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MOLE DRAINAGE CONSTRUCTION

OPTIMUM SOIL MOISTURE CONTENT

AND

CORRESPONDING POWER REQUIREMENT

by

Kitcha Polparsi

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Irrigation and Drainage Engineering

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NOTATION

A	cross-sectional area of flow through mole channel, ft^2
A_B	contact area of footing with the soil foundation, in^2
A_b	cross-sectional area of blade, in^2
A_t	cross-sectional area of torpedo, in^2
B	width of the footing, in
B_H, B_V	horizontal and vertical components of the distributed stress of the ground on the beam, lbs
b	thickness of the blade, in
C	cohesion of soil based on effective stresses, lb/in^2
C_i	channel irregularities, dimensionless
C_{sat}	cohesion at the saturation stage, lb/in^2
C_H, C_V	horizontal and vertical components on the cartridge and the following bob or plug, lbs
c	stress on the cartridge, lb/in^2
D	diameter of the bearing area of torpedo, in
D_1, D_2	readings from the calibrated proving rings No. 1 and 2, in
d	distance from soil surface to center line of torpedo, in
d_f	depth of footing below the soil surface, in
e	void ratio, dimensionless
F	total resisting force of soil on the mole plow, lbs

F_A^H, F_A^V horizontal and vertical components of the force acting on the hinge at A, lbs

F_B bearing resistance of soil on the projected area of the mole plow, lbs

F_E resultant of resisting forces acting on the mole plow, as obtained from experiments, lbs

F_E^H, F_E^V horizontal and vertical components of the resultant force F_E, lbs

F_F frictional resistance of soil against the exterior surface of the mole plow, lbs

F_1, F_2 forces read by means of proving ring No. 1 and 2, lbs

f the skin friction, lb/in^2

f_b, f_t frictional resistance of soil acting on the blade and torpedo, lbs

f_c coefficient of friction of the roller bearings, dimensionless

f_1, f_2 frictional forces of the roller bearing No. 1 and 2, lbs

h distance from the hinge A to the vertical component of the resultant F_E^H, in

h_1 length of portion of the blade embedded under the soil surface, in

h_2 distance from F_2 to the hinge at A, in

j stress on the bob or plug, lb/in^2

K coefficient of the effective area, dimensionless

k constant equals to $1.49\ R^{2/3}\ S^{1/2} A$, $ft^3\ ft^{1/6}$ / sec

L beam-length from the hitch 0 to the blade, in

l_1 spacing between the two roller bearings, in

l_2 distance from the hinge at A to the nearest roller bearing, in

M resisting blade force with no vertical component, lb

m stress on the blade, lb/in^2

N_c, N_γ, N_q bearing capacity factors dimensionless

n Manning's coefficient of roughness, ft 1/6

P effective stress of soil, lb/in^2

Q discharge of flow through the mole channel, ft^3/sec

Q_b total bearing capacity of the footing, lb/in^2

q uniform foundation pressure, lb/in^2

q_b, q_t bearing resistance of soil on the blade and torpedo, lbs

R hydraulic radius of the cross-section, ft

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

S enery gradient, ft/ft

S_b, S_t gross frictional surface area of the portion of blade and torpedo of the mole plow moving in the soil, in^2

S_e effective frictional area of the mole plow, in^2

S_r surface roughness

T haulage tension, lbs

t width of the pushing beam, in

u neutral stress of soil, lb/in^2

W weight of mole plow, lbs

w moisture content of soil at the time of moling, percent

γ unit weight of soil, lb/in^3

ϕ angle of internal friction, degree

$(\Delta q_s)_u$ ultimate bearing capacity of a long footing, lb/in^2

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ABSTRACT

Mole Drainage Construction, Optimum Soil Moisture Content and Corresponding Power Requirement

by

Kitcha Polparsi, Master of Science

Utah State University, 1970

Major Professor: Dr. Edwin C. Olsen
Thesis Director: Dr. Komain Unhanand
Department: Agricultural and Irrigation Engineering

An investigation was conducted by means of a model to find the relationship between the most efficient form of mole channel and the moisture content of the soil at the time of construction, and to find the corresponding power requirement to operate the mole plow. The mole plow consisted of a steel torpedo 19/32-inch diameter attached to a steel blade 3/16-inch thick and it was pushed through a clay soil contained in a Plexiglas box 10-inch wide, 11-inch high and 18-inch long. The relative efficiency of the form of mole channel was determined by visual inspection and by measuring the discharge rate of flow through the mole channel under a constant head loss. The visual inspection showed that smooth, well-formed mole channels could be obtained when they were constructed in soils having a moisture content higher than the plastic limit of the soil. The result of the

determination by measuring discharge rate agreed with that of the visual inspection method. The range of moisture content of the soil suitable for mole channel construction was between 27 to 29 percent while the plastic limit of the soil was 22 percent.

An equation for determination of the power required to operate a mole plow was developed and expressed as

$$F = A_b \left(C N_c + \frac{\gamma b}{2} N\gamma + \frac{\gamma h_1}{2} N_q\right) + A_t \left(C N_c + 0.9 \frac{\gamma D}{2} N\gamma + \gamma d N_q\right)$$

$$+ K (S_b + S_t) C$$

in which F is the theoretical resisting force of soil against the mole plow and, in this study, was equal to the force required to operate a mole plow. Other terms are the physical properties of the soil, dimensions of the mole plow, and K which was defined as the ratio of the effective frictional area to the actual area of the surface of the portion of mole plow moving through the soil. The theoretical force required to operate the mole plow, assuming K = 1.0, was found to be approximately 25 to 35 percent larger than that obtained experimentally.

Both theoretical and experimental resisting forces indicated that the variation of the force 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.

(100 pages)

INTRODUCTION

Importance of the Problem

Mole drainage is a type of subsurface drainage system. The drain channels in this system are formed by pulling a torpedo-shaped implement through the soil at a depth of about 18 to 24 inches below the surface. Although mole drainage is one of the most economical and effective methods of draining clay soils, results are often disappointing because the technique of mole draining is seldom understood. The process has limitations and depends largely on proper planning as well as good workmanship of construction.

There are many factors influencing the efficiency and durability of mole drains. The literature indicates that the type of soil in which the mole channels are made is the most important factor. Heavy clay soils have been considered to be the most suitable for moling. However, the clay content alone cannot always be taken as an index because the clay characteristics vary considerably depending on the properties of the clay minerals. Mole channels in some soils containing a greater clay content have been found to fail faster than ones in soil containing less clay.

Another important factor having influence on the drain

efficiency and durability is the moisture condition of the soil during and after moling. In the same kind of soil, a mole channel pulled under suitable moisture condition appears to have better form than the one pulled under unfavorable moisture conditions. If the soil is too dry, not only an unnecessarily high amount of power is required to pull the mole, but excessive shattering of the soil also takes place, and a smooth, stable channel cannot be obtained. Moling in wet soil generally results in channels of poor form.

Information regarding the optimum moisture condition for constructing the most desirable forms of mole channels as well as keeping the power requirement to a minimum is needed. From such information it may be possible to find a relationship of the power requirement, the dimensions of the moling plow, and the soil properties. This relationship can then be used for the determination of the size and type of a tractor required for moling work.

Objectives

The objectives of this study are:

1. To investigate the effect of moisture content of the soil on the form of mole channels by using a model.

2. To test the drainage capability of the constructed mole channels.

3. To find the magnitude of forces required to pull the moling plow through certain soil under different moisture conditions.

4. To evaluate the optimum moisture condition for the best mole form and the corresponding force required to pull or push the mole plow.

5. To formulate the relationship of the moling force, dimensions of the moling plow, depth of the mole channel, and soil properties.

REVIEW OF LITERATURE

History of Mole Drainage

There is evidence indicating that mole drains have been used in England since the early eighteenth century as reported by Richardson and Fussell (1922). During these early stages of development, the mole channel was formed by laying a few feet of pipe in a trench. Then a fill was compacted around the pipe to the desired level and the pipe was pulled out. The procedure was repeated until the entire mole channel was obtained.

According to Klippart (1867), the mole drain was introduced in the United States as early as 1859. It was constructed by using a horse to pull a torpedo attached to a blade through the subsoil at some depth to form unlined channels. The basic purpose of these drains was to collect the excess water which flows out of the soil and carry it to a suitable outlet channel. Newer mole drains were constructed by pulling a mole plow with a tractor. Sometimes a plug or follower was attached at the rear end of the torpedo to smooth the surface of the mole channel. Mole drains were installed between open ditches spaced from 1/8 to 1/4 mile apart in the Florida Everglades (Clayton and Jones,1941). They were used in some areas in California such as in the Sutter Basin, (Luthin, 1957).

However, as appeared in the Soil Conservation Service, National Engineering Handbook (1958), mole drainage has not been successfully used in the United States due to:

(a) a lack of extensive farmland suited for mole drain installation,

(b) the past high cost of adequate power equipment to install the drains,

(c) many past failures of such drains because they were improperly planned and constructed. The failures could be attributed to the lack of understanding of the requirements and limitations of mole drains.

The average life of mole drains when properly installed in locations suitable to them has been indicated to be three to five years and might, with diminishing effectiveness, provide drainage for as much as three to five years longer. Cultivation of moled lands reduced the effective life of such drains. Mole channels might be redrawn to restore their effectiveness. Nicholson (1942), Hudson and Hopewell (1940) stated that the maximum life of mole drains was between ten to fifteen years.

Investigations have been conducted to find the durability of the unlined and plastic lined mole channels by Willardson (1962). He installed systems of mole drains which consisted of both unlined and plastic lined mole channels in Cache Valley, Utah, U.S.A. He found that both types of drains were effective in removing water and salt from the soil during the initial period of continuous flooding. The unlined mole drain collapsed and did not produce water at all during

the second period of flooding. The plastic lined mole drain successfully survived three flooding cycles in addition to overwintering.

Gattis (1949) and Schwab (1947) reported that the principal advantage of mole drainage was its low first cost. The estimated cost of mole drains at a depth of 30 inches and a spacing of 20 feet was less than one-tenth of that for tile drainage. The major disadvantage was its short life in most soils.

Hooghoudt (1952) mentioned that the use of mole drains was increasing in the Netherlands even though they had to be pulled every two years.

Suitable Soil Moisture and Time to Construct Mole Drains

There were many factors that influenced the adequacy and durability of mole drains: soil type, outlets, length, slope, depth and spacing of mole lines, moisture content of soil under construction period, kind of equipment, and operation. The most suitable time for mole drain construction was when the subsoil was favorably moist and the soil surface was sufficiently dry to provide traction for haulage. A smooth channel was obtained when the moisture in the subsoil was such that it was in the plastic stage. Generally, the best time for moling was in late spring and, sometimes, late autumn (Soil Conservation Service, National Engineering Handbook, 1958).

Many investigators such as Saveson (1946), Henderson, Lindt,

and Pearl (1954), stated that mole drain was most suitable in heavy clay soil but Piper (1958) mentioned that not all clay was suitable for moling. The sandiness and mechanical properties of clay minerals should be considered. Piper pointed out that the plasticity and consistency of soil at the time of mole channel construction played an important part in the mole drain durability. He also stated that the ideal time for moling was in late spring and early summer (New Zealand).

Schwab (1947) discussed that the best time to install mole drains was when the soil surface was sufficiently dry and firm enough to support the power unit, and at the same time the subsoil was suitably wet and plastic to produce a smooth channel behind the moling torpedo. He also stated that a smooth, stable channel could not be formed in excessive dry soil due to the fracture of soil.

Mayo (1955) suggested that in order to obtain a good form, the mole channel should be constructed as late as possible in spring (New Zealand) before the subsoil was too dry and crumbly. Otherwise the channel surface disintegrated and resulted in a channel of poor form. Many other investigators also reported that construction of the mole channel while the soil is too dry resulted in excessive shattering and scaling of the channel surface which led to early collapse when submerged in water (Soil Conservation Service, National Engineering Handbook, 1958 and Schwab, 1947).

Hudson, Hopewell, Bowler, and Cross (1962), and Scott (1961) concluded that cracking or scaling of the wall of mole channel would not occur if the clay was sufficiently moist. Instead a smooth, clean, and tightly packed surface was obtained. Construction of a mole channel when the soil was excessively wet, coupled with heavy rain following the pulling, resulted in a very rapid breakdown.

Henderson, Lindt and Pearl (1954) stated that if the land were to be preirrigated by flooding, it would be essential to mole after preirrigation because the mole channels collapsed or filled with loose material when the land was flooded. They also mentioned that moling should be done after any subsoiling operation or after preirrigation and before seedbed preparation.

Power Requirements

Fouss and Donnan (1962) found from their experiments that the power required to pull a mole plow varied with soil type and moisture content at the time of pulling. A track-type tractor capable of developing 15,000 to 24,000 pounds of drawbar pull was required to pull a mole plow at a depth of 28 inches and an operating speed of 100 to 125 foot per minute in a heavy clay soil.

Mayo (1955) stated that for the power required to construct mole drains, a track laying tractor of the 30 to 40 horse-power class was absolutely necessary in rolling country. Wheel tractors fitted

with steel grippers of 30 to 40 horse-power had completed the work using 2 1/2-inch mole torpedo in flat country.

Piper (1958) discussed that the power required for a light mole plow with 2-inch diameter plug and a 1/2-inch thick blade pulling at a depth of 8 inches, under average conditions, could be supplied by a tractor of at least 25 drawbar horse-power. The traction depended on the condition of the soil surface.

Schwab (1947) indicated that track-type tractors or cable winches were suitable to pull the mole plow. At depths of 2 and 3 feet the power varied from 30 to 70 horsepower, respectively. The power requirement also depended on the speed of tractor, soil moisture, soil type, and size of the mole channel.

Hudson, Hopewell, Bowler, and Cross (1962) found that the size of a tractor required to install mole drains depended on many factors. Of major consideration were the heaviness and moistness of the clay, size of torpedo or plug, depth of mole channel, the setting and maintenance of the plow, and the wetness of the soil surface. The extent of the effect on draft of change in the moisture content of the clay subsoil was not generally realized. The results of draft measurements of a mole plow researched at the Massey College, New Zealand, emphasized the importance of soil moisture conditions. The experiments were made by using a light Reid and Gray plow fitted with a 2 1/2-inch diameter plug to install mole drains at a depth of 17 inches. The Reid

and Gray mole plow consisted of a blade attached to a torpedo. This mole plow had a vertical adjustment at the head of the plow for attachment of the drawbar. The skids at the front of the plow could be pressed lightly on the surface of the ground in order to obtain minimum draft consistent with the plow maintaining an even depth. Results of the experiments were reported as follows:

In August when the subsoil was moist, the average power required was 2,100 pounds. A wheel tractor of 18 to 20 drawbar horse-power class was suitable with an assumption that the tractor obtained satisfactory grip.

In October when the clay was still moist and considerably drier than in August, the surface conditions were ideal (dry and firm), and the average power required was about 4,000 pounds. A wheel tractor in the 35 to 40 drawbar horse-power class could be used. But actually, the pull varied from 3,200 to 4,600 pounds. Although a wheel tractor gave a satisfactory traction, it lacked power at some point where the power required was high. A crawler tractor in the 21 to 25 drawbar horse-power class was recommended because a lower gear ratio was available in this type of machine.

