft with the result that there was a constant strain through the point of resistance trying to get into line with the draw-bar at the front end of the beam. Practice had shown that the most suitable length for the beam was in the proportion of 5 to 1 with the depth at which most of the work was to be done.

THEORY

Forces Acting on the Mole Plow Based on Static Pile Formulas

The mole plow consists of a blade and a torpedo. In most arrangements the resisting force of soil against the mole plow is equal to the force required to pull the mole plow. The total resisting force is equal to the sum of the friction resistance, F_f, and bearing resistance, F_b, as shown in Figure 3 and may be expressed as

$$F_{static} = F_b + F_f \tag{11}$$

where

F_{static} is total resistance under static conditions, lbs.

F_b is total bearing resistance of the soil acting to the front of the blade and torpedo on the direction of movement, lbs.

F_f is the friction resistance of the soil acting to the side surfaces of the blade and torpedo in the direction of movement, lbs.

Bearing Resistance

The bearing capacity of a soil is the ability of the soil to carry a load without failure within the soil mass. The load carrying capacity of soil varies not only with its strength but also with the

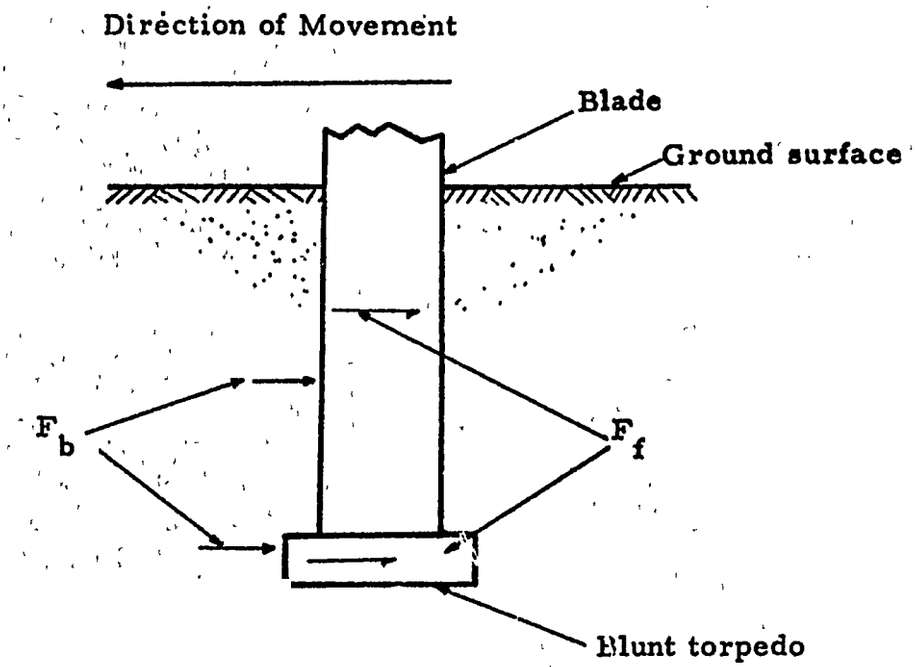


Figure 3. Resistances acting on blunt-front mole plow.

magnitude and distribution of the load. When a load is applied to a soil in gradually increasing amounts, the soil deforms, making a load settlement curve. The load settlement curve goes through a point of maximum curvature, indicating failure within the soil mass. Different curves are obtained, depending on the character of the soil that is loaded.

It is seen that failure of soil in front of the blade and torpedo takes place in a number of stages. First, the soil in front of the blade or torpedo deflects forward and bulges outward like a barrel. Second, there is cracking of the soil around the perimeter of the blade and torpedo. Third, a cone or wedge of soil forms in front of the blade and torpedo which forces the soil forward and outward.

According to Sowers and Sowers (1961), Terzaghi-Meyerhof gives the general expression for bearing capacity for a long footing as follows:

$$(\Delta q_s)_u = CN_c + \frac{\gamma B}{2} N_\gamma + \gamma d_f N_q \tag{12}$$

where

$(\Delta q_s)_u$ is the ultimate bearing capacity of long footing, lbs./in.^{2}

C is cohesion of the soil based on effective stress, lbs./in.^{2}

γ is the unit weight of soil, lbs./in.^{3}

B is the width of footing, in.

d_f is the depth of footing below the soil surface, in.

N_c, N_γ and N_q are the dimensionless bearing capacity factors that are functions of the angle of internal friction. The term containing factor N_c shows the influence of the cohesion, that of N_γ shows the influence of soil weight and foundation width, and that of N_q shows the influence of the surcharge. The values for these factors are given in Figure 4.

The analysis of Terzaghi assumes that the base of the foundation is rough. This prevents the lateral movement of the soil in contact with it and confines the soil as if it were a part of the foundation itself. As a result, the vertical load of the foundation is transmitted directly through the wedge into the soil below, and the angle of the wedge with the horizontal can be assumed equal to ϕ. The surface of

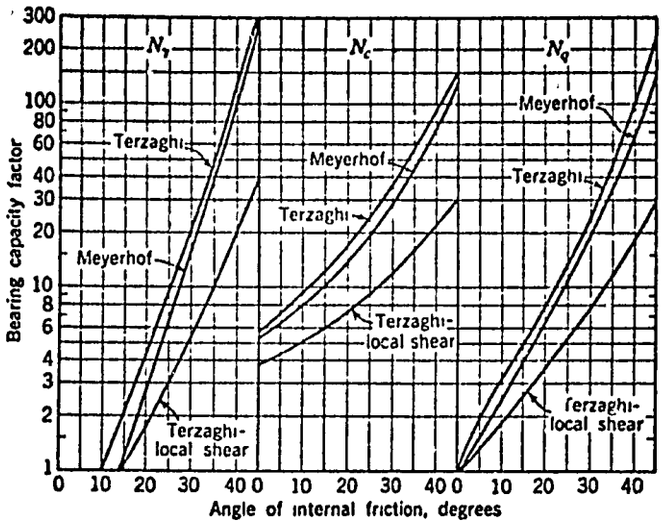


Figure 4. Bearing capacity factors for the general bearing capacity equation (G. A. Leonards 1962 Foundation Engineering, McGraw-Hill Book Company, Inc., New York, 542 pp.).

shear is approximated by a combination of straight lines and logarithmic spirals.

The analyses of Meyerhof differs from that of Terzaghi in a number of respects. First, the angle of the wedge is not assumed to be ϕ. Second, it is assumed that the shear zone extends above the foundation level. As a result, the bearing capacity factors are somewhat lower than those given by Terzaghi

According to Leonard (1962) the choice of which method of analysis is best for any given situation is difficult because only limited test data are available on full-sized foundations to verify the computed bearing capacities. For cohesive soils there is some evidence that

the Meyerhof factors are better. The very limited data for partially saturated clays indicate that both Terzaghi and Meyerhof factors are high.

Bearing resistance on the blade. The total bearing capacity of a soil which is the maximum load the soil can support without failure is equal to the ultimate bearing capacity multiplied by the area to which it applies. Assuming this condition is applicable to the slowly moving blade, bearing resistance on the blade may be expressed as

$$Q_b = A_b \, (\Delta q_s)_{ub} \tag{13}$$

where

A_b is the projected area of the front of the blade in the direction perpendicular to motion, as shown in Figure 5, in.^{2}

Q_b is the bearing resistance on the blade, lbs.

$(\Delta q_s)_{ub}$ is the bearing capacity of the soil for the blade based on Terzaghi's suggestion, lbs./in.^{2}

General bearing capacity equations directly applicable to continuous foundations whose length is greater than 10 times the width are not greatly in error for footings where length is 5 times the width. The analysis is also based on a general shear failure of an ideally plastic material whose volume and strength are unchanged by local rupture. In materials whose strength is reduced by local rupture, the local shear at the edges of the foundation can bring about progressive failure with little increase in load.

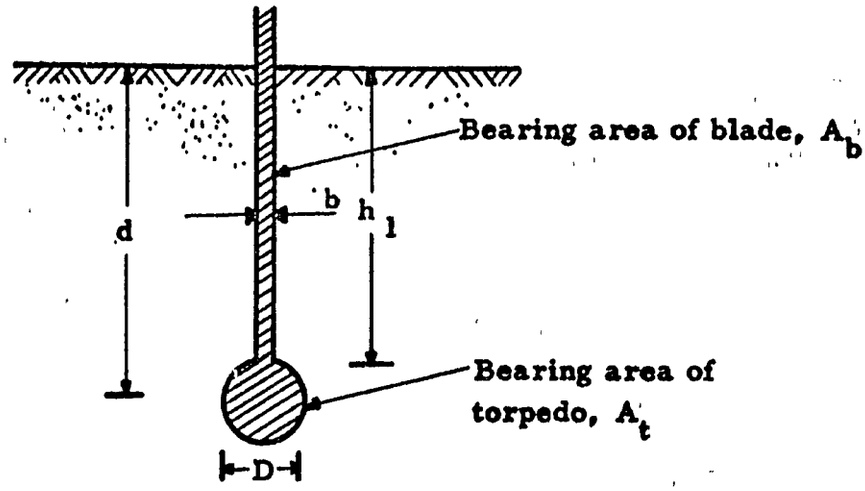


Figure 5. Bearing area of the blade and torpedo of the mole plow.

In materials that change volume under the load or that undergo large strains before reaching failure, forward movement of the soil wedge in front of the blade and torpedo may only compress or distort the soil without straining it sufficiently to produce general shear failure. No rational analysis for this condition has been derived. Terzaghi has suggested an empirical correction to the bearing capacity factors in such soils by using ϕ' for ϕ,

where

$$\tan \phi' = \frac{2}{3} \tan \phi \tag{14}$$

and replacing the cohesion C by $C' = \frac{2}{3} C$.

For a mole plow moving very slowly through clay soil, the bearing capacity for the blade assuming as a continuous foundation can be

expressed as

$$(\Delta q_s)_{ub} = \frac{2}{3} C N_c' + \frac{\gamma b}{2} N_\gamma' + \frac{\gamma h_1}{2} N_q' \tag{15}$$

in which

h_1 is the depth of the blade underground, in.

b is the thickness of the blade, in.

C and γ are the same as previously defined

N_c', N_γ' and N_q' are dimensionless bearing capacity factors for continuous foundations obtained from Figure 4 for ϕ' in which $\tan \phi' = \frac{2}{3} \tan \phi$.

Bearing resistance on the torpedo. Several approximate theoretical analyses have been made for the bearing capacity of round footings. All are based on theoretical considerations plus experimental data, and from the practical standpoint, the differences in the predictions are slight. Based on the equation for bearing resistance on a circular footing suggested by Sowers and Sowers (1961), the bearing resistance on the torpedo front may be expressed as:

$$(\Delta q_s)_u = CN_c + \frac{0.9\,D}{2} \gamma N_\gamma + \gamma d N_q \tag{16}$$

where

D is the diameter of the torpedo, in.

d is the depth of the torpedo from the soil surface to the centerline of the torpedo, in.

γ, C, N_c, N_γ and N_q are the same as previously defined.

In a normally consolidated clay, local shear failure occurs at a much lower value than ultimate. On the other hand, in overconsolidated clay, the bearing capacity based on local and that based on general shear is quite similar. According to Lambe and Whitman (1969) the following equation considers the affect of local shear and may be used to find the bearing capacity $(\Delta q_s)_{u_1}$

$$(\Delta q_s)_{u_1} = f\,C\,N_c + \frac{0.9\,D\,\gamma}{2}\,N_\gamma + \gamma d\,N_q \tag{17}$$

where

$(\Delta q_s)_{u_1}$ is the bearing capacity of the soil in normally consolidated clay for round footing, lbs./in.^{2}

f is a factor for local shear failure varying between $\frac{2}{3}$ for a stiff clay to 1 for a soft clay.

C, γ, D, d, N_c, N_γ and N_q are the same as previously defined.

