AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523

BIBLIOGRAPHIC INPUT SHEET

FOR AID USE ONLY
0101

1. SUBJECT CLASSIFICATION

A. PRIMARY: Agriculture — AP12-0000-0000

B. SECONDARY: Drainage and irrigation--Colombia

2. TITLE AND SUBTITLE

Irrigation and drainage by mole systems

3. AUTHOR(S)

Unhanand, Komain

4. DOCUMENT DATE: 1972

5. NUMBER OF PAGES: 59p.

6. ARC NUMBER: ARC 631.7072.U57

7. REFERENCE ORGANIZATION NAME AND ADDRESS

Utah State

8. SUPPLEMENTARY NOTES *(Sponsoring Organization, Publishers, Availability)*

9. ABSTRACT

10. CONTROL NUMBER

PN-RAA-050

11. PRICE OF DOCUMENT

12. DESCRIPTORS

Colombia
El Salvador
Field tests
Mole drainage?
Subsurface drainage

13. PROJECT NUMBER

14. CONTRACT NUMBER

CSD-2167 Res.

15. TYPE OF DOCUMENT

AID 590-1 (4-74)

IRRIGATION AND DRAINAGE BY MOLE SYSTEMS

Progress report prepared by

Komain Unhanand

Agricultural and Irrigation Engineering Department

Utah State University

January 1972

PREFACE

The research work reported was conducted as a part of the sub-program PO-7 under contract AID/csd-2167, "Water Management Research in Arid and Sub-Humid Lands of the Less Developed Countries," between Utah State University and the United States Agency for International Development.

The objective of sub-program PO-7 is to develop and promote the use of land and water conservation management techniques for the beneficial and efficient use of on-farm water for optimum crop production.

ACKNOWLEDGMENT

The author would like to express his gratitude to Dr. A. Alvin Bishop whose continuing assistance and encouragement enabled the project to be initiated.

Sincere appreciation is extended to Professor Byron C. Palmer for his valuable advice and assistance in reviewing the report. Recognition is given to Dr. Bertis Embry for his helpful suggestions and assistance during the field experiment, and to Mr. Jed Merrill for his special attention in the fabrication of mole plows and the force measuring device.

TABLE OF CONTENTS

	Page
SUMMARY	1
BACKGROUND	4
WORK PLANS	7
Work Plan 1 - Design and Fabrication of Double Mole Plows	8
Work Plan 2 - Field Studies of Mole Drains	15
Work Plan 3 - Laboratory Studies	29
Work Plan 4 - Field Studies on Power Requirement	39
Work Plan 5 - Field Tests in Latin American Countries	50

LIST OF FIGURES

Figure		Page
1	Mole Plows Used in Field Tests in 1971	6
2	Mole Channels Constructed with Double Mole Plow Design 8 Shows a More Desirable Configuration than those by Design 4	11
3	Cracks Around Mole Channels	12
4	Proposed Design of a New Double Mole Plow . . .	14
5	Layout of Mole Drain Experiment Plot Constructed in July 1970	16
6	Water Discharges from Double Mole Drain Outlets During the Test in August 1971. The Drains Were Constructed in July 1970	18
7	The Single Mole Outlets Discharge Drainage Water During the Test in August 1971. These Drains Were Pulled in July 1970	18
8	New Mole Drainage System Constructed in September 1971	19
9	Double Mole Plow Design 8, Attached to a D-6 Tractor, is Being Lifted Above Soil Surface After Finishing a Mole Line	21
10	The Double Mole Plow, in Full Operating Condition, Just Starting New Mole Line	21
11	Electrical Conductivity of Saturation Extract of Soil Samples Taken from 6 Inches Depth Along Line "A"	23
12	Electrical Conductivity of Saturation Extract of Soil Samples Taken from 12 Inches Depth Along Line "A"	24
13	Electrical Conductivity of Saturation Extract of Soil Samples Taken from 18 Inches Depth Along Line "A"	25

LIST OF FIGURES (Continued)

Figure		Page
14	Electrical Conductivity of Saturation Extract of Soil Samples Taken from 6 Inches Depth along Line "B"	26
15	Electrical Conductivity of Saturation Extract of Soil Samples Taken from 12 Inches Depth Along Line "B"	27
16	Electrical conductivity of Saturation Extract of Soil Samples Taken from 18 Inches depth Along Line "B"	28
17	Mole Plows Consisting of Steel Torpedoes Having Different Front Angles Attached to Steel Blades .	34
18	Mole Plow Blades and Torpedoes Designed to Have Side Friction Eliminated	35
19	Pushing Beam Equipped with Proving Rings and Mole Plow (Soil Box Not in Place)	36
20	Mole Plow Being Pushed Through the Soil in the Soil Box	37
21	Force Measuring Device During an Actual Field Test to Measure the Soil Resistance on a Mole Plow	40
22	Diagrammatic Sketch Showing the Arrangement of Hydraulic Cylinders on a Mole Plow for Soil Resistance Measurement	42
23	Shear Strength of Undisturbed Soil Samples Taken from Mole Plow Testing Area.	45
24	Dimensions of Mole Plows Used in Field Tests on Soil Resistance on Mole Plows.	48
25	Bearing Capacity Factors for the General Bearing Capacity Equation	48

LIST OF TABLES

Table		Page
1	Field Test Data	44
2	Examples of Computation for Horizontal Soil Resistance on Mole Plow by Equation 2	46

SUMMARY OF PROGRESS OF WORK ON IRRIGATION AND DRAINAGE BY MOLE DRAINS

1. Design, fabrication and testing of mole plows.

a. Design and fabrication – New double mole plows were designed and fabricated on three new concepts: the spacing of torpedoes was reduced from 18 inches to 12 inches to reduce soil resistance, the elimination of followers to reduce the plow cost, and the use of oval section torpedoes in place of circular ones to obtain a better channel form. A proposed design, which was expected to require much less power to pull, was made using information from laboratory studies.

b. Testing – Mole channels constructed with the new mole plows showed considerable improvement of the channel form. The new plows were used in the construction of a new mole drain testing area.

2. Field studies on mole drains.

a. Effectiveness and durability of mole drains – All single mole drains and most double mole drains installed in the summer of 1970 still functioned and discharged a reasonably good quantity of water after 15 inches of water had been applied to the area in the 1971 summer. The apparent inferiority of the double mole drains to the single mole drains had been expected when the double mole channels were found to be excessively deformed during construction.

b. Removal of salts by mole drainage – The E.C. of saturation extract of soil samples taken from the mole drained area, after one year

of installation and 15 inches of sprinkler irrigation, was compared with those taken before the installation. The salt concentration, as indicated by the E.C., was reduced more in the area with drains than in the control area, indicating that mole drains assisted in making leaching more effective which may result in a saving of leaching water.

3. Laboratory studies of mole plows and mole channels.

Two laboratory model studies were completed and submitted as two M.S. theses in 1970. A part of the new study on the effect of shape and speed of mole plow on the soil resistance was presented as an M.S. thesis in the summer of 1971. In this thesis two equations for the determination of soil resistance were derived.

4. Field studies on the power required to pull mole plows.

A device, designed and constructed for measuring the soil resistance, was used to measure the soil resistance on the single and double mole plows. The theoretical soil resistance, computed by the equation derived during the laboratory studies, agreed satisfactorily with the field measured values. The force required to pull the double mole plows, at 21 inch depths in the Drainage Farm, was found to be about 5,500 lbs, which indicates that a wheel tractor of 80 - 100 hp class can operate the plow if the soil surface condition is favorable.

5. Field tests in Latin American countries.

In Colombia, the Department of Agriculture's research arm, ICA,

constructed a mole plow to USU specifications, and Professor Bertis Embry was sent in February 1971 to assist in installing drains at the Tibaitata research station near Bogota and also designed the evaluation program. In the same trip Professor Embry assisted researchers at the El Salvador Ministry of Agriculture in the Zapotitan project to design an experiment to find out if the moles could be used for drainage in the wet season and irrigation in the dry season.

IRRIGATION AND DRAINAGE BY MOLE SYSTEMS

Background

Studies on the possibility of using mole systems for irrigation and drainage started in 1970 aiming primarily to find the most efficient and economical means of draining excess water from the soil in order to accelerate the drying of the land surface to allow seed bed preparation and planting to the best advantage. This is important in the wet-dry climatic zones of Latin America and other regions.

Mole drains have been used for more than a century in England and are still being used in many other countries such as New Zealand and Australia. They are constructed by pulling a chisel-shaped implement through the soil, leaving behind a small diameter channel which functions in a similar manner as a tile drain.

In Japan a combined mole-pipe drainage system consisting of main tile lines and lateral mole lines is found to be superior to other methods for sub-surface drainage of the ill-drained land reclaimed from the sea. With this arrangement the mole lines may be reinstalled as often as needed at a modest expense.

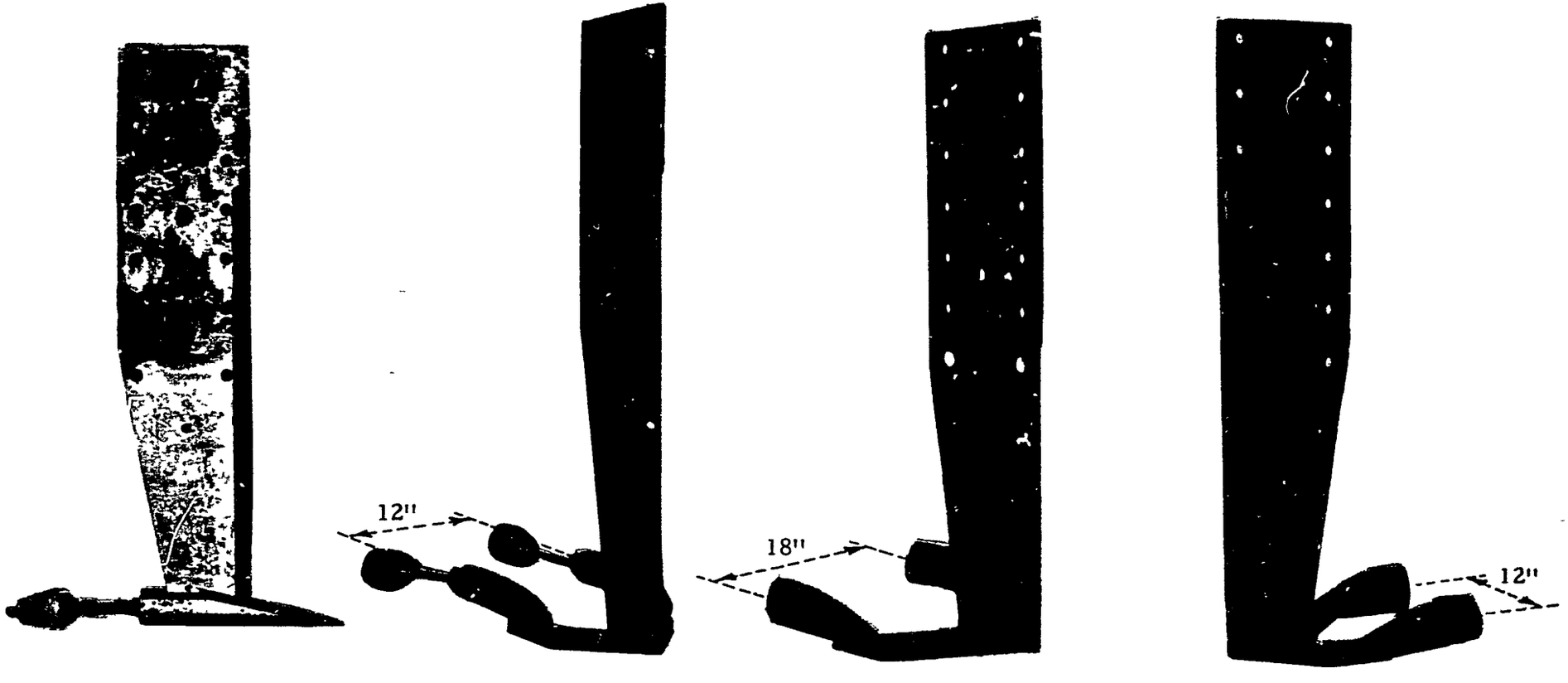
Mole drainage is inexpensive and requires very little initial cost to install which makes it very attractive for developing countries. But it has disadvantages: some important ones being its short life, its requirements of machine power for installation, and its suitability only in clay soil.

A conventional or single mole plow consists of a chisel-headed steel cylinder attached to a steel blade (see Figure 1). The single mole channel, constructed by the mole plow, has a vertical slit formed above the channel. The excess water in the soil and runoff enter the slit, deposit sediment in the channel and thus not only reduce its flow capacity but also shorten its useful life. The double mole plow was designed with the concept that the mole channels constructed by it will have the slit located midway between the channels such that the sediment deposition in the channels is minimized.

The program of investigation consists of the laboratory model study, the design and fabrication of mole plows, field tests of the fabricated implement, and the study of the possibility of using the combined mole-pipe system for irrigation and drainage.

The laboratory testing was conducted primarily to provide the information needed or useful in the design of a mole plow and in planning field tests. Such information was the optimum moisture of the soil most suitable for moling, the shape of mole plow which produces the most desirable form of the channel, and the power required to pull the plow. The study utilized an approximate one to six scaled model of mole plows and the soil taken from the same field in which the prototype mole plows were later tested.

The prototypes were designed and successively modified according to the available information obtained from the laboratory and field tests.



SINGLE MOLE PLOW DESIGN 6 DESIGN 7 DESIGN 8

FIGURE 1 - MOLE PLOWS USED IN FIELD TESTS IN 1971

They were fabricated in the Technical Services shop of Utah State University. The field tests, conducted at the University Drainage Farm, were intended to yield not only the information on the durability of the mole drains and the power required to operate the plows, but also to provide information on the necessary modification of the design. The investigation was also extended to study whether the mole drains assist in making the leaching of salts from clay soils more effective. Similar field tests were conducted in a selected area in Latin America in an attempt to study the effectiveness of the mole drains and to solve some actual problems of the area.

Furthermore, a unique study was planned to investigate the possibility of using the combined mole-pipe system for both irrigation and drainage in an area where clay soil is predominant.

Work Plans

The following work plans were prepared to initiate the program of investigation.

Work Plan 1 - Design and fabrication of double mole plows.

Work Plan 2 - Field studies of mole drains.

A. Effectiveness and durability of mole channels.

B. Removal of salts by mole drains.

Work Plan 3 - Laboratory studies

A. Mole drainage construction - optimum moisture content and corresponding power requirement.

B. Durability of double mole drains.

C. Effect of shape and speed of mole plow on soil resistance.

Work Plan 4 - Field Studies on power required to pull mole plows.

Work Plan 5 - Field tests in Latin American countries.

Work Plan 1 - Design and Fabrication of Double Mole Plows

Objective. To design and fabricate a double mole plow which produces an efficient and durable mole channel.

Progress.