In November the clay had dried, and tests showed that the power required was 6,500 pounds. A 40 drawbar horsepower tractor was used. Because the clay was too dry, the mole channel surface was shattered and loose.

In September the soil surface was wet which resulted in lack

of traction. Two wheel tractors fitted with steel extensions could not pull the mole plow satisfactorily and a crawler tractor was found to be more suitable under this condition.

The authors also indicated that in heavier soils, the power required would be increased but not so greatly if the subsoil was wet. There were reports from farmers that when the soils started to dry out, the draft increased considerably.

Childs (1942) analyzed the nature of the forces acting on the mole plow and also the conditions for equilibrium as follows:

The elements of a mole plow and forces acting on it are shown in Figure 1, in which

T is the haulage tension, lbs

B is the distributed stress of the ground on the beam, lbs

m is the stress on the blade of mole plow, lb/in^2

c is the stress on the cartridge or torpedo, lb/in^2

j is the stress on the bob or plug, lb/in^2

Childs described the nature of the forces on the mole plow that there was no vertical component of the tension, T, because the direction of force was assumed to be parallel to the ground surface. Considering the whole surface of the blade, cartridge, and bob which was in contact with the soil, there was a pressure normal to the surface. As an addition, owing to the friction between the steel and soil, there was a shear stress parallel to the line of intersection of

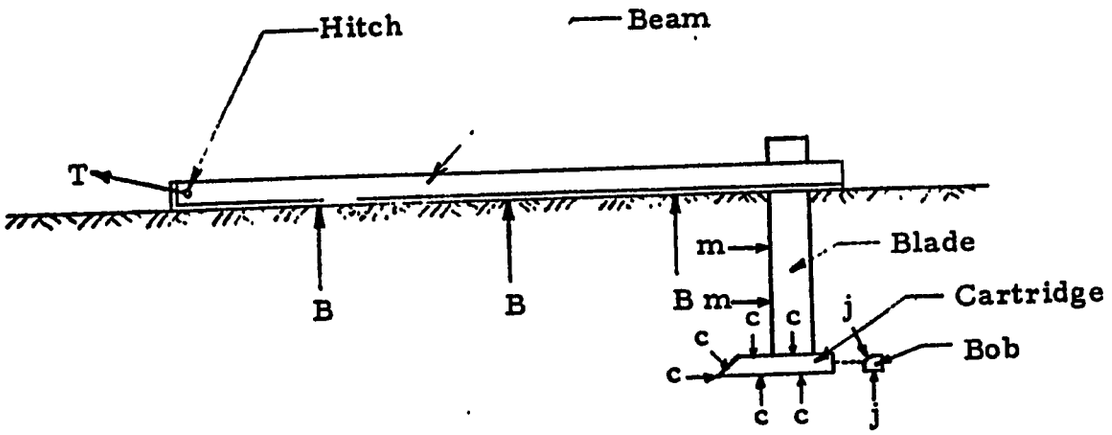


Figure 1. Diagramatic sketch showing elements of mole plow and forces acting on it.

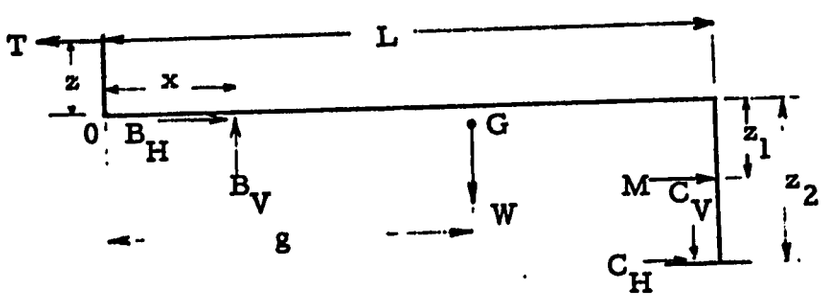


Figure 2. Force-diagram for a mole plow.

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 force was zero. The frictional force was a function of the velocity of the mole plow moving through the soil.

In this case the system of mole plow was assumed to move through the soil at a constant speed, and the blade was set perpendicular to the direction of moving which was considered to be horizontal. All distributed forces could be replaced by their corresponding resultants and shown as the components parallel and perpendicular to the direction of movement at various parts of the mole plow as shown in Figure 2, in which

T is the tension having no vertical component acting at the distance z from the hitch 0, lbs

M is the resisting blade force with no vertical component acting at the depth z_1 from the beam, lbs

B_H and B_V are the horizontal and vertical components, respectively, of the force on the beam acting at the distance x from the hitch, lbs

C_H and C_V are the horizontal and vertical components on the cartridge and the following bob acting at the distance z_2 from the beam, lbs

W is the weight of mole plow acting at the center of gravity G which is at a distance g, behind the hitch 0, lbs

z_2 is the average depth of mole channel, and the mole plow is to be considered working steadily at this depth, in

L is the beam-length from the hitch 0, to the blade, in.

Childs explained that the force on the bob was wholly horizontal because of its symmetry and also because the bob was trailing freely behind the cartridge; therefore, this horizontal force might be included in C_H. Since the bob was not part of the rigid body, no separate force on the bob was considered in Figure 2.

Childs developed three equations based on the conditions for static equilibrium as shown below.

For $\Sigma Fx = 0,$

$$T = B_H + M + C_H. \quad (1)$$

For $\Sigma Fy = 0,$

$$B_V = W + C_V. \quad (2)$$

For $\Sigma M = 0,$

$$x B_V + z_1 M + z_2 C_H + z T = g W + L C_V. \quad (3)$$

Childs mentioned that the measurements of the forces on the individual parts of the mole plow were not easily obtained, with the exception of the tension T, and consequently little information was available. The drawbar pull required to haul a mole plow in a typical moist claysoil, at a depth of 24 inches and constructing a mole channel

3.5-inch diameter, was about 5,000 to 6,000 pounds. This drawbar pull might be less for a shallow depth and a small size mole work, and might be as high as 10,000 pounds for a mole channel of 3 1/4 or 4-inch diameter drawn at a depth of 30-inch in dryish clay.

In his experiments he used the average value drawbar pull of 6,000 pounds for a mole channel 3.5 inch diameter at a depth of 2 feet. The friction between the beam and the ground was negligible in comparison with the large forces acting against the blade and cartridge. Substituting the above values in Equation (1), obtained

$$M + C_H = 6{,}000 \text{ lb.} \tag{4}$$

The neglect of B_H was only justifiable for an approximate calculation. Hudson and Hopewell (1940) cited evidence concerning B_H which supported Childs' statement.

Experiments with a model gave the ratio of $M/C_H = 2.0$, for a shallow work. Using this value and combining with Equation (4), yields

$$M = 4{,}000 \text{ lb.}$$

and

$$C_H = 2{,}000 \text{ lb.}$$

The value of C_V could be calculated by substituting the appropriate values of various terms in Equation (3). In this case Childs obtained $C_V = 550$ pounds. The value of M, C_H and C_V could be used for the design of a mole plow.

THEORY

Form of Mole Channel

The discharge of flow through a mole channel may be computed by the Manning formula

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2} \qquad (5)$$

in which

Q is the discharge of flow through the mole channel, ft^3/sec

R is the hydraulic radius of the cross-section, ft

S is the energy gradient, ft/ft

n is the Manning's coefficient of roughness, $ft^{1/6}$

A is the cross-sectional area of flow, ft^2.

In open channel flow Manning's n depends on the surface roughness, vegetation, channel irregularity, channel alignment, silting and scouring, obstruction, size and shape of the channel, stage of discharge, seasonal change, suspended material, and bed load.

The flow in a mole channel may be considered as being similar to the open channel flow. In this case the value of Manning's depends on the surface roughness, channel irregularities, channel

alignment, silting and scouring, size and shape of the channel, and stage of discharge.

In this study, the size and shape of channel, the flow cross section, and the channel alignment are the same in every test run. Silting and scouring are not permitted to exist by controlling the flow velocity. Therefore, Manning's n for a mole channel in a particular soil may be expressed as

$$n = f\,(S_r,\ C_i) \tag{6}$$

in which

S_r is surface roughness, and

C_i is the channel irrigularities.

From previous experiences in mole drainage construction, the character of the mole channel surface varies considerably depending on the moisture content of the soil in which the mole is drawn or pushed through. If the soil is too dry, a shattered and scaled surface is formed.

Therefore, if all factors affecting Manning's n are kept constant except the surface roughness and channel regularities, the value of n for a mole channel may be expressed as

$$n = f_1\,(w) \tag{7}$$

in which

w is the moisture content of soil at the time of moling.

In Equation (5), if R is kept constant by using the same mole plow and maintaining the same depth of flow through the mole channel in every test run, the energy gradient, S, is maintained constant by using the same head loss through the mole channel in all test runs. Then Equation (5) may be written as

$$Q = \frac{k}{n} \tag{8}$$

in which

$$k = 1.49\ A\ R^{2/3}\ S^{1/2}$$

and is constant throughout the study.

If the form of the mole channel is defined as being efficient when the surface roughness and channel irregularities are small, it is evident from Equation (8) that the value of Q may be taken as an index for the efficiency of the form of the mole channel. Large value of Q indicates good and efficient forms while small Q indicates poor channel forms.

Substituting n from Equation (7) in Equation (8)

$$Q = \frac{k}{f_1(w)} \tag{9}$$

or may be written as

$$Q = f_2(w)\ , \tag{10}$$

Equation (10) indicates that the form efficiency of mole channels is dependent on the moisture content of the soil in which the mole plow is moving through.

Forces Required to Pull Mole Plow

When a mole plow, consisting of a torpedo and a blade as shown in Figure 3, is drawn through the soil, two resisting forces acting on it are the bearing force F_B, and the frictional force F_F.

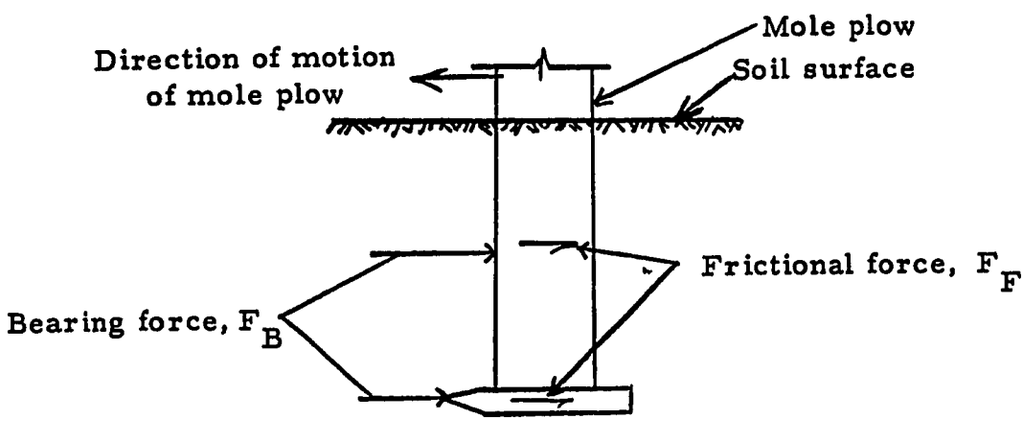


Figure 3. Resisting forces acting on the mole plow.

The total force required to move the mole plow through the soil may be written as

$$F = F_B + F_F \tag{11}$$

in which

F is the total force, lbs

F_B is the bearing resistance of soil on the projected area of the mole plow in the direction of motion, lbs

F_F is the frictional resistance of soil against the exterior surface of the mole plow, lbs.

Bearing resistance

The bearing resistance F_B of the soil on the blade may be written as

$$F_B = q_b + q_t \tag{12}$$

in which

q_b is the bearing resistance on the projected area of the blade, lbs

q_t is the bearing resistance on the projected area of the torpedo, lbs.

Resistance on the projected area of the blade. According to Lambe and Whitman (1969), Terzaghi's general bearing capacity of a long footing on a soil foundation may be expressed as

$$(\Delta q_s)_u = C N_c + \frac{\gamma B}{2} N\gamma + \gamma d_f N_q \tag{13}$$

in which

$(\Delta q_s)_u$ is the ultimate bearing capacity of a long footing, lb/in^2

C is the cohesion based on effective stresses, lb/in^2

γ is the unit weight of soil, lb/in^3

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

B is the width of the footing, in

N_c, N_γ, and N_q are the bearing capacity factors as a function of friction angle ϕ and may be obtained from Figure 4, dimensionless.

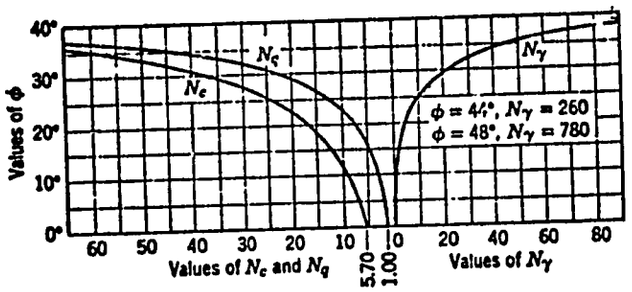


Figure 4. Bearing capacity factors according to Terzaghi. p. 58. Wayne C. Teng 1962. Foundation Design. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 466 pp.

The total bearing capacity of the footing, Q_b, is

$$Q_b = A_B (\Delta q_s)_u \tag{14}$$

in which

A_B is the contact area of footing with the soil foundation, in^2.

In the case of a mole plow, if A_b is the projected area of the blade normal to the direction of motion (see Figure 5), the bearing resistance on the blade q_b may be

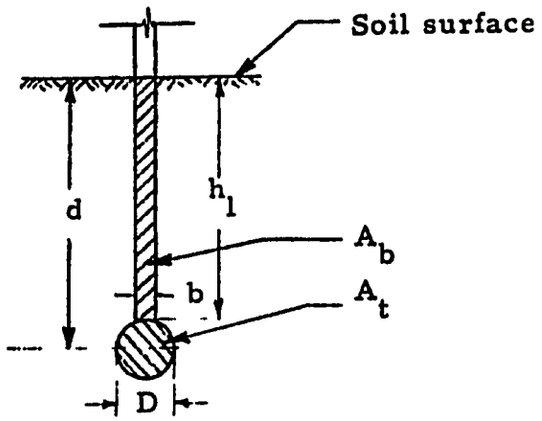


Figure 5. Projected area of the blade and torpedo of the mole plow.

expressed as

$$q_b = A_b (\Delta q_s)_u \tag{15}$$

In this case

$$(\Delta q_s)_u = C N_c + \frac{\gamma b}{2} N\gamma + \frac{\gamma h_1}{2} N_q \tag{16}$$

in which

h_1 is the length of the portion of the blade embedded under the soil surface, in

b is the thickness of the blade, in

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

<u>Resistance on the projected area of the torpedo.</u> When the bearing area is circular, $(\Delta q_s)_u$ is expressed as

$$(\Delta q_s)_u = C\,N_c + \frac{\gamma(0.9\,D)}{2}\,N_\gamma + \gamma d\,N_q \qquad (17)$$

in which

D is the diameter of the bearing area of torpedo, in

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

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

The bearing resistance of the soil on the torpedo may be written as

$$q_t = A_t\,(\Delta q_s)_u \qquad (18)$$

in which

q_t is the bearing resistance of soil on the torpedo, lbs

A_t is the projected area of the torpedo normal to the direction of pull (see Figure 5), in^2

$(\Delta q_s)_u$ is as shown in Equation (17).