The bearing capacity for torpedoes having a sharp front end may be expressed as

$$(\Delta q_s)_{ut} = K_1\,(f\,C\,N_c + \frac{0.9\,D\,\gamma}{2}\,N_\gamma + \gamma d\,N_q) \tag{18}$$

where

$(\Delta q_s)_{ut}$ is the bearing capacity of torpedoes with different front end shapes, lbs./in.^{2}

K_1 = bearing capacity reduction factor for ellipsoidal bearing area of torpedoes with different front end shapes, dimensionless

Other terms are as defined previously.

The bearing resistance of the soil on the torpedo is equal to the product of the bearing capacity on the torpedo and projected area of the front of the torpedo and is given by the equation:

$$Q_t = A_t \cdot (\Delta q_s)_{ut} \tag{19}$$

in which

Q_t is the bearing resistance of the soil on the front of the torpedo

A_t is the projected bearing area of the torpedo perpendicular to the direction of motion, in.^{2}

$(\Delta q_s)_{ut}$ is the same as previously defined.

The total bearing resistance on the mole plow F_b is the sum of the Q_b and Q_t and can be expressed as follows:

$$F_b = Q_b + Q_t \tag{20}$$

or

$$F_b = A_b (\Delta q_s)_{ub} + A_t (\Delta q_s)_{ut} \tag{21}$$

Frictional Resistance

According to Lambe and Whitman (1969) the frictional resistance along the pile surface is as follows:

$$S_s = C + \bar{\sigma} \tan \phi \tag{22}$$

where

S_s is the shaft resistance of the pile, lbs. /in.^{2}

C is the cohesion based on effective stresses, lbs. /in.^{2}

$\bar{\sigma}$ is the effective stresses, lbs. /in.^{2}

ϕ is the angle of internal friction angle, dimensionless.

Sowers (1961) expressed that shaft resistance acting along the pile is equal to the sum of the friction and adhesion of the soil on the pile or to the shear strength of the soil immediately adjacent to the pile, whichever of the two is the smaller. If S_s is the shaft resistance, then

$$S_s = C + \bar{\sigma} \tan \phi, \text{ or} \tag{23}$$

$$= \alpha + \bar{\sigma} \tan \delta, \text{ whichever is smaller.} \tag{24}$$

where

S_s is the shaft resistance, lbs. /in.^{2}

α is adhesion to the surface, lbs. /in.^{2}

δ is the angle of friction of the soil on the pile surface, degree

C, $\bar{\sigma}$ and ϕ are the same as previously defined.

Typical values for α range from 0.8 C to 1.0 C, depending on the surface roughness. Sowers also mentioned that tan δ varies between 0.2 and 0.4 for smooth steel.

The effective stress of soil is defined by the equation.

$$\bar{\sigma} = \sigma - u \tag{25}$$

where

$\bar{\sigma}$ is the effective stress, lbs. /in.^{2}

σ is the total stress, lbs. /in.^{2}

u is the pore pressure, lbs. /in.^{2}

If external loads increase such that the induced pore pressures develop as high as the total stress acting on the soil, shear strength from Equation (22) becomes

$$S_s = C \tag{26}$$

The total friction resistance is equal to the product of the shear strength and the effective frictional area on which it acts. According to Lambe and Whitman (1969), in stiff clay soils there is evidence that the entire area of the pile shaft is not in full contact with the soil.

For a mole plow with a blunt front on the torpedo as shown in Figure 6, the frictional area of the blade is the surface on both sides of the portion of the blade below ground surface. The frictional area of the torpedo is the area of the cylindrical surface of the torpedo. The total effective frictional area of a mole plow may be expressed as

$$S_e = K_2 (S_b + S_t) \tag{27}$$

where

S_e is the total effective frictional area of the mole plow, in.^{2}

S_b is the actual frictional area of the blade, in.^{2}

S_t is the actual frictional area of the torpedo, in.^{2}

K_2 is the coefficient of the effective frictional area, dimensionless.

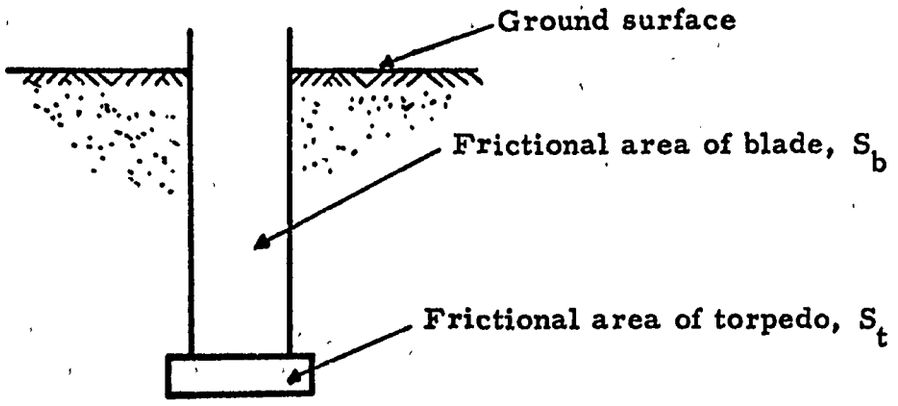


Figure 6. Frictional areas of the blade and torpedo with a blunt front.

From this concept, the total frictional resistance of a mole plow in clay soil and $\bar{\sigma} = 0$ is as follows:

$$F_f = K_2 (S_b + S_t) C \tag{28}$$

where

F_f is the total frictional resistance, lbs.

K, S_b, S_t and C are the same as previously defined.

By combining Equations (15), (18), (21), and (28), the total resistance of the clay soil on a mole plow based on foundation and pile formulas may be written as

$$F_{static} = A_b \left(\frac{2}{3} C N_c' + \frac{b}{2} \gamma N_\gamma' + \frac{h_1}{2} \gamma N_q'\right) + A_t \left(f C N_c + \frac{0.9 D \gamma}{2} N_\gamma + \gamma d N_q\right) K_1 + K_2 (S_b + S_t) C \qquad (29)$$

This equation indicates that the force required to pull the mole plow through a clay soil at a very low speed may be determined if the cohesion, the angle of internal friction, the unit weight of the soil and the coefficient of the effective frictional area are known.

Dynamic Resistance on the Mole Plow

In practice a mole plow is drawn at a speed of 1-1/2 mph, and therefore the soil resistance on the plow should be based on the dynamic failure conditions rather than the foundation and pile equations. When drawing a mole plow through plastic soil such as clay soil, the relation between temporary dynamic resistance and permanent resistance is uncertain. In comparison with pile driving, Leonards (1962) indicated that the friction during driving is much less than the friction later, but the bearing resistance is far greater than the resistance under a static load.

Schimming, Haas and Saxe (1966) had developed a direct shear device on which the shearing resistance of the entire range of soil types could be measured under both static and dynamic testing conditions. They stated that all soils could be categorized by one of the envelopes. Thus, if the effect of time to failure can be related to the "apparent cohesion (C_1)" and "friction angle (ϕ)" which are functions

of soil properties, there exists the potential postulate of a unified description of the effect of test duration on maximum shear resistance for all soils. The apparent cohesion may be expressed as

$$ACR = \frac{(C_1)\ \text{dynamic}}{(C)\ \text{static}} \tag{30}$$

where

ACR is the apparent cohesion ratio, dimensionless.

The authors indicated that the dynamic failure envelope of partially saturated clay soils indicated the significantly consistent response of a doubling of the apparent cohesion intercept while the friction angle remained unchanged as shown in Figure 7.

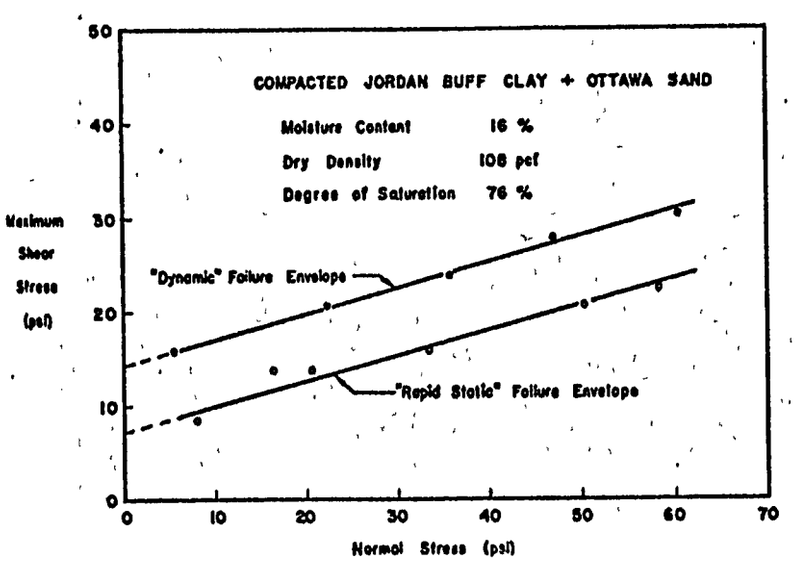


Figure 7. Typical failure response on partially saturated Jordan Buff Clay plus Ottawa Sand (Schimming, Hoas, and Saxe, 1966 study of dynamic and static failure envelopes, Proceedings of the ASCE, March 1966).

From Equation (29), the total soil resistance on a mole plow based on a foundation static pile formula may be expressed as

$$F_{static} = f_1 \text{ (shape and dimensions of plow, } \phi, C, K_1, K_2) \quad (31)$$

For partially saturated clay soils in dynamic condition, the internal of friction angle ϕ is independent of speed. The cohesion, varying with the speed of the mole plow as indicated by Equation (30), is equal to $ACRX(C)_{static}$. Assuming K_1 and K_2 are independent of speed of the mole plow, the dynamic resistance on the mole plow may be written as

$$F_{dynamic} = A_b \left(\frac{2}{3} C_1 N_c' + \frac{b}{2} \gamma N_\gamma' + \frac{h_1}{2} \gamma N_q'\right) + A_t \left(f C_1 N_c + \frac{0.9\, d\, \gamma}{2} N_\gamma + \gamma d N_q\right) K_1 + K_2 (S_b + S_t) C_1 \quad (32)$$

in which $C_1 = ACRX(C)_{static}$ and all other terms are the same as previously given.

From this equation force required to pull the mole plow through the soil at a certain speed may be determined if the apparent cohesion ratio, angle of internal friction, the unit weight of soil, the coefficient of the effective frictional area K_2 and reduction factor K_1 are known.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Equipment

Soil box. A box with internal dimensions of 10 inches wide, 18 inches long, and 11 inches high was made of Plexiglas 1/4 inch thick. To provide a passage for the mole plow, two slits about 1 inch wide and 6-5/8 inches long were cut in the short sides of the box as shown in Figure 8. The slits weakened the strength of the box, therefore detachable side plates 5 inches wide and 8 inches long were attached to strengthen the sides during the soil compacting process. Horizontal lines indicating 1/2-inch layers were marked around the box to facilitate soil compacting as will be described in the test procedure. The entire soil box was supported on the outside by a steel frame as shown in Figure 8.

Mole plow. Two sets of mole plows were built for use in the experiments. The first set consists of 5 mole plows as shown in Figure 9. Mole plow "a" has only the blade 1-3/4 inches wide and 1/8 inch thick. Mole plow "b" has the same size of blade as "a" but it also has a torpedo 5/8 inch diameter and 2-1/4 inches long with a blunt front end attached. Mole plows "c", "d" and "e" have similar arrangements as "b" except that the front end of the torpedoes was sharpened to an angle of 45°, 30° and 15°.