Design and fabrication. Mole plows of Design 1 through 4 were constructed and tested in the spring and summer of 1970. (Drawings of these designs are in the 1970 Progress Report.) During the tests, excavations were made to examine the configuration and interior surface of the mole channels which were found to be satisfactory. However, the examination during the installation of the extensive system of mole drains revealed that the channels constructed with mole plow Design 4 were excessively deformed due to the closing in of the slits following the pulling. Since the deformation appeared to such an extent that the durability was impaired (Figure 2a), two new mole plows of Design 5 and 6 were built. There were two major modifications in the new designs; the spacing of torpedoes was reduced to 12 inches from the previous 18 inches, and the cross-section of the followers was made oval instead of circular as in the former designs. In order to maintain the major axes of the followers in a vertical direction, the followers were attached to

the torpedoes by stiff rods as showr in Figure 1 . The 18-inch spacing between the torpedoes was used to avoid the interaction of one torpedo or follower on the other while the plow was moving through the soil. The new spacing of 12 inches was believed to be sufficient to prevent such interference while offering an advantageous reduction in the size and weight of the plow as well as the soil resistance.

Designs 7 and 8, based essentially on the same idea as for Designs 5 and 6, used oval-shaped torpedoes and eliminated the followers to reduce the fabrication cost. A follower is a must for a single mole plow in order to smooth the interior surface of the channel and enlarge its diameter to close the slit on its roof. In double mole construction, no slit is formed on the channel roof and the horizontal slit closes by the weight of soil above it, and hence a follower is not necessary. Design 7 has the oval torpedoes spaced 12 inches apart which is the same as in Design 6. Design 8, having the torpedoes spaced at 18 inches, was intended to be used for comparison of the performance with Design 7.

Testing. Mole plow of Designs 5, 6, 7, and 8 were pulled by a D-6(955) crawler tractor in the same soils having approximately the same moisture content. The results of observation may be summarized as follows:

1. Designs 5 and 6 produced channels of almost identical configuration and interior surface.

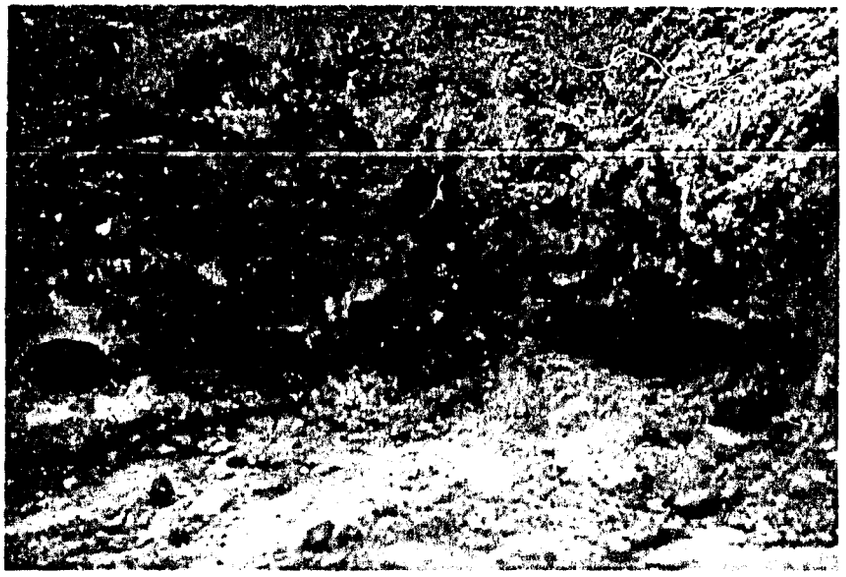
2. The stiff rods, used for attaching the oval followers to the torpedoes in Design 5 and 6, were awkward and liable to damage at the location where the tractor had to turn around to start a new mole line.

3. More power was required for operating mole plow Design 7 than for Design 8. This was evidenced by the fact that the tractor, while pulling mole plow Design 7, slipped, had difficulty in maintaining the alignment and could not move as fast as when it did with mole plow Design 8.

4. Both Design 7 and 8 plows using no followers produced well-shaped channels with a smooth interior similar to those by Design 5 and 6 which used followers.

5. The configuration of the mole channel pulled with Designs 5, 6, 7, and 8 was improved considerably over those constructed with Design 4 in the summer of 1970 (See Figure 2).

The location and extent of cracks in the soil are important factors affecting the durability and effectiveness of the mole channels. Figure 3 shows mole channels produced by various types of mole plows and the cracks, sketched from actual photographs, around them. Most cracks are located on the top of the single mole channel and they are on the sides of the double mole channels. As the cracks weaken the soil strength, the soil at the top of the single mole channel tends to crumble and fall down by gravity more easily than in the case of the double mole channels. Figure 3 also shows that in the single mole channel the sediments



a. MOLE CHANNELS PRODUCED BY DOUBLE MOLE PLOW DESIGN 4

b. MOLE CHANNELS CONSTRUCTED WITH DOUBLE MOLE PLOW DESIGN 8

FIGURE 2 - MOLE CHANNELS CONSTRUCTED WITH DOUBLE MOLE PLOW DESIGN 8 SHOWS A MORE DESIRABLE CONFIGURATION THAN THOSE BY DESIGN 4

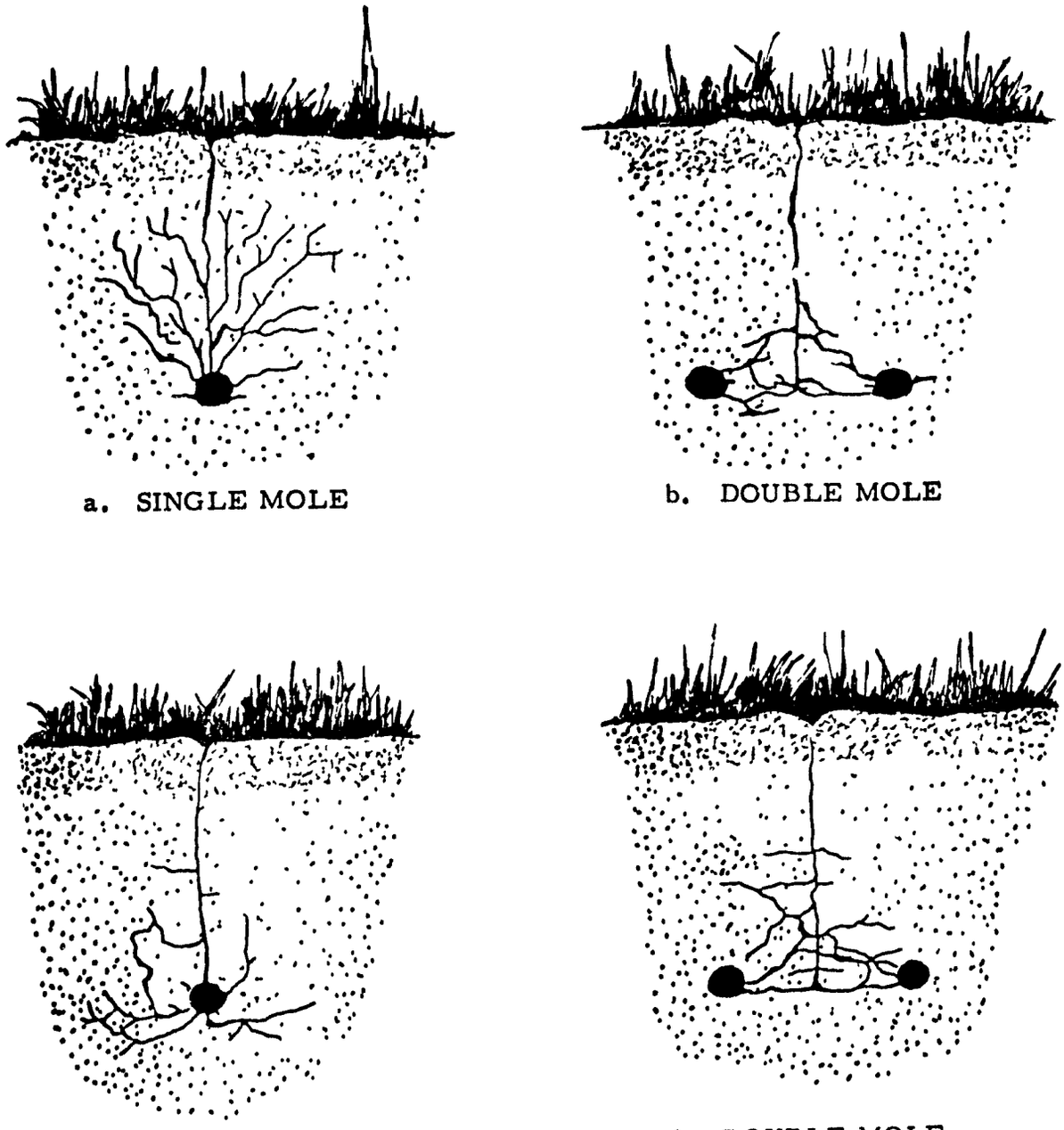


FIGURE 3 - CRACKS AROUND MOLE CHANNELS. FIGURE a. IS SKETCHED FROM PHOTOGRAPH IN THEOBALD, G. H. "METHODS AND MACHINES FOR TILE AND OTHER TUBE DRAINAGE," FIGURES b., c., AND d. ARE FROM PHOTOGRAPHS TAKEN DURING TESTS AT UTAH STATE UNIVERSITY.

which enter the slit may deposit directly in the channel causing blockage, while in the double mole the sediments deposit away from the channels.

Proposed design. The result of field tests of mole plows and information obtained from laboratory studies may be summarized as follows:

1. The shape and dimension of the blades and torpedoes as in Designs 7 and 8, without followers, gives satisfactory mole channels. Both designs have 3/4-inch vertical blades and 1/2-inch horizontal blades. In earlier tests the horizontal blade made of 40 ksi steel was found slightly bent, so it was replaced with a 60 ksi steel.

2. The plow with torpedoes spaced at 12 inches, Design 8, required less power to pull than the plow with the torpedo spacing of 18 inches, Design 7. Both plows produced satisfactory mole channels with similar soil crack patterns.

3. Laboratory studies indicate less soil resistance may be obtained if the frictional area on the blades and torpedoes is reduced.

The double mole plow shown in Figure 4, designed on the basis of the above information, may give the most satisfactory performance. The spacing of the torpedoes is shortened to 12 inches to reduce the power requirement for pulling the plow, the front edge of the vertical blade is thickened to reduce the frictional resistance while it is moving through the soil. This front edge may be made of a separate piece of high quality steel and welded to the main part of the blade. When it is

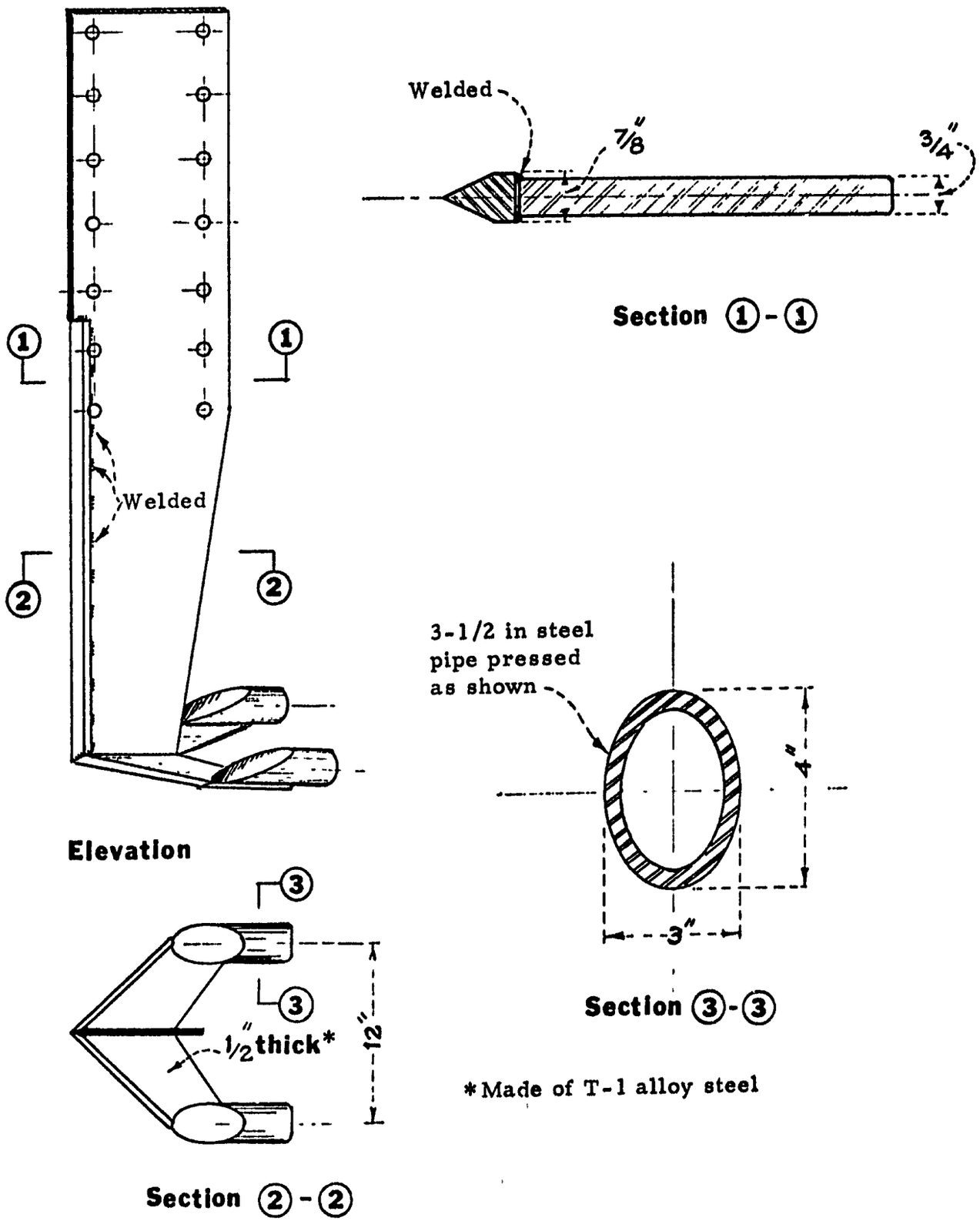


FIGURE 4 - PROPOSED DESIGN OF A NEW DOUBLE MOLE PLOW

worn out, it may be removed and replaced by a new piece. The thickening of the front edge increases the bearing area and, consequently, the bearing resistance of the soil. But this increase is small in comparison with the reduction in frictional soil resistance resulting from the elimination of the frictional area behind the front edge.

Work Plan 2 - Field Studies of Mole Drains

A. Effectiveness and durability of the mole channels.

Objectives. To investigate the effectiveness of mole drains in drainage and the durability of the mole channels.

Progress. The mole drainage system was constructed according to the layout shown in Figure 5 in the summer of 1970. Mole lines 1 through 18 and 55 through 60 were built with double mole plow Design 4, and lines 19 through 53 were constructed with the single mole plow shown in Figure 1. The mole plows were pulled by a D-6(955) crawler tractor at a speed of approximately 1-1/2 miles per hour and no attempt was made to close the slits on the surface. After the installation was complated, water was applied to the area by a sprinkler system and, by visual inspection, the water was seen to discharge from all outlets in an appreciable quantity.

