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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

CANAL EROSION AND TRACTIVE FORCE STUDY--ANALYSIS OF DATA FROM A BOUNDARY SHEAR FLUME

Report No. Hyd-532

Hydraulics Branch
DIVISION OF RESEARCH

OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

December 12, 1963

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ABSTRACT

In recent years, studies have been in progress to establish better design criteria for earth-lined and unlined canals constructed in fine, cohesive soils. To continue these studies a recirculating flume was constructed and tests conducted on several 8-inch-diameter /20.32 cm/ soil samples. Soil density, soil moisture content, and temperature of flowing water in the flume were well controlled. Samples were tested by gradually increasing the boundary shear acting on the sample until shear became critical and the sample began to erode. Tests indicated that the time increment used for increasing the boundary shear on the soil was not critical within the range used and that minor increases in temperature of the flowing water had little effect on the discharge necessary to produce erosion. For the soil tested, the boundary shear required to erode the soil was a function of the moisture content at which the soil was compacted. However, the tests were inconclusive regarding the effect of the soil densities.

17 references are given.

DESCRIPTORS--*Tractive forces/ erosion/ *erosion control/ movable bed models/ *scour/ sediment control/ sedimentation/ sediments/ stable channels/ soil moisture/ soil compaction/ water/ temperature/ *cohesive soils/ fine-grained soils/ gradation analysis/ boundary shear/ unlined canals/ optimum moisture content/ laboratory tests/ canal design/ earth linings/ velocity/ flumes/ saturation

IDENTIFIERS--Tractive force apparatus/ critical tractive force/ relative soil density

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Office of Chief Engineer
Division of Research
Hydraulics Branch
Special Investigations Section
Denver, Colorado
December 12, 1963

Laboratory Report No. Hyd-532
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CANAL EROSION AND TRACTIVE FORCE STUDY
ANALYSIS OF DATA FROM A BOUNDARY SHEAR FLUME

SUMMARY

In continuing tests to establish better design criteria for earth-lined and unlined canals, a recirculating flume, Figure 1, was constructed and tests were conducted on several soil samples. The samples used were 8 inches (20.32 cm) in diameter and the properties of density and moisture content could be well controlled. Samples were tested by gradually increasing the boundary shear acting on the sample until the shear became critical and the sample began to erode. Tests indicated that the time increment used for increasing the boundary shear on the soil was not critical in the range used, and that minor increases in the temperature of the flowing water had little effect on the discharge necessary to produce erosion. They also indicated that, for the soil tested, the boundary shear required to erode the soil was a function of the moisture content at which the soil was compacted. However, the tests provided conflicting evidence regarding the effect of the soil density.

The desirability for additional tests was indicated.

INTRODUCTION

In recent years, studies have been in progress to establish better design criteria for earth-lined and unlined canals constructed through fine, cohesive soil material. References 1/, 4/, 5/, 6/, 8/, describe field and laboratory studies conducted on 46 test reaches in canals and laterals in which discharges varied from approximately 2.0 to 3,000 cubic feet per second, and channel conditions varied from deposition to scour.

1/Numbers refer to references in the Bibliography.

In the data analyzed in the previous studies, it was noticed that in several tests considerable unexplained deviation from expected values of critical boundary shear occurred. Due to lack of complete control of variable factors during the field tests, it was usually difficult to explain these deviations. The tests herein described were devised to investigate some of the possible reasons for these deviations. The tests were conducted in a recirculating flume, Figure 1, and conditions, such as soil density, moisture content at time of compaction, the temperature of flume water, and forces acting on the soil, could be fairly well controlled.

A calibration curve was established for the flume so that the average boundary shear acting on the sample area could be determined for any test discharge. Following the calibration, a standard test procedure was developed and two soil materials which appeared to have relatively uniform properties and were readily available in large quantities, were selected for testing. Tests were then conducted to determine the effect of water temperature changes, soil moisture content, and soil density on the critical boundary shear.

EQUIPMENT

Description of Flume

The flume used, Figure 1, was 8 feet (2.44 meters) long, 2 feet (0.61 meters) wide, and 4 inches (10.16 cm) high. It contained a tailbox 9 feet (2.74 meters) square and 5 feet (1.52 meters) high, and a headbox 6 feet 6 inches by 5 feet (1.98 by 1.52 meters) which was 7 feet (2.13 meters) high. A pump located in the tailbox circulated water through the model. Discharge was measured by a Venturi meter in the recirculating system. Tailwater was held constant by allowing a small continual overflow from a weir. Water for the overflow was provided from the city water supply. The elevation of water in the headbox varied with the discharge set in the model.

Calibration of Flume

To determine the force per unit area exerted on the boundary by water flowing over the sample area two methods were used. In the first method, the boundary shear was determined from the velocity gradient above the leading edge of the sample in the following manner: It is generally well accepted that where flow is developed the velocity at a distance y from the boundary may be explained by a formula of the type:

$$U_y = \sqrt{\frac{T_o}{P}}\, C \log \frac{(C_1 y)}{(\Delta)}$$

where:

U_y = the velocity at the point y
T_o = the boundary shear
P = density
C, C_1 and Δ are constants
y = the distance from the boundary

Using this formula and subtracting the velocity at one point from the velocity at a lower point i.e., $Y_2 > Y_1$ results in:

$$U_{y_2} - U_{y_1} = \sqrt{\frac{T_o}{P}}\, C \left[\log \frac{C_1\, Y_2}{\Delta} - \log \frac{C_1\, Y_1}{\Delta}\right]$$

and defining C_2 as

$$C_2 = \frac{P}{\left[C \log \frac{Y_2}{Y_1}\right]^2}$$

results in:

$$T_o = C_2 \left(U_{y_2} - U_{y_1}\right)^2$$

Thus by determining the velocities at two points above the boundary, a value of boundary shear may be determined. In this method the boundary shear is dependent on the velocity gradient, and it is therefore important to establish this gradient with as much accuracy as possible.

Simply accepting velocities measured at two fixed points above the boundary would, of course, be the simple way to solve the preceding equation. However, with this type approach, either point being in error would subject the final calculations to considerable error. To more satisfactorily define the velocity gradient, a pitot tube bank, Figures 2 and 3(a), was used. This bank indicated four velocity values simultaneously and could be raised in small increments to obtain additional data where desired.

To establish more accurately the velocity head when velocities were small, a sloping manometer board was used, Figure 3(b). The slope of this board could be readily adjusted so that fairly large deflections in the manometer tubes could be obtained for the velocity range of interest.

Velocities were obtained from the deflections on the manometer board by:

$$U_y = G\sqrt{d}$$

where:

G = a constant which depends on the slope of the manometer board and contains the square root of the gravitational acceleration

d = the deflection along the manometer board

Velocities obtained from this formula were plotted as a function of the distance from the boundary and a curve fitted to them. The velocity gradient of the fitted curve was used to obtain the resulting boundary shear. This procedure was followed for numerous discharges and the resulting calibration curve, which shows the boundary shear as related to the discharge set in the flume, is shown on Figure 4 as the dashed-line curve.

To check this curve, a number of uniform noncohesive sands were obtained and tested in the flume. These were uniform sands with size ranges as shown in Table 1. The sands were placed in the sample container and the discharge in the flume was increased until general movement of the sand occurred. The boundary shear which created this movement1/, 4/, 8/ was computed from:

$$T_o = 70\ D$$

where:

T_o = boundary shear in gms per square meter

D = diameter of particle in mm

Note: (The formula is $T_o = 0.0143D$ if the boundary shear in pounds per square foot is desired.)

The resulting curve obtained from these data is shown on Figure 4 as the solid line.

It may be noticed that at larger discharges, there is disagreement in the boundary shears obtained from the two methods. As precedence had been established from determining tractive forces necessary to move noncohesive materials1/, 4/, 8/, 10/, 11/ and as only relative results were desired for this study, the solid-line curve obtained from the relation, $T_o = 70D$, was used for the final calibration curve.

Test Procedure

Test procedures were based primarily on experience gained from preliminary tests. Some changes in procedures were made during the preliminary tests and the method which evolved was as follows:

Samples were prepared for flume tests in the following manner. The soil was raised to the desired moisture content by adding a calculated volume of water to the dry soil. The sample was then mixed thoroughly and the amount of soil which would result in the density desired for a given soil volume in the sample container was carefully weighed. The sample container was placed on a compacting unit, Figure 5, and the soil was placed in the container and distributed evenly. The container bottom was next placed over the soil and the sample was compacted to the desired density by applying pressure with the jack unit. Bottom stops were placed on the container bottom, Figure 6, to hold the sample in place.

After compacting, samples were thoroughly saturated by submergence in water for a minimum of 48 hours to simulate the condition which would occur in an operating canal or lateral. After being saturated, the sample surface was smoothed off as nearly as possible in the same manner for each test, to the top elevation of the sample container.

Measurements on the sample surface were then taken with an erosion gage, Figure 7. The erosion gage consisted essentially of a level bubble, a movable point gage with vernier control, supports for the point gage and three adjustable legs. To obtain standard measurements with the gage, a template was placed over the sample and measurements of the distance to the sample surface were taken through holes in the template. The template was merely a device to help eliminate bias in selecting points for determining surface elevations. Readings taken with this erosion gage before or after a test were averaged to obtain an average elevation of the sample surface.

The difference between the before and after readings were used to determine the amount of erosion which had occurred during a test. After preparing the sample in the preceding manner, it was secured in place in the boundary shear flume and the flume was filled with water to the desired elevation. The desired tailwater elevation was maintained in the model by allowing a small overflow discharge from an especially designed weir set at a desired elevation. After filling the flume, the pump was started and a small recirculating discharge set. After an operation period of 5 minutes, the discharge was gradually increased by a small increment and the surface of the sample was observed. This procedure was repeated until the sample lost its capacity to maintain its stability and erosion started to occur. The value of the discharge at the point where erosion of the sample started (incipient erosion), determined the critical boundary shear which was acting on the sample. After the critical boundary shear was reached, the model was operated for 1 hour; the model was then turned off, drained, and the sample removed. Excess water was sponged from the sample surface, and erosion measurements were made with the erosion gage and template. Photographs were taken of the final erosion. Other data recorded included time, tailwater elevation, temperature, discharge, comments, and observations.