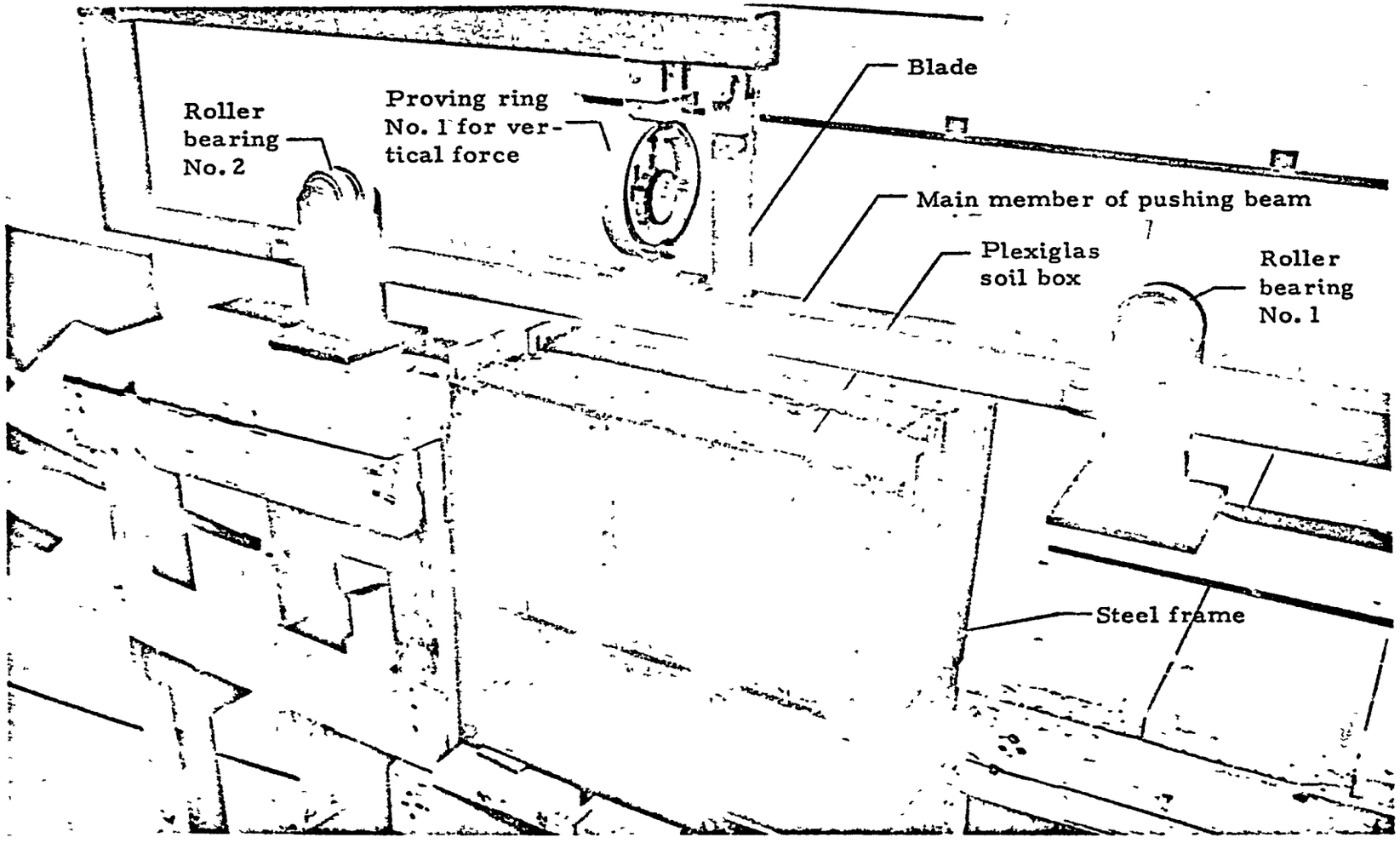


Figure 8. Mole plow being pushed through the soil in the soil box.

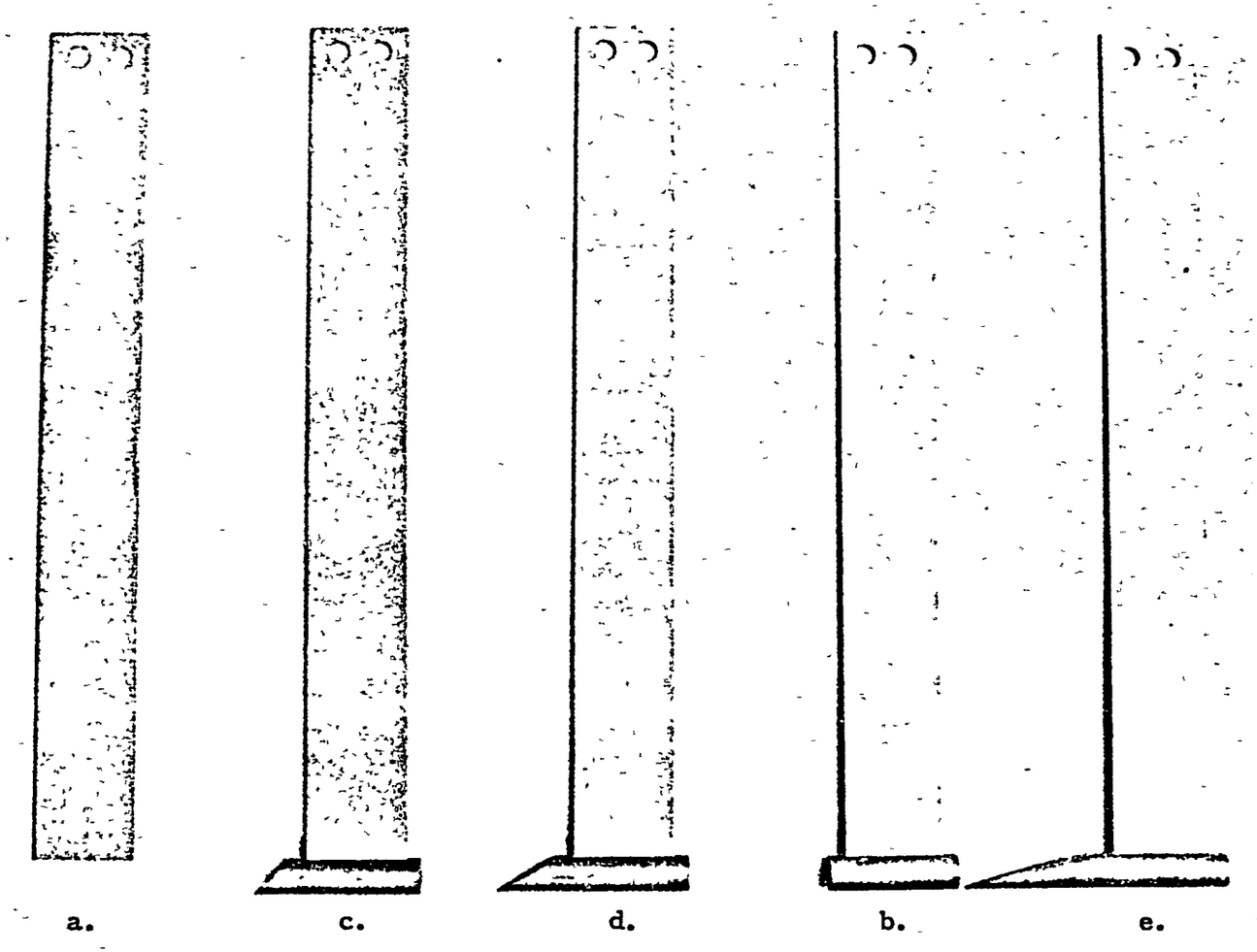


Figure 9. Mole plows consisting of steel torpedoes having different front angles attached to steel blades.

The mole plows in the second set are similar to those in the first set except that the sides of the blade on "a" were made thinner than the front edge to eliminate the frictional resistance, and the cylindrical surface of the torpedoes was removed in order to eliminate the friction on the torpedoes as shown in Figure 10.

Tamper. A tamper was made of a steel plate 3/32 inch thick, 5 inches by 5 inches in area, welded to a handle 1-7/8 inches in diameter, and 11 inches long. The total weight of the tamper was 10 pounds.

Pushing beam. A specially designed pushing beam equipped with two calibrated proving rings as shown in Figure 11 was used to push the mole plow through the soil in the box. The force required to push the mole plow and vertical force during the experiments was measured by the two proving rings which had been calibrated prior to the tests. With the known deflection of the proving ring read from the dial indicators, the corresponding horizontal and vertical forces were obtained from the calibration curves. The general arrangement of the pushing beam and soil box is shown in Figures 8 and 11.

Method of Procedure

The soil used in the experiments was taken from the Irrigation and Drainage Farm of Utah State University, Logan, Utah.

The soil was dried and pulverized before mixing with the water to the 27 percent moisture content. The bulk density of the

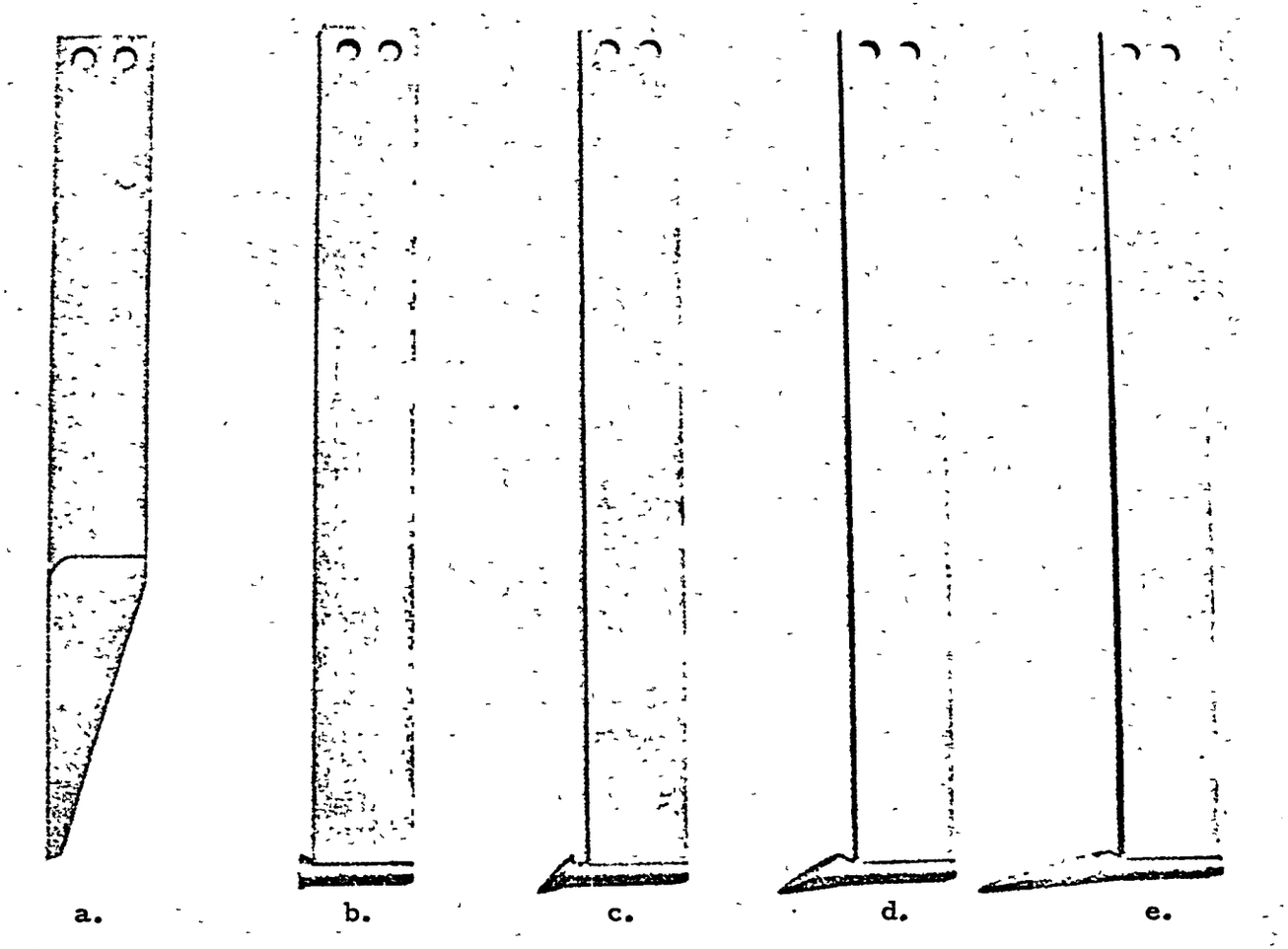


Figure 10. Mole plow blades and torpedoes designed to have side friction eliminated.

