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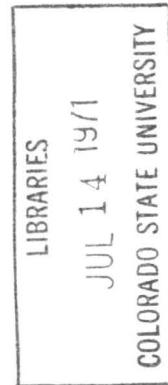
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

PERMEABILITY OF SOILS AT
ELEVATED PERMEANT PRESSURES

(Master of Science Thesis by James P. Bennett
of Colorado State University)

Report No. EM-736

Soils Engineering Branch
DIVISION OF RESEARCH



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DENVER, COLORADO

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PREFACE

Mr. James P. Bennett, a student obtaining his Master of Science degree at Colorado State University, expressed interest in research on Soil Mechanics in the Bureau. With Professor R. D. Dirmeyer, he visited the Soils Engineering Laboratories and discussed our Soils Research Program. A subject of mutual interest to them and the Bureau was soil permeability and its measurement. Plans were made for Mr. Bennett to conduct the laboratory permeability tests described in this report during the Summer of 1965 between regular spring and fall semesters at Colorado State University.

By letter of agreement with the University, arrangements were made for the Bureau to provide the facilities, equipment, and soil for the study without cost to the University. Also provided by the Bureau was the supervisory assistance in outlining and reviewing the general requirements for the program and overseeing Mr. Bennett's work. This was done by Research Engineer John Merriman. Funds for Mr. Bennett's use were provided by the University through a National Science Foundation grant.

Therefore, this study is considered a distinct part of the Bureau's research efforts and mutually beneficial to the University. With the permission of the University, the resulting thesis is being reprinted in this form to provide enough copies for the Bureau's records and future continued study in this subject.

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ABSTRACT

Laboratory studies were made to develop and evaluate test apparatus and procedures for pressurized soil permeability tests. Pressures were applied to headwater and tailwater to reduce the volume of free air in the soil and dissolve the air in the permeant water. Primary objective was to determine feasibility of using the high-pressure permeability test as a standard, since the test can be performed in as little as 1/10 the time of the standard test now in use. Analytical equations were developed for predicting the increment of pressure required to saturate a given soil as a function of initial degree of saturation, pore air pressure, and coefficient of air solubility in water. Some conclusions were: (1) Dry density increases during the test with accompanying decrease in permeability. (2) Specimen compaction method considerably influences permeability values obtained. (3) In general, saturation is not achieved using the saturation pressure increment as computed by equations based on assumed final conditions. (4) Main advantage of the test procedure is the speed with which maximum permeability values can be obtained. Has 34 references.

DESCRIPTORS-- *permeability/ silts/ sands/ *saturation/ soil tests/soil mechanics/ soil compaction/ dry density/ soil moisture/ remolded soil samples/ *high pressures/ research and development/ pore water pressures/ *pore air pressures/ percolation/ solubility/ test procedures/ laboratory tests/ bibliographies

IDENTIFIERS-- *permeability tests/ equations

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NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
A	Area of a soil sample perpendicular to the direction of flow.	L^2
a	Area of a water supply volume tube.	L^2
c	Soil conductivity.	L/T
e, f	Unspecified constants.	-
G_s	Specific gravity of solids .	-
H	Coefficient of solubility of air in water.	-
h	Amount of water head dissipated in flow through a length of soil.	L
i	Head gradient h/l .	-
k	Coefficient of permeability.	L/T
l	Length of a soil sample.	L
n	Number of values used in computing an average.	-
P	Pore air pressure, without a subscript indicates final conditions, with a subscript o indicates initial conditions.	F/L^2
Q	Volume flow rate.	L^3/T
R_i	An individual value used in the computation of an average.	-
S	Degree of saturation of a soil sample V_w/V_v , subscript o indicated initial conditions, f indicates final conditions.	-

NOMENCLATURE (continued)

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
V	Volume, subscripts a, g, l, s, v, and w indicate air, gas, liquid, solids, voids, and water respectively.	L ³
W	Weight, subscripts s and w indicate solids and water respectively.	F
w	Water content W_w/W_s .	-
X	Superficial flow velocity in a soil sample Q/A.	L/T
γ	Dry density W_s/V_s , subscripts o and f indicate initial and ^s saturation pressure conditions respectively.	F/L ³
ΔP_s	Saturation pressure increment.	F/L ²
Δt	Time elapsed during a permeability test run.	T
$\overline{\Delta y}$	Average change in water surface elevation in volume tubes.	L
μ	An average.	-
σ	Standard deviation.	-