In the summer of 1971 the water was again applied to the area by a sprinkler system in order to investigate the durability of mole drains. Drainage water started to flow out uniformly from the outlets after

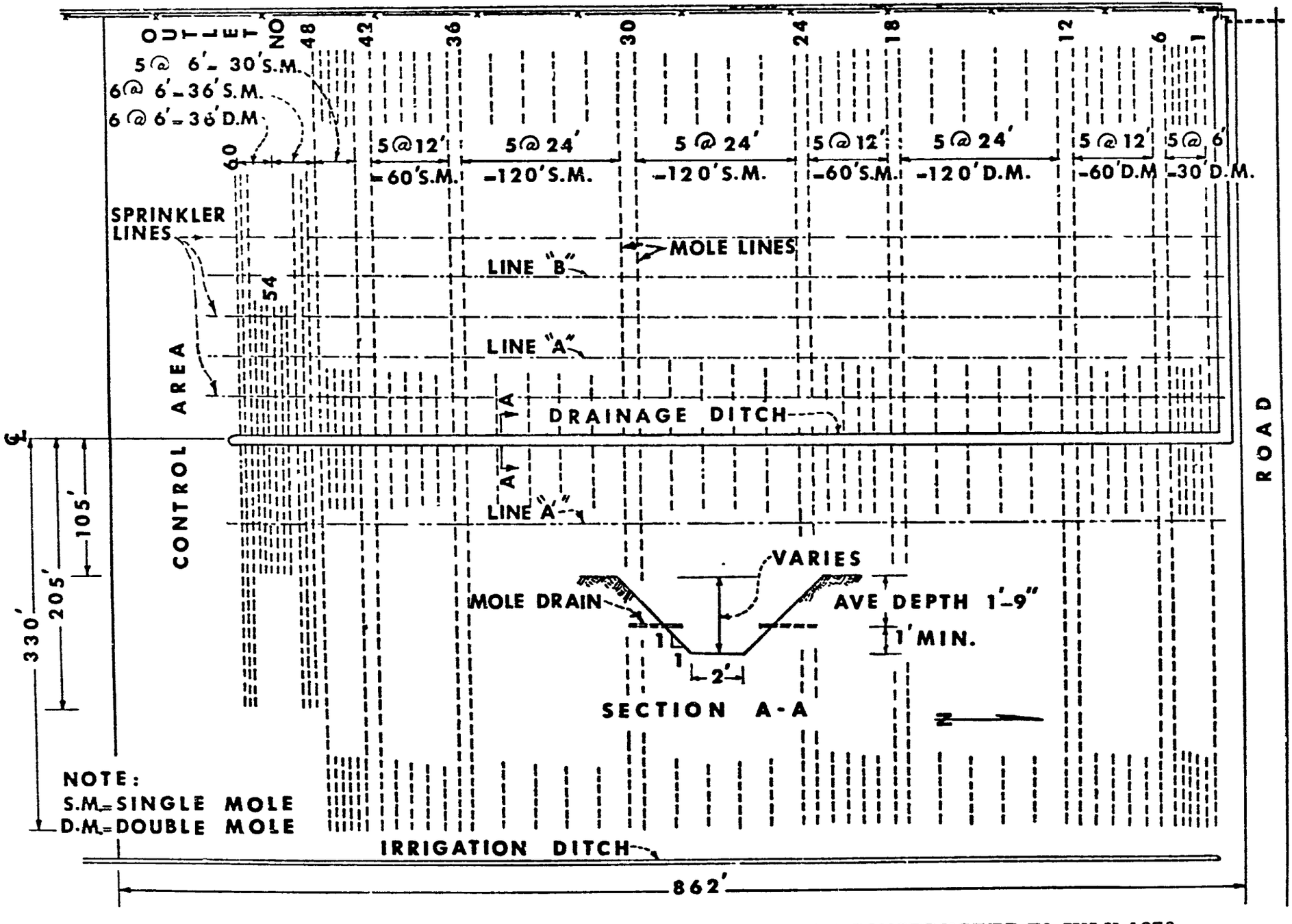


FIGURE 5 - LAYOUT OF MOLE DRAIN EXPERIMENT PLOT CONSTRUCTED IN JULY 1970

approximately 10 inches of water had been applied to the area at a rate of about 0.1 inch per hour. All single mole drains discharged water and almost all double mole drains still functioned (Figures 6 and 7). No measurement of the discharge rate was made, but on the average a single mole outlet appeared to produce more drainage water than a double mole outlet. This is not a surprise because, first, two double mole lines served in the same capacity as one single mole line. Therefore, if all other factors influencing the drainage ability are the same, one should expect the discharge rate of one double mole line to be only one-half that of one single mole line. Second, as mentioned earlier in this report, all double mole lines under this investigation were constructed with mole plow Design 4 which was found to give excessively deformed channels.

A new mole drainage system as shown in Figure 8 was located just south of the one constructed in the summer of 1970. Mole lines in the new system were built with a single mole plow and double mole plows Design 6, 7, and 8. Before the installation of drains, the entire area was sprinkled with about 5 inches of water in an attempt to bring the moisture content of the soil to a suitable level. Then the surface was allowed to dry until the average moisture content of the soil at the depth where the mole channel was to be drawn was about 26-28 percent on a dry weight basis which is optimum for moling. The D-6(955) tractor, which started the work with mole plow Design 7 (i.e., using oval torpedoes spaced at 18 inches), slipped and had difficulty in maintaining

FIGURE 6 - WATER DISCHARGES FROM DOUBLE MOLE DRAIN OUTLETS DURING THE TEST IN AUGUST 1971. THE DRAINS WERE CONSTRUCTED IN JULY 1970

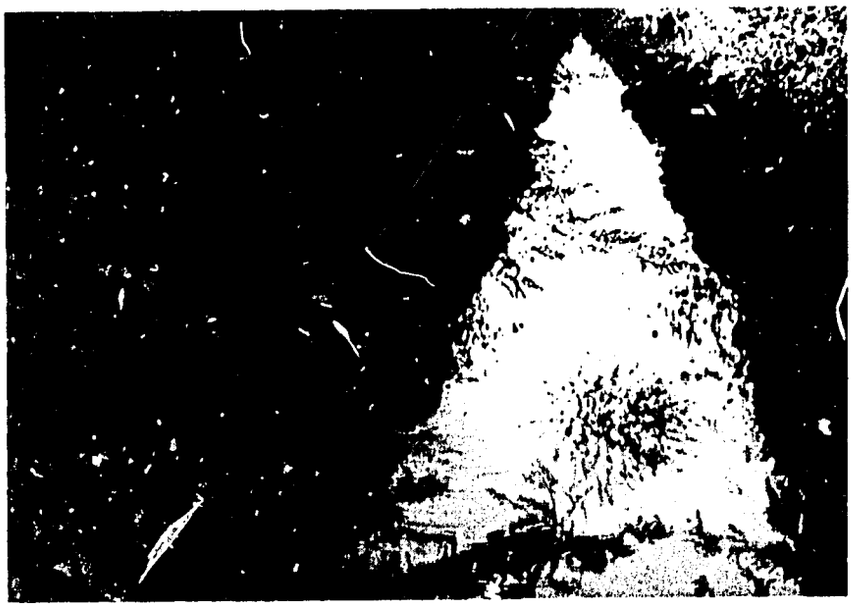


FIGURE 7 - THE SINGLE MOLE OUTLETS DISCHARGE DRAINAGE WATER DURING THE TEST IN AUGUST 1971. THESE DRAINS WERE PULLED IN JULY 1970

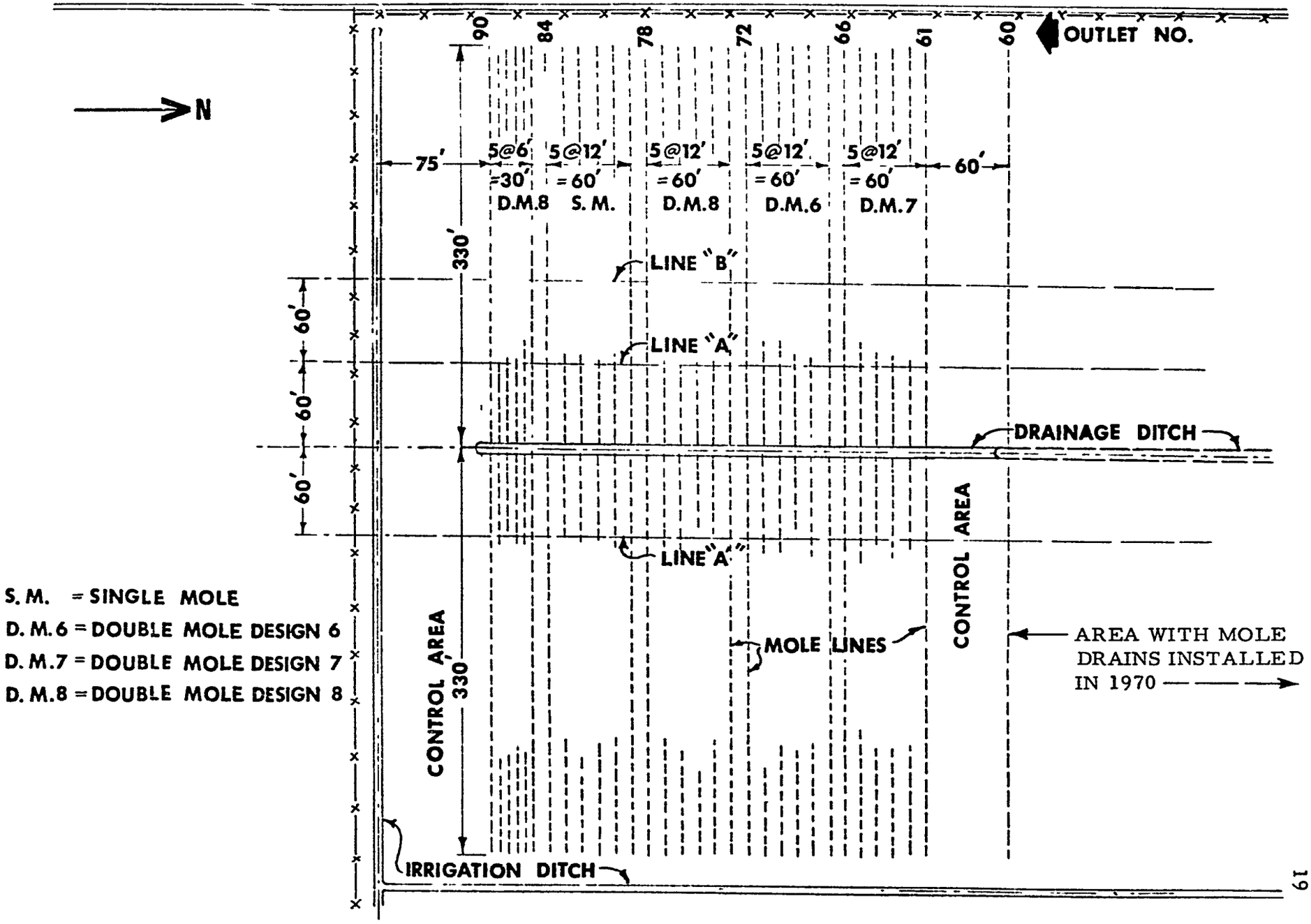


FIGURE 8 - NEW MOLE DRAINAGE SYSTEM CONSTRUCTED IN SEPTEMBER 1971

their alignment, so the work had to be postponed to permit the soil surface to dry. The same tractor performed the work with other mole plows without any problem on a similar ground surface. The excavation of the drainage ditch which started three days after the completion of the mole lines caused the cave-in at the places where mole channels joined the the ditch. Unfortunately, it rained about 0.5 inch before the drain outlets could be installed and the rainwater, unable to flow out of the mole channels into the ditch due to the cave-ins, might have done some damage to the channels by depositing sediments blocking the channel to a certain extent. The caved-in channel had to be carefully cleaned at the time the outlets were installed.

Figure 9 shows a double mole plow Design 8, attached to a tractor with a simple arrangement, being lifted off the ground after finishing a line. A few minutes later the plow was in full operating condition as shown in Figure 10.

B. Removal of salts by mole drains.

Objective. To conduct a preliminary investigation of the possibility of using mole drains as an efficient means of removal of salts from the soils.

Progress. In the summer of 1970, soil samples were taken for the electrical conductivity tests from depths of 6, 12, and 18 inches at various locations along lines A and B (see Figure 5). The sampling locations were set at the mid-point between two consecutive mole lines and at one foot

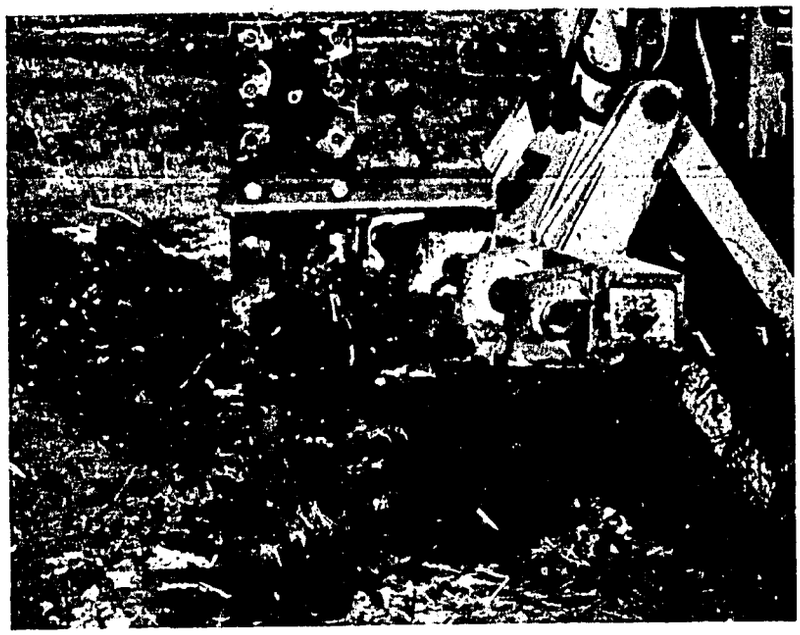


FIGURE 9 - DOUBLE MOLE PLOW DESIGN 8, ATTACHED TO A D-6 TRACTOR, IS BEING LIFTED ABOVE SOIL SURFACE AFTER FINISHING A MOLE LINE

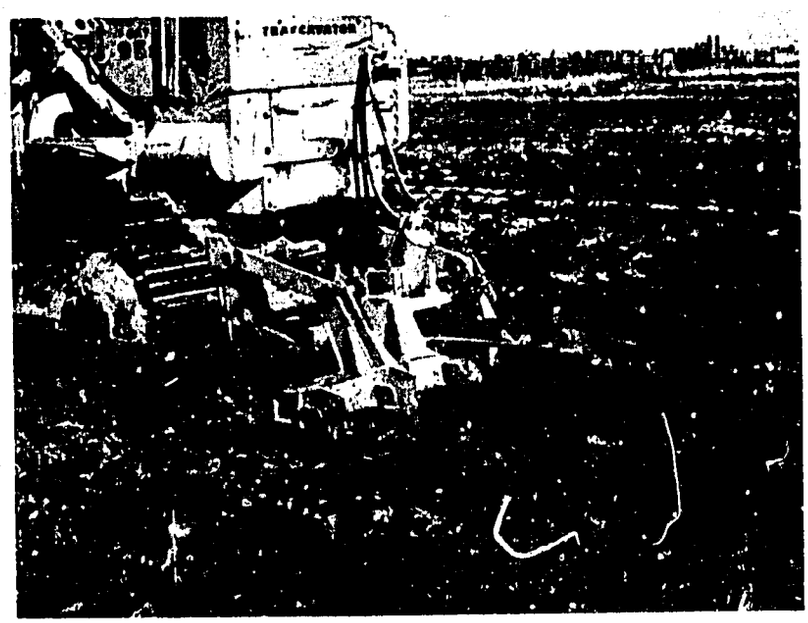


FIGURE 10 - THE DOUBLE MOLE PLOW, IN FULL OPERATING CONDITION, JUST STARTING A NEW MOLE LINE

distances from each of the mole lines. The samples were taken from at least 3 points for each spacing and one point in the no-drain or control area.