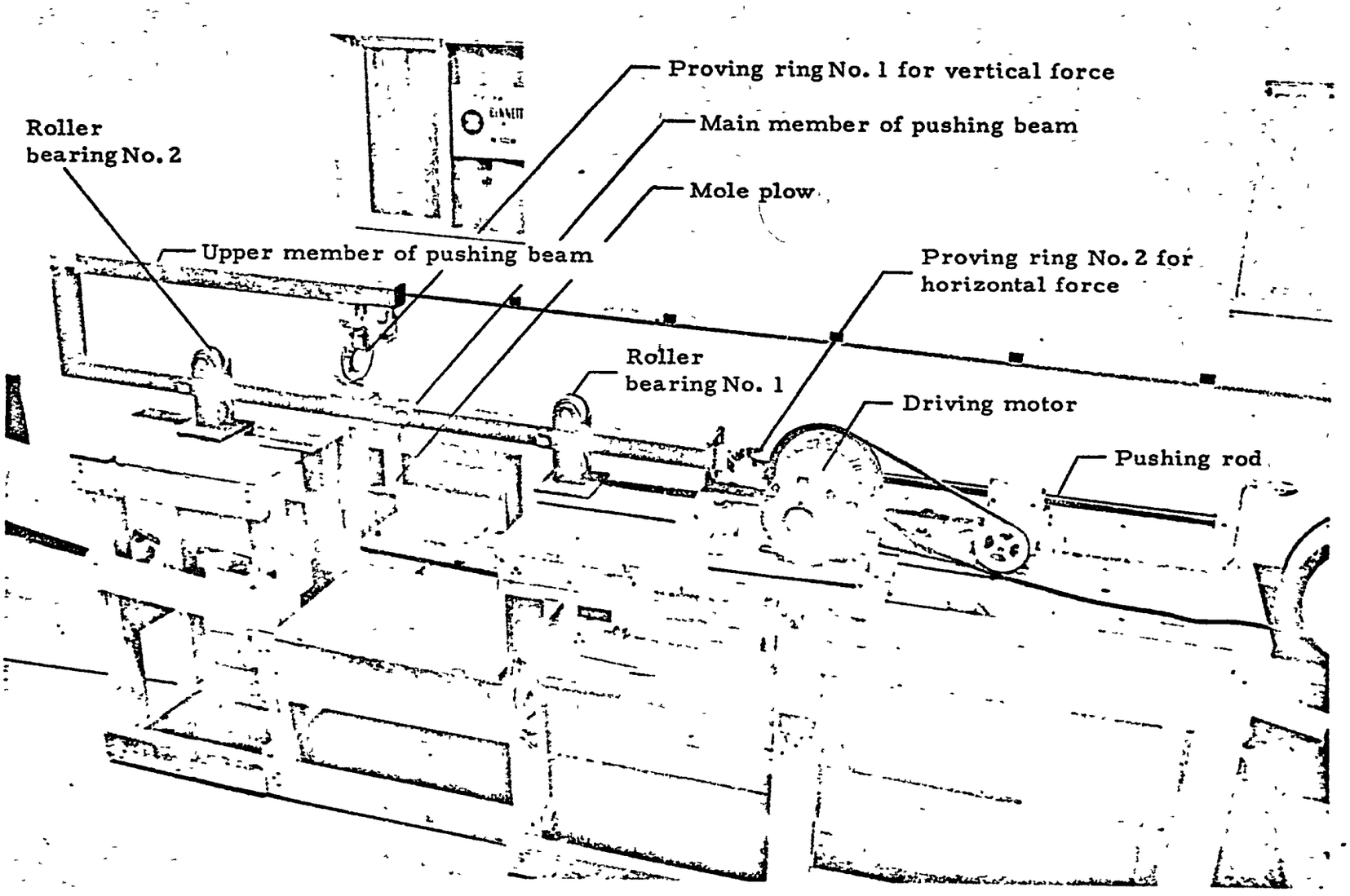


Figure 11. Pushing beam equipped with proving rings and mole plow (soil box not in place).

undisturbed soil was 1.32 grams per cubic centimeter.

In each test run a predetermined amount of soil that would fill the Plexiglas soil box to the top layer mark after being compacted to a uniform bulk dry density of 1.32 grams per cubic centimeter, was put in a 1.5 cubic foot electric mixer. A pre-estimated amount of water was added to the soil by a sprayer while the mixer was in motion to assure a uniform moisture distribut on.

After the soil had been thoroughly mixed to the desired moisture content, it was removed from the mixer and separated into 20 equal parts by weight. Each part was kept in a water tight plastic bag until it was ready to be compacted in the soil box.

Then the soil from a plastic bag was spread evenly in the soil box and compacted to fill a layer mark in the box. A similar procedure was repeated until all the soil from the 20 plastic bags was compacted and filled 20 layers in the box. This method was used to obtain a uniformity of soil density throughout the box.

The mole channel was constructed by pushing the mole plow through the soil in the Plexiglas box with the pushing beam. Readings were taken from the dial gauges of the calibrated proving rings while the plow was passing points at 0, 3, 6, 9, 12, 15 and 18 inches from the beginning. But for 0.05 and 0.10 mph speeds, readings were taken only at the points 3, 9 and 15 inches, from the beginning, because gauge reading is difficult at high speeds.

Following the force measurements, 6 soil samples were taken from 6 locations in the box for the determination of the actual moisture content of the soil. The moisture content was determined by gravimetric method: drying the sample in an oven and finding the weight loss and the dry weight of the soil.

Six undisturbed soil samples were also taken from the 6 locations in the box for direct shear tests. The shear tests were conducted to find the relationship between the cohesion and the angle of internal friction of the soil versus the moisture content.

Altogether 55 test runs were conducted. It was intended to produce the moisture content of the soil of 27 percent in each test run. But the actual moisture content varied from 26.5 percent to 27.5 percent on a dry weight basis.

RESULTS AND DISCUSSION

Experimental Resistance of the Soil on a Mole Plow

The plow was attached to the pushing beam by a frictionless hinge at point A. The pushing beam was designed in such a way that the magnitude of the horizontal and vertical resistances can be read from the proving rings. A sketch of the pushing beam equipped with the mole plow and proving rings is shown in Figure 12.

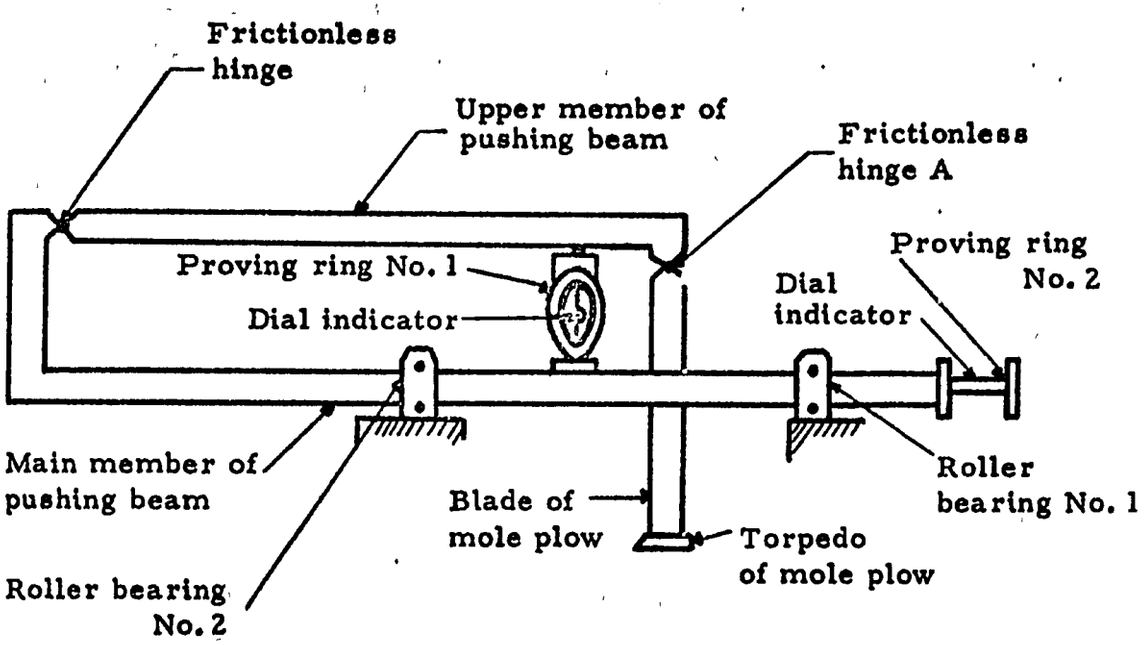


Figure 12. Diagrammatic sketch of pushing beam equipped with the mole plow and proving rings (scale 1" = 1').

The relationship of the forces on the mole plow and the pushing beam may be described as follows.

F^R is the resultant of the resistance of soil acting on the mole plow, lbs.

F^H and F^V are horizontal and vertical components of the resultant force F^R, lbs.

F_1^H is the horizontal force acting on the blade at roller bearing B, lbs.

F_2^H and F_2^V are the horizontal and vertical components of the forces acting on the blade at hinge A, lbs.

F_5^V is the vertical force acting on the pushing beam; can be read from proving ring No. 1, lbs.

ℓ_4 is the length of upper member of the pushing beam, in.

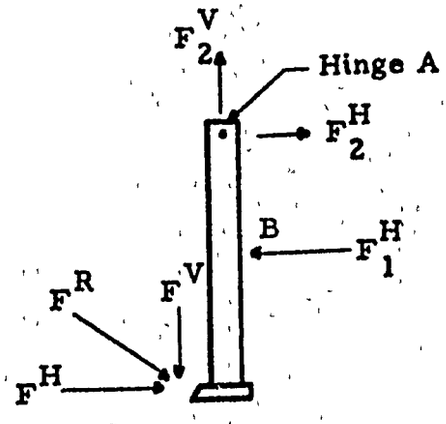
ℓ_5 is the distance from F_5^V to the end of the upper member, in.

R_1 and R_2 are the reactions on the roller bearing support No. 1 and No. 2, lbs.

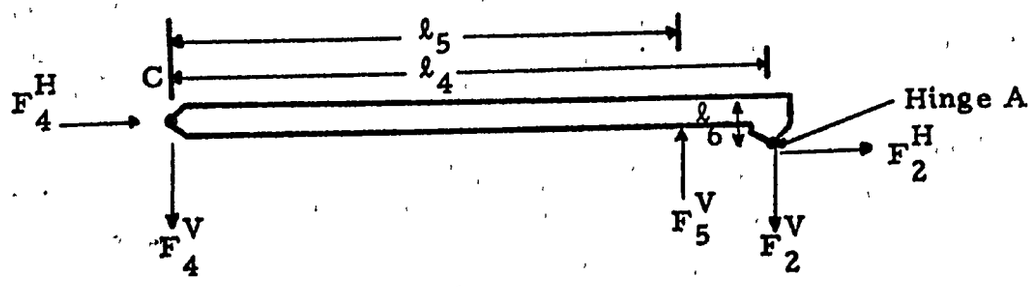
F_6 is the horizontal force to pull the plow acting on the beam; can be read from proving ring No. 2, lbs.