TESTS CONDUCTED

Tests to Determine Effect of Discharge Time Increment

To determine the effect of changing the time increments (used in raising the discharge) on the critical boundary shear, the following tests were conducted. Three samples were prepared from the same soil sample, in the same manner, and were each tested in the flume. Tests were similar except for the time increment used in raising the discharge. In the first tests, the discharge was increased by a standard increment every 2 minutes; in the second test, every 4 minutes; and in the third test, every 6 minutes. Results of the tests are shown in Figure 8; it is apparent that the rate of raising the discharge by these time increments had little effect on the critical boundary shear.

Tests to Determine the Effect of Temperature Changes

As the flume contained its own recirculating system, some heat was added to the water during a test. This resulted in a slight rise in the temperature of the flowing water. This rise in temperature was approximately 1° to 2° C for a test. Some concern was felt regarding the effect of this temperature rise on the critical boundary shear. To determine the effect of temperature changes in the flume water on a soil (22L-1), Figure 9, three soil samples were prepared in the same manner from the same batch of material. Density and moisture content were held constant and tests were conducted on each sample in which the temperature of circulated water was changed for each test. The temperature of the water was raised to the desired values and maintained by an independent source of water supply.

For the three tests, temperatures were maintained near 18.2°, 27°, and 32° C. Figure 10 shows the results of the tests. The tests indicated that a rise in the temperature of the water required a small increase in discharge to produce critical boundary shear. For this soil, the rate of apparent increase in boundary shear was approximately 0.0036 pounds per square foot per degree Centigrade.

This rate of change indicated little effect from temperature changes of the magnitude of 1 to 2°.

Effect of Moisture Content at Which Soil is Compacted

To investigate the effect of water content at which a soil is compacted on the soils ability to resist erosion, several samples of Soil 22L-1 were compacted to 90 percent of the maximum density using different water contents. The water content varied from 3 to 35 percent of dry weight. Following compaction, the samples were then completely submerged in water at 15° C for 48 hours. After 48 hours of soaking, the amount of swelling of a given soil appears to be a function of the moisture content at which the soil was compacted, Figures 11 and 12. As the moisture content at which the soil is compacted increases, the amount of swelling decreases.

After making measurements of the swelling, the samples were subjected to the erosion tests as previously discussed. Results of these tests are presented in Figures 13 and 14. They indicate that, for the soil tested, as the moisture content at which the soils are compacted increases, the soils resistance to erosion increases. In other words, the critical tractive force necessary to erode the soil increases and the rate of erosion, after the critical tractive force has been reached, decreases.

Effect of Density at Which Soil is Compacted

A number of tests were conducted to determine the effect of the density of a soil on its resistance to erosion. The results of these tests are difficult to explain. For instance, when Soil 22L-1 was first used, results indicated that as the density increased, the soil became more resistive to erosion, Figure 15. However, when the soil was salvaged for re-use, dried, brought up to optimum moisture content, and recompacted to various percent maximum densities, it appeared to become less resistant to erosion as the density increased, Figure 15. It should be noted that all soils were compacted at optimum moisture content.

After these results were observed, another soil was obtained (24G-103), Figure 16. Several samples of this soil were compacted to various densities at optimum moisture content. As shown in Figure 15, results indicated that the soil became more resistive to erosion as the density increased. Time was not available to conduct re-use tests on this soil.

DISCUSSION OF TESTS

Although soil compaction and flume tests were well controlled and what appeared to be significant data trends were readily established, some scatter in data was evident. Scatter is, in part, due to the large number of variables involved, and indicates that a statistical analysis of a large number of data sets would be desirable in analyzing these types of data. Large data sets were difficult to obtain because of the length of time involved in preparing a sample and conducting a test. Time available limited the number of tests and the number of variables which could be investigated.

Consideration should be given to continued research on this project, but with a small model (perhaps of plastic) utilizing small samples which can be prepared rapidly. A model of this type would allow several tests with several variables to be conducted in a relatively short time. A small unit which was used to test unsaturated soils has been discussed by Grissinger7/, and a small testing apparatus was used by Moore and Masch13/ to collect data on scour experiments. Information presented in these two references would be of some aid in designing an apparatus to allow large data sets to be taken.

Some of the data scatter may be explained by internal structure and components of the soil as suggested by Grissinger7/. Petrographic analyses of soils should be included in future studies. If enough time is available to study several soils, petrographic analysis may be of particular value in explaining results.

On some samples, the selection of a critical point was not difficult as erosion started quite suddenly. On other samples, the selection of a critical point was difficult and different observers may identify different boundary shears as the critical point. This difficulty in establishing a critical point was, no doubt, the reason for some data scatter. In continued tests of this type, thought should be given to using other measures to help define the effect of the boundary shear. For instance, if small samples are used, the loss of weight due to a given discharge may be an easily measured quantity which would be significant.

In future tests, attempts should be made to find some simple test to correlate a soil with its critical boundary shear. One test that could be checked is the dispersion ratio discussed by Middleton12/, Flaxman3/, and Smerdon and Beasley16/. It may also be of some value to utilize one of the small motor-driven shear machines now on the market which may be an improvement over those used by Dunn2/, Simons14/, and the Bureau 10/.

Shearing the tops of the samples to place the sample surface in the floor plane should also be eliminated in additional tests. As channel beds are not sheared before or during operation, this creates an unnatural surface condition.

This series of tests indicates why some of the scatter in previous tests resulted and indicates the desirability of additional tests and desirable changes in test procedure.

ACKNOWLEDGMENTS

Hydraulic model studies herein reported were conducted in the Hydraulics Branch, Division of Research, Bureau of Reclamation, Denver, Colorado, during the first half of 1963. The study was conducted by P. F. Enger under the supervision of E. J. Carlson, Head of Sediment Investigations in the Special Investigations Section, Hydraulics Branch. A. J. Peterka is head of the Special Investigations Section and H. M. Martin is Chief of the Hydraulics Branch. Data were primarily collected by Mr. Ralph Baumer, an engineer trainee, and Mr. Abel Latif Montaser, a trainee from UAR, Egypt. Mr. Ralph Baumer was especially helpful in organizing data from several tests.

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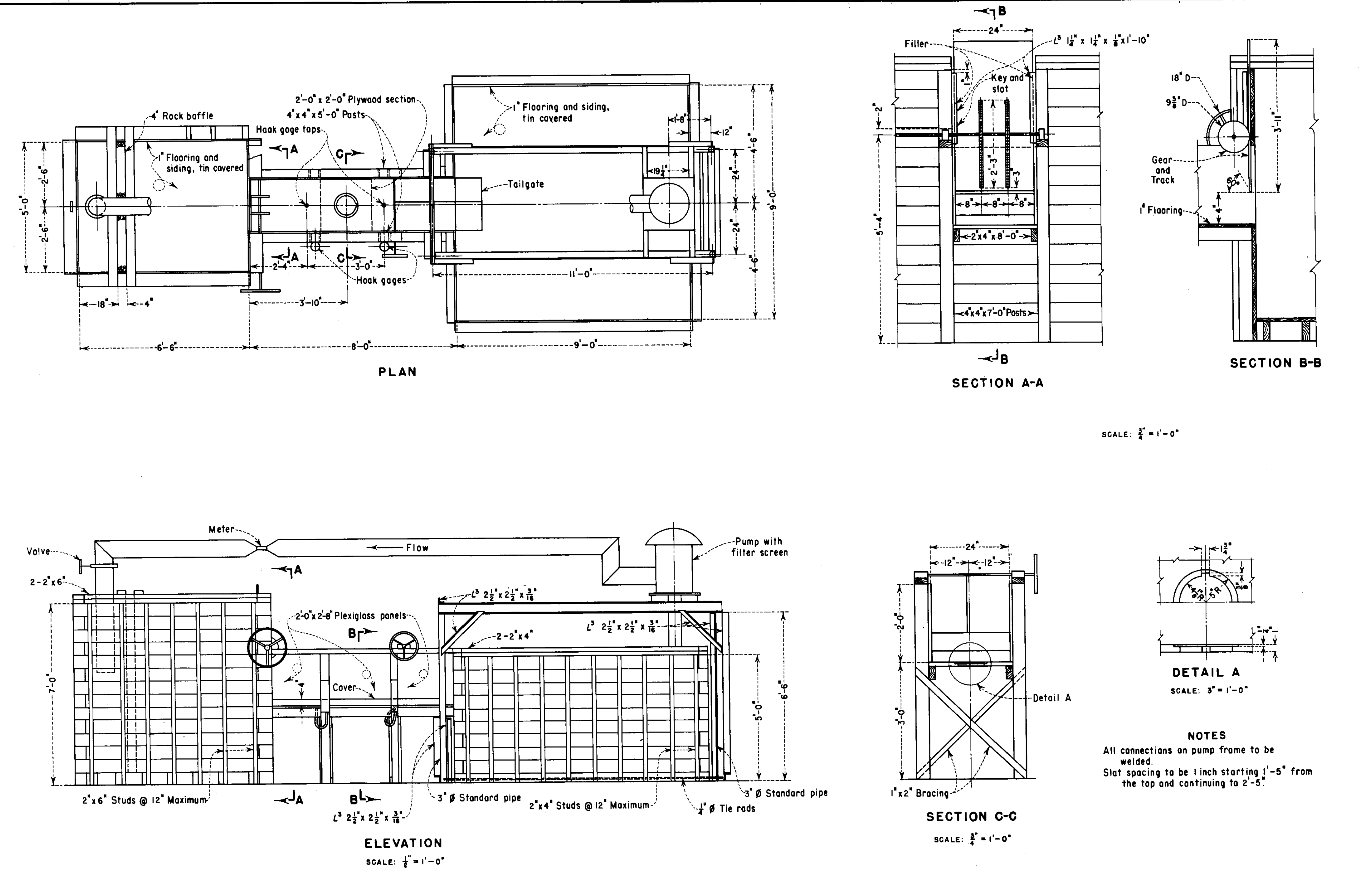
Table 1

SANDS USED FOR CALIBRATION

Sand No.	Size mm
Pan	0.037-0.149
100	0.149-0.3
50	0.3 -0.59
30	0.59 -1.19
16	1.19 -2.38
8	2.38 -4.76
4	4.76 -9.52