Substituting q_b from Equations (15) and (16), q_t from Equations (17) and (18) into Equation (12), the total bearing resistance may be expressed as

$$F_B = A_b\left(C\,N_c + \frac{\gamma b}{2}\,N_\gamma + \frac{\gamma h_1}{2}\,N_q\right) + A_t\left(C\,N_c + \frac{\gamma(0.9\,D)}{2}\,N_\gamma + \gamma d\,N_q\right) \qquad (19)$$

Frictional resistance

Sowers and Sowers (1961) wrote an equation for the skin friction which acts along a pile shaft as follows

$$f = C + P \tan \phi \tag{20}$$

in which

f is the skin friction, lb/in^2

$\bar{P}$ is the effective stress, lb/in^2

ϕ is the angle of internal friction, dimensionless

$\bar{C}$ is the cohesion of soil in which the pile is driven, lb/in^2.

The skin friction based on Equation (20) may be used for the determination of the frictional resistance of the soil on the surface of the mole plow.

The effective stress in soil is determined from the equation

$$\bar{P} = p - u \tag{21}$$

in which

p is the total stress, lb/in^2

u is the neutral stress, lb/in^2

In this study, the plow was pushed through a clay soil at a speed of approximately 0.25 foot per minute. This relatively high speed of shearing action in the heavy clay soil usually results in the neutral stress being as high as the total stress acting on the soil, or

$$u = p.$$

Taking u = p in Equation (21)

$$P = 0. \tag{22}$$

Substituting Equation (22) into Equation (20) yields

$$f = C. \tag{23}$$

Lambe and Whitman (1969) stated that not the entire area of the pile shaft is fully in contact with the soil, especially in stiff clays. From this concept the effective frictional area of a mole plow is less than the actual surface area of the portion moving through the soil, and may be written as

$$S_e = K\,(S_b + S_t) \tag{24}$$

in which

S_e is the effective frictional area of the mole plow, in^2

S_b and S_t are the gross frictional surface area of the portion of blade of the mole plow moving in the soil and the gross frictional surface area of the torpedo, respectively, in^2

K is the coefficient of the effective area, dimensionless.

The total frictional resistance is the product of the skin friction and the effective area, which may be expressed as

$$F_F = K\,(S_b + S_t)\,f\ . \tag{25}$$

Substituting the value of f from Equation (23), Equation (25) becomes

$$F_F = K (S_b + S_t) \ C. \tag{26}$$

Equation (26) may be written as

$$F_f = f_b + f_t,$$

in which

F_F is the frictional resistance of soil acting on the mole plow, lbs

f_b is the frictional resistance of soil acting on the blade and is equal to $K S_b C$, lbs

f_t is the frictional resistance of soil acting on the torpedo and is equal to $K S_t C$, lbs.

The total force required to move the mole plow through the soil is found by substituting the values of F_B from Equation (19) and F_F from Equation (26) into Equation (10) and simplified,

$$F = A_b \left(C N_c + \frac{\gamma b}{2} N_\gamma + \frac{\gamma h_1}{2} N_q\right) + A_t \left(C N_c + 0.9 \frac{\gamma D}{2} N_\gamma + \gamma d N_q\right)$$

$$+ K (S_b + S_t) \ C. \tag{27}$$

Equation (27) may be used to determine the total force required for pulling or pushing mole plow through a clay soil when the cohesion, angle of internal friction of the soil, unit weight of soil, plow dimensions, and K are known.

Effect from sides of box

By using the diagram showing the distribution of pressure in the soil due to a load on the surface (see Figure 6), the pressure due to moving mole plow at the nearest side-wall of the soil box was found to be negligible.

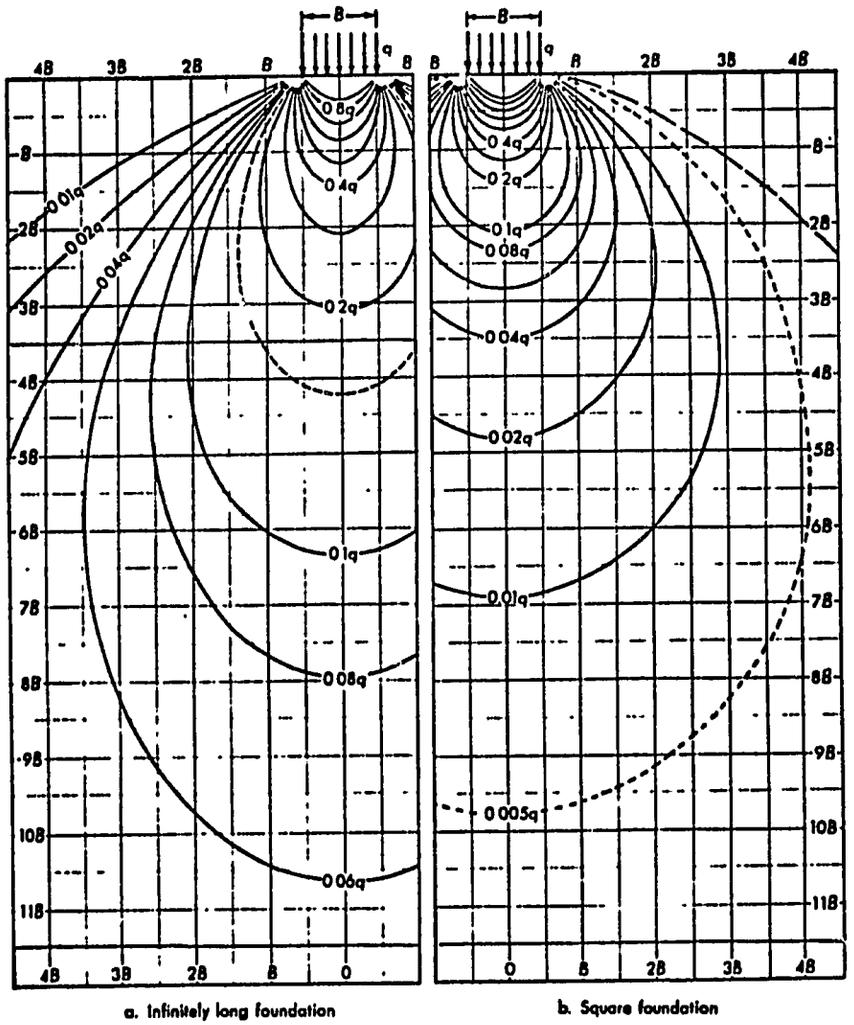


Figure 6. Curves of equal vertical stress beneath a foundation--The Boussinesq analysis [Taken from Sowers and Sowers 1961. p. 163].

Note: q is the uniform foundation pressure, lb/in^2

B is the width of the footing, in.

EXPERIMENTAL APPARATUS AND PROCEDURE

Apparatus

Soil box

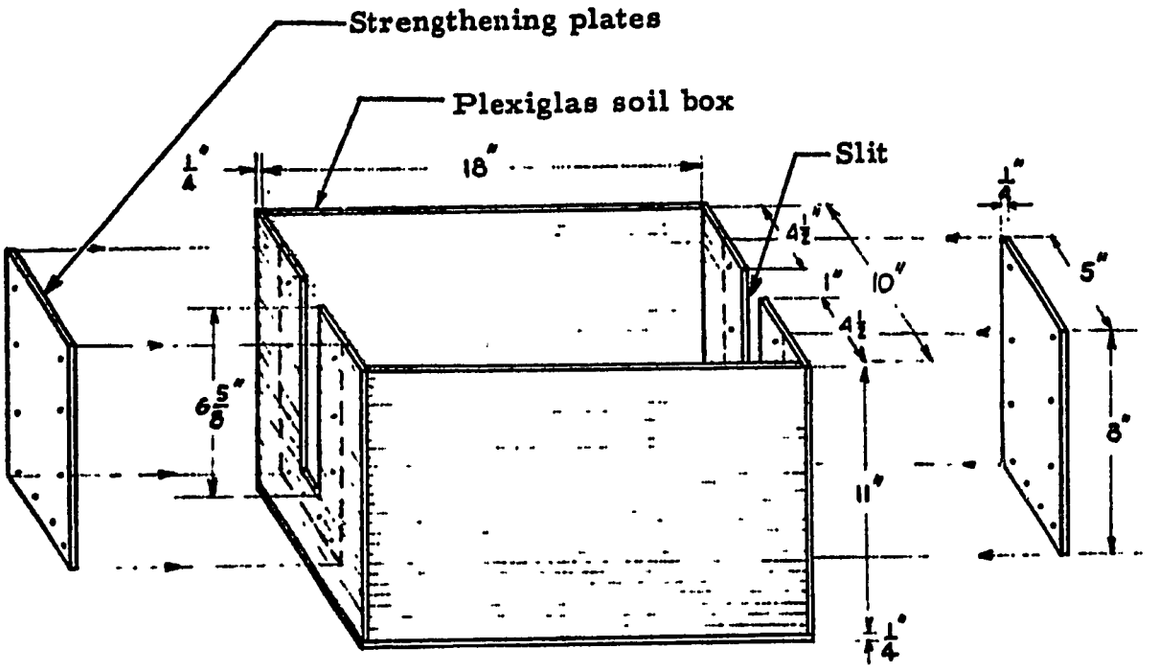
A box made of 1/4-inch thick Plexiglas was used to contain the soil in which a mole plow was pushed through to form a mole channel. The box was constructed with internal dimensions of 10-inch wide, 18-inch long, and 11-inch high. To provide a passage for the mole plow, two slits about 1-inch wide and 6 5/8-inch long were cut in the short sides of the box as shown in Figure 7a. The slits weakened the strength of the box, therefore detachable side plates 5-inch wide and 8-inch long were used 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 described in the test procedure. The entire soil box was supported on the outside by a steel frame as shown in Figure 7b.

Tamper

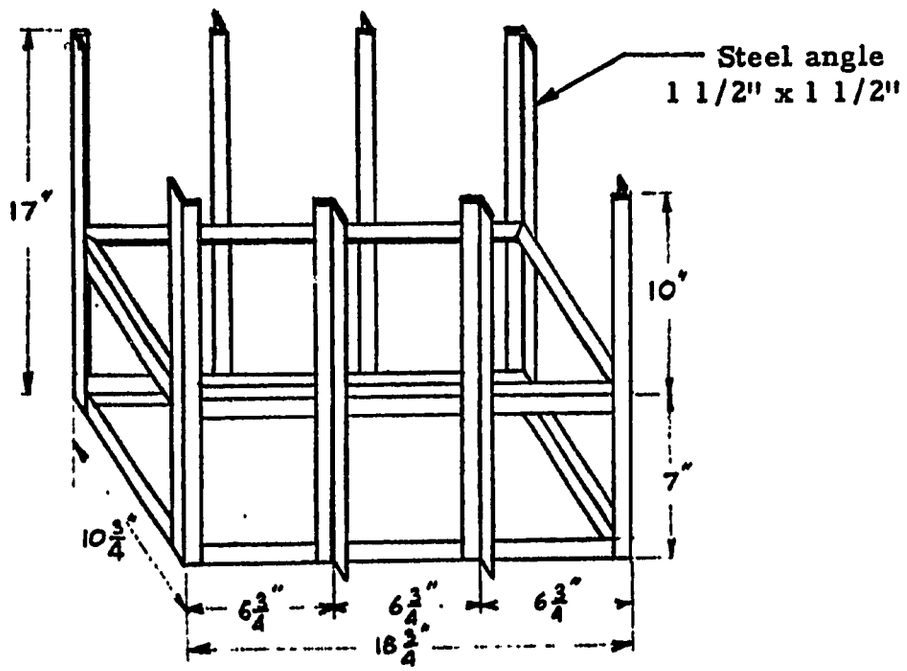
A tamper shown in Figure 8 was made of a steel plate 3/32-inch thick, 5-inch by 5-inch in area, welded to a handle 1 7/8-inch diameter and 11-inch long. The total weight of the tamper was 10 pounds.

Mole plow

The mole plow consisted of a steel torpedo 19/32-inch diameter



a. Plexiglas soil box with detachable side plates.



b. Steel frame for supporting the Plexiglas soil box.

Figure 7. Plexiglas soil box and steel frame.

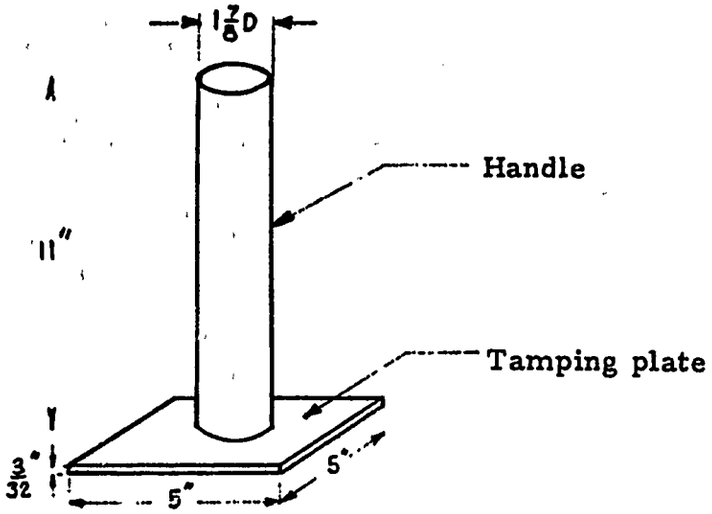


Figure 8. Steel tamper for compacting soil.

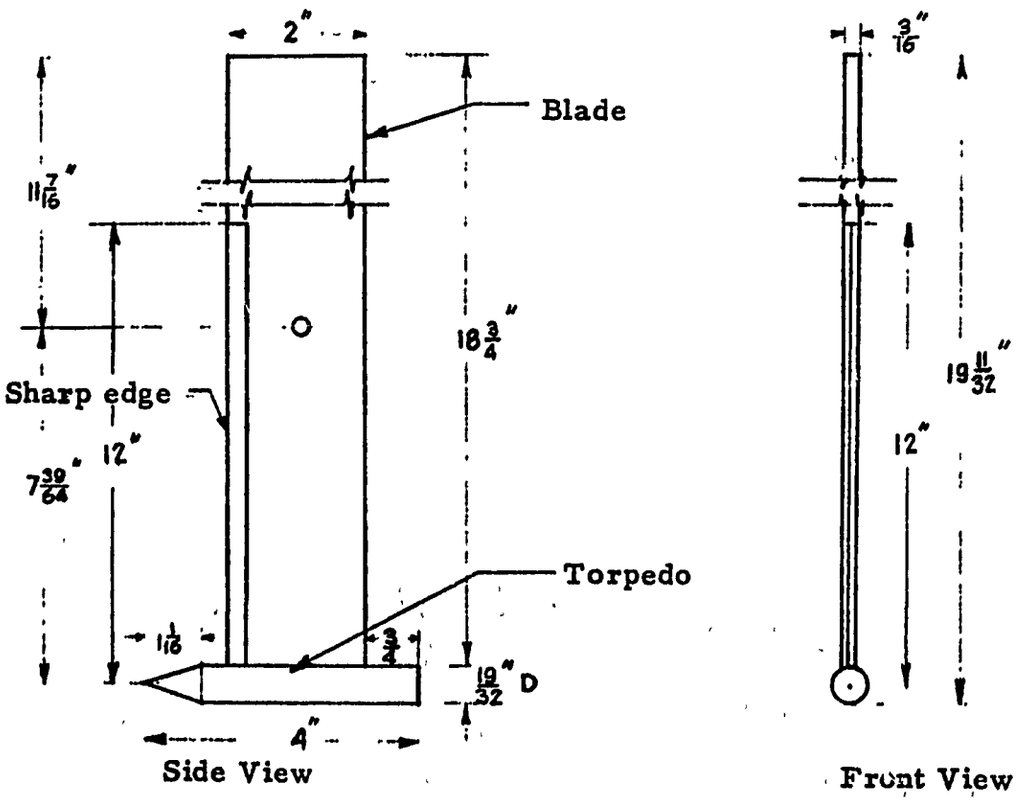


Figure 9. Moling plow implement consisting of a steel torpedo attached to a steel blade.

and 4-inch long welded to a 2-inch wide, 3/16-inch thick, and 18 3/4-inch long steel blade. The blade section was tapered at the leading edge for a length of 12 inches from the torpedo as shown in Figure 9.