In the summer of 1971 the entire area was leached with about 15 inches of water by a sprinkler system and soil samples were again taken from the same depths and locations. The total precipitation between July 1970 and August 1971 was approximately 24 inches.

The electrical conductivity of the saturation extract of soil samples, presented graphically in Figures 11 through 16, shows an appreciable reduction in the salt concentration in the soil in the area with mole drains where soil samples taken in the 1971 summer show the E. C. higher than 4 mmhos/cm. Actually, most samples show the E. C. less than 3 mmhos/cm, while the value was as high as 6.5 mmhos/cm in the previous summer. There is practically no change in the salt concentration in the area without drain or the control area from where most soil samples show no change or a slight reduction in the E. C. after one year and the leaching. One sample, taken at a depth of 18 inches along line A in the control area, still has the E. C. higher than 5 mmhos/cm after leaching. The E. C. before leaching of the soil from the same location was 7.4 mmhos/cm in the preceding summer.

The result of investigations indicates that mole drains assist in making leaching more efficient as evidenced by the larger reduction in the E. C. of the soil samples taken from the area with mole drains in

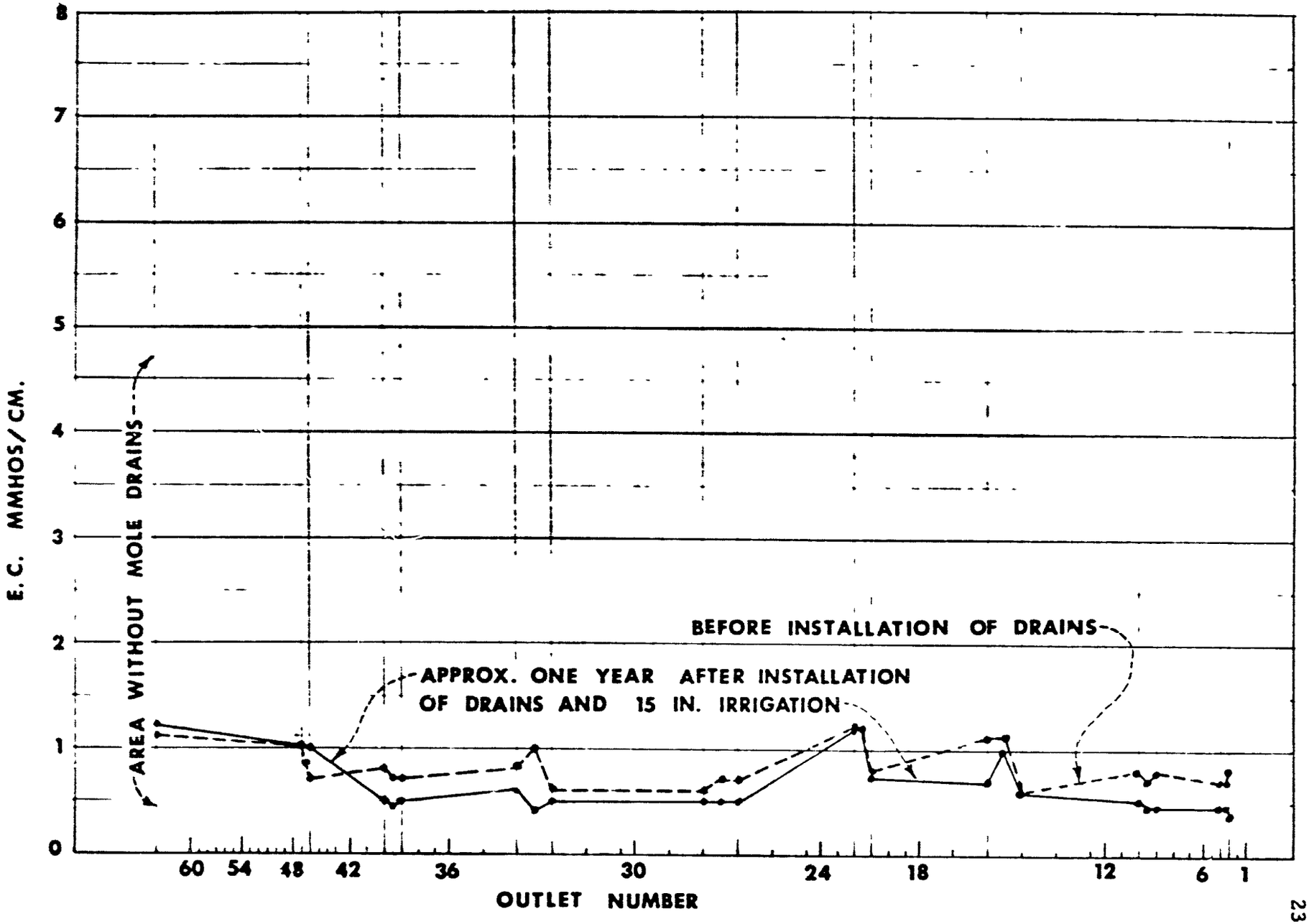


FIGURE 11 - ELECTRICAL CONDUCTIVITY OF SATURATION EXTRACT OF SOIL SAMPLES TAKEN FROM 6 INCHES DEPTH ALONG LINE "A".

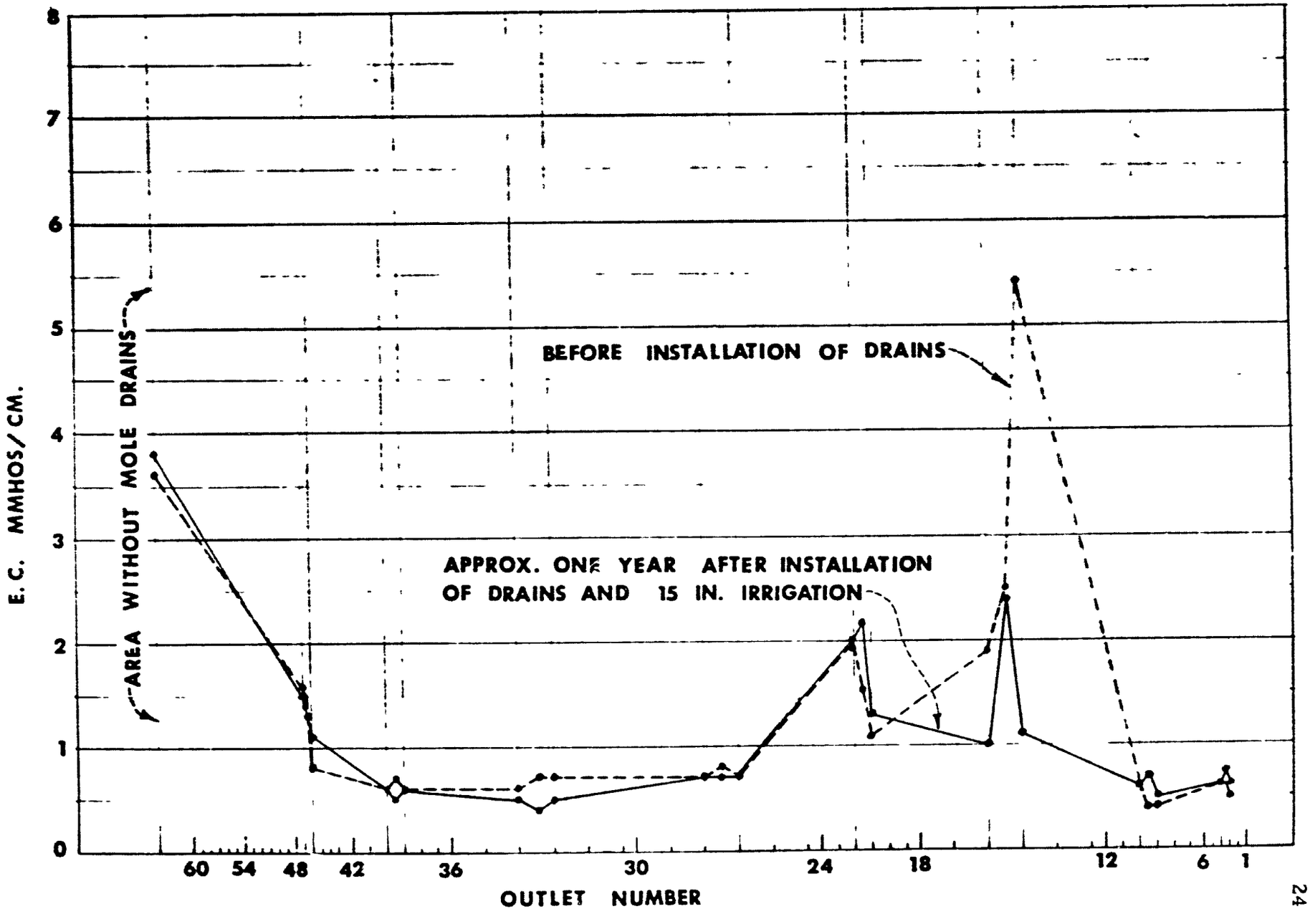


FIGURE 12 - ELECTRICAL CONDUCTIVITY OF SATURATION EXTRACT OF SOIL SAMPLES TAKEN FROM 12 INCHES DEPTH ALONG LINE "A".

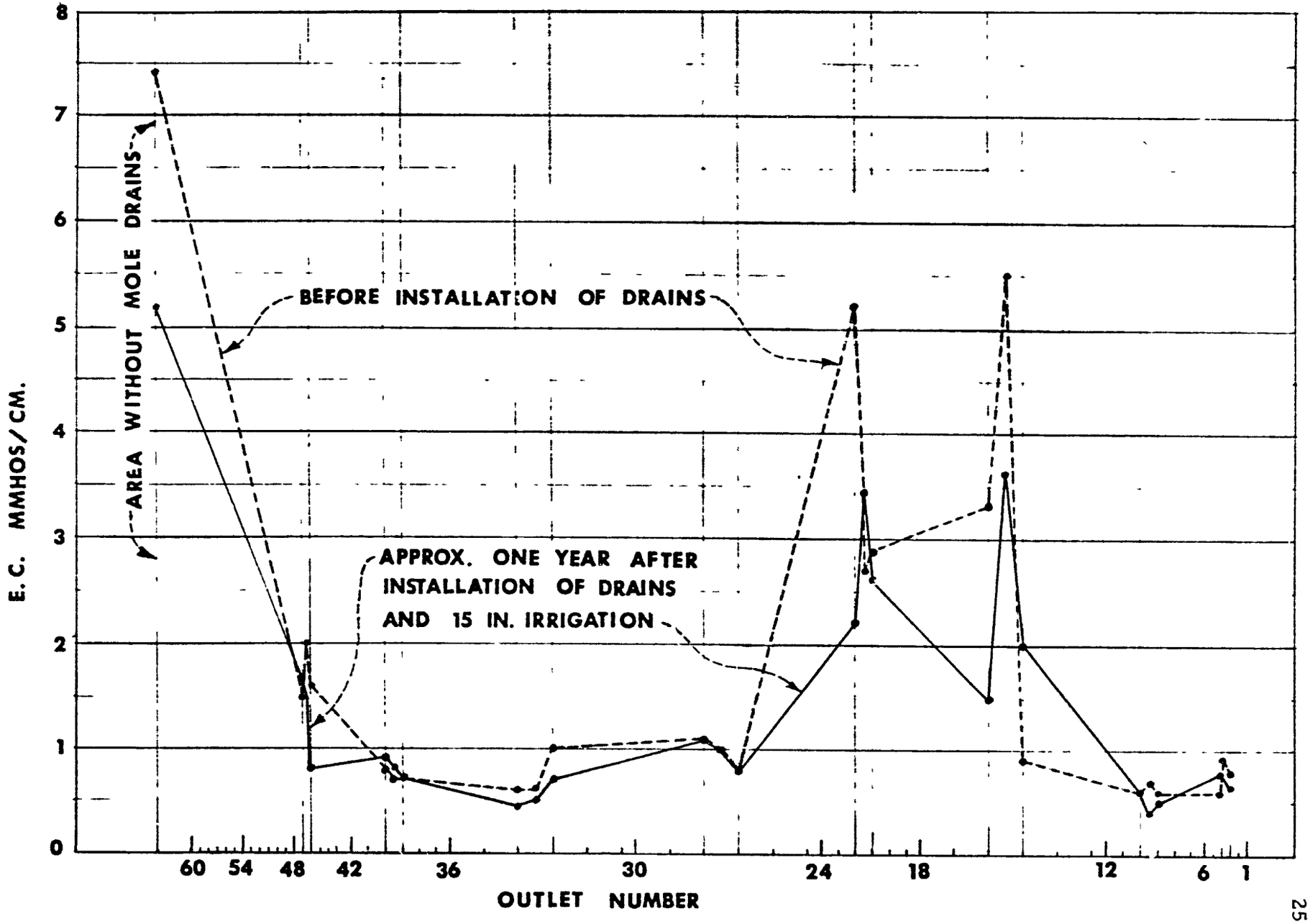


FIGURE 13 - ELECTRICAL CONDUCTIVITY OF SATURATION EXTRACT OF SOIL SAMPLES TAKEN FROM 18 INCHES DEPTH ALONG LINE "A".