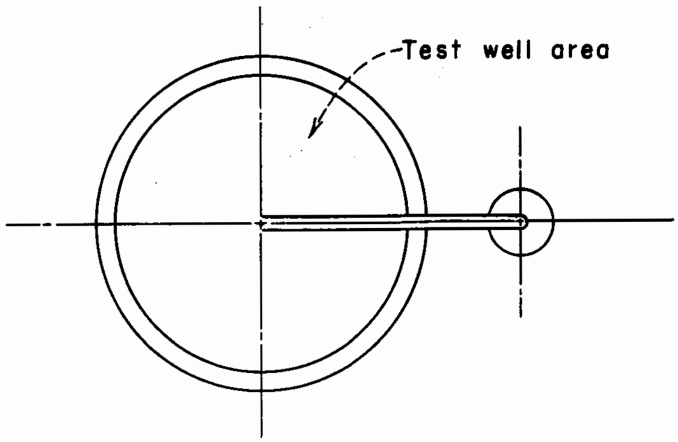
FIGURE 1
REPORT HYD 532



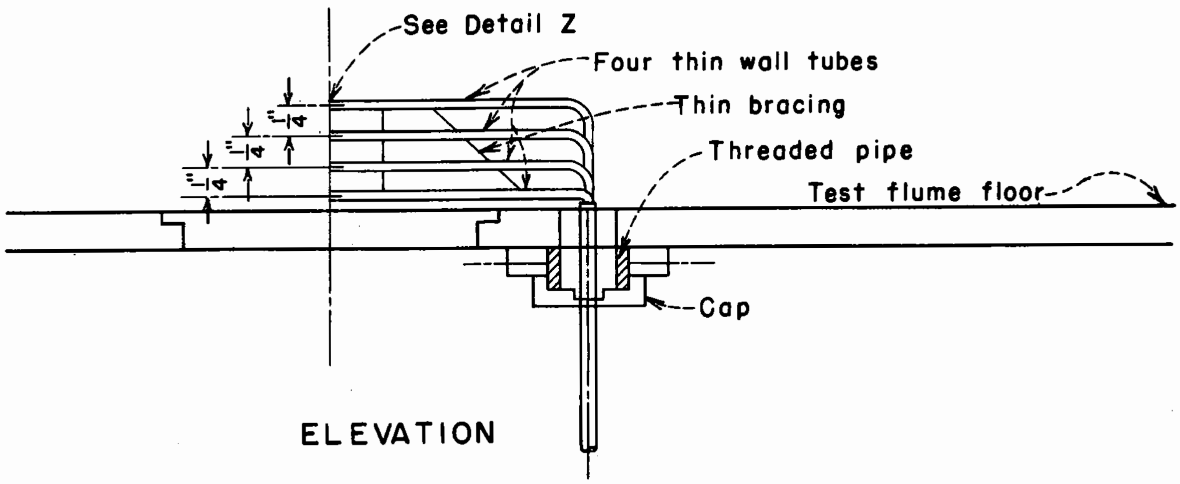
HYDRAULICS BRANCH

MODEL PLAN

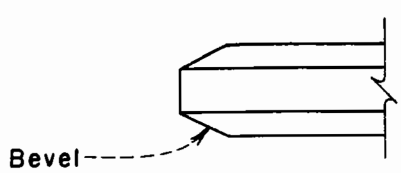
BOUNDARY SHEAR FLUME



PLAN



ELEVATION



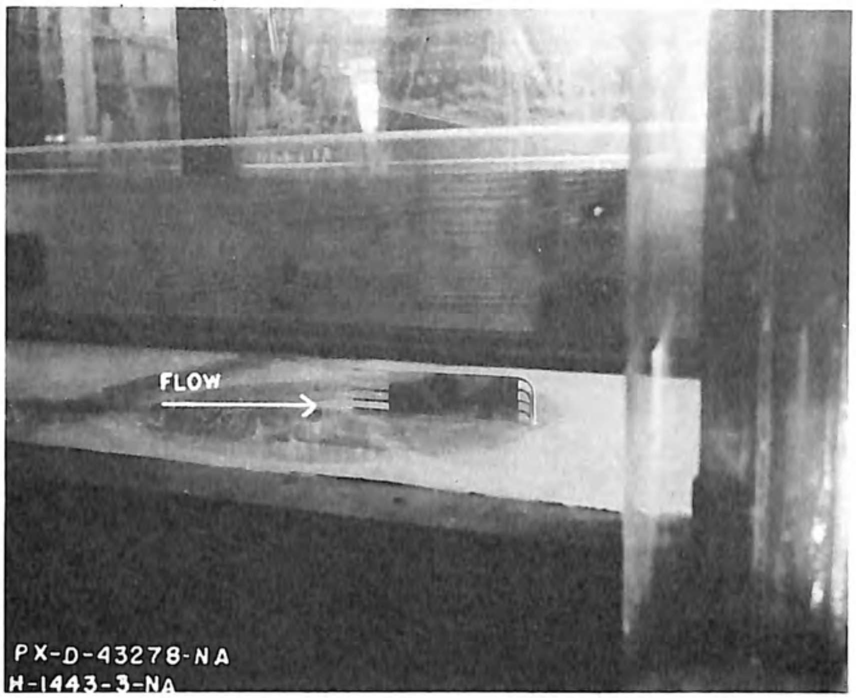
DETAIL Z

HYDRAULICS BRANCH

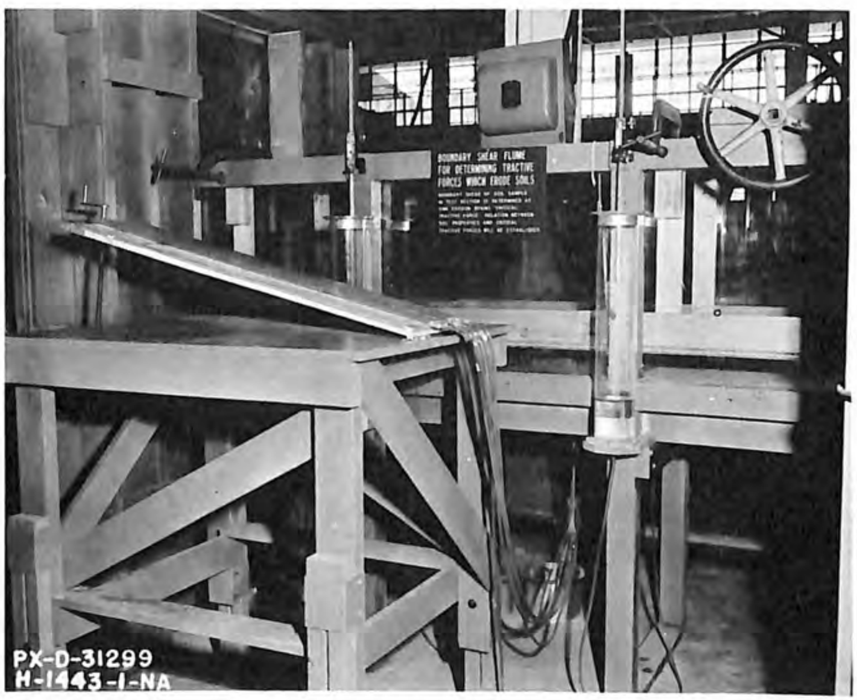
PITOT TUBE BANK

BOUNDARY SHEAR FLUME

Figure 3
Hyd-532

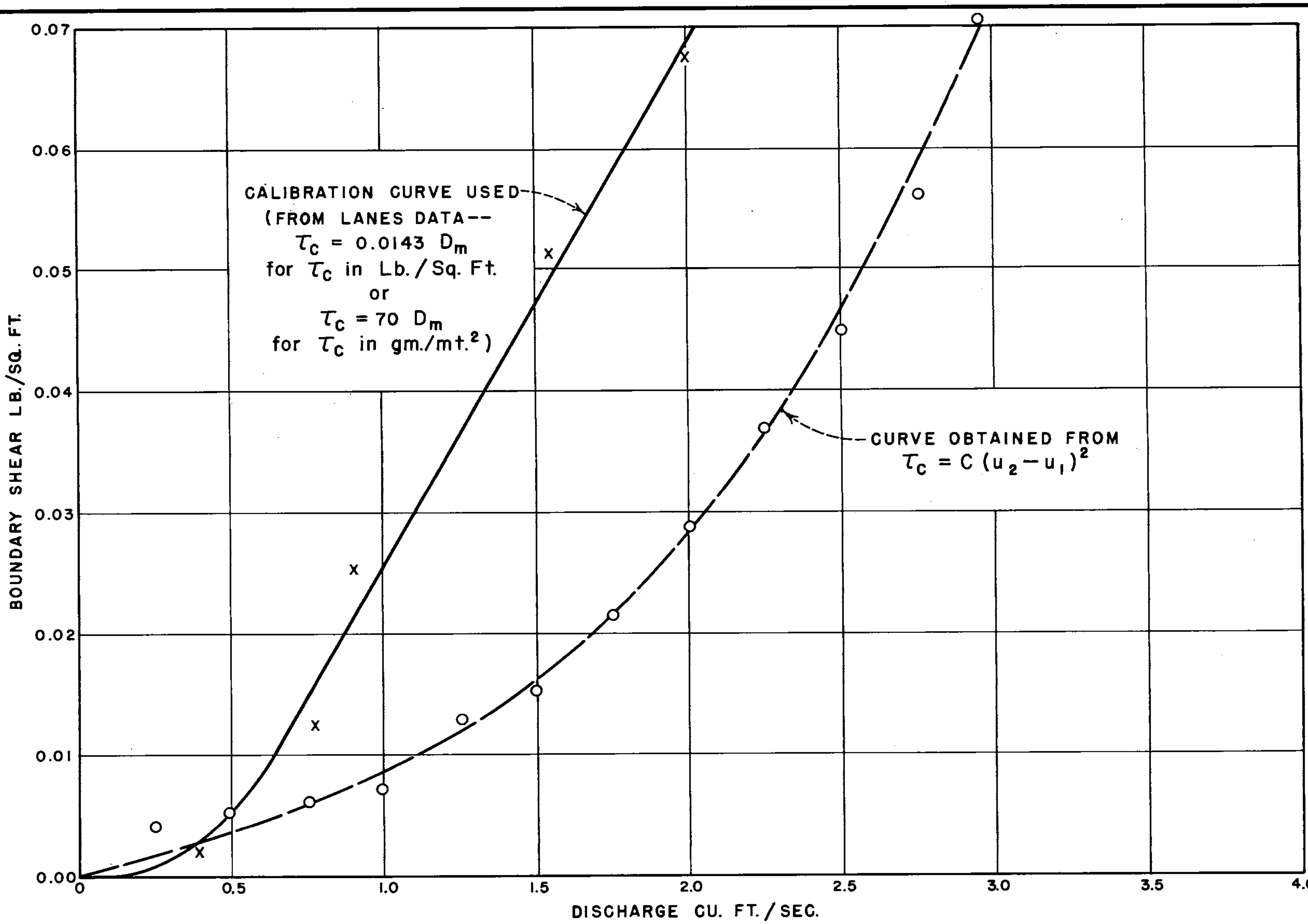


(a) Pitot Bank



(b) Manometer Board

Hydraulics Branch
COMPACTION EQUIPMENT
Boundary Shear Flume

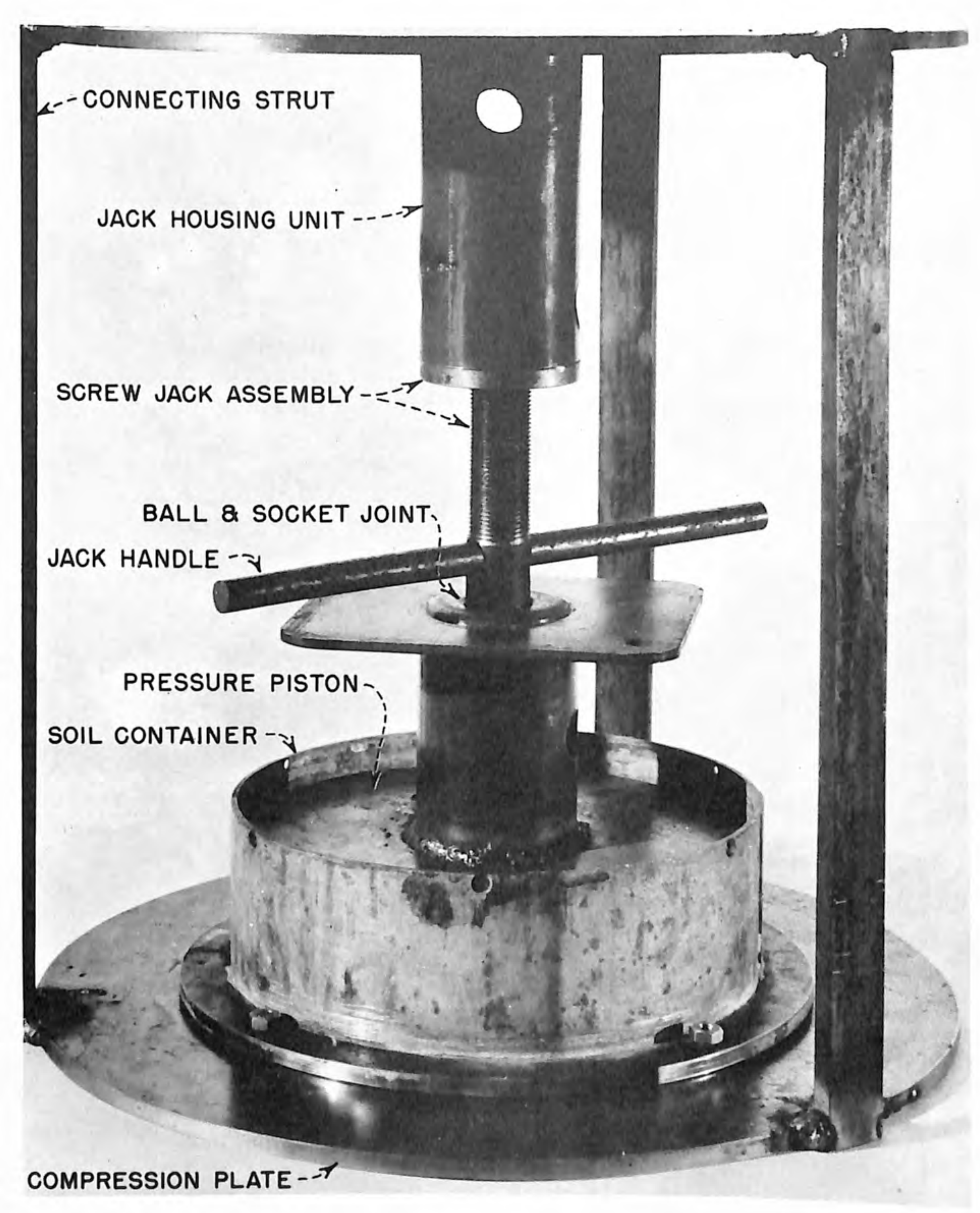


HYDRAULICS BRANCH

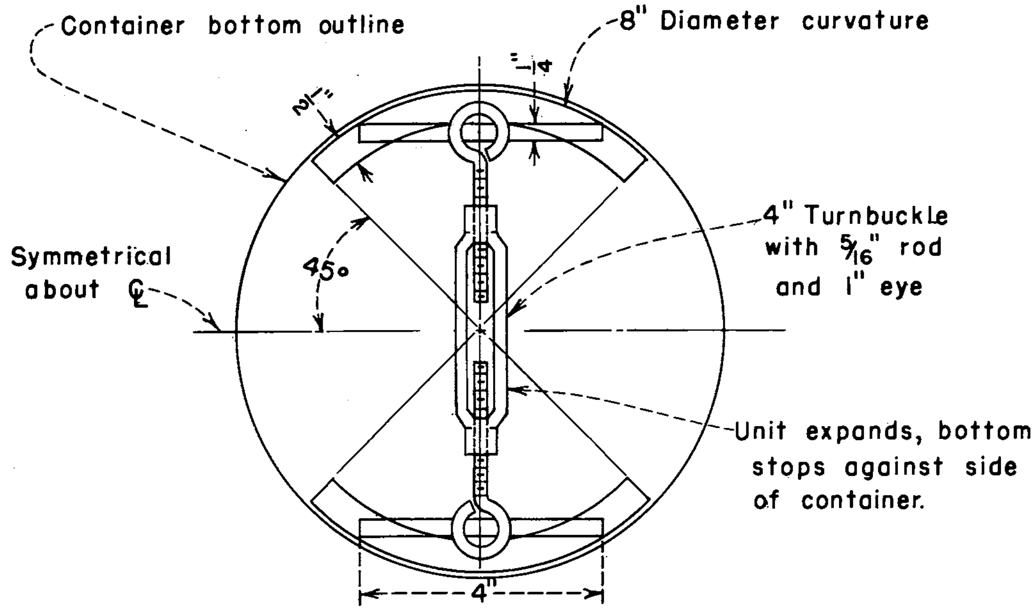