Pushing beam

A specially designed pushing beam equipped with two calibrated proving rings shown in Figure 10 was used to push the mole plow through the soil in the soil box. The force required to push the mole plow was measured by reading the deflection of the two proving rings which had been calibrated prior to the tests. With the known deflection of the proving ring read from the dial gages, the corresponding forces were obtained from the calibration curves.

The general arrangement of the pushing beam of the soil box is shown in Figure 11.

Discharge rate measuring apparatus

The discharge rate measuring apparatus is shown in Figure 12. The two detachable inlet and outlet boxes were attached to the soil box after a mole channel was constructed. A plastic tube, 11/32-inch inside diameter, was connected from a water supply tank having a constant head throughout the entire study to the inlet box. The water flowed through the mole channel into the outlet box and discharged through a plastic tube, 1/4-inch inside diameter, into a calibrated

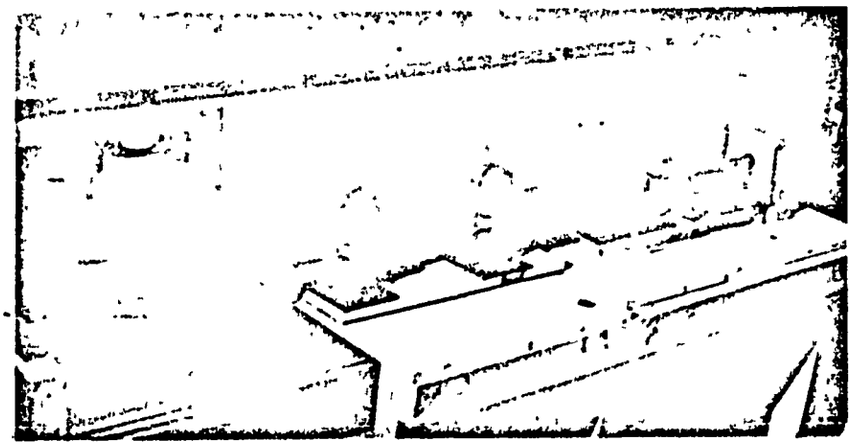


Figure 10. A specially designed pushing beam installed on the platform.

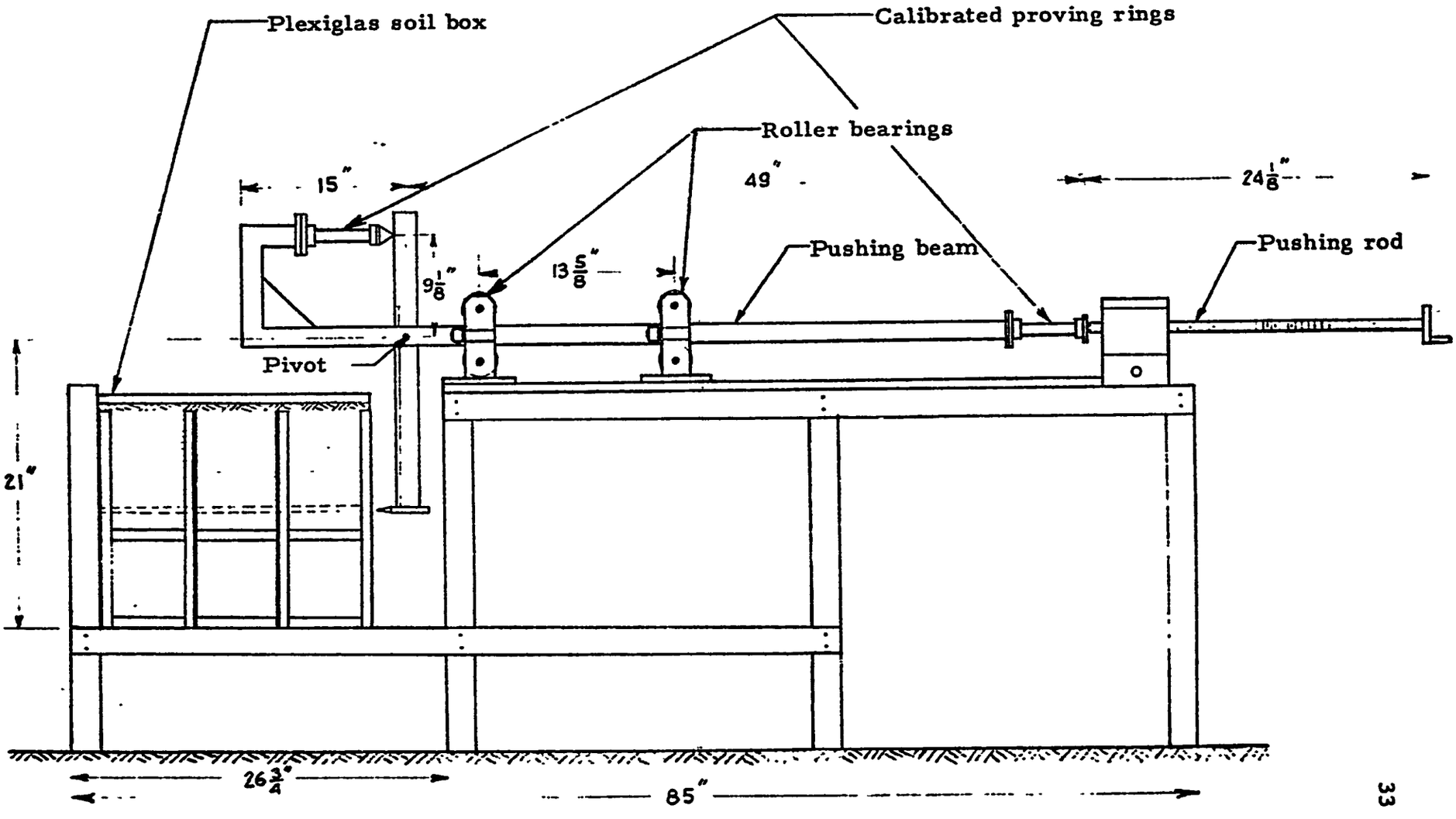


Figure 11. Pushing rod equipped with force measuring devices (not to scale).

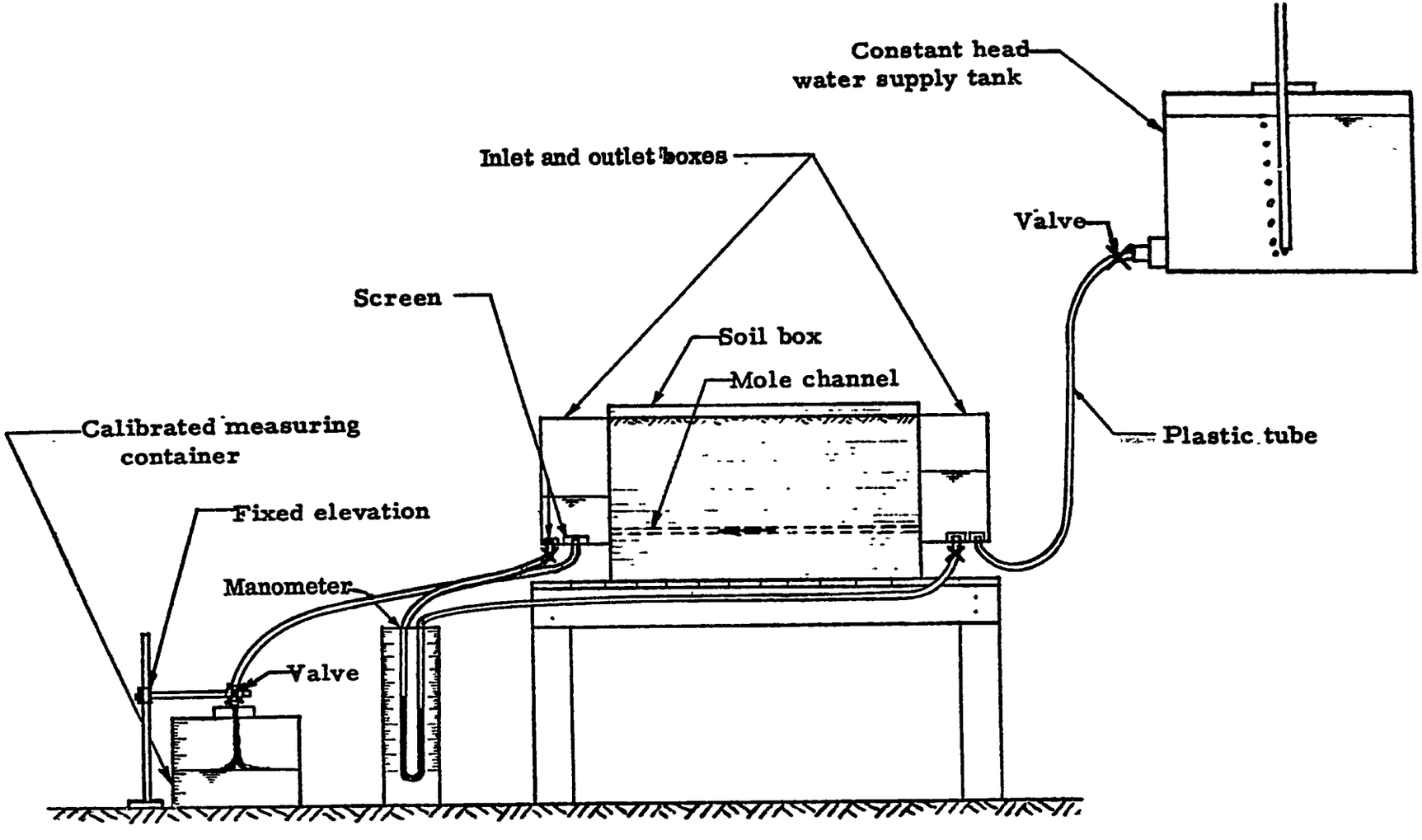


Figure 12. General arrangement of equipment for measuring the discharge rate of the mole channel.

measuring container. The discharge rate was measured by means of a stop watch. The difference in the water level in the inlet and outlet boxes which indicated the head loss of flow through the mole channel was maintained constant by the use of valves in the inlet and outlet plastic tubes (see Figure 12). The manometer, filled with Merium No. D-8325 fluid having a specific gravity of 1.75, was used for measuring the differential water level at the inlet and outlet boxes.

Experimental Procedure

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

The soil was dried and pulverized before mixing with water to the desired moisture content. The physical properties of the soil after pulverization are shown in Table 1.

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 dry bulk density of 1.32 grams per cubic centimeter was put in a 1 1/2 cubic foot electric mixer. A predetermined amount of water was added to the soil by an electric sprayer while the mixer was in motion to assure uniform moisture distribution.

Altogether 11 test runs were conducted. The moisture content of the soil in each test run varied and ranged from 20 percent by dry weight basis to complete saturation.

Table 1. Physical properties of the soil used in the experiments

Soil type	Silty clay (Clay 53%, Silt 47%)
Void ratio	0.958
Porosity	48.9 percent
Specific gravity	2.59
Bulk density (dry)	1.32 grams per cubic centimeter
Liquid limit	44 percent
Plastic limit	22 percent
Plasticity index	22 percent

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

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

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 calibrated proving rings while the mole plow was passing points at the distances of 6, 9, 12, and 15 inches from the beginning, respectively. Calibration curves were used to convert the readings to the equivalent forces.

The actual moisture content of the soil in each test run was determined by taking a soil sample from the soil box and drying in an oven.

After the mole channel was constructed, the mole form was observed by a visual inspection. Photographs of the mole channel and the slit cut by the blade of the mole plow were taken.

For additional information about the mole form, the discharge rate of the mole channel was measured by connecting the discharge rate measurement apparatus to the soil box as described previously under "Apparatus." The depth of flow at the inlet was kept constant at 1 1/2 inches above the channel bottom in each test and the head loss through the channel in all test runs was also maintained constant at 3/8 inch which was indicated by the difference of 1/2 inch in the level of the manometer fluid. The discharge rate was determined by means of a volumetric measurement of the discharge in the calibrated measuring container and the corresponding duration of the discharge. Four readings were taken to assure that the discharge rate was constant.

After measuring the discharge rates, the soil in the box was

carefully removed to expose the condition of the mole channel, and photographs were taken.

Direct shear tests were conducted to find the relationships between the cohesion of the soil versus the soil moisture content and between the angle of internal friction versus moisture content. The soil samples for these shear tests were taken from the soil in the box which had been moistened and compacted in the same manner as when used in constructing the mole channel.

The soil used in the experiments was also tested to find the moisture content at 1/3-bar tension.

ANALYSIS OF EXPERIMENT RESULTS AND DISCUSSION

Form of Mole Channel

The relationship between the moisture content of the soil and the form of the mole channel was investigated by visual inspections and by measuring the discharge rates of flow through the mole channels under a constant head loss. Visual inspections were made in each experiment immediately after the mole channels were constructed. The inspection was repeated after the discharge rate was measured. Table 2 shows results of the visual inspection of the form of mole channels constructed under different moisture contents of the soil at the time of moling.

Photographs showing the surface of the mole channels and general mole forms before and after measurement of discharge rates are shown in Figures 13 through 15.