From Figure 13 a, for static equilibrium of forces,

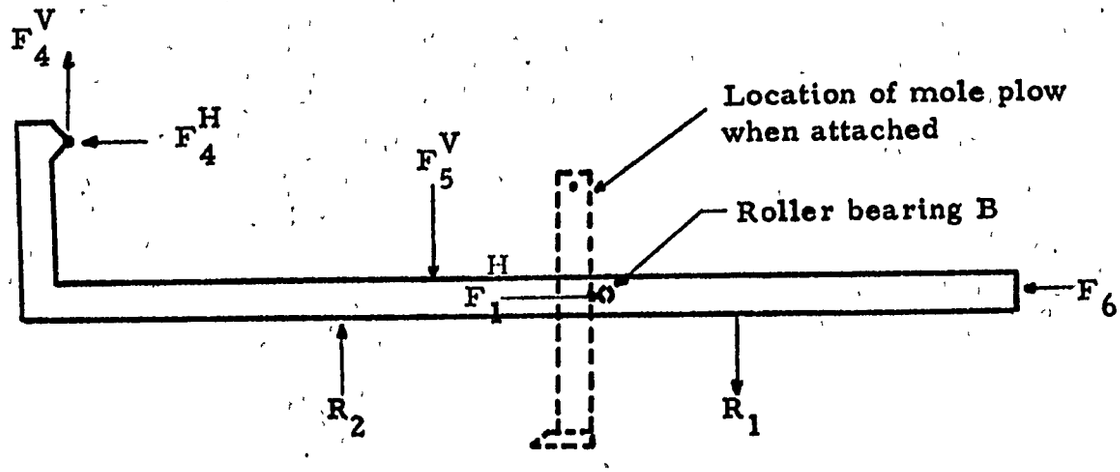
$$F^V = F_2^V \tag{33}$$



a. Mole plow



b. Upper member of pushing beam



c. Main member of pushing beam

Figure 13. Diagrammatic sketch of forces acting on the mole plow and pushing beam

and $$F^H = F_1^H - F_2^H \tag{34}$$

From Figure 13 b, for static equilibrium of forces,

$$F_2^V = F_5^V - F_4^V \tag{35}$$

and $$F_2^H = F_4^H \tag{36}$$

Similarly, for the main member of the pushing beam,

$$F_4^H = F_1^H - F_6 \tag{37}$$

and $$F_4^V = R_1 - R_2 + F_5^V \tag{38}$$

Members of the pushing beam and the mole plow are attached to each other by hinges made with ball bearings. The friction at these hinges are quite small and can be neglected.

From Figure 13 b, taking moment $\Sigma M_c = 0$

$$F_5^V \ell_5 = F_2^V \ell_4 - F_2^H \cdot \ell_6 \tag{39}$$

or $$F_2^V = F_5^V \frac{\ell_5}{\ell_4}, \text{ neglecting } F_2^H \frac{\ell_6}{\ell_4} \tag{40}$$

Combining Equation (33) with Equation (40),

$$F^V = F_5^V \frac{\ell_4}{\ell_5} \tag{41}$$

By combining Equation (34), (36), and (37),

$$F^H = F_6 \tag{42}$$

Equation (42) shows that the horizontal component of the resistance of the soil acting on the mole plow is equal to the force read from

proving ring No. 1. Table 1 shows the horizontal resistance F^H which is the horizontal component of the total resistance of soil acting on the mole plow as obtained from experiments using the first set of mole plows. Therefore the resistances shown are the combined bearing and frictional resistances. The same table lists the moisture content of the soil in each test run. The curves showing the variation of these resistances with the speed were prepared as shown in Figure 14.

Similar experiments were conducted using a second set of mole plows which made it possible to find the bearing and frictional resistances separately. The first column in Table 2 shows the horizontal bearing resistance of the soil acting on the blade. Other columns show the sum of both frictional and bearing resistances on the blade and only the bearing resistance on the torpedo. From Table 2, curves showing the variation of these forces with speed for torpedoes of different shapes are shown in Figure 15.

From the values in Table 1 and Table 2 the experimental frictional resistances acting on the mole plow (i.e., blade and torpedo) were computed as shown in Table 3 and plotted in Figure 16.

The experimental bearing resistances on the torpedoes of different shape are computed in a similar manner and are shown in Table 4. Figure 17 shows the variation of these resistances on the torpedoes of different shapes and moving at different speeds. The equations showing on the curves for resistance versus speed on the torpedoes of

Table 1. Experimental horizontal frictional and bearing resistances acting on the mole plow

Speed mph	Blade Only		90° Torpedo (Blunt Front)		45° Torpedo		30° Torpedo		15° Torpedo	
	Horiz. Force lb.	M. C. %	Horiz. Force lb.	M. C. %	Horiz. Force lb.	M. C. %	Horiz. Force lb.	M. C. %	Horiz. Force lb.	M. C. %
0.0085	150.0	27.1	255.0	27.1	261.0	26.7	253.0	26.9	257.0	27.1
0.0085	150.0	27.0	252.0	27.0	-	-	-	-	-	-
0.0107	155.0	26.5	260.0	26.8	-	-	260.0	26.5	-	-
0.0136	158.0	26.5	262.0	26.8	-	-	262.0	26.5	-	-
0.0511	166.0	26.7	278.0	26.7	272.0	26.6	270.0	26.9	265.0	27.1
0.1022	177.5	27.2	295.0	26.7	282.5	27.2	277.5	26.7	270.0	26.9

Note: M.C. = moisture content.

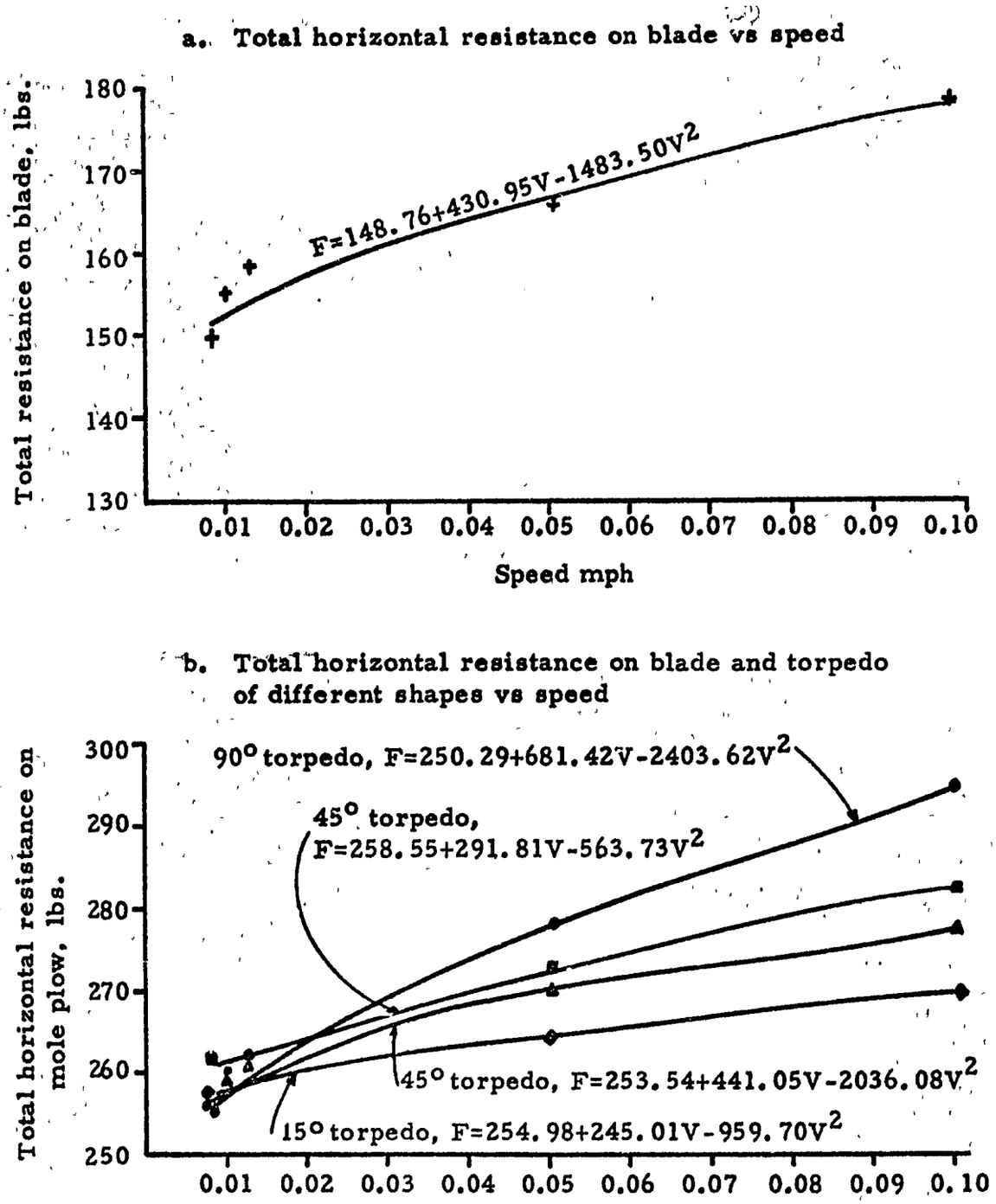
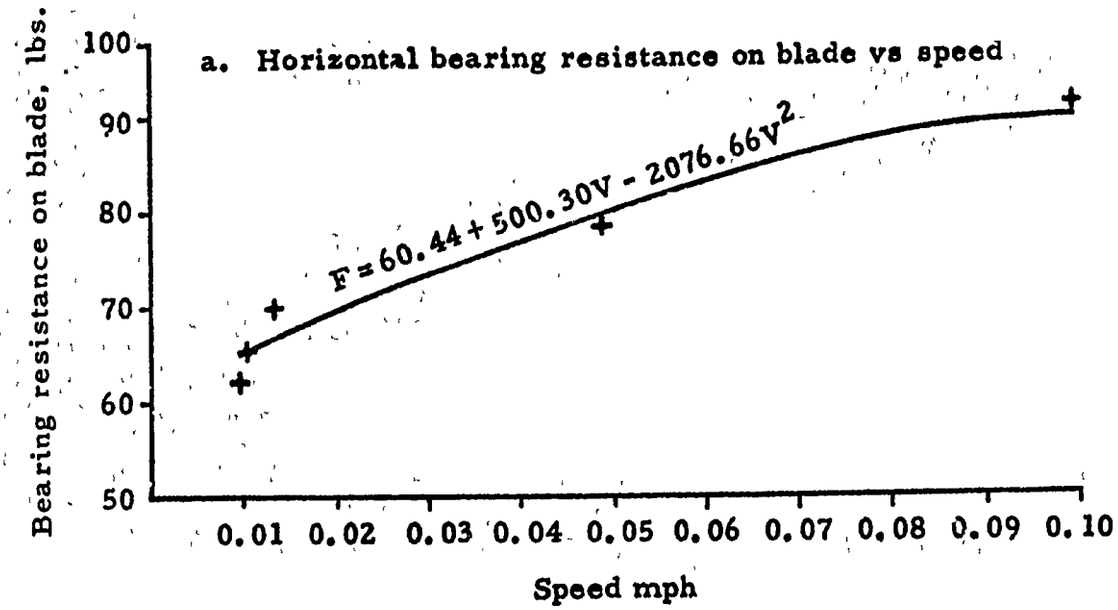


Figure 14. Experimental horizontal frictional and bearing resistances on mole plows of different shapes

Table 2. Experimental horizontal frictional and bearing resistances on the blade plus bearing resistance on torpedoes of different shapes

Speed mph	Blade Only		90° Torpedo (Blunt Front)		45° Torpedo		30° Torpedo		15° Torpedo	
	Horiz. Force lb.	M. C. %	Horiz. Force lb.	M. C. %	Horiz. Force lb.	M. C. %	Horiz. Force lb.	M. C. %	Horiz. Force lb.	M. C. %
0.0085	62.5	26.5	227.5	26.8	232.5	26.6	228.0	26.5	226.5	27.3
0.0107	65.0	26.6	232.5	26.7	-	-	230.0	26.8	-	-
0.0136	70.0	26.6	235.0	26.7	-	-	232.0	26.8	-	-
0.0511	80.0	26.7	242.0	26.6	240.0	26.9	237.0	26.6	232.0	27.0
0.1022	90.0	26.7	257.0	27.1	250.0	26.9	245.0	26.9	237.5	26.8

Note: M. C. = moisture content.