CALIBRATION CURVE

BOUNDARY SHEAR FLUME

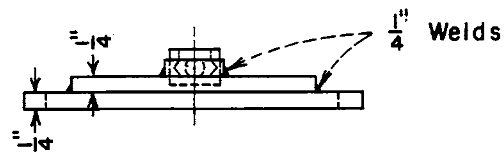
Figure 5
Hyd-532



Hydraulics Branch
CALIBRATION EQUIPMENT
Boundary Shear Flume



PLAN



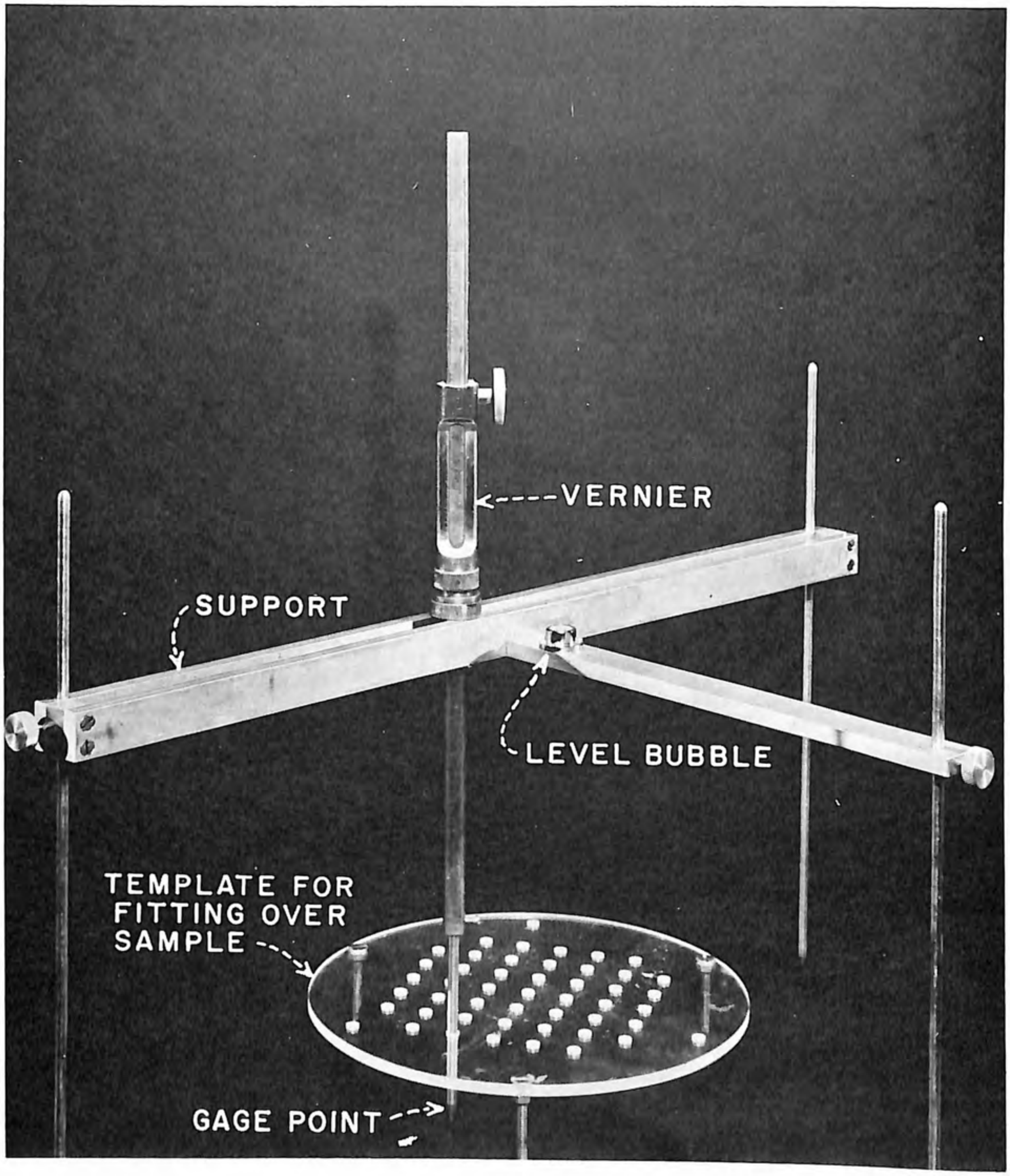
ELEVATION OF BOTTOM STOP

SCALE: 1/3 ACTUAL SIZE

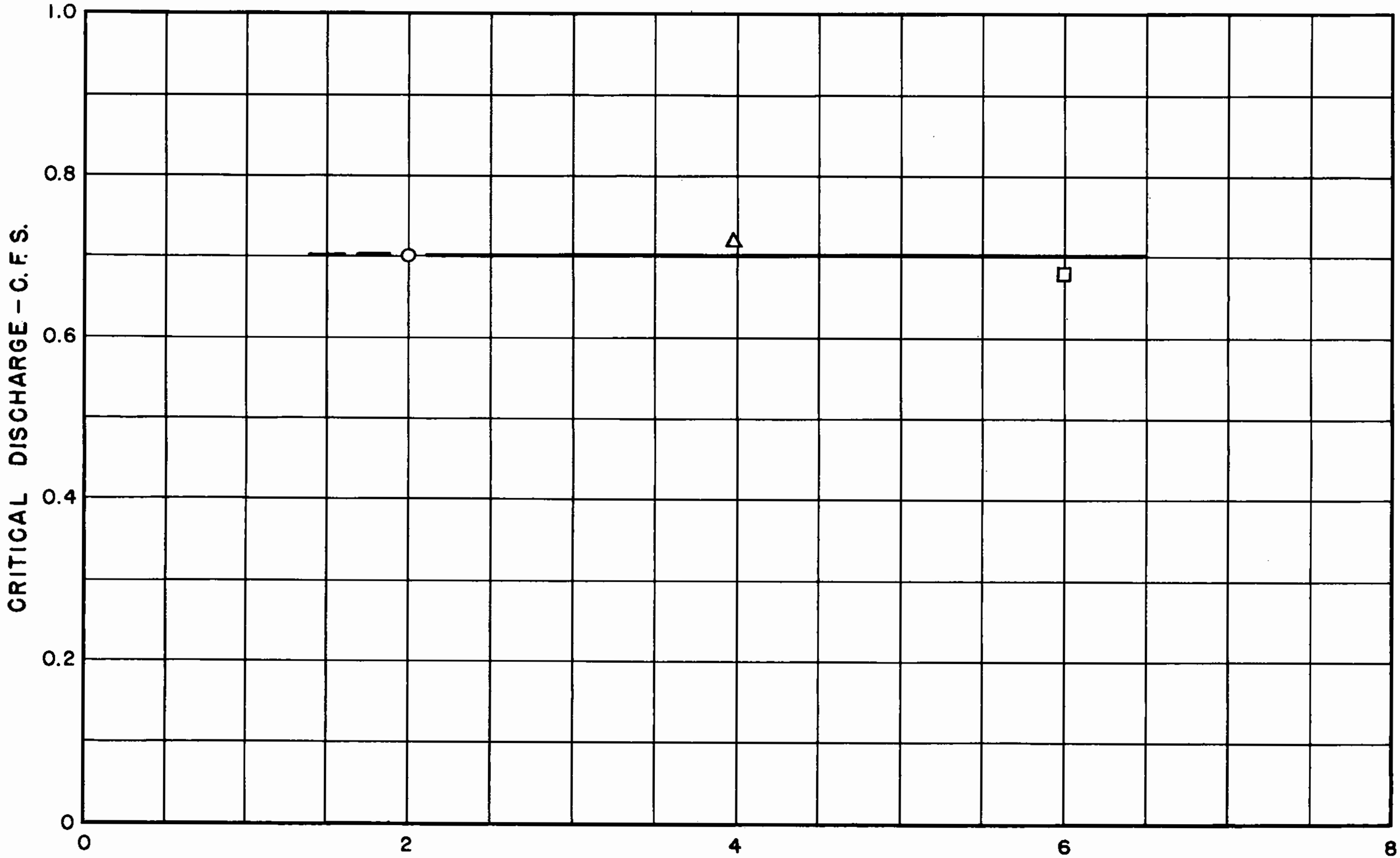
HYDRAULICS BRANCH

CONTAINER BOTTOM STOP

BOUNDARY SHEAR FLUME



Hydraulics Branch
EROSION GAGE
Boundary Shear Flume



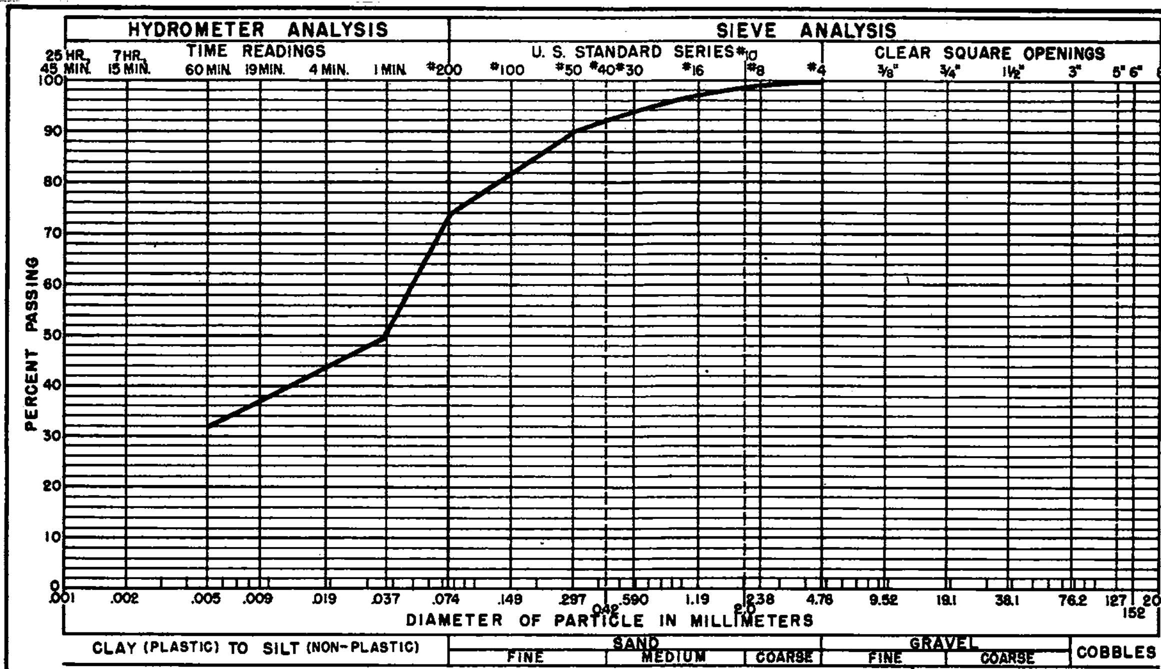
HYDRAULICS BRANCH

EFFECT OF CHANGING DISCHARGE TIME INCREMENT ON ONE SOIL

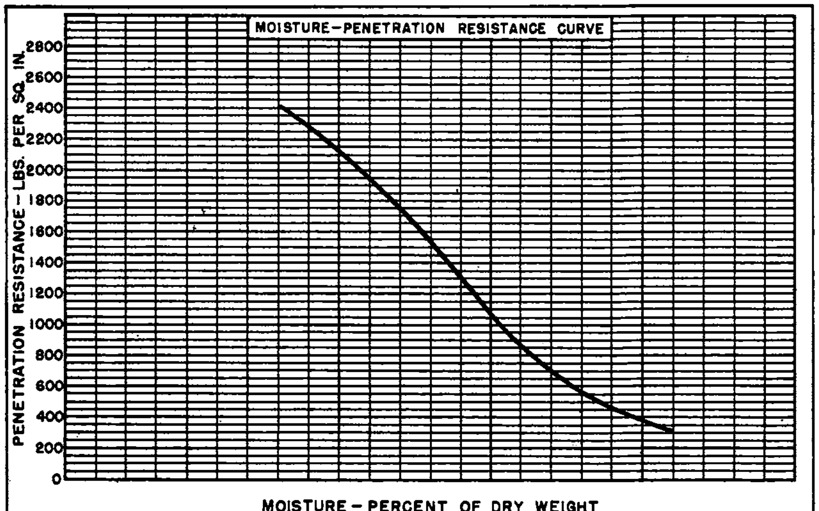
BOUNDARY SHEAR FLUME

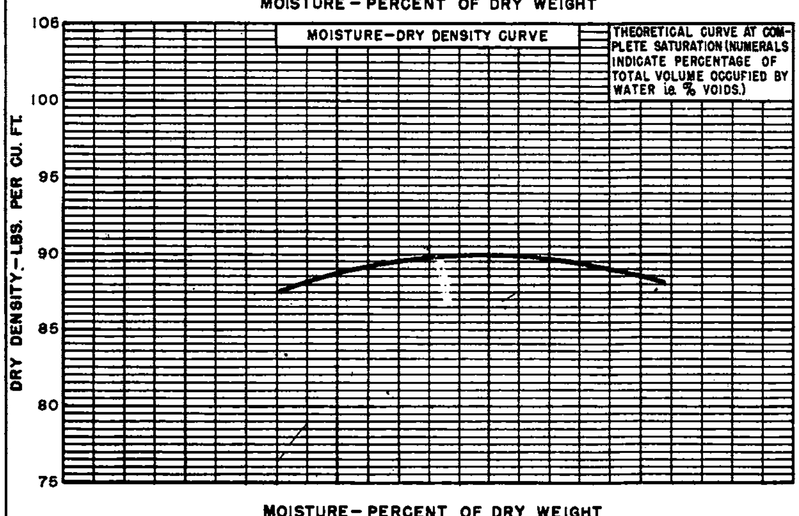
FIGURE 8
REPORT HYD 532

FIGURE 9
REPORT HYD 532



GRAVEL.............. ___ %
SAND................ ___ %
SILT TO CLAY...... ___ %





COMPACTION-PENETRATION RESISTANCE CURVES

STANDARD PROPERTIES SUMMARY

CLASSIFICATION SYMBOL ________

SPECIFIC GRAVITY ________

ATTERBERG LIMITS

LIQUID LIMIT ________

PLASTICITY INDEX ________

SHRINKAGE LIMIT ________

COMPACTION

% LARGER THAN TESTED ________

MAX. DRY DENSITY (P.C.F.) ________

OPTIMUM MOIST. CONT. (%) ________

PENETRATION RESIST. (P.S.I.) ________

PERCOLATION SETTLEMENT

PLACEMENT CONDITION ________

PERMEABILITY (FT./YR.) ________

SETTLEMENT (%) UNDER

____ P.S.I. LOAD ________

NOTES:

HYDRAULICS BRANCH

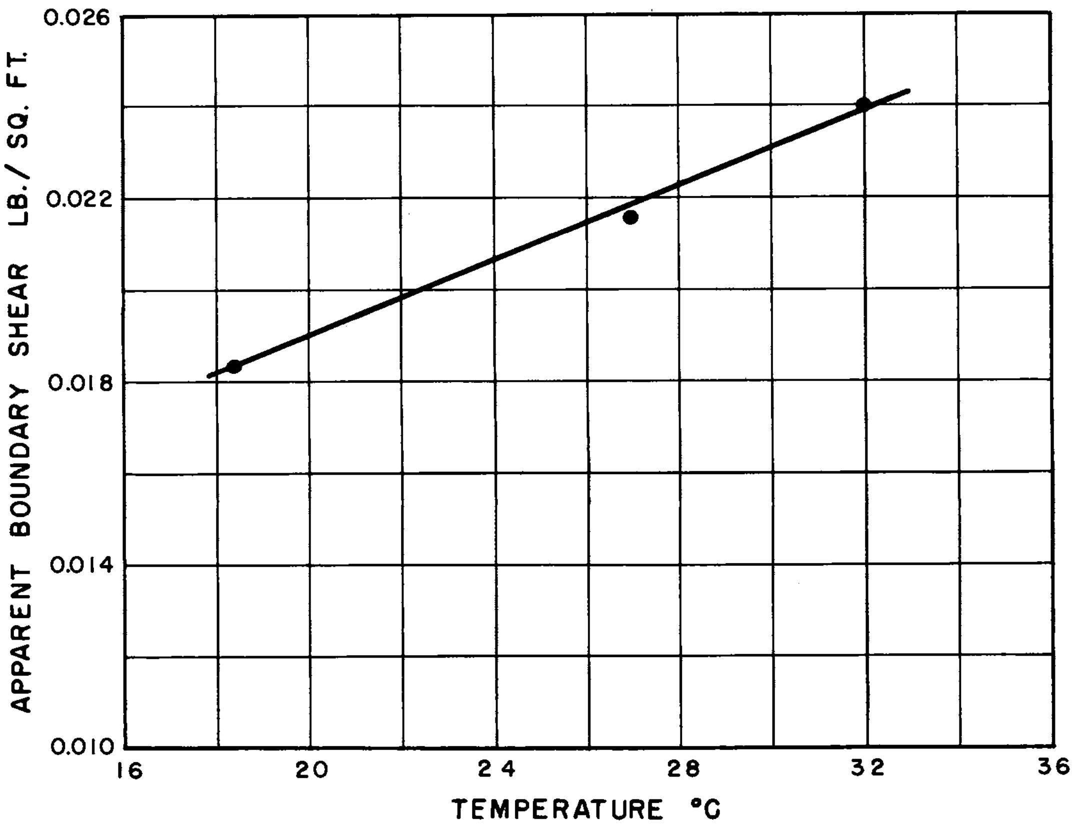
SOIL PROPERTIES

22L-1

BOUNDARY SHEAR FLUME

LABORATORY SAMPLE No. 22L-1 FIELD DESIGNATION ________ EXCAVATION No. ________ DEPTH ________ FT.

FIGURE NO.



HYDRAULICS BRANCH

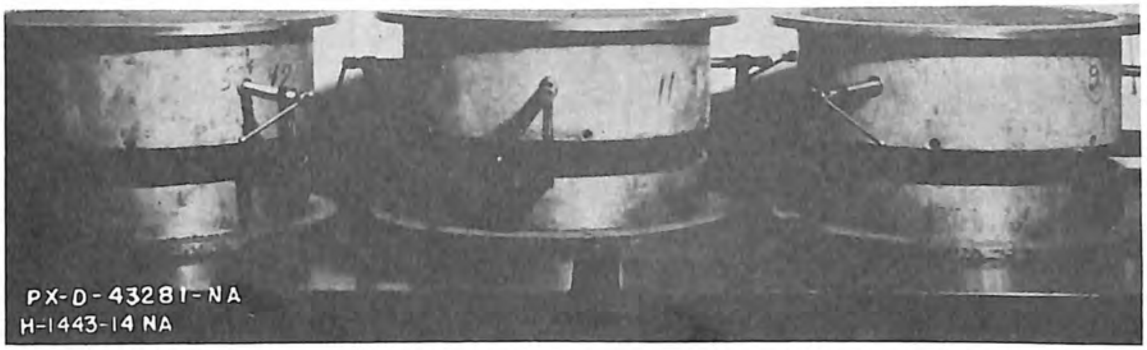
EFFECT OF TEMPERATURE ON CRITICAL BOUNDARY SHEAR FOR SOIL 22L-1