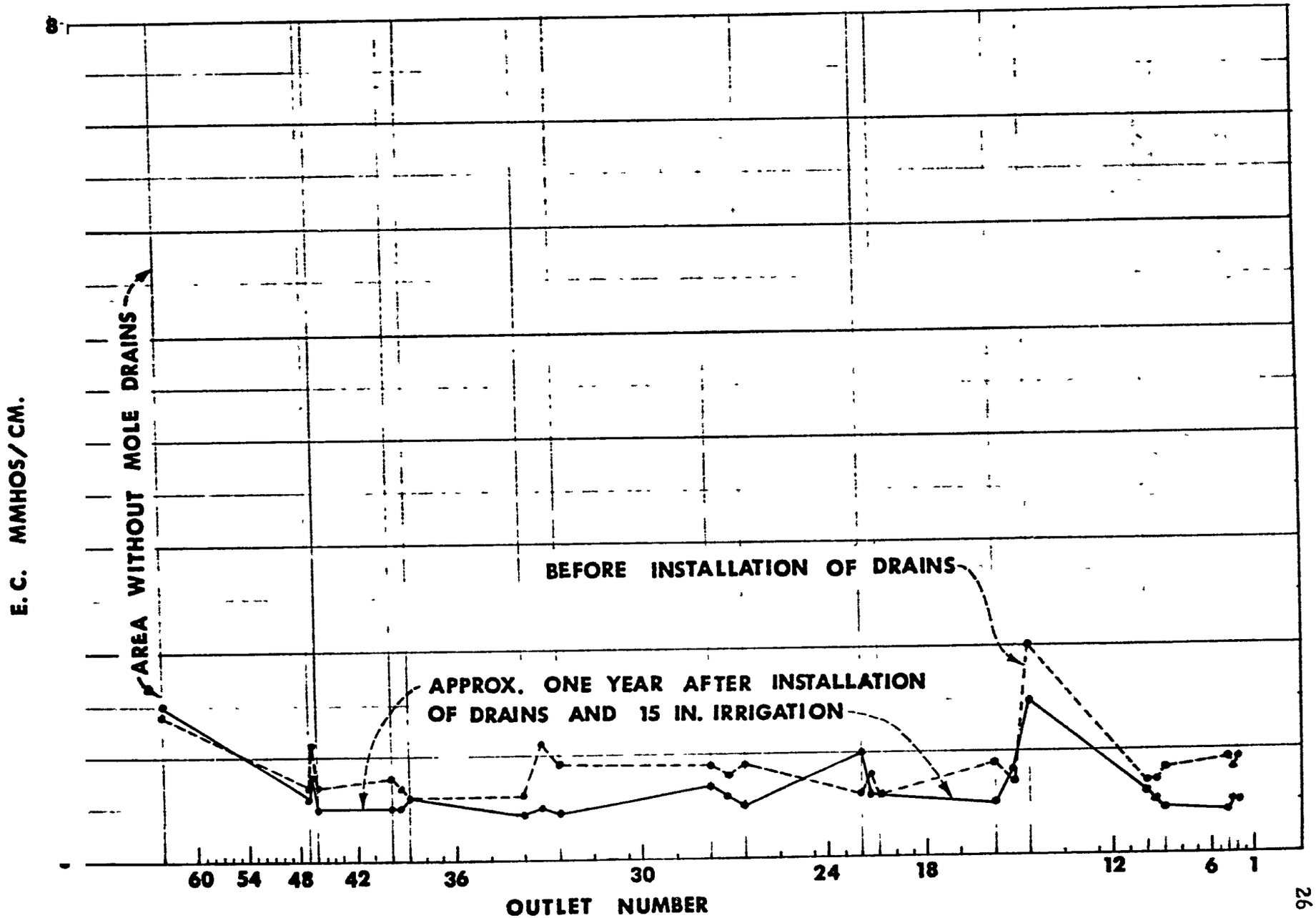


FIGURE 14 - ELECTRICAL CONDUCTIVITY OF SATURATION EXTRACT OF SOIL SAMPLES TAKEN FROM 6 INCHES DEPTH ALONG LINE "B".

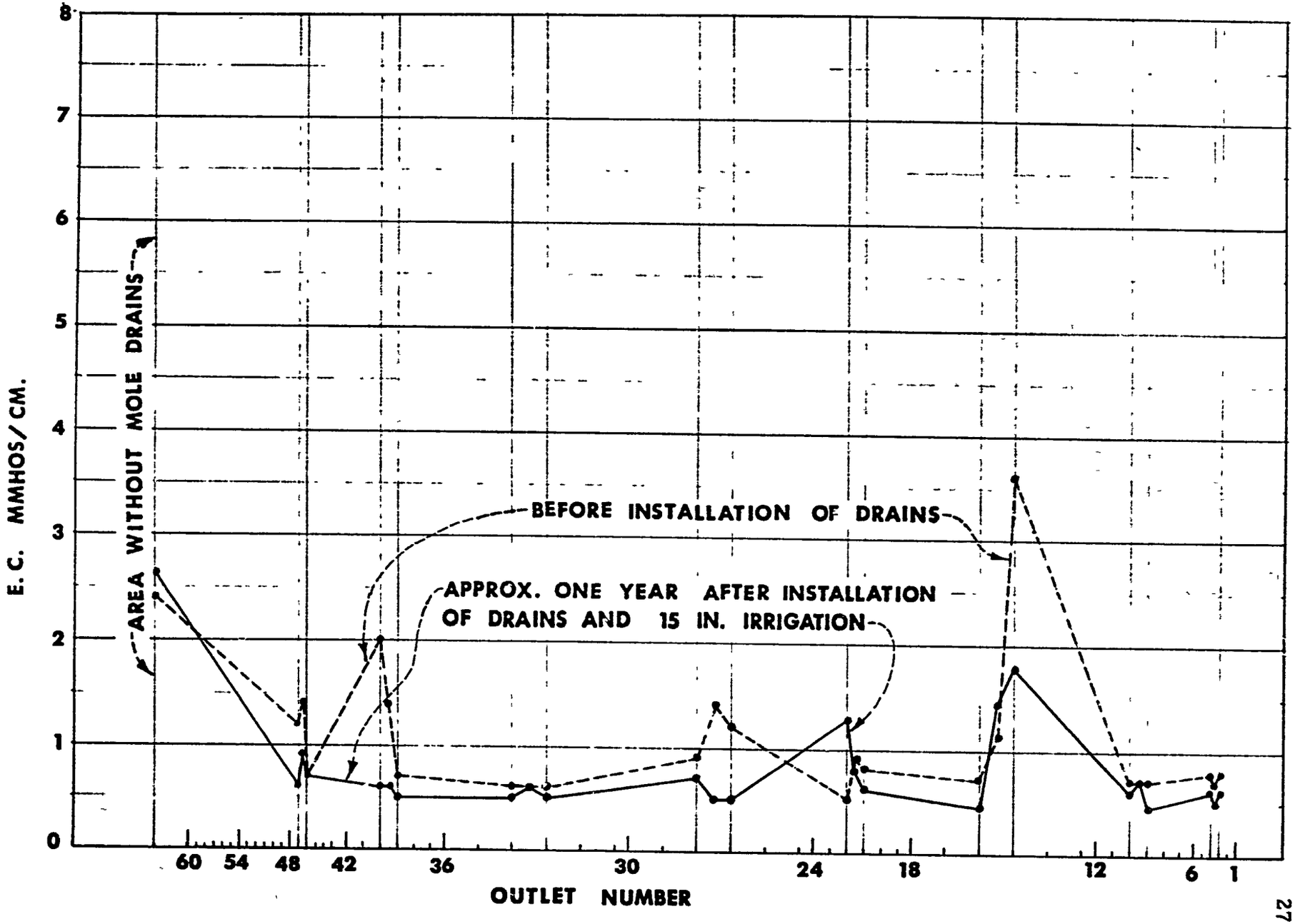


FIGURE 15 - ELECTRICAL CONDUCTIVITY OF SATURATION EXTRACT OF SOIL SAMPLES TAKEN FROM 12 INCHES DEPTH ALONG LINE "B".

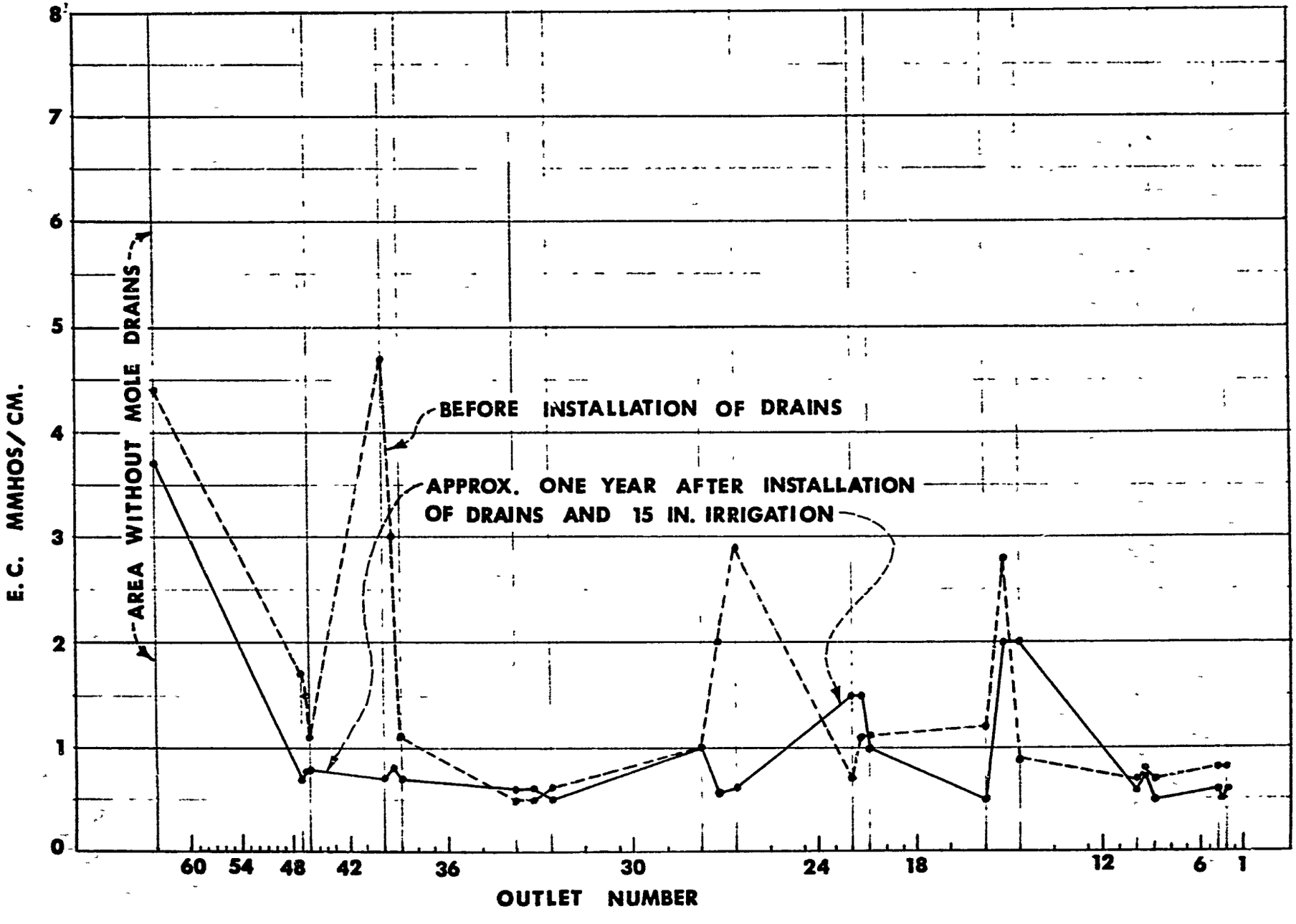


FIGURE 16 - ELECTRICAL CONDUCTIVITY OF SATURATION EXTRACT OF SOIL SAMPLES TAKEN FROM 18 INCHES DEPTH ALONG LINE "B".

comparison with that of the control area. In short, mole drains do not only provide drainage for the land, but they also enhance the salt removal process which means the reduction in the quantity of leaching water.

The observation and study on the durability and effectiveness of mole drains will continue. Crops will be grown in the area to study the improvement of land as the result of leaching.

Work Plan 3 - Laboratory Studies

The objectives of the laboratory studies were to use scale models to predict the performance of the prototypes. The information obtained was used as a guide to design the prototype and planning of a full size experiment. The advantages of model study, to name a few, are that it is much less expensive than a full size study, it also renders information in a shorter time and a wider range of experiment may be covered. To date, three studies have been conducted and presented as theses for the degree of Master of Science in Agricultural and Irrigation Engineering at Utah State University.

Mole drainage construction - optimum moisture content and corresponding power requirement.

The work was completed and presented as a thesis for an M.S. degree in Irrigation and Drainage Engineering in 1970 by Kitcha Polparsi who investigated, by means of a model, the relationship between the form of mole channel and the moisture content of the soil at the time of moling, and to find the corresponding power requirement for

operating the plow. The model mole plow, consisting of a steel torpedo 19/32-inch diameter attached to a steel blade 3/16-inch thick, was pushed through a clay soil contained in a Plexiglas box 10 inches wide, 11 inches high, and 18 inches long. The relative efficiency of the form of mole channel was determined by visual inspection and by comparing the discharge rates of flow through the mole channel under a given head loss. By visual inspection, the mole channels appeared to be well-formed with smooth surfaces when they were constructed in a soil having a moisture content slightly higher than the field capacity. The determination by comparing the discharge rates agreed with that by visual inspection. If the construction was done when the soil was too dry, scales were formed extensively on the surface and, when saturated with water, they disintegrated. A mole channel built in a saturated soil had a very poor form and surface.

Polparsi developed an equation for the determination of the power requirement for operating a mole plow as follows:

$$F_i = A_b \left(CN_c + \frac{\gamma b}{2} N_\gamma + \frac{\gamma h_i}{2} N_q\right) + A_t \left(CN_c + 0.9 \frac{\gamma D}{2} N_\gamma + \gamma d\, N_q\right) + K_2 (S_b + S_t)\, C \quad \ldots\ldots\ldots\ldots (1)$$

in which F_i is the theoretical resistance of soil acting

lbs;

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

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

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

N_c, N_γ, and N_q 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_i is the depth of blade underground, in.

D is the diameter of torpedo, in.

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

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

S_b, and S_t are the frictional areas of the blade and torpedo, respectively, in^2.

The theoretical forces determined by Equation 1, assuming $K_2 = 1.0$, were found to give the values approximately 25 to 35 percent larger than those obtained experimentally in the range of soil moisture between 27 to 29 percent.

B. Durability of double mole drains.

Anan Sukwiwat, a graduate student in the Department of Agricultural and Irrigation Engineering, used a model to study and compare the durability of mole channels constructed with a single and a double mole plow. The result of his work was submitted as a Master of Science thesis in 1970. In his experiment both mole plows consisted

of 1/4-inch thick blades and 3/4-inch torpedoes. He used both types of mole plow to construct mole channels in the clay soil having a moisture content of 29 percent. The initial discharge capacity of mole channel, which is defined as the discharge rate through the channel under a total head loss of 0.375 inch, was measured. Then the water was applied at a certain constant rate to the soil by a simulated sprinkler apparatus. When the application depth reached 1 inch, the sprinkler was turned off, and the discharge rate of the channel under the same head loss was again measured. The deterioration of the mole channel as a result of the sprinkler water was determined by observing the reduction in the discharge rates in comparison with its initial rate. More water was added by the sprinkler and similar measurements were made at the application depths of 2, 3, and 4 inches. The same procedure was used for testing other mole channels but with a different rate of water application. Altogether, four application rates were used.

From the study, he concluded that the double mole channels are more durable than the single mole ones. The deterioration of the single mole channel, determined from the reduction of the discharge rate of the channel, was very high as found from the experiments that, with an application rate of 1/2 inch per hour, the discharge rate was almost zero at the application depth of 1 inch. For double mole channels, the deterioration increases with the application rate, but the rate of

increase with respect to the application depth was very small when the application rate was 1 inch per hour.

C. Effect of shape and speed of mole plow on soil resistance.

An investigation on the effect of speed of the mole plow on soil resistance was conducted by Rustu Kasap, a graduate student who submitted his work as a thesis for an M.S. degree in Agricultural and Irrigation Engineering, Utah State University, in 1971. The objectives of his study are to find the shape of a mole plow which reduces the soil resistance, and to find the relationship of the mole plow speed and the soil resistance. Two sets of mole plows were used in these experiments. The first set (Figure 17) consisted of five mole plows of which one has only a blade and the other four have similar blades with torpedoes having different front angles. The second set is similar to the first set except the sides of the blades and torpedoes were removed or made thinner to eliminate the frictional areas (see Figure 18). These plows were pushed through the soil, contained in a Plexiglas box, by the equipment shown in Figures 19 and 20. The vertical and horizontal components of soil resistance are computed from the readings of the dial gauges nos. 1 and 2.