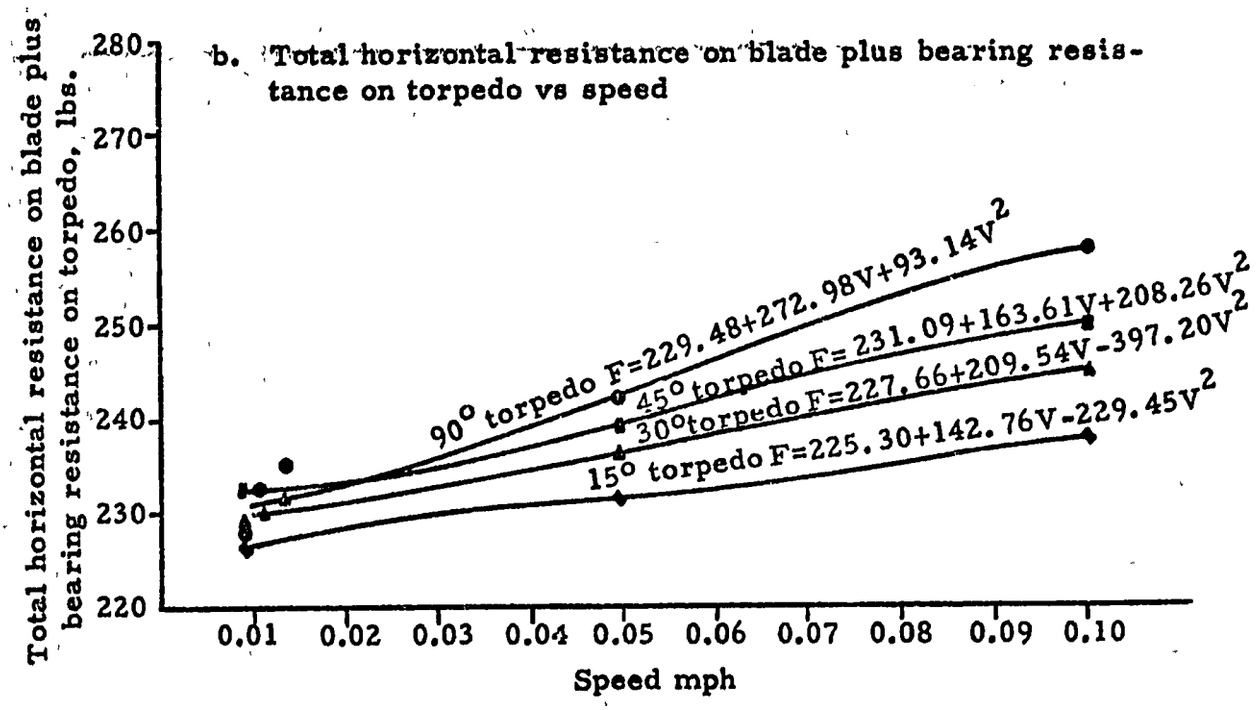


Figure 15. Experimental resistance on the blade and torpedoes of mole plows of different shapes

Table 3. Experimental frictional resistance on the blade and torpedo of different shapes

Speed mph	Blade Only lb.	90° Torpedo (Blunt Front) lb.	45° Torpedo lb.	30° Torpedo lb.	15° Torpedo lb.
0.0085	87.5	27.5	28.5	25.0	30.5
0.0085	87.5	24.5	-	-	-
0.0107	90.0	27.5	-	30.0	-
0.0136	88.0	27.0	-	30.0	-
0.0511	86.0	36.0	32.0	33.0	33.0
0.1022	87.5	37.5	32.5	32.5	32.5

Table 4. Experimental bearing resistance on torpedoes of different shapes

Speed mph	90° Torpedo (Blunt Front) lb.	45° Torpedo lb.	30° Torpedo lb.	15° Torpedo lb.
0.0085	77.5	82.5	78.0	76.5
0.0107	77.5	-	75.0	-
0.0136	77.0	-	74.0	-
0.0511	76.0	74.0	71.0	66.0
0.1022	80.0	72.5	67.5	60.0

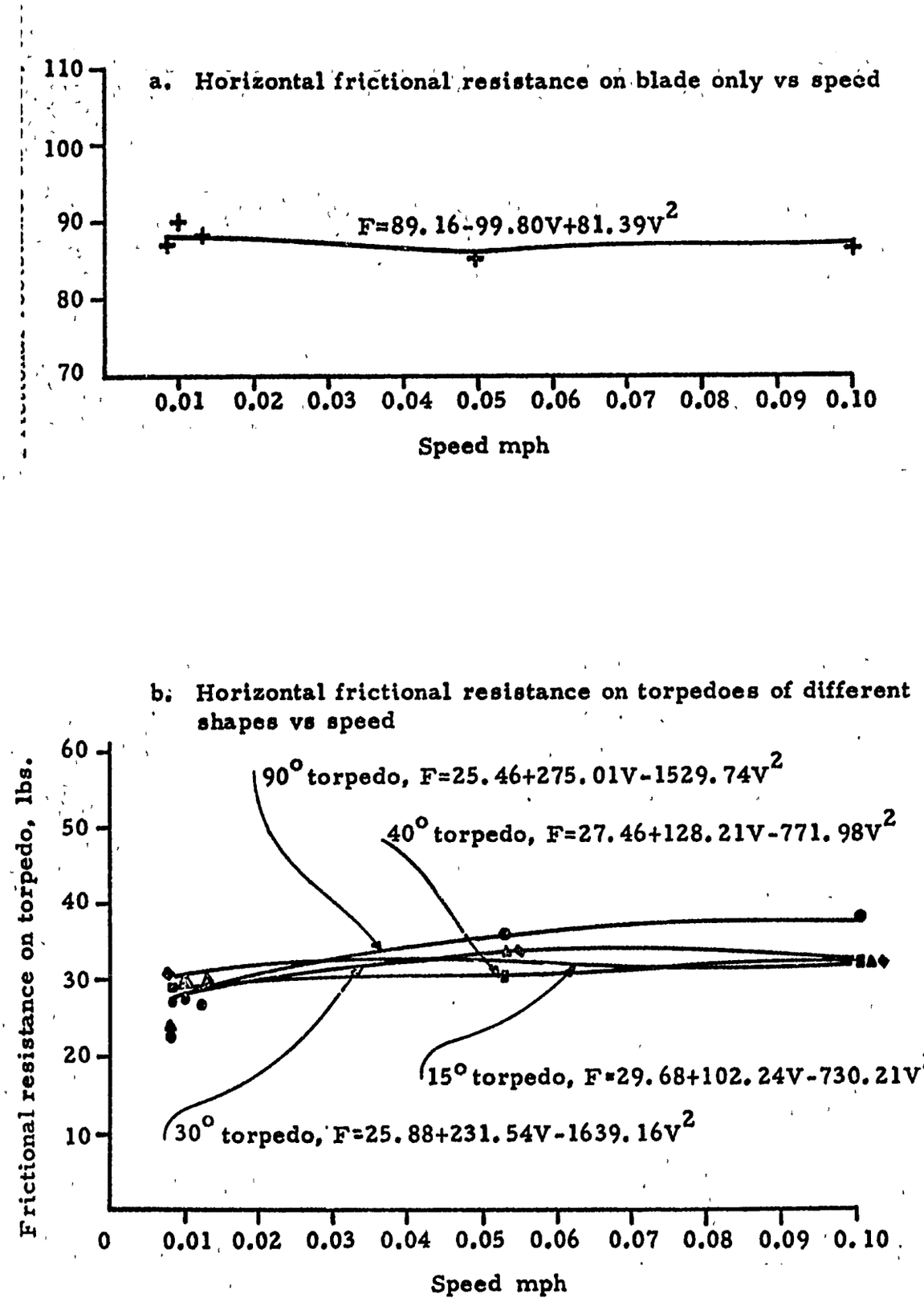
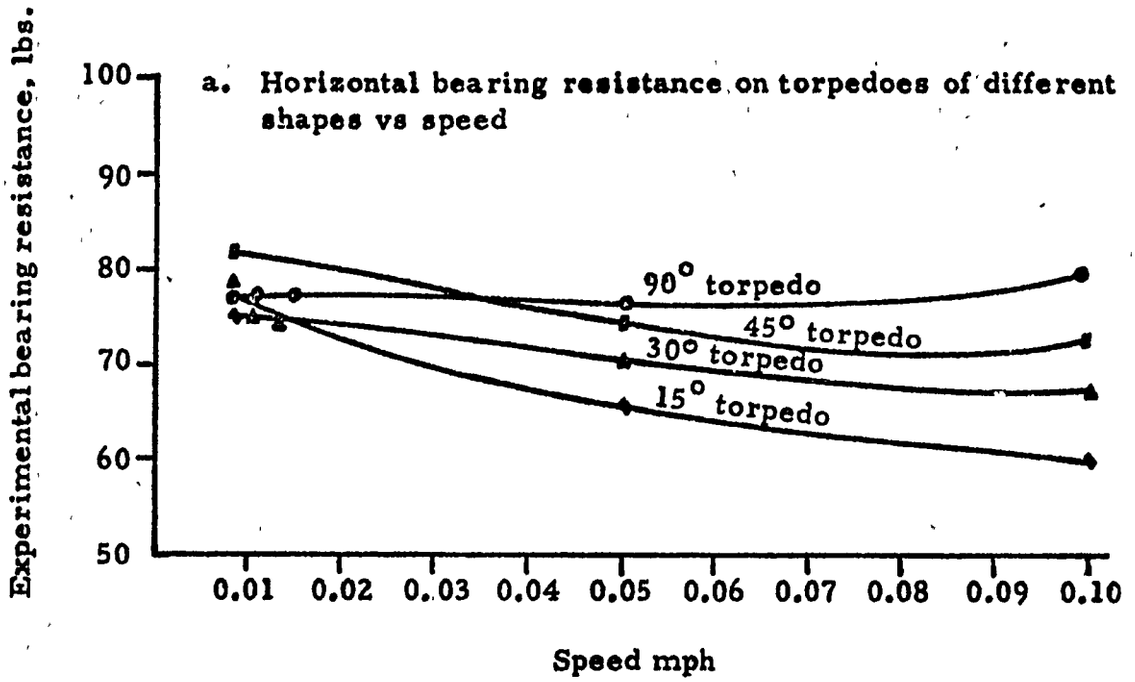


Figure 16. Experimental frictional resistance on the blade and torpedoes of different shapes



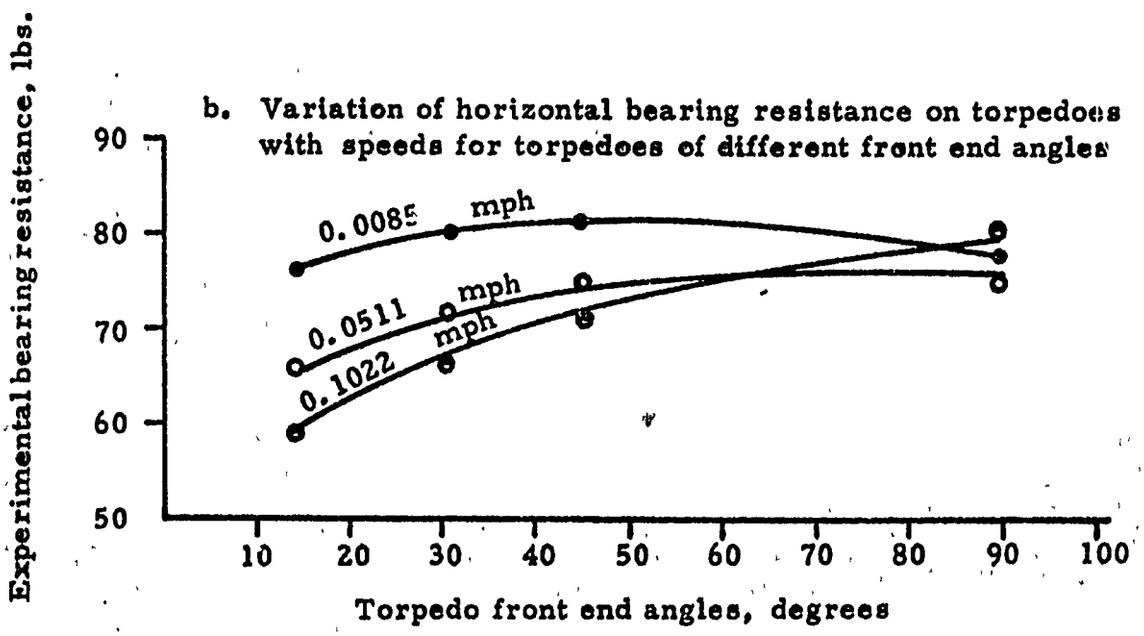


Figure 17. Experimental bearing resistance on torpedoes of different shapes

different shapes in Figures 14, 15 and 16 were obtained from corresponding experimental data in Tables 1, 2 and 3 by regression analysis on computer programs.