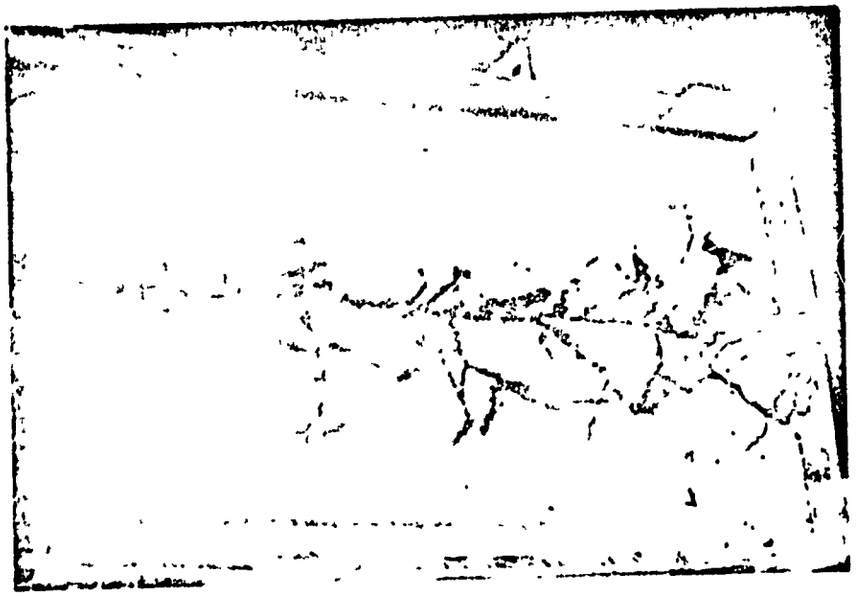
The discharge rate may be used as an indication of the efficiency of the form of a mole channel as shown by Equation (8). The discharge rates through mole channels under a constant total head loss of 3/8 inch are shown in Table 3. The curve showing the relationship between the discharge rate and the moisture contents of the soil at the time of mole channel construction is shown in Figure 16.

The moisture content of soil at 1/3-bar moisture tension was found as shown in Figure 16.

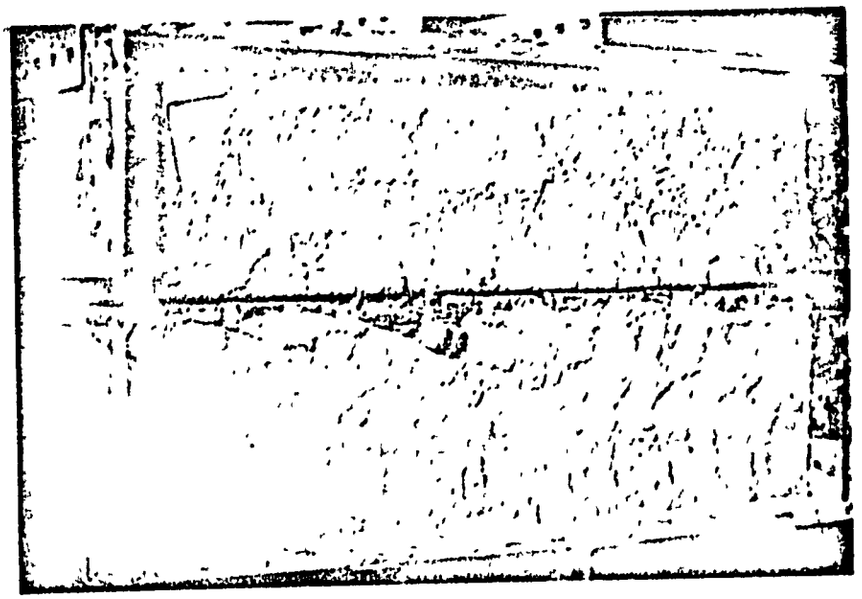
Table 2. Results of visual inspection of mole channel condition.

Test run No.	Moisture content, %	Condition of mole channel	
		Before discharge rate measurement	After discharge rate measurement
1	20.1	Scaling surface, large quantity of fallen soil particles in channel.	*
2	21.7	Moderate scaling surface and quantity of fallen soil particles in channel.	*
3	23.7	Surface slightly scaled, less quantity of fallen soil particles than in test run No. 2.	*
4	25.6	Smooth, slightly fallen soil particles in channel.	Mole channel was approximately half filled with sediments.
5	26.6	Smooth and clean surface, no fallen soil particle in channel.	Approximately 1/4 of the mole channel was filled with sediments.
6	27.1	Smooth and clean.	Approximately 1/4 of the mole channel was filled with sediments.
7	27.7	Smooth and clean	Approximately 1/4 of the mole channel was filled with sediments.
8	29.1	Smooth and clean.	Approximately 1/4 of the mole channel was filled with sediments.
9	37.0 (Saturated)	Irregular surface and appeared unstable. Movement of soil noticeable.	

*The mole channel collapsed before the measurement of discharge rate was completed.

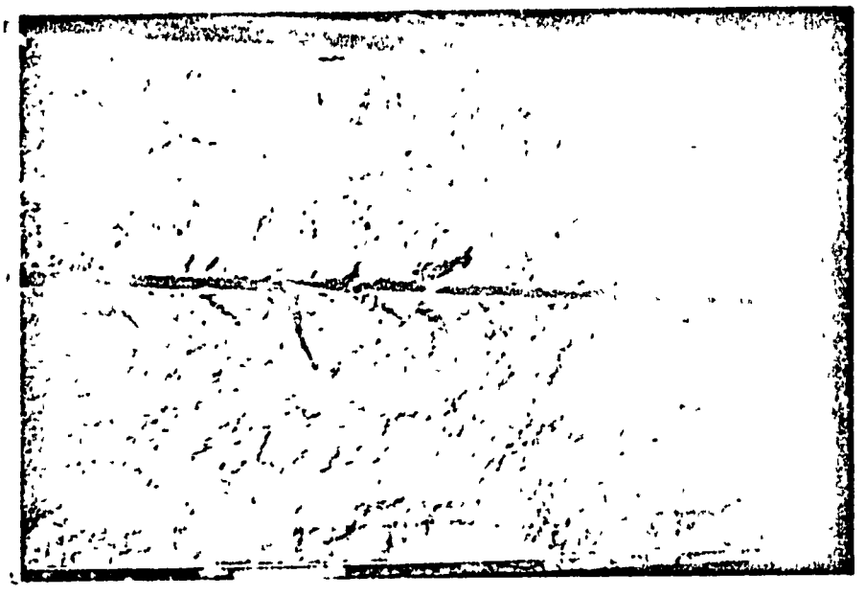


a. Moisture content of soil = 20.1 percent



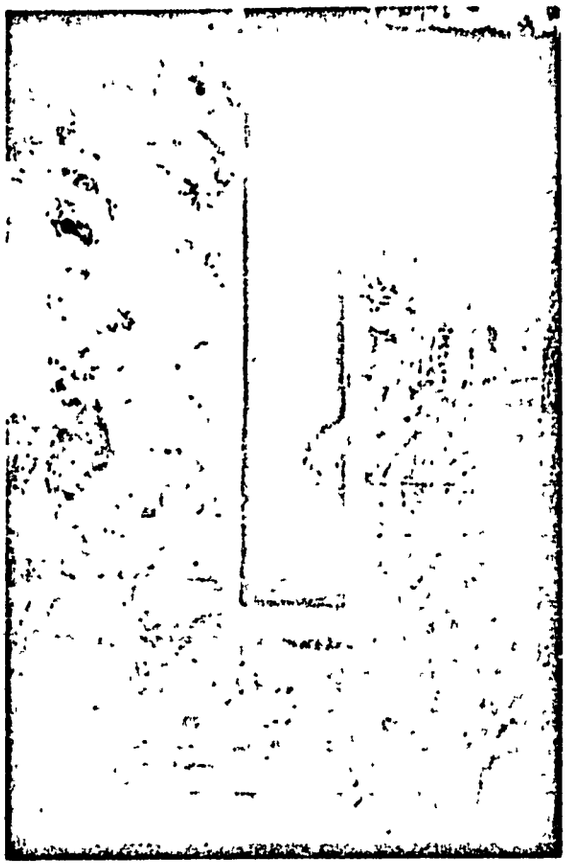
b. Moisture content of soil = 27.1 percent

Figure 13. Soil surface immediately after mole channel construction



c. Saturated condition. (37.0 percent)

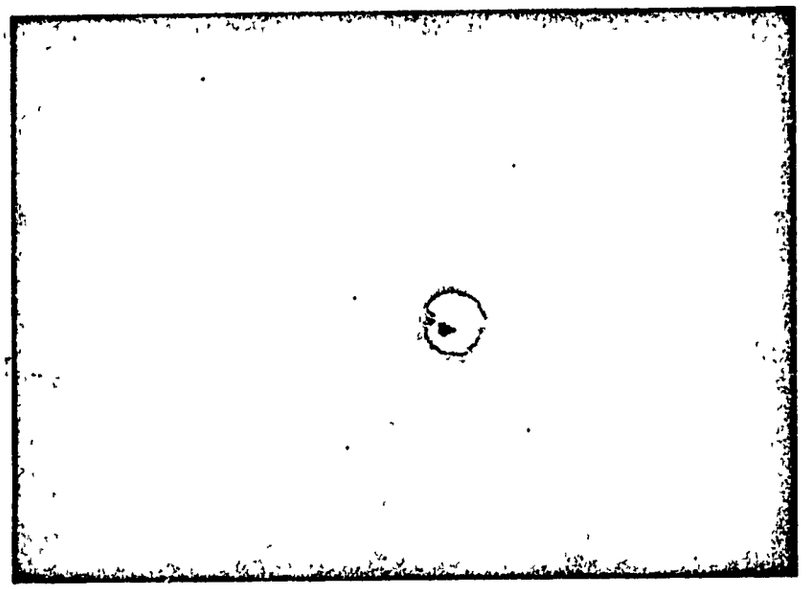
Figure 13. (continued)



a. Moisture content = 20.1 percent

Figure 14. General appearance of mole channel immediately after being built.

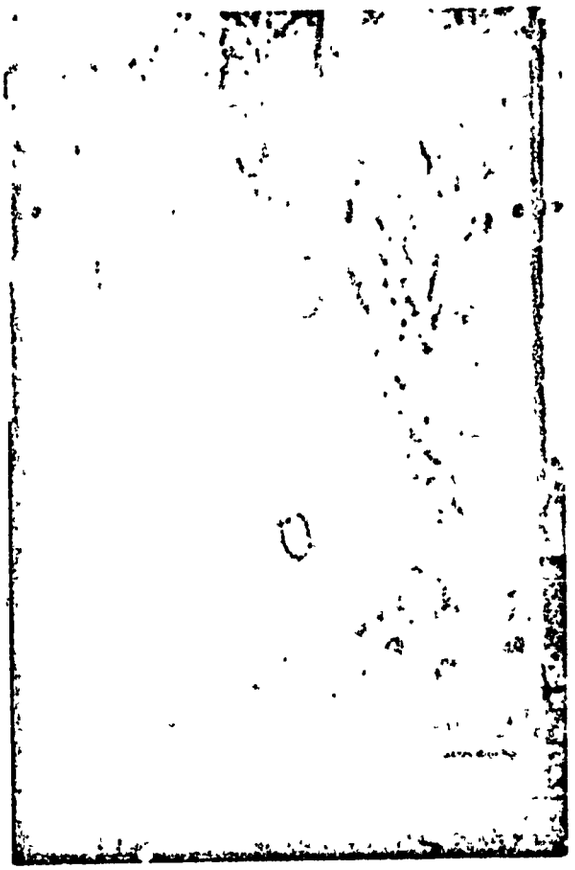
Note: Large quantity of soil particles in the mole channel.



b. Moisture content = 27.1 percent

Figure 14. (continued)

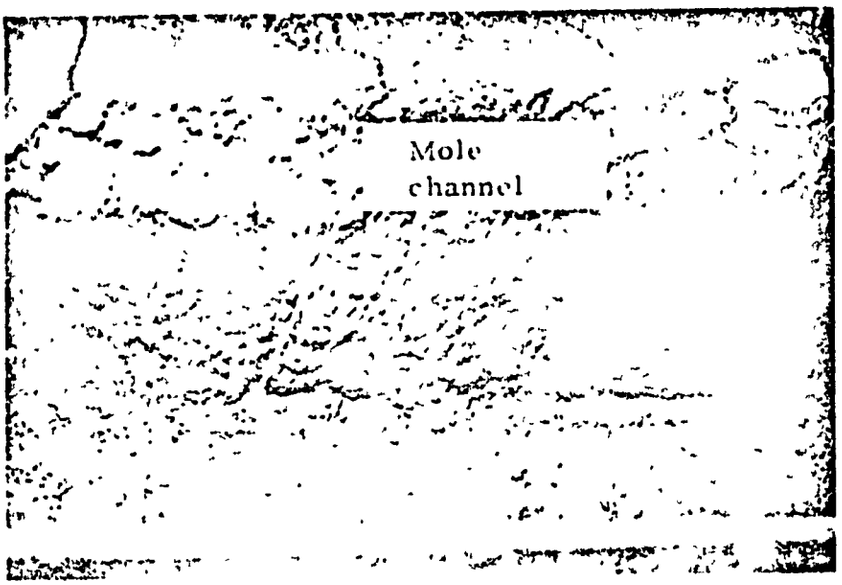
Note: Smooth and clean mole channel.



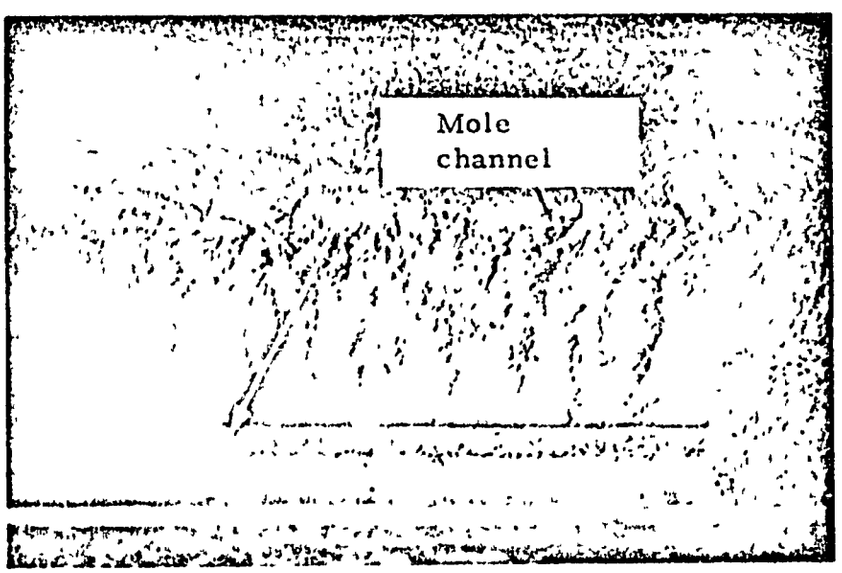
c. Saturated condition

Figure 14. (continued)

Note: Irregularities of surface of mole channel.



a. Moisture content = 20.1 percent

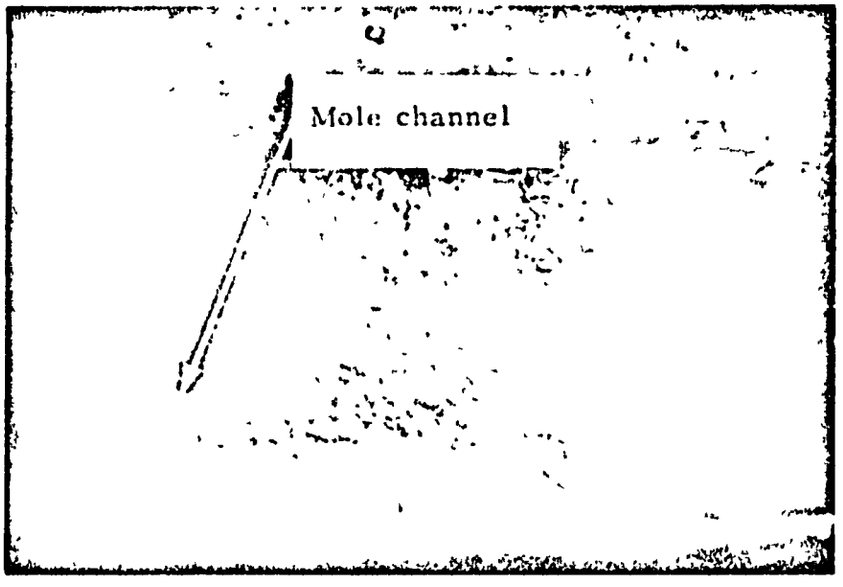


b. Moisture content = 27.7 percent

Figure 15. Condition of mole channel after the discharge rate measurement.

c. Moisture content = 27.7 percent

Note: The relatively good form of mole channel.



d. Saturated condition

Figure 15. (continued)

Note: The mole channel could hardly be identified after the water was discharged through the mole channel.