Kasap modified the equation for determination of the soil resistance on the plow, previously developed by Polparsi in 1970, to include the effect of speed of pulling as follows:

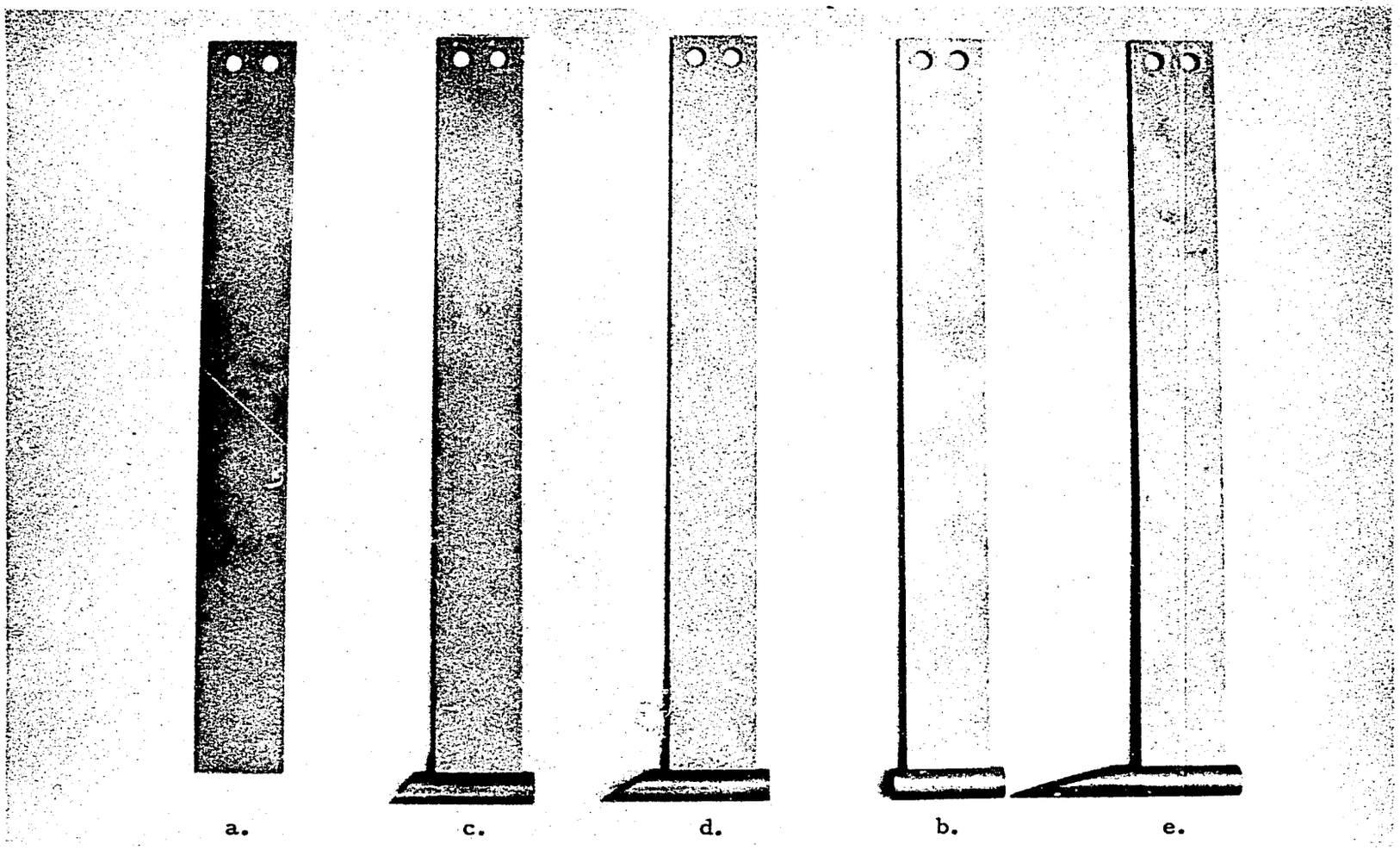


Figure 17 - Mole plows consisting of steel torpedoes having different front angles attached to steel blades.

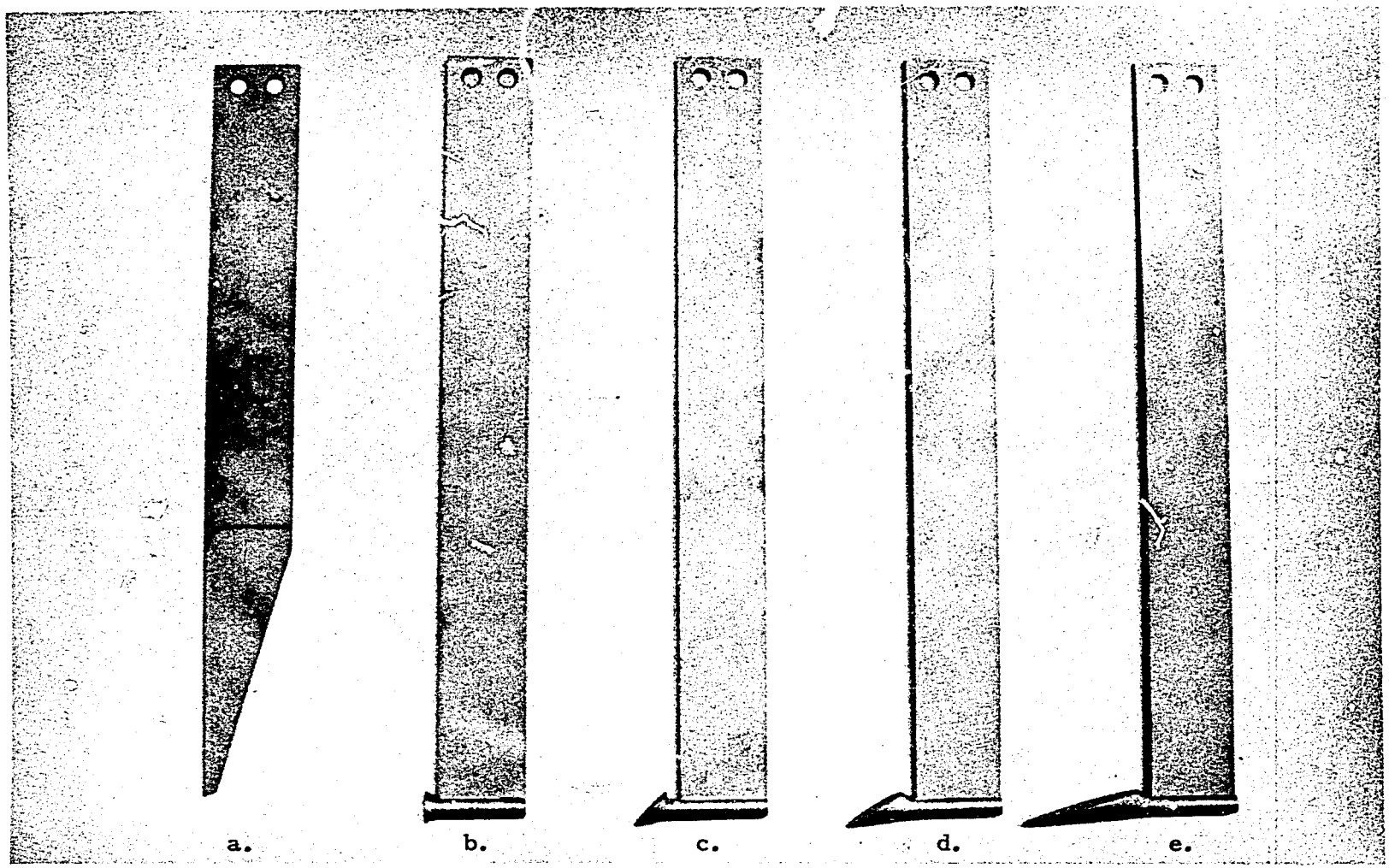


Figure 18 - Mole plow blades and torpedoes designed to have side friction eliminated.

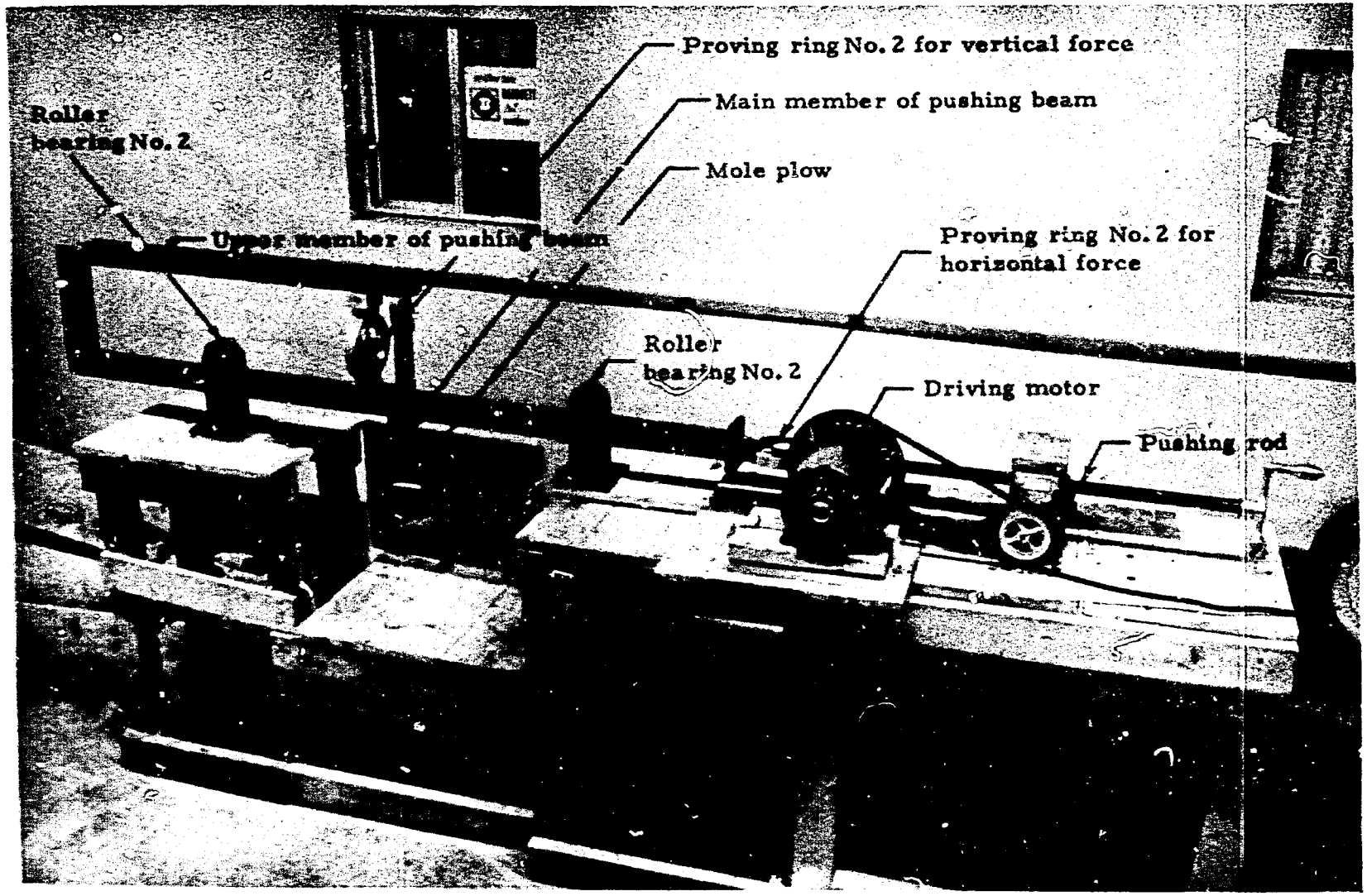


Figure 19 - Pushing beam equipped with proving rings and mole plow (soil box not in place).

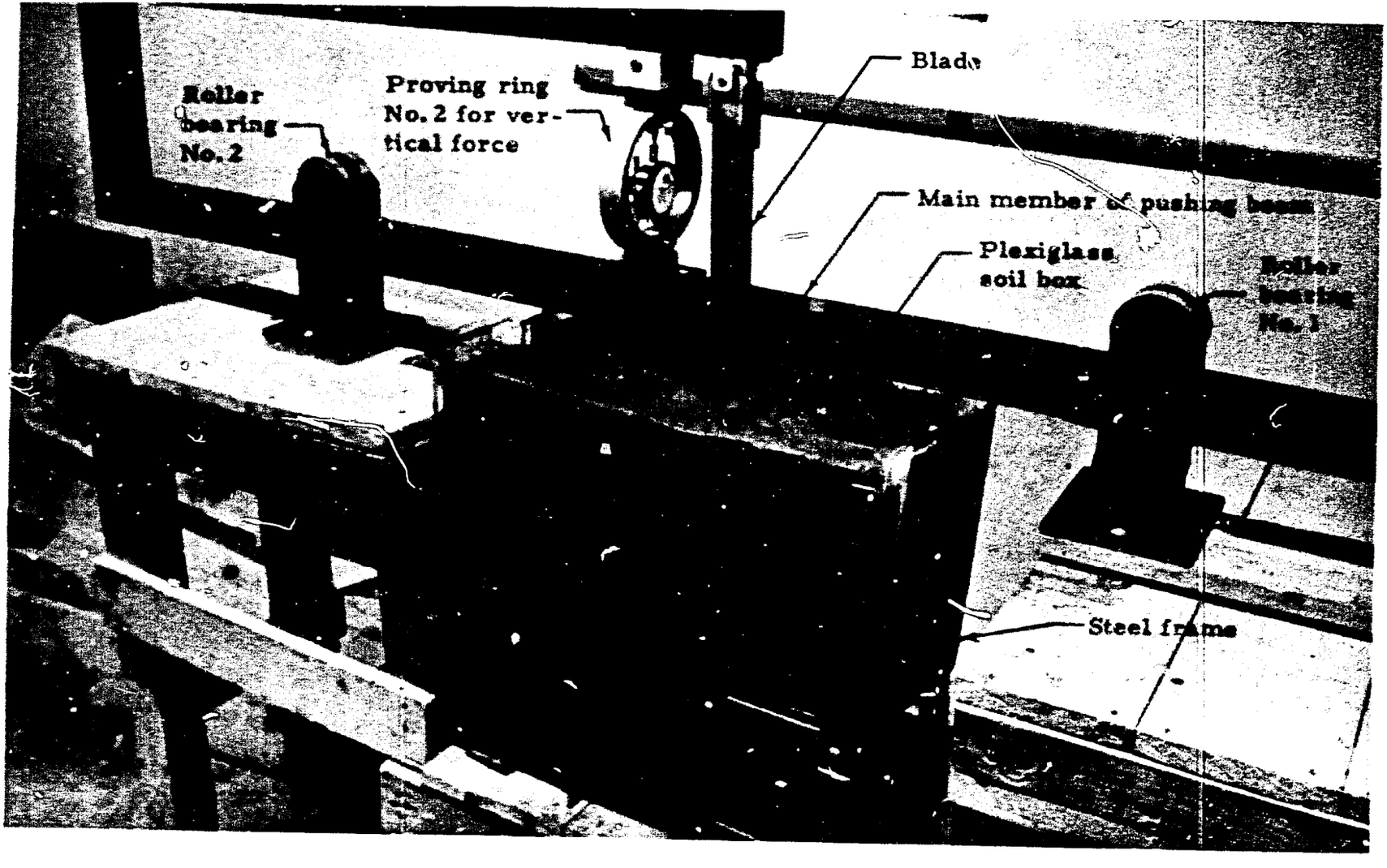


Figure 20 - Mole plow being pushed through the soil in the soil box.