In Equation (32), C_1 is the dynamic cohesion of the soil which varies according to the test duration used on the shear stress apparatus. The test duration may be set to simulate the speed of the mole plow moving through the soil. In this research the shear apparatus capable of measuring the shear stress under dynamic conditions is not available. Consequently, no data on dynamic cohesion of soil are available and the theoretical dynamic resistance of soil on a mole plow cannot be computed.

Theoretical Resistance of the Soil on a Mole Plow

The shear strength of the soil at the time the mole drain was constructed was found by direct shear tests. As mentioned earlier, 6 samples were taken from the soil box in each test run for direct shear tests which were performed to find the cohesion and angle of internal friction of the soil. The result of the test is shown in Figure 18.

All the tests were intended to be conducted with the soil having moisture content of 27 percent on a dry weight basis. But it was difficult to obtain such a constant moisture content in all test runs. The actual moisture content varied from 26.5 to 27.5 percent. In order to be able to make an adjustment on the resistance in the case where the actual soil moisture content in the test differs from 27 percent,

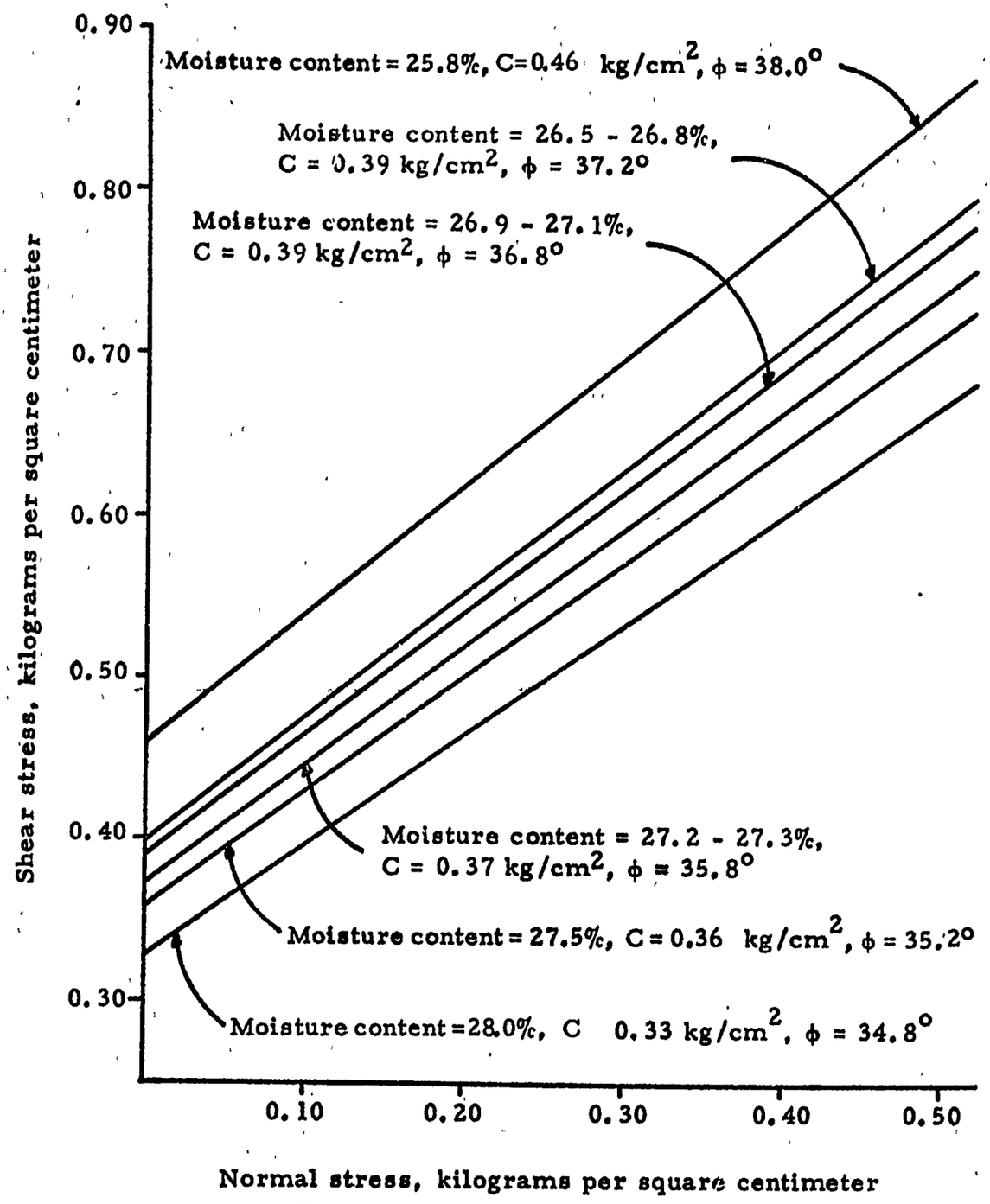


Figure 18. Relationship of shear strength and moisture content of the soil

Figures 19 and 20 were plotted from the results of the direct shear tests to be used for such adjustments.

Theoretical force required to pull the mole plow with the blunt front end or 90° torpedo based on static formula was computed by Equation (29) as shown in Table 5.

For the mole plows with torpedoes having different shapes of the front end, Equation (29) may be used if K_1 is known. In this study no data for K_1 are available and therefore the total resistances on the mole plows based on static condition for other shapes of torpedoes could not be computed.

If the speed of moving the mole plow is high, the effect of speed on the soil resistance has to be considered and Equation (32) may be applied. Dynamic cohesion C_1 may be obtained from a specially designed shear apparatus.

Discussion

There are several factors effecting the force required to pull the mole plow of which the soil type, moisture content, bulk density, shape of plow and speed of operation are the major factors among them.

Influence of moisture content on soil resistance. The influence of the moisture content of the soil on the resistance is obvious. From the shear test results of the clay soil used in the research shown in Figure 18, the cohesion decreases rapidly as the moisture content increases while the angle of internal friction is only slightly affected by

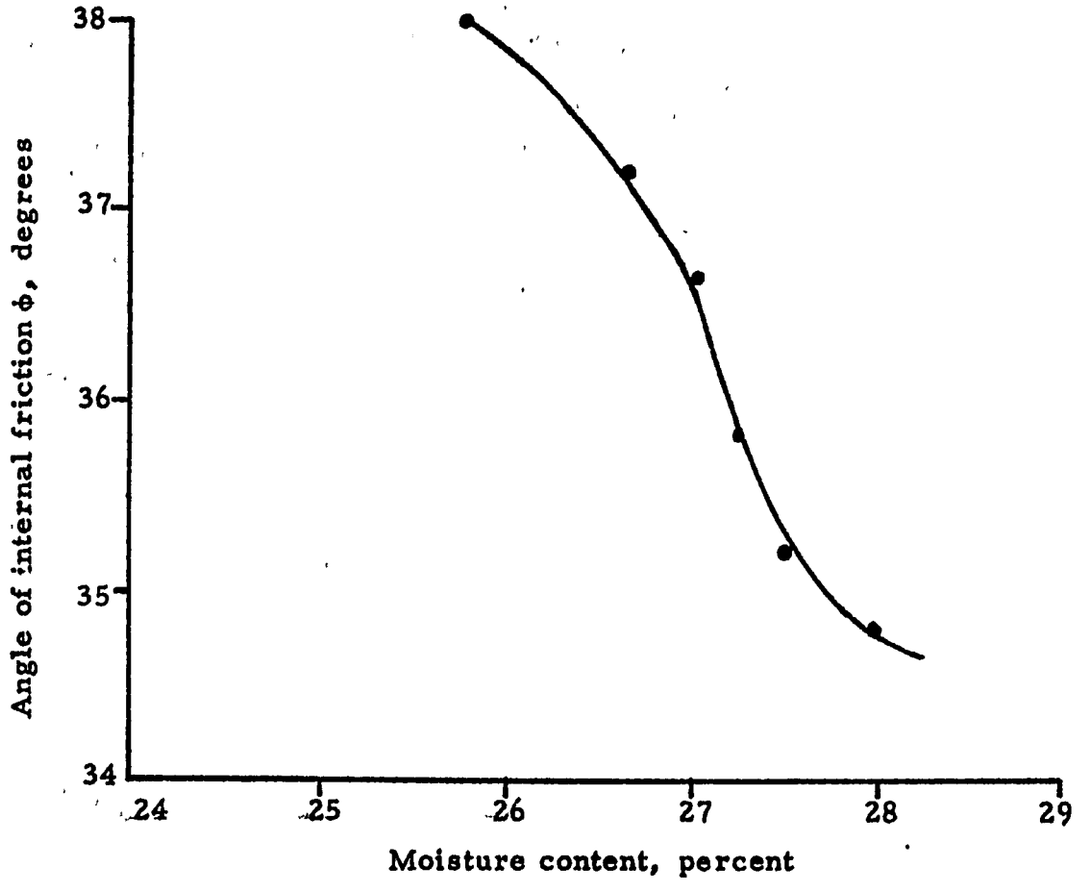


Figure 19. Relationship of the angle of internal friction of the soil and moisture content

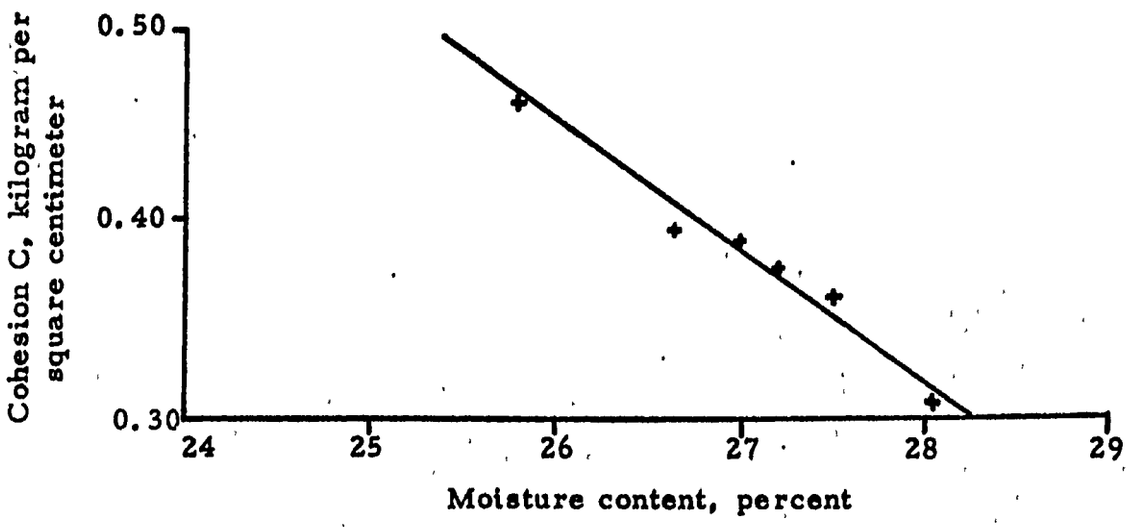


Figure 20. Relationship of the cohesion of the soil and moisture content

Table 5. Computation for frictional and bearing resistances on the mole plow with 90° (blunt front) torpedo

a. Values of ϕ, C, N_c, N_γ, N_q, γ for soil used and h_1, d for mole plow

M.C. %	ϕ Degree	C Kg/cm^2	C $lb./in.^2$	Nc	N_γ	N_q	$lb./in.^2$	h_1 in.	d in.
27.1	36.8	0.392	5.41	65	55	52	0.061	4.87	5.18

b. Correction of ϕ, C, N_c, N_γ and N_q values for the blade.