Table 3. Discharge rate through mole channel.

Test run No.	Soil Moisture content, %	Q cm^3/sec.	Remarks
1	20.1	--	Mole channel collapsed before discharge rate could be measured.
2	21.7	--	Mole channel collapsed before discharge rate could be measured.
3	23.7	5.53	Mole channel collapsed after only one reading was obtained.
4	25.6	21.50	--
5	26.6	24.08	--
6	27.1	25.15	--
7	27.7	26.88	--
8	29.1	26.46	--
9	37.0 (Saturated[1])	20.65	Mole channel collapsed after only two readings were obtained.

[1] In this test run, the mole channel was constructed while the soil was in a saturated condition. The dry bulk density of the soil was kept the same as in other test runs. To assure a complete saturation, the water was allowed to pond on the soil surface for three days.

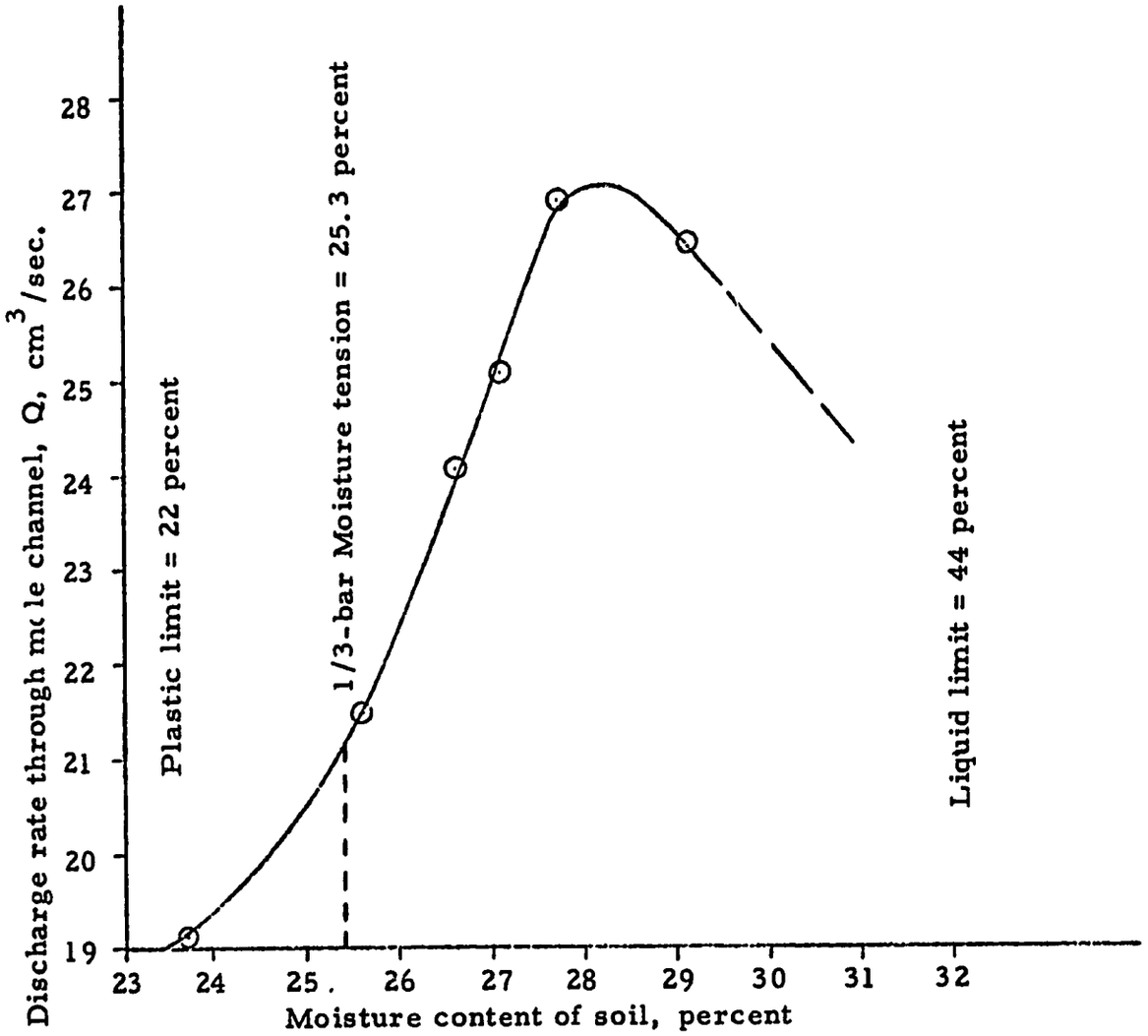


Figure 16. Discharge rates through mole channels constructed in soil under different moisture conditions.

Note: 1. For mole channels built in the soil having moisture contents of 20.1 and 21.7 percent, the channel collapsed immediately.

2. At a moisture contents of 23.7 percent the mole channel collapsed only after one reading was obtained.

3. At saturation, mole channel collapsed after only two readings were obtained.

Forces Required to Pull Mole Plow

The force required to pull a mole plow in a certain soil is equal to the total resistance of the soil against the mole plow. If the mole plow were attached to a tractor in such a manner that only the torpedo and the blade were in contact with the soil, the force required to operate the plow would be equal to the resistance of the soil acting on the blade and torpedo.

Experimental resisting forces

The experimental resisting forces were determined by using Equation (48). The values of F_1 and F_2 were read from the calibration curves for the proving rings using the known values of D_1 and D_2 obtained during the tests.

Appendix A shows the table of values of D_1, D_2 and the average values obtained from the experiments. It was found that the experimental resisting forces varied with the moisture content of the soil as shown in Table 4 and by curve C in Figure 17.

Derivation of Equation (48) is as follows:

The forces acting on the mole plow are shown in Figure 18 a. The mole plow was attached to the pushing beam by a hinge at A during the construction of the mole channel in the experiments.

The pushing beam and the mole plow were designed in such a way that the magnitude of the resisting forces on the mole plow may

Table 4. Experimental resisting forces acting on the mole plow.

Test run No.	Soil moisture content, %	D_1 * $\times 10^3$ in	F_1 lb	D_2 * $\times 10^3$ in	F_2 lb	F_E lb
1	20.1	1.64	335.0	5.10	240.0	333.29
2	21.7	1.49	306.0	4.82	220.0	305.44
3	23.7	1.32	269.0	4.47	192.0	267.64
4	25.6	1.03	210.0	3.92	150.0	208.94
5	26.6	0.85	172.0	3.45	126.0	171.16
6	27.1	0.72	145.0	2.85	107.0	144.24
7	27.7	0.67	135.0	2.65	100.0	134.29
8	29.1	0.55	110.0	2.10	81.0	109.42
9	37.0 (Saturated)	0.30	59.0	0.95	43.0	58.69

*Average values of D_1 and D_2 taken from Appendix A.

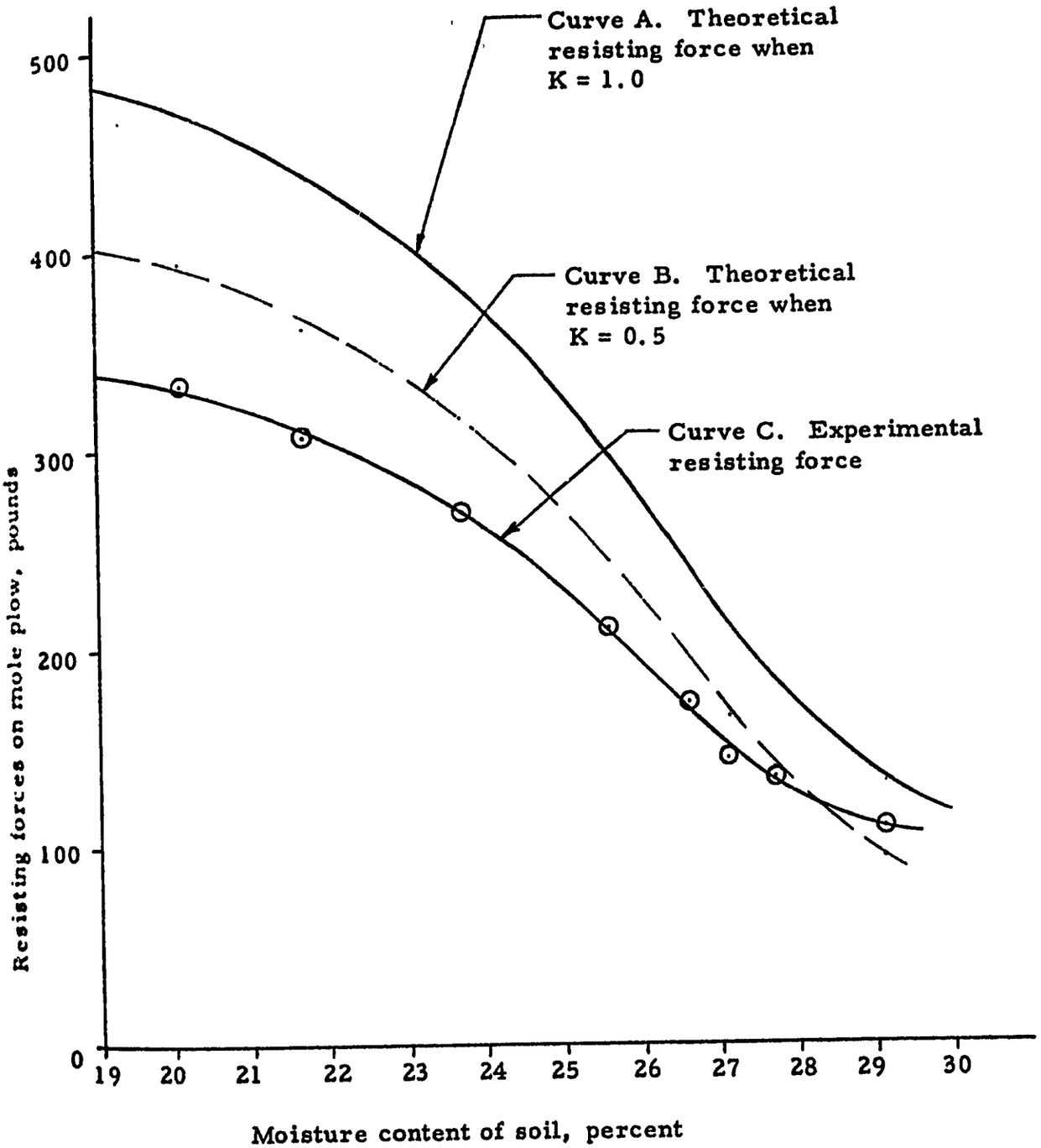
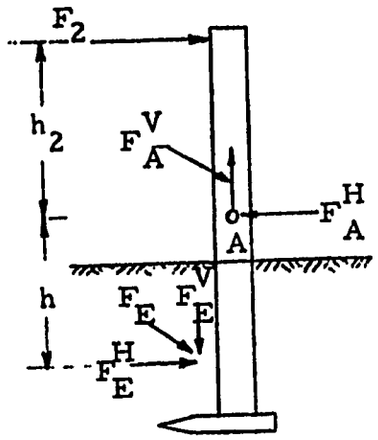
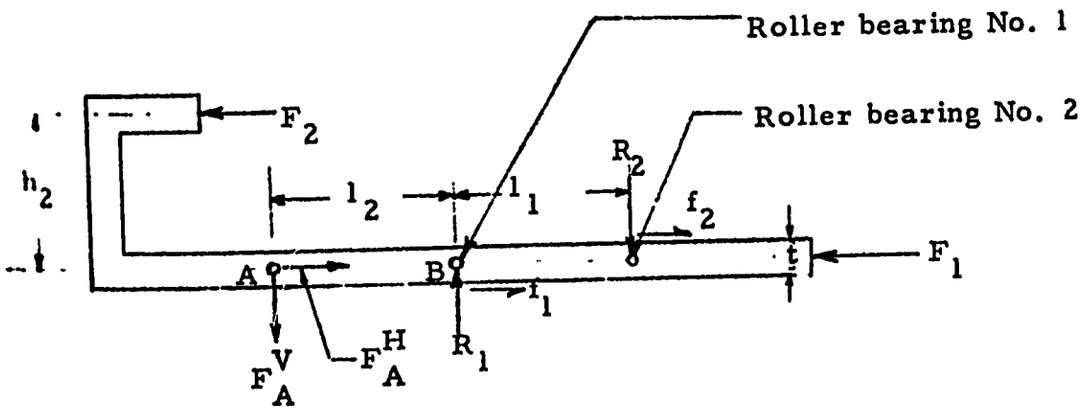


Figure 17. Experimental and theoretical resisting forces on mole plow under different moisture conditions of the soil.



a. Mole plow



b. Pushing beam

Figure 18. Diagramatic sketch showing forces acting on the mole plow and pushing beam.

be determined from the reading on the two proving rings attached to the pushing beam.