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

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

in which

F_{static} is the theoretical resistance of soil on a very slowly moving mole plow, lbs.

$F_{dynamic}$ is the theoretical resistance of soil on a moving mole plow, lbs.

K_1 is the bearing capacity reduction factor for shape of the front end of torpedo, dimensionless.

C_1 is the dynamic cohesion, lbs/in^2, which is defined as C_1 = ACR x C, in which ACR is the apparent cohesion ratio, dimensionless.

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

Other terms are the same as previously defined.

Equations 2 and 3 were expressed as a function of the mole plow dimensions and the physical properties of soil which already included the effect of pulling speed. One of the equations was verified by experiments for the case of a very slowly moving plow with the blunt front end,

and the theoretical resistance computed by Equation 2 agreed satisfactorily with the experimental results.

The study also indicated that by modifying the shape of mole plow to eliminate the frictional areas from the sides of the blade and torpedo, the soil resistance or the corresponding power required to pull the plow, may be reduced as much as 30 - 40 percent. Such modification was done by reducing the blade thickness just behind the front edge and the diameter of torpedo behind the front end.

Work Plan 4 - Field Studies on Power Requirement

Objectives. To measure the power required for pulling the plow in the field and to verify by field tests the equations developed previously during the laboratory studies.

Progress. A force measuring device, designed and built at Utah State University, was ready for a preliminary test in June of 1971. The device was designed to give the readings from which the vertical and horizontal components of soil resistance acting on the plow may be computed. In order to keep the cost down, no attempt was made to include sophisticated features such as automatic speed recorder and gauge reading recorder. During the preliminary tests, modifications were found necessary and the device was not ready for the actual test until the end of summer of 1971.

A photograph of the device in Figure 21 shows three gauges which register the pressure of the fluid in the hydraulic cylinders installed

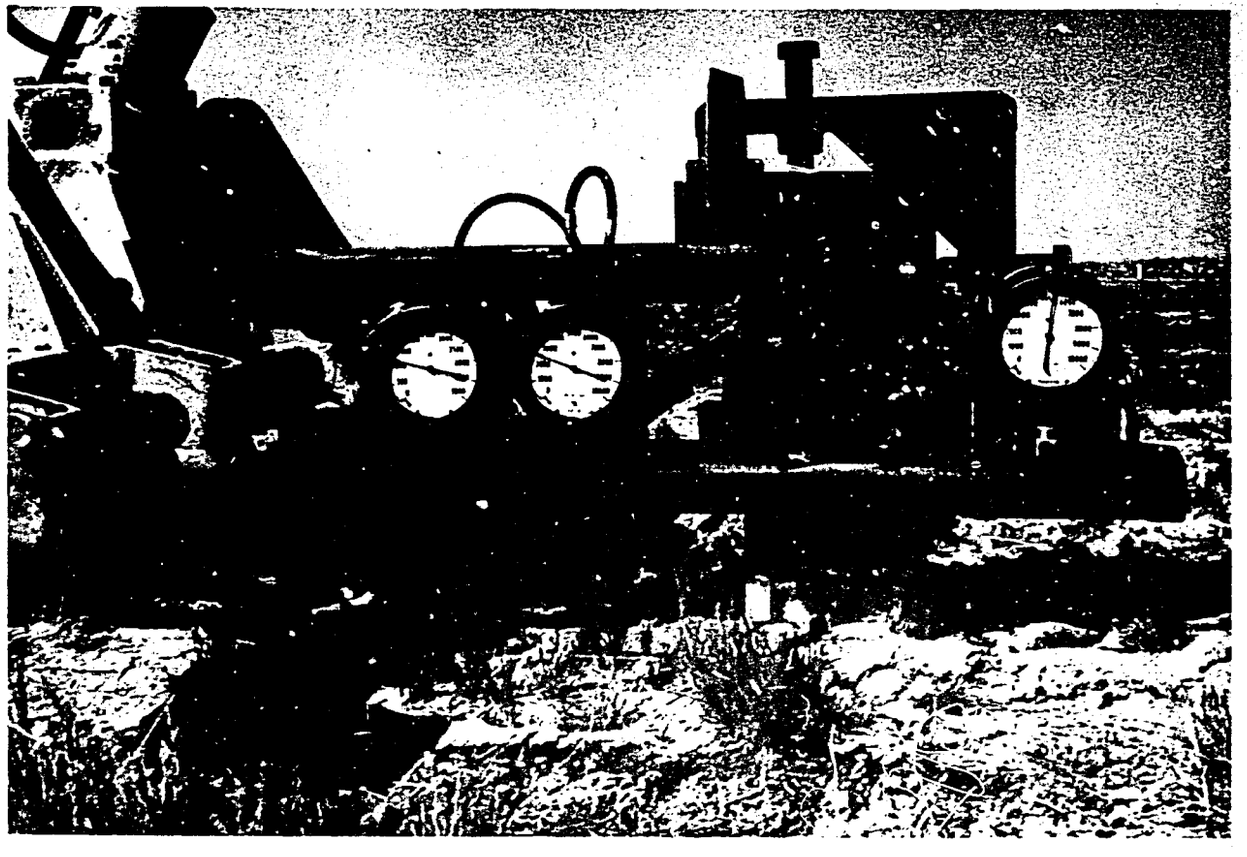


FIGURE 21 - FORCE MEASURING DEVICE DURING AN ACTUAL FIELD TEST TO MEASURE THE SOIL RESISTANCE ON A MOLE PLOW

as shown diagrammatically in Figure 22. With the arrangement shown, the readings from the pressure gauges multiplied by the corresponding piston areas give the forces exerted on the mole plow. The vertical and horizontal components of the soil resistance, F_y and F_x, may be computed by Equations 4 and 5 (see Figure 22).

$$F_x = (G_3 - G_2 - 0.779\, G_1)\, 2.23 \quad . \; . \; . \; . \; . \; . \; . \quad (4)$$

$$F_y = 1.416\, G_1 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

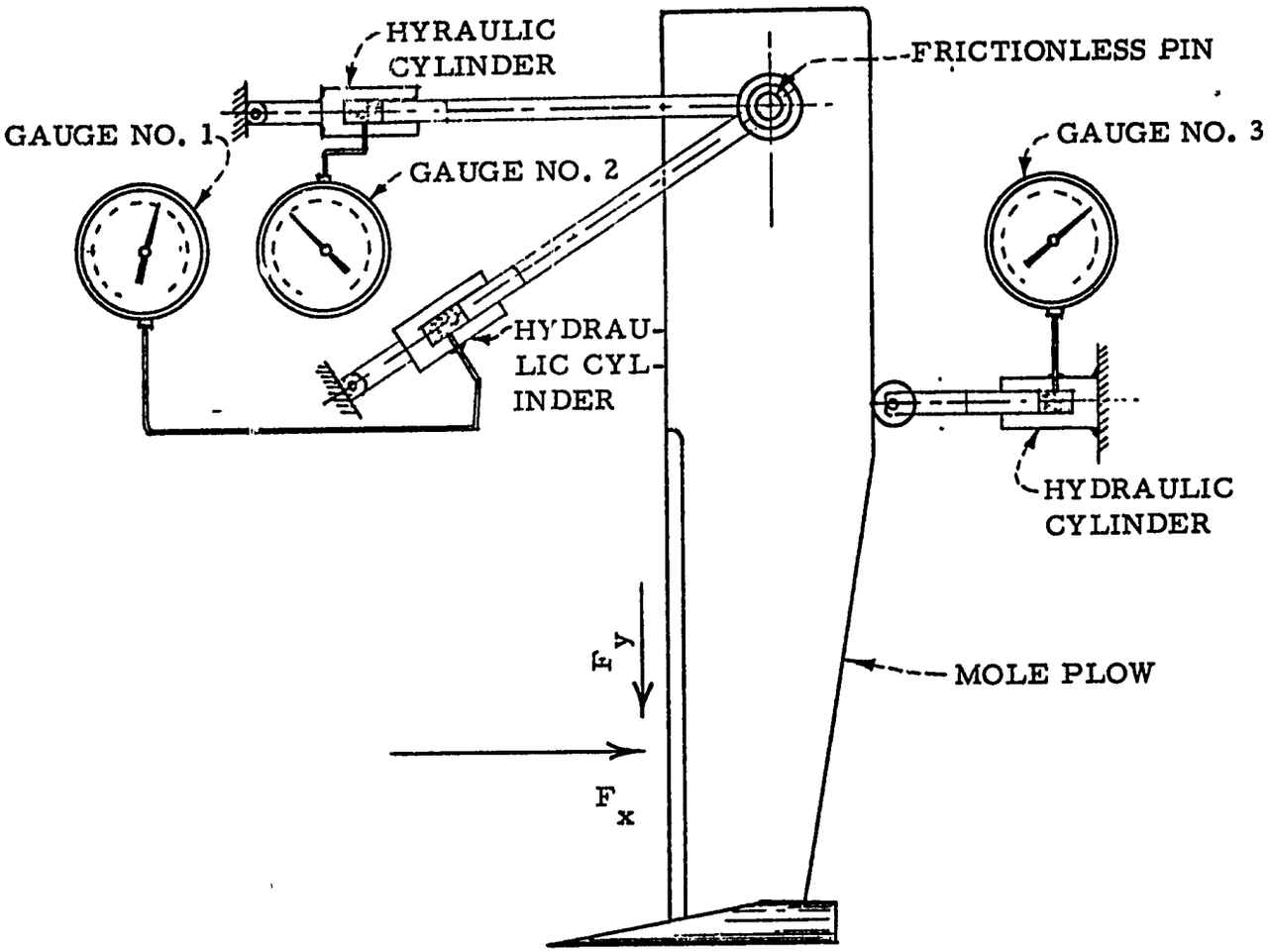
in which

F_x is the horizontal component of soil resistance, lbs.

F_y is the vertical component of soil resistance, lbs.

G_1, G_2, and G_3 are readings from gauges No. 1, 2, 3, respectively, lbs/in^2.

The field tests consisted of the measurements of the soil resistance on the single mole plow (Figure 1) with the follower removed, and double mole plow Design 8. The force measuring device, with the plow attached, was pulled by the D-6(955) tractor, and the gauges were read when the average speeds of the tractor and plow were 1.70 and 2.90 miles per hour. As it was necessary to read all three gauges simultaneously, cameras were used to capture the gauge readings. For example, Figure 21, which is the photograph of the force measuring device taken during the actual test to measure the soil resistance on the single mole



$$F_x = (G_3 - G_2 - 0.779G_1)\ 2.23$$

$$F_y = 1.416\ G_1$$

in which

F_x = HOR. SOIL RESISTANCE IN LBS.

F_y = VERT. SOIL RESISTANCE IN LBS.

G_1, G_2, and G_3 = READINGS FROM GAUGE NO. 1, 2, and 3, RESPECTIVELY, IN PSI.

FIGURE 22 - DIAGRAMMATIC SKETCH SHOWING THE ARRANGEMENT OF HYDRAULIC CYLINDERS ON A MOLE PLOW FOR SOIL RESISTANCE MEASUREMENT

plow, shows the gauge readings in pounds per square inch. Substituting these gauge readings in Equations 4 and 5, the vertical and horizontal components of the soil resistance are obtained. The test data and the corresponding soil resistances computed from the data are shown in Table 1.

After the soil resistance measurements were finished, four undisturbed soil samples were taken from the depths between one and two feet at the locations where the gauge readings were made. These undisturbed samples, about one foot cube in size, were carefully sealed with wax to prevent the loss of moisture prior to the direct shear tests. The result of shear tests from which the angle of internal friction and cohesion were determined is shown in Figure 23.

The computation of the theoretical soil resistance shown in Table 2 was computed by Equation 2. Actually, because the plow was moving considerably faster than what is considered to be a very slow speed in soil mechanics, Equation 3 would be more applicable than Equation 2. Equation 5 was not used in the determination due to the unavailability of the value of the dynamic C_1 or a facility to find it.

In applying Equation 2, the values of A_b, b, A_t, D, S_b, S_t, d, h_i were obtained from the dimensions of the plows and the depths of moling during the tests (see Figure 24), K_1 and K_2 were given

Table 1. Field Test Data

Station	Type of Plow	Speed mph	Reading No.	Gauge Reading psi			Soil Resistance lbs	
				G_1	G_2	G_3	F_x	F_y
S1	Single	1.70	1	780	1,150	2,700	2,100	1,100
			2	800	1,150	2,700	2,067	1,130
S2	Single	*	1	1,100	2,400	5,100	4,110	1,560
			2	1,100	2,400	5,100	4,110	1,560
S3	Single	2.90	1	1,100	2,700	5,400	4,110	1,560
			2	1,000	2,400	5,100	4,284	1,420
S4	Single	**	1	500	1,450	2,650	1,808	710
			2	500	1,950	3,600	2,812	710
D1	Double	1.70	1	850	2,200	4,700	4,099	1,210
			2	900	2,000	4,400	3,789	1,300
D2	Double	*	1	2,100	2,550	6,100	4,268	2,970
			2	2,300	2,900	7,250	5,705	3,260
D3	Double	2.90	1	2,200	2,800	7,000	5,544	3,120
			2	2,200	3,000	7,200	5,544	3,120
D4	Double	**	1	1,950	2,500	5,700	3,749	2,760
			2	2,200	2,400	6,200	4,652	3,120

*Speed slightly less than 2.90 mph.