2/3 ϕ Degree	2/3 C $lb./in.^2$	N_c'	N_γ'	N_q'
24	36.1	25	12	14

c. Computation for bearing resistance of the soil on the blade

$lb./in.^2$	$\frac{\gamma b}{2} N_\gamma'$ $lb./in.^2$	$\frac{\gamma h_1}{2} N_q'$ $lb./in.^2$	$(\Delta q_s)_{ub}$ $lb./in.^2$	A_b $in.^2$	Q_b lbs.
90.250	0.045	2.599	92.895	0.61	56.666

Table 5. Continued

d. Computation for bearing resistance of the soil on the plow with a 90° torpedo

$2/3\ C\ N_c$ lb./in.^{2}	$\frac{0.9\ \gamma D}{2}\ N_\gamma$ lb./in.^{2}	$\gamma d\ N_q$ lb./in.^{2}	$(\Delta q_s)_{ut}$ lb./in.^{2}	A_t in.^{2}	Q_t lbs.
234.433	0.944	16.431	251.808	0.31	78.060

e. Computation for friction resistance of the soil on the blade and the mole plow with a 90° torpedo

C lb./in.^{2}	S_b in.^{2}	S_t in.^{2}	$K_2\ S_b\ C$ ($K_2 = 1$) lbs.	$K_2\ S_t\ C$ ($K_2 = 1$) lbs.	$F_f = K_2(S_b+S_t)C$ ($K_2 = 1$) lbs.
5.41	17.00	4.42	87.500	27.500	115.000

f. Comparison of the experimental and theoretical resistance on the blade with a 90° torpedo

Type of Resistance		Experimental Resistance	Theoretical Resistance, Speed 0.0085 mph, lb.
Blade	Friction	87.500	91.970
	Bearing	62.500	56.666
Torpedo	Friction	27.500	23.912
	Bearing	77.500	78.060
Total Resistance		255.000	250.608

the change of the moisture content in the range tested. By examining Equations (29) and (32) it may be seen that variation of the cohesion of the soil has a large, direct effect on the soil resistance.

Effect of the speed and shape. From Figure 14 b, the soil resistance on the mole plow at low speed appears to remain the same regardless of the shape of the front end angle of the torpedoes used. When the speed increases, the effect of the shape of torpedoes begins to appear. At the speed of 0.10 mph, the mole plow with the torpedo of 15° front angle shows approximately 10 percent less resistance than that for 90° torpedo.

In order to analyze the effect of the shape of the torpedo and the speed of the mole plow on the soil resistance, it is necessary to study each part of the mole plow, i.e., the blade and torpedo, separately.

Figure 21 shows that the frictional resistance of the blunt blade does not increase with the increase in speed. This can be explained that while the cohesion, C, increases with the speed, K_2 may decrease proportionally and result in almost constant frictional resistance. The bearing resistance increases approximately 40 percent when the speed changes from 0.01 mph to 0.10 mph. Therefore, the increase in total soil resistance derives from the increase in bearing resistance of the the blade due to the effect of speed which causes the cohesion of the soil to be higher.

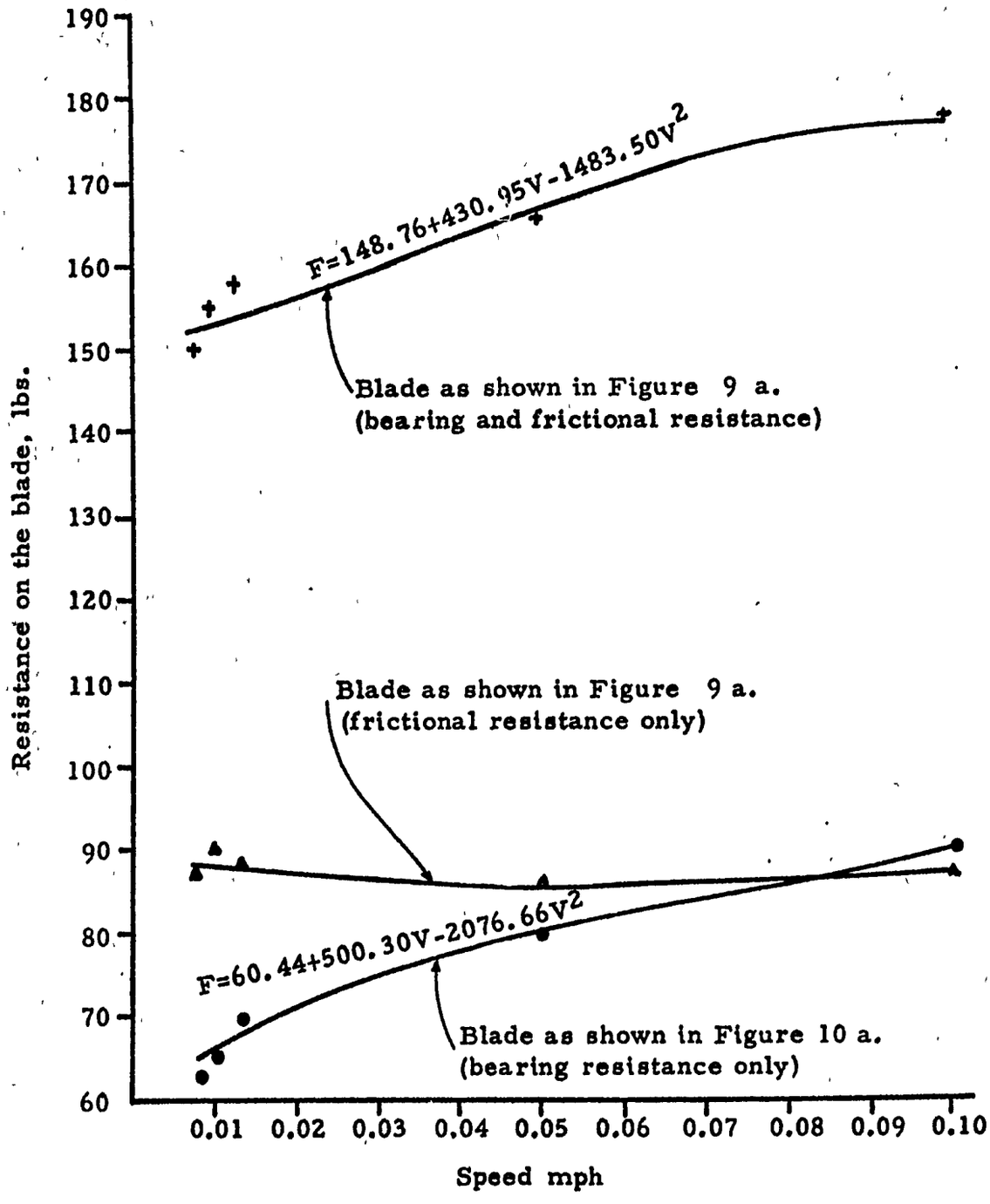


Figure 21. Experimental soil resistance on the blade

The shape of the torpedo appears to have no significant effect on frictional resistance (see Figure 16 b) whether at a low or high speed used in the experiment. This phenomena may be explained in a similar manner as for the blade that while the cohesion of the soil increases with the speed, the value of K_2 decreases proportionally to maintain almost a constant frictional resistance. An interesting finding on the effect of the shape of the torpedo is that Figure 17 a indicates the decrease in soil bearing resistance on sharp front angle torpedoes as the speed increases in the range experimented. The explanation of this phenomena is that K_1 decreases with the speed at the rate higher than the increase of the soil cohesion with the speed. Evidently K_1 appears to vary with the shape and speed of the mole plow.

From the above discussion it may be concluded that the frictional resistance on the mole plow is not affected by the shape and speed of the mole plow. The bearing resistance on the torpedo with the blunt front increases slightly with the speed but this resistance appears to decrease with the speed for the torpedoes with sharp front ends. The increase in total resistance on the mole plow with speed is the result of an increase in the bearing resistance of the blade which, in this case, has a blunt leading edge.

It is necessary to emphasize that all the results, discussion and conclusion presented in this report are limited to the soil type used,

speed range of the tests, and the shape and dimension of the mole plows used in this research. Even though Equations (29) and (32) are generalized equations, more intensive investigation is necessary in order to verify the theory.

Modification of design to reduce resistance. From the foregoing analysis on the soil resistance on the blade and torpedo of the mole plow, the bearing resistance on the blunt blade used in the study increases with the speed. But the bearing resistance on the torpedo having a sharp front end decreases as the speed increases. From this finding, it may be possible to reduce the bearing resistance on the blade by sharpening the front edge.

Furthermore, the study reveals that 30 percent of the soil resistance on the mole plow derived from the frictional resistance on the blade (see Figures 14 and 21). The frictional resistance may be reduced by making the rear portion of the blade thinner than the leading portion, or it can be done by attaching a shin plate thicker than the blade at the leading edge of the blade. Removal of frictional resistance on the torpedo reduces only 10 percent of the total soil resistance and it is not recommended because the cylindrical surface of the torpedoes is required for smoothing and guiding the alignment of the mole channel during construction.

SUMMARY AND CONCLUSIONS

The study to investigate the effect of shape and speed of a mole plow on soil resistance was conducted by using a model having approximately a 1 to 6 scale ratio to the prototype.

A total of 55 test runs were performed. Eleven of them failed to give any data due to either too high or too low moisture content in the soil. Only 44 test runs yielded complete data for the use in the analysis for results.

In this investigation equipment was designed such that the power required to operate the mole plow was equal to the total resistance of soil against the plow.

Two equations for determination of the soil resistance were developed. Equation (29) is applicable in the case of a very slow moving plow, while Equation (32) is for the plow moving at a higher speed.

$$F_{static} = A_b \left(\frac{2}{3} C N_c' + \frac{b}{2} \gamma N_\gamma' + \frac{h_1}{2} \gamma N_q'\right) + A_t\left(f C N_c + \frac{0.9 D \gamma}{2} N_\gamma + \gamma d N_q\right) K_1 + K_2 (S_b + S_t) C \qquad (29)$$

$$F_{dynamic} = A_b\left(2/3\, C_1 N_c' + \frac{b}{2} \gamma N_\gamma' + \frac{h_1}{2} \gamma N_q'\right) + A_t\left(f C_1 N_c + \frac{0.9 D \gamma}{2} N_\gamma + \gamma d N_q\right) K_1 + K_2 (S_b + S_t) C_1 \qquad (32)$$

The two equations have the same form and differ only in the term of cohesion of the soil. In Equation (29) static cohesion of the soil is used while the dynamic cohesion is required in Equation (32).

Static cohesion of the soil may be obtained from slow shear tests. In order to find the dynamic cohesion, undisturbed samples of the soil in which the mole channel is to be constructed have to be taken from the field and tested for dynamic cohesion C_1 under the simulated condition for the actual speed of the plow.

Furthermore, with large scale and intensive soil investigation, it is possible to group the soil and designate the value of the cohesion and the apparent cohesion ratio for certain ranges of practical speed of the mole plow operation. If such grouping is accomplished, one can apply Equation (32) to determine the total soil resistance on a plow with known dimensions. However, K_1 and K_2 have to be assumed. For practical purposes, K_1 and K_2 may be assumed to be equal to unity which will result in a larger resistance on the plow.

RECOMMENDATIONS FOR FURTHER STUDY

The following laboratory and field investigations should be considered.

1. Verification of the results of the study presented in this thesis by field study.

2. Investigation should be conducted to compare the effect of the shape and speed on soil resistance for a given type of soil under different moisture contents and different bulk density.

3. Laboratory experiments should be conducted to find dynamic cohesion related to the speed of the mole plow for different types of soil.

4. Bearing resistance correction factors should be evaluated for different shapes of torpedo.

5. Investigation should be conducted to find the coefficient of the effective frictional area to the actual area for certain designs of a mole plow for various soil types and moisture contents. The effect of speed of the mole plow on this coefficient should also be investigated.

6. Field and laboratory experiments should be conducted to find the range of the values of γ, c, ϕ of typical clay soils suitable for mole channel installations. Such practical results may be used in the determination of the theoretical resistance by means of Equation (32).

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