BOUNDARY SHEAR FLUME

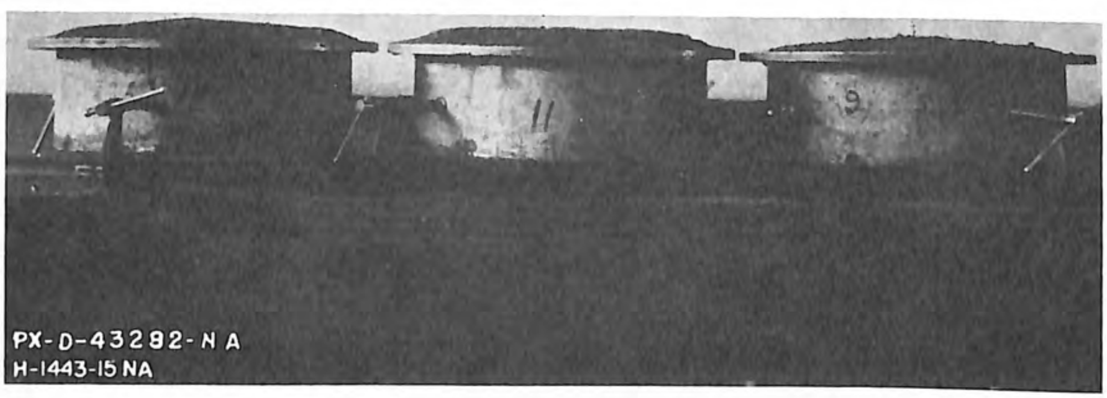
FIGURE 10
REPORT HYD 532

Percent Water Content at Time of Compaction

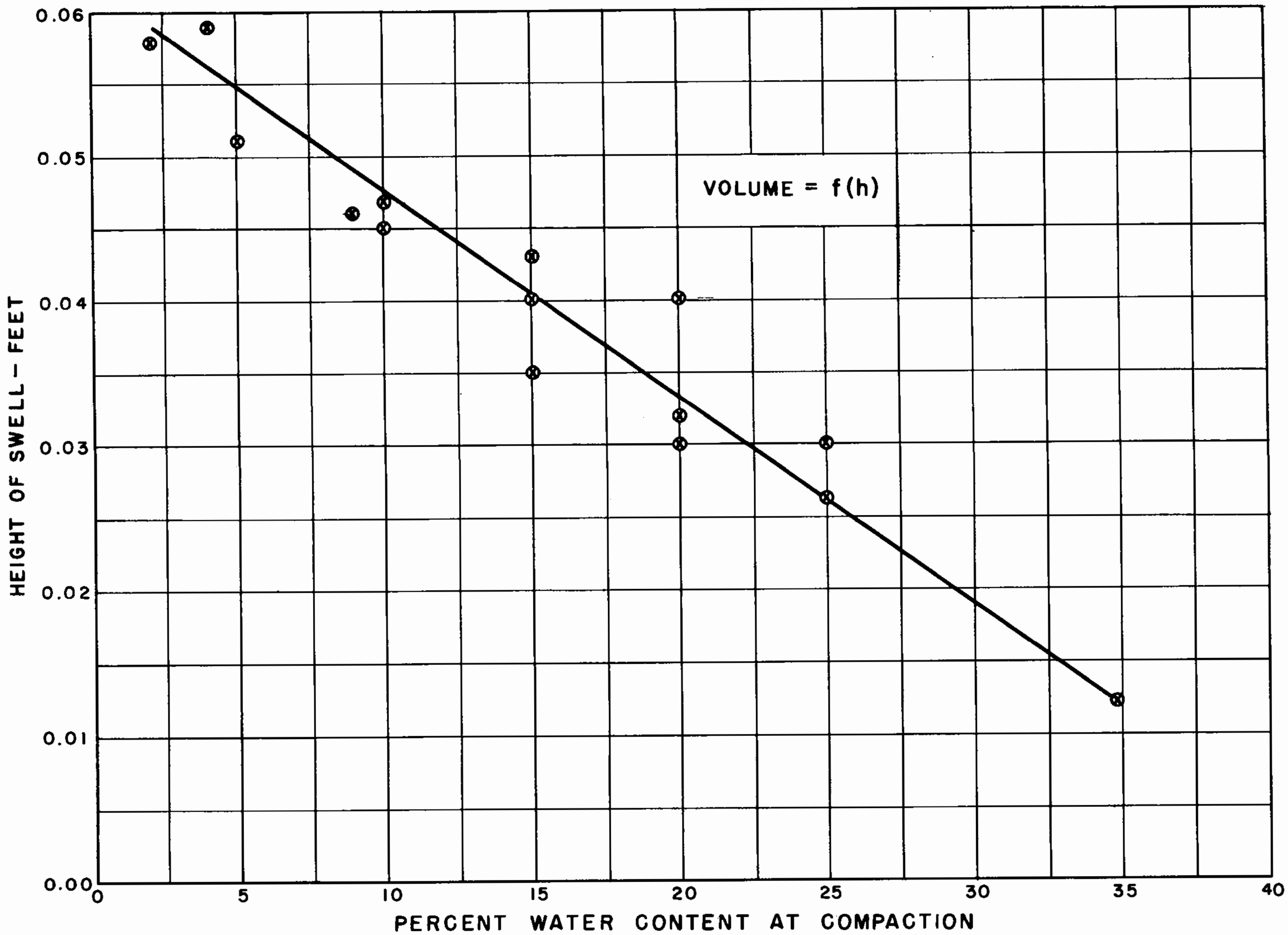
6.8 ↓ 15 ↓ 25 ↓



(a) Before saturation



Hydraulics Branch
EFFECT OF WATER CONTENT ON SWELL
Boundary Shear Flume

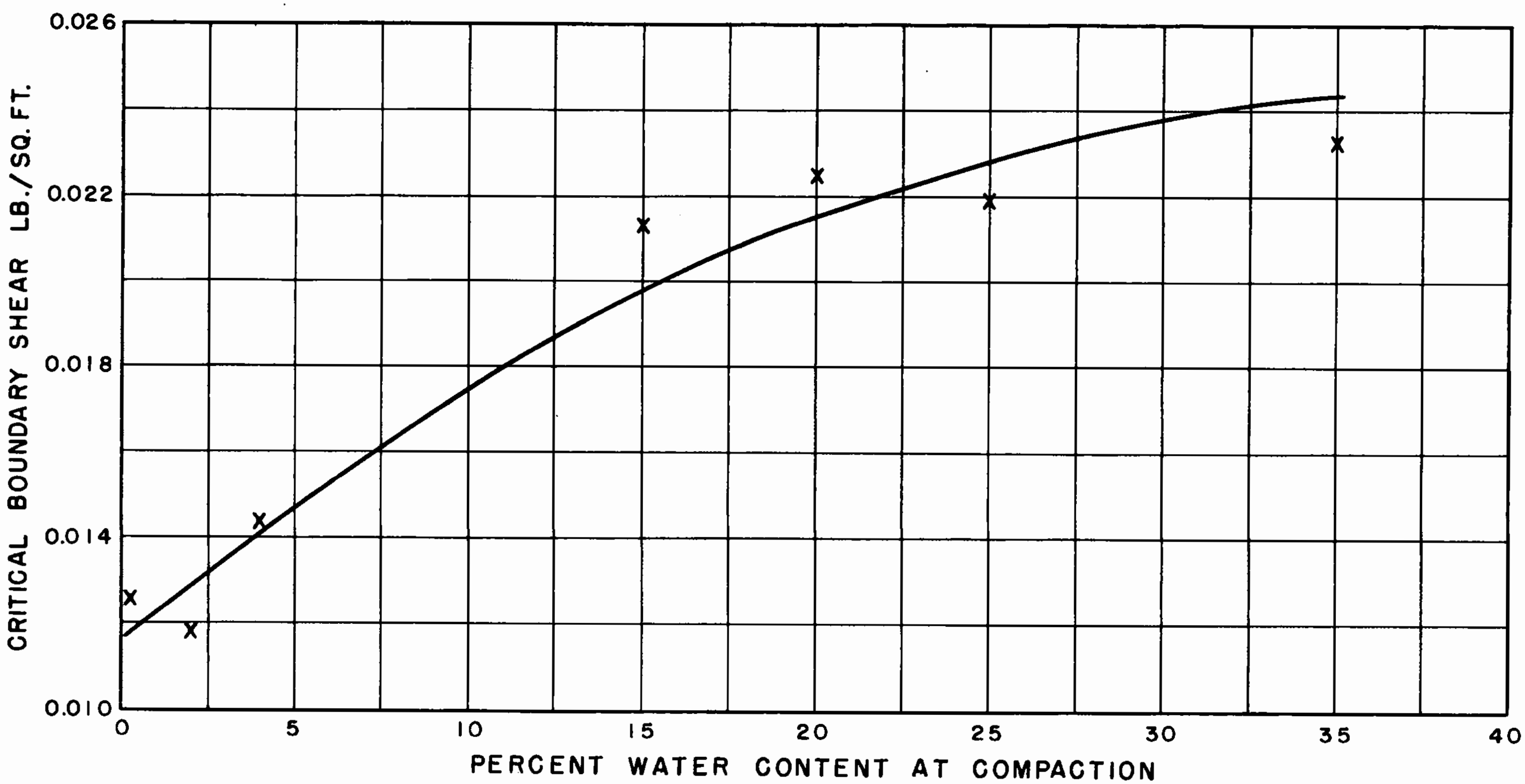


HYDRAULICS BRANCH

SOIL SWELL vs. WATER CONTENT FOR SOIL 22L-1

BOUNDARY SHEAR FLUME

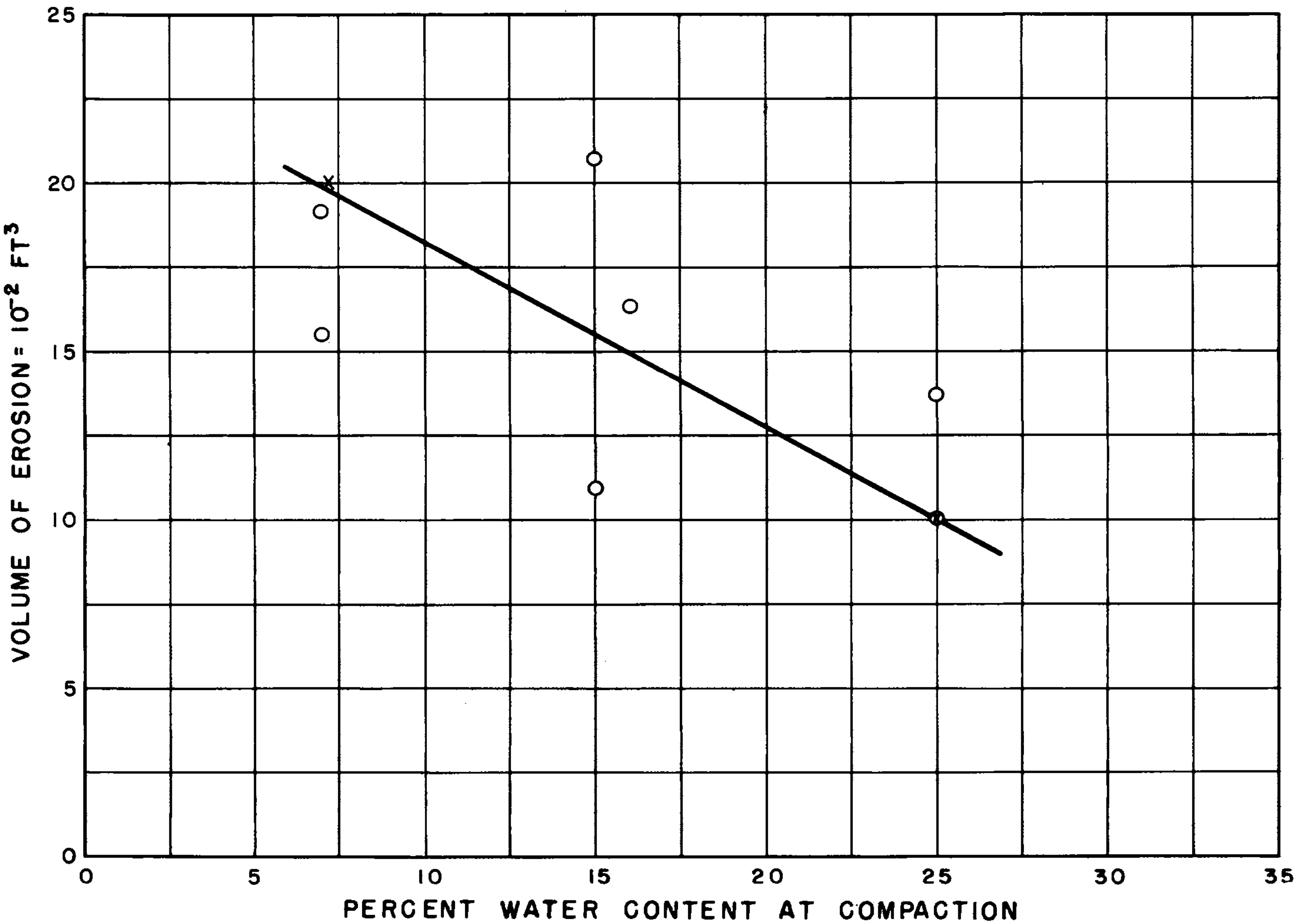
FIGURE 12
REPORT HYD 532



HYDRAULICS BRANCH

EFFECT OF WATER CONTENT
ON CRITICAL SHEAR
FOR SOIL 22L-1

BOUNDARY SHEAR FLUME



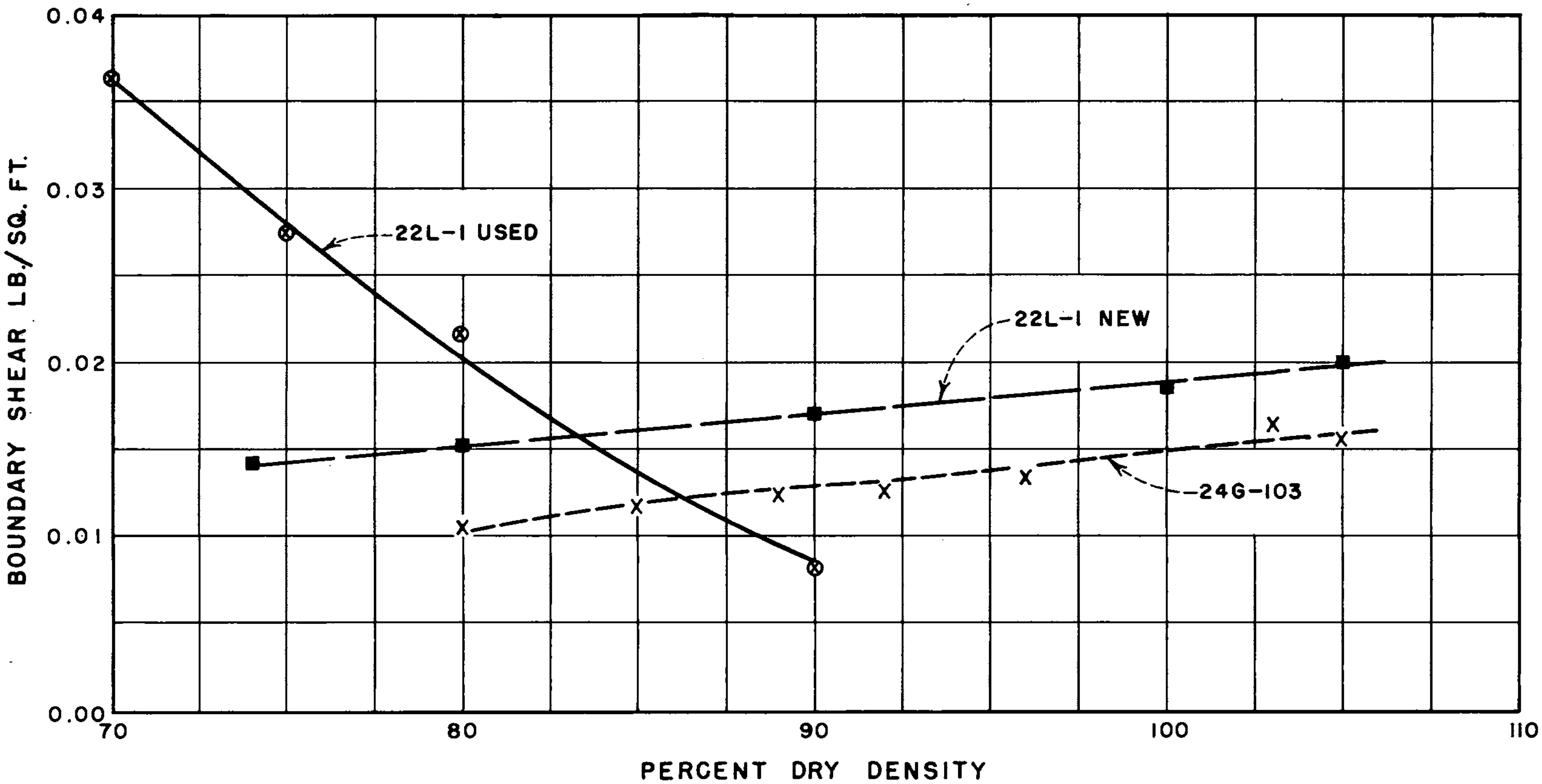
HYDRAULICS BRANCH

EFFECT OF WATER CONTENT ON EROSSION FOR SOIL 22L-1

BOUNDARY SHEAR FLUME

FIGURE 14
REPORT HYD 532

FIGURE 15
REPORT HYD 532



HYDRAULICS BRANCH

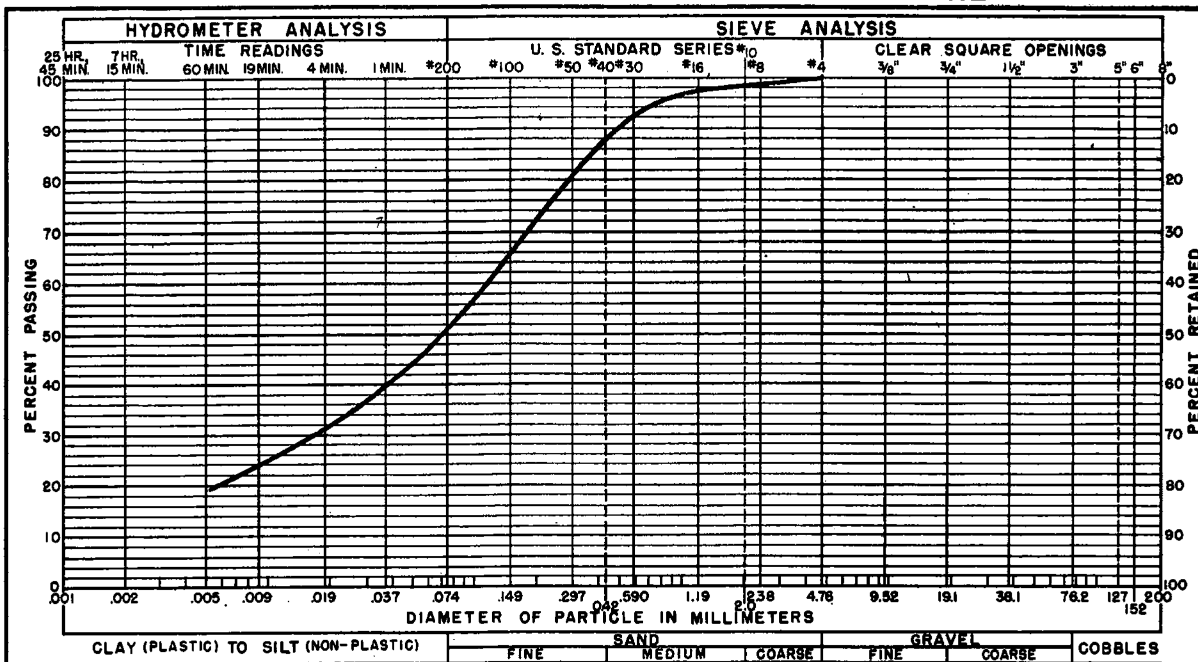
EFFECT OF DENSITY ON BOUNDARY SHEAR

BOUNDARY SHEAR FLUME

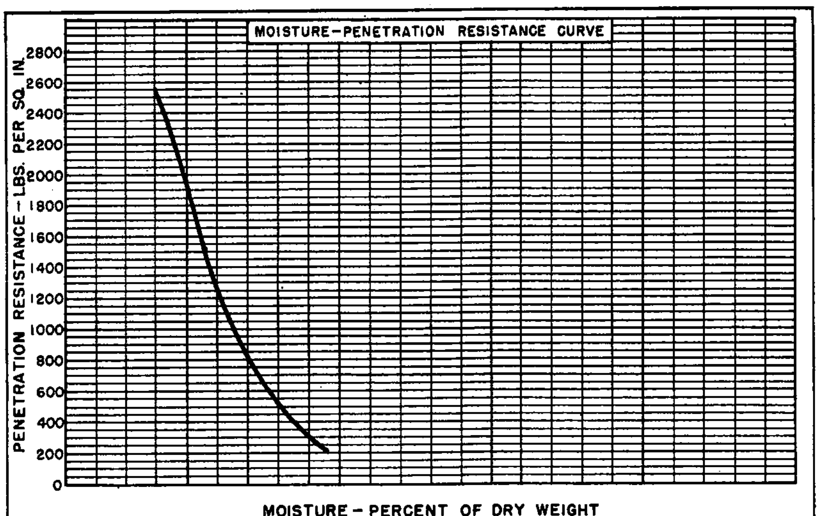
FIGURE 16
REPORT HYD 532

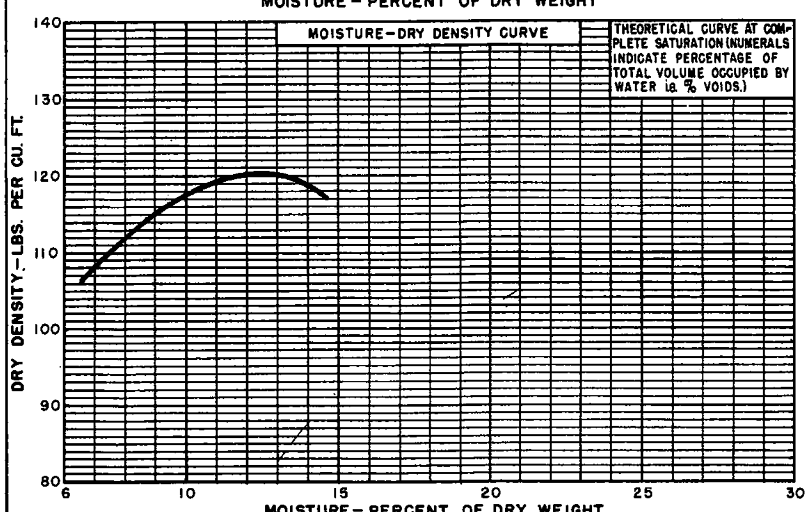
EL-511
(7-58)
BUREAU OF
RECLAMATION

STANDARD PROPERTIES SUMMARY



GRAVEL	0 %
SAND	50 %
SILT TO CLAY	50 %





COMPACTION-PENETRATION RESISTANCE CURVES

STANDARD PROPERTIES SUMMARY

CLASSIFICATION SYMBOL	SC-CL
SPECIFIC GRAVITY	2.66
ATTERBERG LIMITS	
LIQUID LIMIT	23
PLASTICITY INDEX	9
SHRINKAGE LIMIT	
COMPACTION	
% LARGER THAN TESTED	0
MAX. DRY DENSITY (P.C.F.)	120.2
OPTIMUM MOIST. CONT. (%)	12.4
PENETRATION RESIST. (P.S.I.)	640
PERCOLATION SETTLEMENT	
PLACEMENT CONDITION	95%
PERMEABILITY (FT./YR.)	0.5
SETTLEMENT (%) UNDER 20 P.S.I. LOAD	0.3

NOTES:
HYDRAULICS BRANCH
SOIL PROPERTIES
24G-103
BOUNDARY SHEAR FLUME

BUREAU OF LAND MANAGEMENT

LABORATORY SAMPLE No. 24G-103 FIELD DESIGNATION ______ EXCAVATION No. ______ DEPTH ______ FT.

GPO 840-915

FIGURE NO.

ABSTRACT

In recent years, studies have been in progress to establish better design criteria for earth-lined and unlined canals constructed in fine, cohesive soils. To continue these studies a recirculating flume was constructed and tests conducted on several 8-inch-diameter /20.32 cm/ soil samples. Soil density, soil moisture content, and temperature of flowing water in the flume were well controlled. Samples were tested by gradually increasing the boundary shear acting on the sample until shear became critical and the sample began to