Figure 18 shows the forces acting on the mole plow and pushing beam which may be described as follows:

F_E is the resultant of resisting forces acting on the mole plow as obtained from experiments, lbs

F_E^H is the horizontal component of the resultant force F_E, lbs

F_E^V is the vertical component of the resultant force F_E, lbs

h is the distance from the hinge A to the resultant F_E^H, lbs

F_1 is the force read by means of proving ring No. 1, lbs

F_2 is the force read by means of proving ring No. 2, lbs

F_A^H and F_A^V are the horizontal and vertical components, respectively, of the force acting on the hinge at A, lbs

R_1 is the reaction on the roller bearing No. 1, lbs

R_2 is the reaction on the roller bearing No. 2, lbs

f_1 and f_2 are the frictional forces of the roller bearings No. 1 and 2, respectively, lbs

f_c is the coefficient of friction of the roller bearings, dimensionless

t is the width of the pushing beam, in

l_1 is the spacing between the two roller bearings, in

l_2 is the distance from the hinge at A to the nearest roller bearing, in

h_2 is the distance from F_2 to the hinge at A, in,

In Figure 18a, from equations of static equilibrium, $\Sigma F_H = 0$,

$$F_A^H = F_2 + F_E^H \tag{28}$$

and $\Sigma F_V = 0$,

$$F_E^V = F_A^V. \tag{29}$$

In Figure 18b, taking $\Sigma F_H = 0$,

$$F_A^H = F_1 + F_2 - f_1 - f_2 \tag{30}$$

and $\Sigma F_V = 0$,

$$F_A^V = R_1 - R_2. \tag{31}$$

Taking $\Sigma M_B = 0$,

$$R_2 = \frac{1}{l_1} (F_2 h_2 + F_A^V l_2 + f_1 \frac{t}{2} - f_2 \frac{t}{2}). \tag{32}$$

Multiplying Equation (32) by two, adding to Equation (31), and rearranging yields

$$R_1 + R_2 = F_A^V + \frac{1}{l_1}\left[2F_2h_2 + 2F_A^V l_2 + t(f_1 - f_2)\right]. \qquad (33)$$

From the principle of friction,

$$f_1 = f_c R_1 \qquad (34)$$

$$f_2 = f_c R_2 \qquad (35)$$

Inserting the values of f_1 and f_2 from Equation (34) and (35) into Equation (33) yields

$$R_1 + R_2 = F_A^V + \frac{F_2h_2}{l_1} + \frac{F_A^V l_2}{l_1} + \frac{t}{l_1} f_c (R_1 - R_2). \qquad (36)$$

Substituting the value of $R_1 - R_2$ from Equation (31), Equation (36) becomes

$$R_1 + R_2 = F_A^V + \frac{2F_2h_2}{l_1} + \frac{2F_A^V l_2}{l_1} + \frac{t}{l_1} f_c F_A^V. \qquad (37)$$

Substituting the values of f_1 and f_2 from Equation (34) and (35) into Equation (30) and differentiating with respect to l_2,

$$\frac{d F_A^H}{d l_2} = \frac{d F_1}{d l_2} + \frac{d F_2}{d l_2} - f_c \frac{d}{d l_2}(R_1 + R_2). \qquad (38)$$

From the experiments F_1 and F_2 appeared to be constant, see Appendix A, and did not vary with l_2 hence

$$\frac{d F_1}{d l_2} = 0 \quad \text{and} \quad \frac{d F_2}{d l_2} = 0$$

F_A^H, the horizontal component of the resisting force of soil on the mole plow does not vary with the distance l_2, therefore

$$\frac{d F_A^H}{d l_2} = 0.$$

Equation (38) becomes

$$f_c \frac{d}{d l_2} (R_1 + R_2) = 0$$

or

$$\frac{d}{d l_2} (R_1 + R_2) = 0. \tag{39}$$

By differentiation of Equation (37), one obtains the following

$$\frac{d}{d l_2} (R_1 + R_2) = \frac{d F_A^V}{d l_2} + 2 \frac{h_2}{l_1} \frac{d F_2}{d l_2} + \frac{2}{l_1} l_2 \frac{d F_A^V}{d l_2} + \frac{2}{l_1} F_A^V + \frac{t}{l_1} f_c \frac{d F_A^V}{d l_2} \tag{40}$$

F_A^V, the vertical component of the resisting force of soil on the mole plow, does not vary with the distance l_2, therefore

$$\frac{d F_A^V}{d l_2} = 0.$$

By taking

$$\frac{d}{d l_2} (R_1 + R_2) = 0, \text{ from Equation (39)} \frac{d F_2}{d l_2} = 0, \text{ and}$$

$\frac{d F_A^V}{d l_2} = 0$, Equation (40) becomes

$$\frac{2}{l_1} F_A^V = 0$$

or

$$F_A^V = 0. \tag{41}$$

Substituting $F_A^V = 0$ into Equation (31) yields

$$R_1 = R_2. \tag{42}$$

With $R_1 = R_2$, Equation (34) and (35) becomes

$$f_1 = f_2. \tag{43}$$

Substituting into Equation (37) the values of F_A^V and R_1 from Equation (41) and (42) solving for

$$R_2 = \frac{F_2 h_2}{l_1}. \tag{44}$$

Inserting the value of f_1, f_2 and R_2 from Equation (34), (35) and (44) into Equation (30) to obtain

$$F_A^H = F_1 + F_2 - 2 f_c \frac{F_2 h_2}{l_1} \tag{45}$$

Equating Equation (28) and (45) and rearranging

$$F_E^H = F_1 - 2 f_c \frac{F_2 h_2}{l_1} . \tag{46}$$

The average value of f_c from Machinery's Handbook (Oberg and Jones, 1949) was approximately 0.0053; h_2 and l_1 were measured from the pushing beam and found to be 9.125 and 13.625 inches respectively. With the values of f_c, h_2, and l_1 substituted in Equation (46), one obtains

$$F_E^H = F_1 - 0.0071 \ F_2. \tag{47}$$

From the principle of applied mechanics,

$$F_E = (F_E^H)^2 + (F_E^V)^2$$

With $F_E^V = 0$ which can be obtained by substituting value $F_A^V = 0$ in Equation (29), Equation (47) may be written as

$$F_E = F_1 - 0.0071 \ F_2. \tag{48}$$

Equation (48) can be used to determine F_E which is the total resisting force acting against the mole plow.

Theoretical resisting force

The theoretical values of the resisting force on the mole plow, F, were computed by Equation (27). The results are shown in Table 9 and in Figure 17. Curve A in Figure 17 is the theoretical resisting force when K is assumed to be unity, and curve B shows the force when K is equal to 0.5.

The shear strength of the same soil as was used in the mole drain construction was found by direct shear tests. The soil was moistened and compacted in the same manner as when installing the mole drains. The shear strength for the soil having different moisture contents was shown by curves in Figure 19.

The curves showing the values of ϕ and C for the soil under different moisture contents are prepared by using the results of shear strength tests in Figure 19 and are shown in Figures 20 and 21.

The values of C, ϕ, N_c, $N\gamma$, N_q, and γ for the soil under different moisture conditions are tabulated in Table 5 and they were used in computation of the bearing and frictional resistance of the soil on the mole plow.

Bearing resistance. The computation for the bearing resistance of the soil against the blade and torpedo of the mole plow is shown in Tables 6 and 7.

Frictional resistance. The frictional resistance of soil on the blade and torpedo is computed and shown in Table 8.

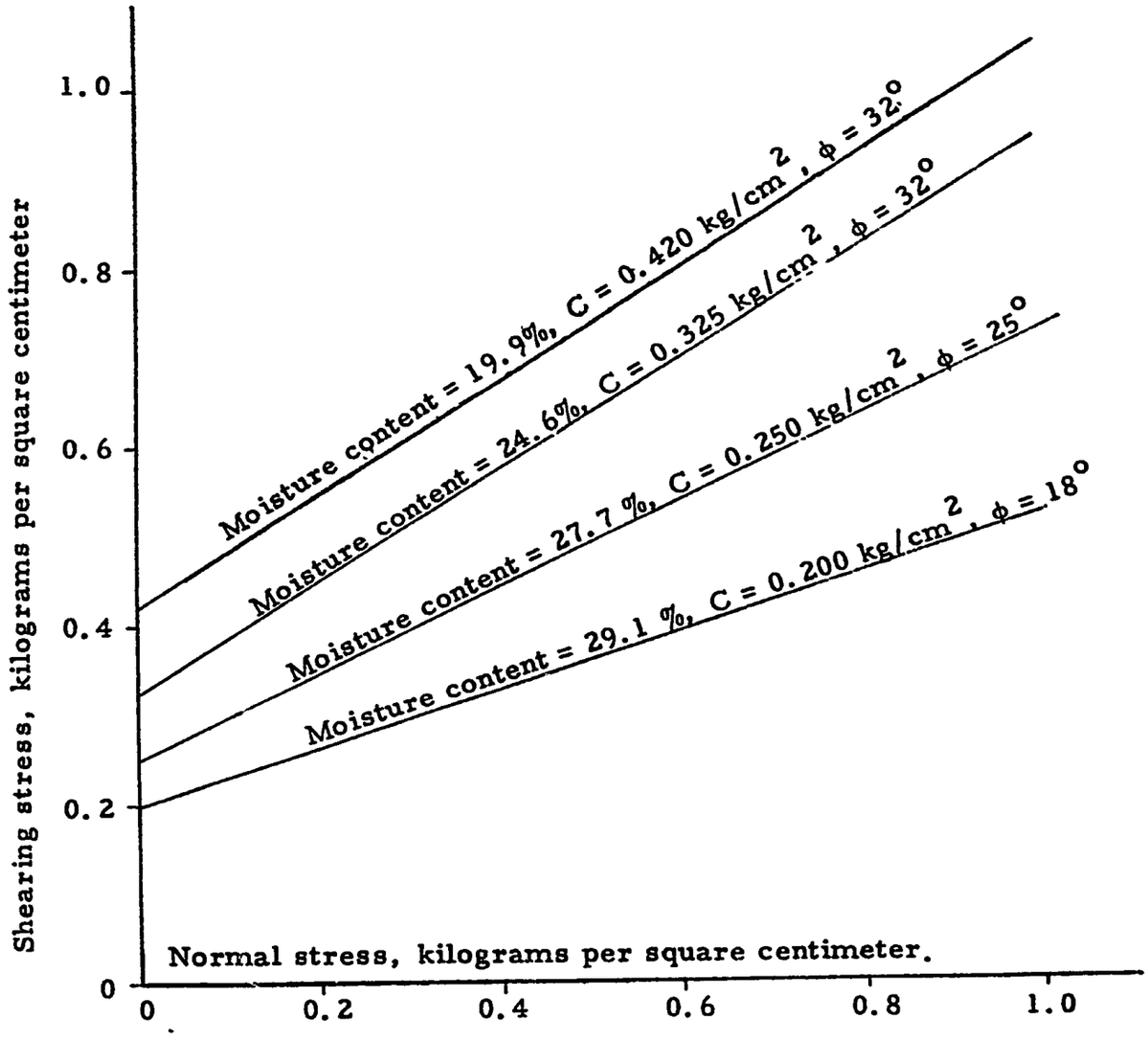


Figure 19. Relationship of shearing stress and moisture content of soils.

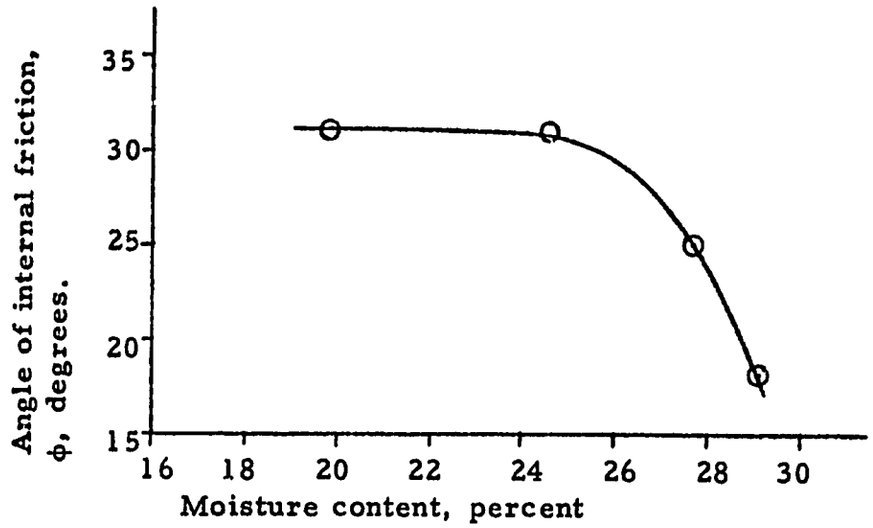


Figure 20. Angle of internal friction of soil having different moisture contents.

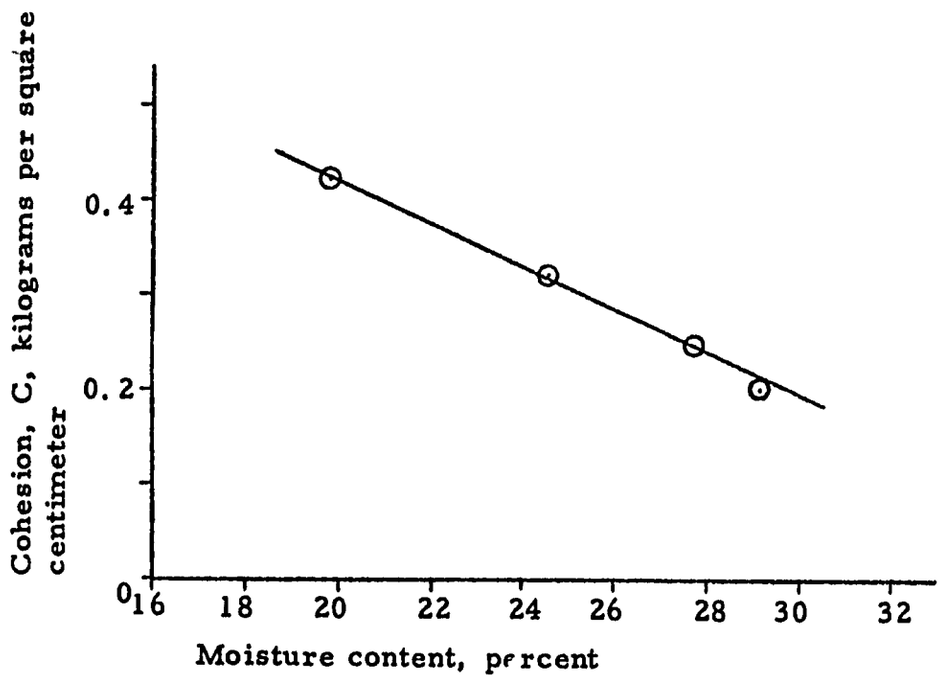


Figure 21. Values of cohesion C for the soil having different moisture contents.

Table 5. Values C, ϕ, N_c, N_q, N_γ, and γ for soil under different moisture conditions.

Test run No.	Moisture Content, %	C kg/cm^2	C lb/in^2	ϕ degrees	N_c	N_q	N_γ	γ lb/in^3	h_1 in	d in
1	20.1	.420	5.98	32	43	26	26	0.057	4.953	5.25
2	21.7	.383	5.45	32	43	26	26	0.058	4.953	5.25
3	23.7	.335	4.76	32	43	26	26	0.059	4.953	5.25
4	25.6	.295	4.19	30	37	23	22	0.060	4.953	5.25
5	26.6	.280	3.98	28	33	18	17	0.060	4.453	4.75
6	27.1	.260	3.70	27	28	16	14	0.061	4.453	4.75
7	27.7	.248	3.53	25	24	13	10	0.061	4.453	4.75
8	29.1	.215	3.06	18	16	7	4	0.062	4.453	4.75

Table 6. Computation for bearing resistance of soil on blade from Equations (15) and (16).

Test run No.	$C N_c$ lb/in^2	$\frac{\gamma b}{2} N_\gamma$ lb/in^2	$\frac{\gamma h_1}{2} N_q$ lb/in^2	$(\Delta q_s)_u$ (For blade) lb/in^2	A_b in^2	q_b lbs
1	257.0	0.138	3.66	260.798	0.928	242.0
2	234.2	0.140	3.72	238.060	0.928	221.0
3	204.5	0.143	3.79	208.433	0.928	193.3
4	155.5	0.123	3.40	159.023	0.928	147.6
5	131.3	0.097	2.41	133.807	0.835	111.7
6	103.6	0.080	2.16	105.840	0.835	88.3
7	84.7	0.057	1.77	86.527	0.835	72.2
8	49.0	0.023	0.97	49.993	0.835	41.7

Table 7. Computation for bearing resistance of soil on torpedo, Equation (17), and total bearing resistance of soil on the mole plow (F_B), Equation (19).