**Speed slightly more than 1.70 mph.

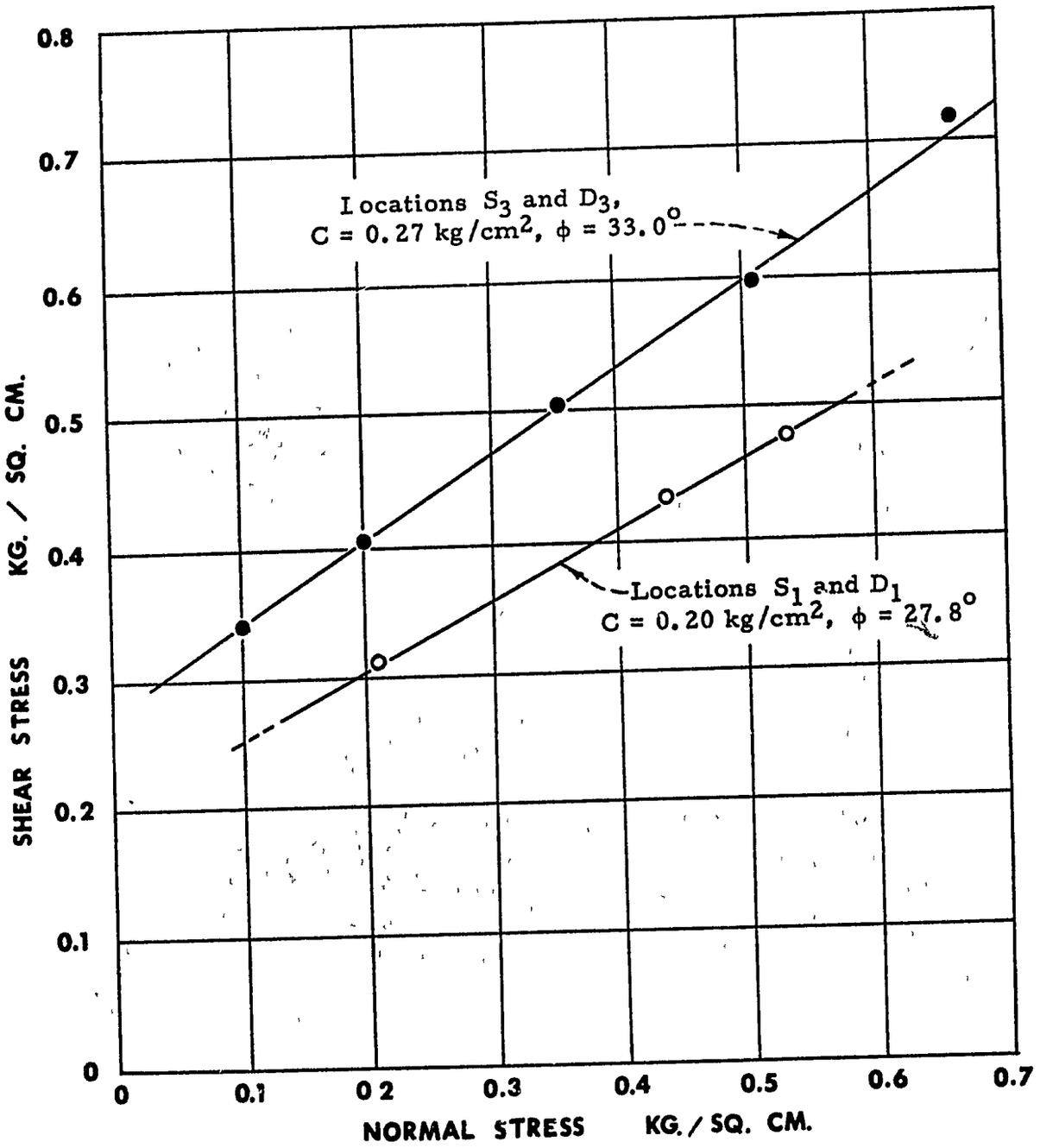


FIGURE 23 - SHEAR STRENGTH OF UNDISTURBED SOIL SAMPLES TAKEN FROM MOLE PLOW TESTING AREA.

Table 2. Examples of Computation for Horizontal Soil Resistance on Mole Plow by Equation 2

a. Values of ϕ, C, N_c, N_γ, N_q, γ

Location	ϕ	Cohesion C, psi	N_c	N_γ	N_q	γ pci
S_1 & D_1	27.8^o	2.85	25	11	15	0.06
S_3 & D_3	33.0^o	3.85	28	28	27	0.06

b. Values of ϕ', C' (= $\frac{2}{3}$ C), N_c' N_γ', N_q'

Location	ϕ	Cohesion C', psi	N_c'	N_γ'	N_q'
S_1 & D_1	19.5^o	1.90	14	2.5	6
S_3 & D_3	23.5^o	2.57	18	5.0	9

c. Geometrical properties of mole plows

Type of Plow	h_i in	d in	b in	D in	A_b in^2		A_t in^2	S_b in^2		S_t in^2
					Hor.	Vert.		Hor.	Vert.	
Single	20	21.5	0.75	3.0	-	14.3	7.1	-	360	138
Double	21	20.0	0.75	3.5	6.5	15.8	19.3	66	368	186

d. Computation for bearing resistance on the vertical blade

Type of Plow	Location	$\frac{2}{3}$ C N_c' psi	$\frac{\gamma b}{2} N_\gamma'$ psi	$\frac{\gamma h_i}{2} N_q'$ psi	$(\Delta q_s)_{ub}$ psi	Bearing on blade Q_b, lbs
Single	S_1	26.60	0.06	3.60	30.26	441
	S_3	46.20	0.12	5.40	51.72	755
Double	D_1	26.60	0.06	3.78	30.44	445
	D_3	46.20	0.12	5.66	51.98	760

Table 2. (Continued)

e. Bearing resistance on the torpedoes

Type of Plow	Location	$\frac{2}{3} C N_c$	$\frac{0.9\gamma D}{2} N_\gamma$	$\gamma d N_q$	$(\Delta q_s)_{ut}$	Bearing on torpedo Q_t, lbs
Single	S_1	47.5	0.89	19.4	67.79	480
	S_3	68.5	2.26	34.7	105.46	746
Double	D_1	47.5	1.04	17.1	65.64	1,260
	D_3	68.5	2.63	30.8	101.93	1,970

f. Bearing resistance on the horizontal blade

Type of Plow	Location	$\frac{2}{3} C N_c'$	$\frac{\gamma b}{2} N_\gamma'$	$\gamma h_i N_q'$	$(\Delta q_s)_{ub}$	Bearing on hor. blade, lbs
Double	D_1	26.60	0.06	7.20	33.86	220
	D_3	46.20	0.12	10.80	57.12	372

g. Friction resistance on the blades and torpedoes

Type of Plow	Location	C	S_b	S_t	$F_f = K_2 (S_b + S_t) C$ Use $K_2 = 1.0$
Single	S_1	2.85	360	138	1,415
	S_3	3.85	360	138	1,915
Double	D_1	2.85	506	186	1,970
	D_3	3.85	506	186	2,667

h. Total resistance (= bearing resistance + frictional resistance)

Type of Plow	Location	Total resistance computed (theoretical)	Field test* (measured)
Single	S_1	2,336	2,084
	S_3	3,416	4,197
Double	D_1	3,893	3,944
	D_3	5,769	5,544

*Average of two readings from Table 1.

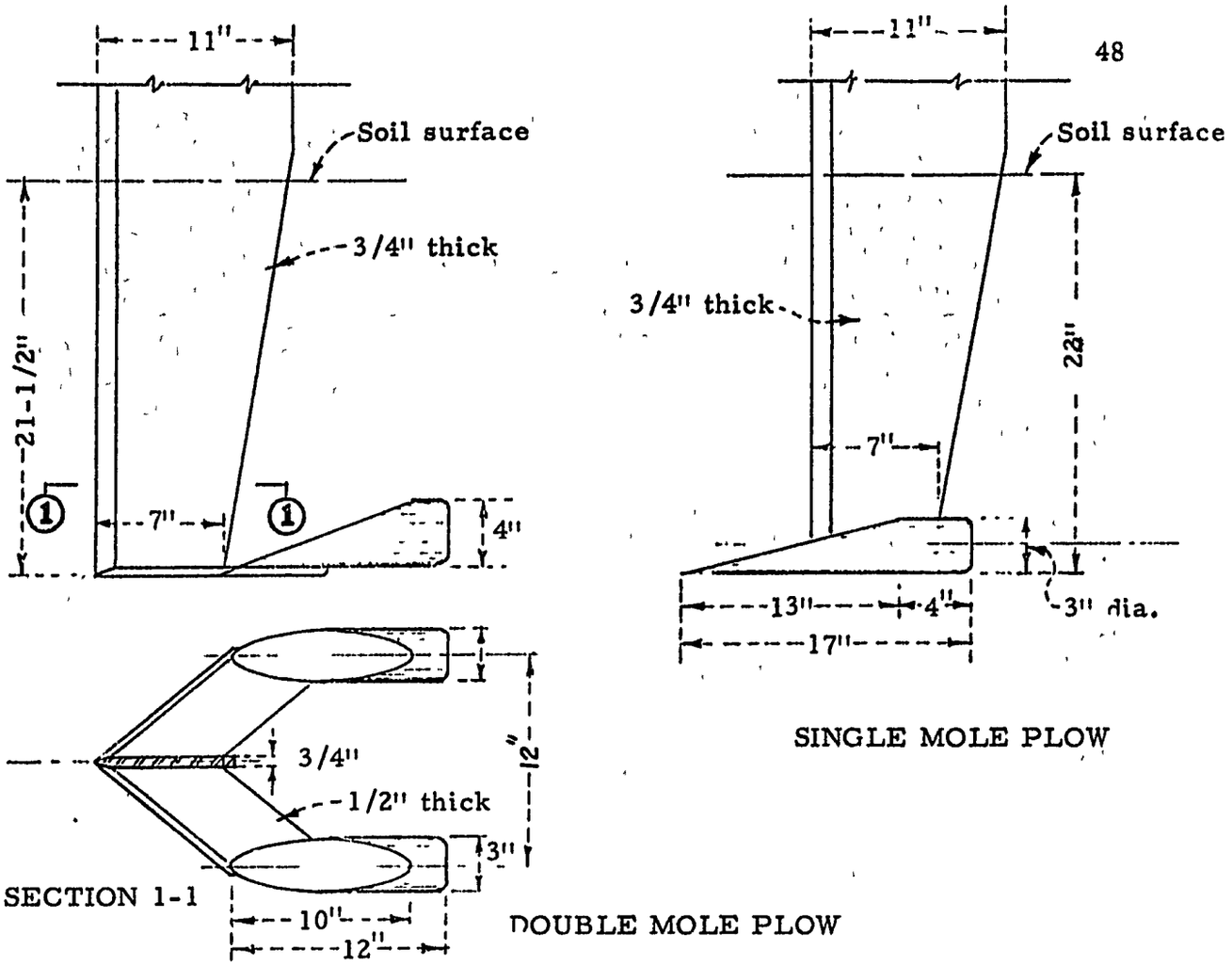


FIGURE 24 - DIMENSIONS OF MOLE PLOWS USED IN FIELD TESTS ON SOIL RESISTANCE ON MOLE PLOWS

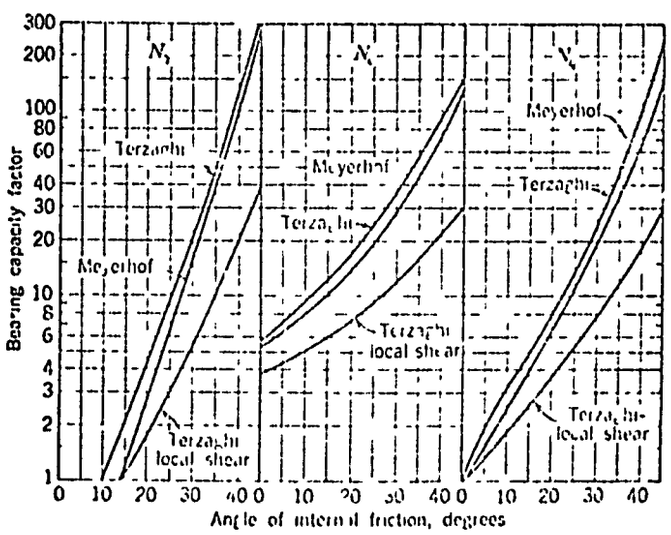


FIGURE 25 - BEARING CAPACITY FACTORS FOR THE GENERAL BEARING CAPACITY EQUATION (G. A. LEONARDS 1962 FOUNDATION ENGINEERING, McGRAW-HILL BOOK COMPANY, INC., NEW YORK, 542 pp.)

the value of unity, C was taken from Figure 23, γ was measured, and N_c, N_γ, N_q, N_c', N_γ', N_q' were read from Figure 25 with proper values of ϕ and ϕ'.

At present, there is no equation for the determination of the vertical component of soil resistance. Even though this component has practically no effect on the power requirement for operating the plow, depending on the design of the plow attachment, it should act in a downward direction in order to maintain the plow in the soil.

It may seem that Equation 3 is of little practical value due to the difficulty in obtaining the value of the dynamic C_1 which requires a special apparatus and a more complicated testing procedure than simple direct shear tests. But this difficulty could be overcome if extensive tests could be conducted to find the apparent cohesion ratios -ACR for some typical soils suitable for mole drainage within some practical range of moisture content. When ACR is known, the dynamic C_1, equal to ACR x C, can be computed and used in the dynamic Equation 3.

The comparison of the theoretical soil resistance and the values measured in the field tests in Table 2h shows a satisfactory agreement between the theoretical and field measured values when the plows were pulled at 1.70 miles per hour. At a higher speed of 2.90 miles per hour the theoretical value is much less than the measured value for the single mole plow, but both values agree for the double mole plow. In general, a conclusion may be drawn at this point that there is a good agreement

between the values of the theoretical soil resistance computed by Equation 2 and the field test values, especially for the plow moving at the speed of about 1-1/2 miles per hour which is within the recommended range. Previous investigations in England indicate that a few drains drawn at a speed of 3-1/2 to 4 miles per hour were of very little use after only two years.

Field tests showed the measured soil resistance on the double mole plow, drawn at the depth of 21 inches in the Drainage Farm clay soil having a moisture content of about 26 percent, was approximately 5,500 lbs. As a force of this magnitude can be furnished by a wheel tractor of 80 - 100 drawbar horsepower moving at a speed suitable for moling, further field tests involving the use of a wheel tractor for pulling mole plows under various soil moisture and surface conditions may yield useful information.

Work Plan 5 - Field Tests in Latin American Countries, written by Bertis L. Embry

Two trips were made to Colombia and El Salvador, one for two weeks in February and March 1971, and the other for five weeks in August and September 1971.

The work in Colombia was done with the National Agricultural Experiment Station at Tibaitata near Bogota with the cooperation of Darrell Watts of the Nebraska University Team. A plot of land was prepared for moling in March, single and double mole plows were built and the moles installed in half the plot, using the other half for control. The plot was then planted in corn. By June the mole holes seemed to be

plugged with silt, so no more water was discharged. Pictures of the moled and unmoled sections show a great improvement in crop growth even though it was a disappointment not to have the moles operated as planned.

In August the first plot was studied. Some theories as to the drain failures were advanced and a different plot chosen for further experimentation. Some reasons for the failure are: 1) the drains were flooded during the heavy rainy season (outlets were not pumped out), 2) the plot was in a transition zone between two soil types, and the clay layer was variable as well as containing considerable silt.

Moles were installed on the second plot with both single and double plows. Data on the discharge and the effect on the crop is supposed to be taken continuously.

A trip was made to Barranquilla to work with Edwin C. Olsen. They did not have a tractor to do any mole drain work, but possible plots were chosen to install some experimental drains when the equipment becomes available from Bogota.

The first trip into El Salvador was exploritory to determine if mole drains could be used there. Tabai engineers from Israel had recommended them. Plans were made to construct a single mole plow. In August it was too wet in the fields to install drains, but the single mole plow was successfully tested. Plans were made to build a double mole plow, and field installations were to have been made in November by Ministry staff.

The soils in the Zapotitan Valley in El Salvador have a very high non-decomposed organic content. Any kind of drainage should be beneficial in introducing oxygen into the subsoil to decompose the organic matter. It is hoped that the initial trials will show beneficial results from moling.