erode. Tests indicated that the time increment used for increasing the boundary shear on the soil was not critical within the range used and that minor increases in temperature of the flowing water had little effect on the discharge necessary to produce erosion. For the soil tested, the boundary shear required to erode the soil was a function of the moisture content at which the soil was compacted. However, the tests were inconclusive regarding the effect of the soil densities.

17 references are given.

Hyd-532
Enger, Phillip F.
CANAL EROSION AND TRACTIVE FORCE STUDY--ANALYSIS OF DATA TAKEN ON A BOUNDARY SHEAR FLUME, Bureau of Reclamation, Denver, Colorado, February 1964, 12 p, 16 figure, ., 17 reference, 1964.

DESCRIPTORS--*Tractive forces/ erosion/ *erosion control/ movable bed models/ *scour/ sediment control/ sedimentation/ sediments/ stable channels/ soil moisture/ soil compaction/ water/ temperature/ *cohesive soils/ fine-grained soils/ gradation analysis/ boundary shear/ unlined canals/ optimum moisture content/ laboratory tests/ canal design/ earth linings/ velocity/ flumes/ saturation

IDENTIFIERS--Tractive force apparatus/ critical tractive force/ relative soil density

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In recent years, studies have been in progress to establish better design criteria for earth-lined and unlined canals constructed in fine, cohesive soils. To continue these studies a recirculating flume was constructed and tests conducted on several 8-inch-diameter /20.32 cm/ soil samples. Soil density, soil moisture content, and temperature of flowing water in the flume were well controlled. Samples were tested by gradually increasing the boundary shear acting on the sample until shear became critical and the sample began to erode. Tests indicated that the time increment used for increasing the boundary shear on the soil was not critical within the range used and that minor increases in temperature of the flowing water had little effect on the discharge necessary to produce erosion. For the soil tested, the boundary shear required to erode the soil was a function of the moisture content at which the soil was compacted. However, the tests were inconclusive regarding the effect of the soil densities.

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