Test run No.	$C N_c$ lb/in^2	$\frac{0.9\gamma D}{2} N_\gamma$ lb/in^2	$\gamma d N_q$ lb/in^2	$(\Delta q_s)_u$ (For torpedo) lb/in^2	A_t in^2	q_t lbs	$F_B = q_b + q_t$ lb
1	257.0	0.395	7.78	265.075	0.28	74.2	316.2
2	234.2	0.400	7.93	242.530	0.28	67.9	288.9
3	204.5	0.408	8.06	212.968	0.28	59.6	252.9
4	155.5	0.352	7.24	163.092	0.28	45.6	193.2
5	131.3	0.274	5.17	136.744	0.28	38.2	149.9
6	103.6	0.227	4.62	108.447	0.28	30.4	118.7
7	84.7	0.163	3.77	88.633	0.28	24.8	97.0
8	49.0	0.066	2.06	51.126	0.28	14.3	56.0

Table 8. Frictional resistance of soil on the mole plow.[a]

Test run No.	Soil moisture content, %	$f = C$ lb/in^2	S_b in^2	S_t in^2	S_b+S_t in^2	$F_F = K(S_b+S_t)\ C$ $(K = 1.0)$ lbs
1	20.1	5.98	19.81	6.43	26.24	157.0
2	21.7	5.45	19.81	6.43	26.24	143.0
3	23.7	4.76	19.81	6.43	26.24	125.0
4	25.6	4.19	19.81	6.43	26.24	110.0
5	26.6	3.98	17.81	6.43	24.24	96.5
6	27.1	3.70	17.81	6.43	24.24	89.8
7	27.7	3.53	17.81	6.43	24.24	85.6
8	29.1	3.06	17.81	6.43	24.24	74.3

Table 9. Computation for total theoretical resisting force acting on the mole plow. For K = 1.0 and 0.5.

Test run No.	Soil Moisture content, %	F_B, lbs	F_F, lbs		$F = F_B + F_F$, lbs	
			For K=0.5	For K=1.0	For K=0.5	For K=1.0
1	20.1	316.2	78.50	157.0	394.70	473.2
2	21.7	288.9	71.50	143.0	360.40	431.9
3	23.7	252.9	62.50	125.0	315.40	377.9
4	25.6	193.2	55.00	110.0	248.20	303.2
5	26.6	149.9	48.25	96.5	198.15	246.4
6	27.1	118.7	44.90	89.8	163.60	208.5
7	27.7	97.0	42.80	85.6	139.80	182.6
8	29.1	56.0	37.15	74.3	93.15	130.3

Two values of the coefficient of effective area, $K = 1.0$ and $K = 0.5$, were assumed and used in the computations.

The experimental values of K were computed by Equation (49) below

$$K = \frac{F - F_b}{(S_b + S_t)\ C} \tag{49}$$

The values of coefficient of effective area versus the soil moisture content at the time of moling are shown in Figure 22.

Discussion

In this study the form of the mole channel was investigated by visual inspection and by measurement of the discharge rate of flow under a constant head loss through the mole channel. The visual inspection showed that the channel appeared to be smooth, straight, and without objectionable quantity of fallen soil particles, except when the soil in which the mole channel was constructed was excessively dry or wet. The range of moisture content giving such a good appearance of the mole channel was wide, and thus, it alone did not give exact information about the most suitable moisture content of the soil for moling.

The investigation for the most efficient form of mole channel by measuring the discharge rate appeared to yield a more exact result. In Figure 16, the discharge rate increases with an increase

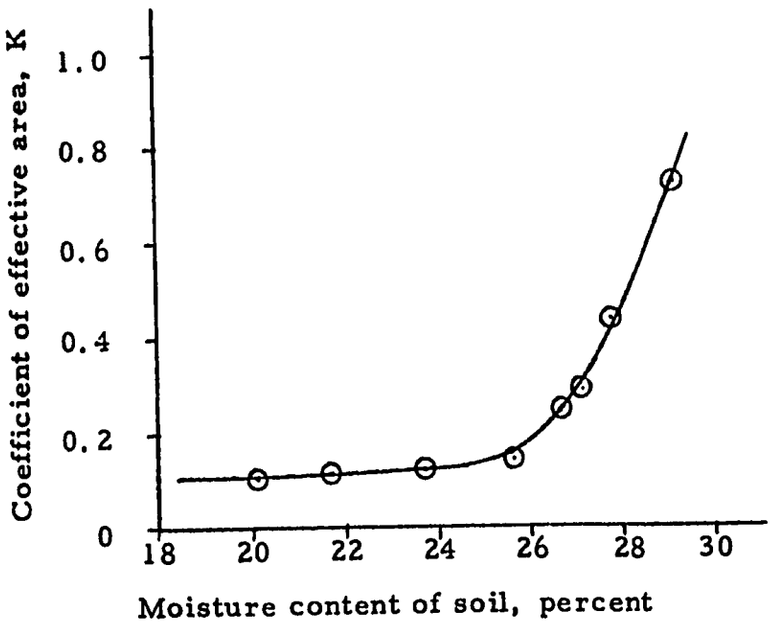


Figure 22. Experimental values of the coefficient of effective area for the soil having different moisture contents at the time of moling.

in the moisture content of the soil until it reaches a most suitable moisture content where the discharge rate starts to decrease.

However, considering that the moisture content of the soil under field conditions could vary over a wide range, visual inspection may serve as an index for predicting the efficiency of the mole channel.

The investigation of the mole channel form by both methods indicated that, for the soil used in this experiment, the most suitable moisture content was between 27 and 29 percent. This range of soil moisture was between the plastic limit and liquid limit of the soil, and was closer to the plastic limit which was found to be 22 percent.

The resistance of the soil on the mole plow, which in this case is equal to the force required to operate the mole plow, was found from the experimental and theoretical analyses for different moisture contents as shown in Figure 17. Both experimental and theoretical curves indicate that the force required to operate the mole plow decreased as the moisture content of the soil increased. When the moisture content was in the neighborhood of the plastic limit, the variation of the force with respect to the moisture content was small as indicated by a relatively flat portion of the curve. This similar characteristic was also found in the range of moisture content nearing saturation. A large variation was found in the range of moisture content yielding a good and efficient form of mole channel. Therefore, in the range of moisture contents suitable for construction

of mole channels, the force required to move the mole plow through the soil varied appreciably more than in the unsuitable range.

The theoretical force (curve A, Figure 17) when K = 1 deviated considerably from the experimental result, curve C, at low moisture content: but the deviation is smaller when moisture content was higher. This is because K, which is the ratio of the effective frictional area to the gross frictional area of the mole plow, was visually observed to be small when the soil moisture content was low, and its value increased with the moisture content of soil. Figure 22 shows the values of K calculated by equating the theoretical resistance of soil computed from Equation (27) to the forces obtained from experiments. The relationship of the calculated K and the soil moisture appeared to agree with the visual observations.

The curve of the theoretical resisting force, assuming K = 0.5, was computed and shown by curve B in Figure 17 with an expectation that it agreed better with the experimental curve because the value of K of 0.5 was an average value of the possible values of K which could range between zero and unity.

However, as appeared in Figure 17, the theoretical resisting force with K = 1.0 in the range of suitable moisture content was approximately 25 to 35 percent larger than the corresponding experimental force. Therefore, considering the practical point of view, the power requirement should be determined from the theoretical resisting force with

K = 1.0 in order to provide extra power which may be required due to variation of moisture content in the field.

SUMMARY AND CONCLUSIONS

This investigation was done by using a model having approximately a 1 to 5 scale ratio.

Altogether 11 test runs were conducted to study the relationship between the form of mole channel and moisture content of the soil in which the mole channel was constructed as well as to find the corresponding forces required to operate the mole plow; only eight tests runs yielded complete data for use in the analysis for results. The others failed to give complete data because the mole channels collapsed before the discharge rate could be measured.

For the soil used in this experiment, the visual inspection and the discharge rate measurement to determine the efficiency of the mole channel indicated that the most suitable moisture content of soil for the construction of mole channel was in the range of 27 to 29 percent. This was considerably higher than the moisture content of 22 percent which was the plastic limit of the soil. The moisture content at 1/3 bar tension was found to be 25.3 percent.

Mole channels constructed in the soil either too dry or too wet resulted in an early collapse of the channels which almost completely clogged the flow passage. The mole channel built in saturated soil also collapsed and clogged in an early stage after the water was allowed to flow through.

In this investigation the power required to operate the mole plow was equal to the resisting forces of soil against the mole plow. The theoretical resisting force was computed by Equation (27) shown below

$$F = A_b \left(C N_c + \frac{\gamma b}{2} N\gamma + \frac{\gamma h_1}{2} N_q\right) + A_t \left(C N_c + 0.9 \frac{\gamma D}{2} N\gamma + \gamma d N_q\right)$$

$$+ K (S_b + S_t) C. \qquad (27)$$

The theoretical forces determined by Equation (27) assuming K = 1.0 were found to give the values approximately 25 to 35 percent larger than those obtained experimentally in the range of soil moisture suitable for constructing the mole channel, which was about 27 to 29 percent in this study.

K which is the ratio of the effective frictional area to the actual frictional area was found visually and by Equation (49) to vary with the soil moisture content: small at low moisture contents and approaching unity at high moisture contents in the range of this experiment.

It was suggested that in the determination for power requirement to operate a mole plow, K in Equation (27) should be assumed to be 1.0 in order to obtain a larger power requirement to take care of additional resistance due to variation of soil moisture in the field.

In application of Equation (27) undisturbed samples of the soil in which the mole channel is to be constructed have to be taken from the field and tested for the cohesion, C, angle of internal friction, ϕ, and unit weight γ. These soil tests are not complicated tests and could

be performed in any soil mechanics laboratory. However, for practical purposes tabulated values similar to those shown in Appendix B would be helpful in the determination of the power requirement for mole construction.

It should be noted that in the derivation of Equation (27), the entire effect of speed of the plow movement through the soil and shape of the front ends of the torpedo and blade is not included.

RECOMMENDATIONS FOR FURTHER STUDY

The following laboratory and field investigations should be considered;

1. Verification of the laboratory results in this study by conducting actual field tests.

2. Verification of the theoretical derivation given in this study by conducting similar laboratory tests using different scale models.

3. To verify the theoretical derivation presented in this study by using the same experimental procedure and equipment but with a different type of soil compacted to a different density.

4. An attempt should be made to find the relationship of the value of K and the moisture content for various types of soil and a certain mole plow.

5. A study should be conducted to investigate the effect of shape and dimension of an object moving through various types of soil on the value of K under different moisture conditions of soil. The result from this study will assist in assuming the value of K for use in the equation for determination of the theoretical resisting forces against a mole plow.

6. Laboratory experiments should be conducted to find the range of the values of ϕ, C, and γ of typical clay soils suitable for mole channel installations. Such values of soil properties should be tabulated in the similar manner as illustrated in Appendix B for practical use in the determination of the theoretical resisting force by means of Equation (27).

7. Logically, the moisture content of soil which results in the most efficient mole form should be more directly related to the soil moisture defined in soil mechanics such as the plastic limit or liquid limit. However, an attempt should be made to relate the suitable range of moisture content of the soil to produce the most efficient mole channel to the soil moisture tension which is the terminology normally used in agricultural practice. In particular, the tension corresponding to the moisture content near field capacity should be investigated further for several soil types. This relationship if it exists, will be helpful to the farmers who are more familiar with such moisture concepts than the plastic limit which is used in soil mechanics.

8. The investigation should be conducted to find the relationship of the most suitable moisture content for moling, the plastic limit, and liquid limit by using several different types of soil.

9. A study should be made to investigate the relationship between the efficient form and the durability of mole channel.

10. The effect of speed of the movement of plow through the soil and shape of the front ends of the torpedo and blade on the resistance of soil on the plow should be investigated.

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APPENDIXES

Appendix A

Appendix A. Dial gage readings from the proving rings in the experiments.

Test run No.	Moisture content, %	D_1 x 1000 Measured at distances					D_2 x 1000 Measured at distances				
		6 in	9 in	12 in	15 in	Average	6 in	9 in	12 in	15 in	Average
1	20.1	1.70	1.60	1.65	1.60	1.64	5.20	5.10	5.10	5.00	5.10
2	21.7	1.50	1.45	1.55	1.45	1.49	4.85	4.75	4.95	4.75	4.82
3	23.7	1.40	1.30	1.30	1.30	1.32	4.63	4.42	4.40	4.43	4.47
4	25.6	1.04	1.03	1.03	1.01	1.03	3.93	3.93	3.92	3.90	3.92
5	26.6	0.86	0.85	0.84	0.84	0.85	3.55	3.50	3.40	3.35	3.45
6	27.1	0.72	0.72	0.73	0.73	0.72	0.85	2.80	2.95	2.80	2.85
7	27.7	0.65	0.67	0.67	0.68	0.67	2.50	2.50	2.70	2.70	2.65
8	29.1	0.55	0.53	0.59	0.55	0.55	2.10	1.95	2.25	2.10	2.10
9	37.0 (Saturated)	0.28	0.29	0.32	0.31	0.30	0.80	0.90	1.10	1.00	0.95

Note:

D_1 is the dial gage reading from Proving ring No. 1, $\frac{1}{10000}$ in

D_2 is the dial gage reading from Proving ring No. 2, $\frac{1}{10000}$ in.

Appendix B

Appendix B. Average Properties of Soils (From Irrigation Operator's workshop, 1967)

Soil[1] classification group	Max. dry[2] density in lb/ft^3	Optimum[2] water content, %	Void ratio, e	Permeability, ft/year feet per year	Shearing strength		
					C lb/in^2	Csat., lb/in^2	ϕ, degree
ML	103±1	19.2±0.7	0.63±0.02	0.59±0.23	9.7±1.5	1.3± *	0.62±0.04
ML-CL	109±2	16.8±0.7	0.54±0.03	0.13±0.07	9.2+2.4	3.2± *	0.62±0.06
CL	108±1	17.3±0.3	0.56±0.01	0.08±0.03	12.6±1.5	1.9+0.3	0.54±0.04
OL	*	*	*	*	*	*	*
MH	82±4	36.3±3.2	1.15±0.12	0.16±0.10	10.5±4.3	2.9±1.3	0.47±0.05
CH	94±2	25.5±1.2	0.80±0.04	0.05±0.05	14.9±4.9	1.6±0.86	0.35+0.09
OH	*	*	*	*	*	*	*

Note: The ± entry indicates 90 percent confidence limits of the average value

* denotes insufficient data

[1] follows Unified Soil Classification as shown in Appendix C.

[2] compacted by Proctor method

Appendix C

Appendix C. Description of soil symbols (Excerpted from Unified Soil Classification, Earth Manual, 1963)

Group Symbols	Typical Names
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity.
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.
OL	Organic silts and organic silt clay of low p plasticity.
MH	Inorganic silts micaceous or diatomaceous fine sandy or silty soils, elastic silts.
CH	Inorganic clays of high plasticity, fat clays.
OH	Organic clays of medium to high plasticity.

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