I. INTRODUCTION

The coefficient of permeability of a porous medium may be defined as (32)¹ "The rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions." It is designated by the symbol k and has units of length divided by time. Because the value of the coefficient of permeability is underestimated when it is measured under partially saturated conditions, it is desirable to measure the permeability of a porous medium when the voids of the medium are saturated with water. The coefficient of permeability of a saturated soil is an important soil mechanics parameter since a knowledge of soil permeability is required for the solution of many of the major problems of soil mechanics and foundation engineering. Some of these problems are: drainage, seepage through earth dams, uplift pressures on concrete dams and other structures below ground water level, dewatering of excavations, computation of seepage pressures, rate of settlement, and slope stability.

1

Figures in parentheses refer to the corresponding reference listed in the bibliography.

There are several methods for producing saturation in a porous medium. One of these methods is to increase the pressure in the pore water in order to accelerate the solution of the pore air in the pore water. This thesis is devoted to analytical development of equations which will predict the increment of pressure required to saturate a given soil as a function of the initial degree of saturation, pore air pressure, and the coefficient of solubility of air in water. The analytical equations were checked experimentally to determine their validity and applicability to practical permeability testing.

The high-pressure permeability test should be of interest to soil mechanics engineers, because it provides a means of achieving saturation much more rapidly than the standard percolation-saturation procedure.

II. LITERATURE REVIEW

A review of the soil mechanics literature leads one to the conclusion that there are three main saturation methods currently in use in conjunction with the permeability testing of soils. The method used depends primarily on the time and equipment available and on the preference of the testing agency.

The equation applicable to the determination of flow quantities through saturated porous media for laminar flow conditions is Darcy's law. Darcy's law may be expressed as

$$Q = kiA, \quad (1)$$

where Q is the volume flow rate of water along a column of the porous media which has a constant cross sectional area A perpendicular to the flow direction and a length l . The coefficient of permeability of the porous medium is k and the gradient is i which is equal to the amount of water head h dissipated by the water in flowing along the length l ; that is $i = h/l$.

Saturation by Percolation

One of the most popular saturation methods is by percolation. This procedure consists of allowing de-aired water to percolate through the soil sample for a time sufficient for all the pore air to be dissolved in the percolating water. The lower the temperature the

greater is the solubility by weight of air in water, thus a condition conducive to the solution of pore air by water is the maintenance the sample at a temperature lower than the storage temperature of the permeant. The natural tendency of air bubbles to rise in water may be used to advantage in the saturation of soil samples by percolation if the flow direction is upward. The time necessary for removal of air from a given soil sample is dependent on its coefficient of permeability, the temperature of the pore water, and the initial degree of saturation of the soil specimen.

Christiansen (10) mentioned three distinct periods which were observed during the long-term percolation of various soils with water. These periods may be distinguished by differences noticeable in the conductivity c obtained by combining measured values of Q , i , and A in the following form:

$$c = \frac{Q}{iA} \quad (2)$$

The form of equation 2 is identical to Darcy's law, but c can not be termed the coefficient of permeability unless the porous medium is saturated and the flow is laminar. The three periods noted by Christiansen were: 1) an initial period in which c decreased from the value obtained at the inception of equilibrium flow conditions, 2) a period in which c increased to as much as 30 times the previous minimum value, and 3) a final period in which c decreased gradually for the remainder of the test. This behavior is typical for

soil specimens saturated by the percolation procedure. Brooks and Corey (8) state that k is usually greater than c . Due to this fact, the maximum value of c is taken to be k when the percolation-saturation procedure is used. The soils tested by Christiansen et al. (11) ranged from a clay loam through a loamy sand, with maximum c values ranging from 288 to 2880 ft/yr. The percolation time required to achieve maximum c values ranged from two to nineteen days. Smith and Stallman (29) report that practically no gas remains in most sand samples after the circulation of de-aired water for eight hours, while Lowe and Johnson (19), quoting Leonards, report that saturation of clays by percolation is impractical due to their low permeability. The saturation of a soil by percolation is a simple procedure, but it can, depending on the type of soil being tested, be a time consuming process, thus other schemes have been tried.

Saturation Under Vacuum

A second method which can be used to saturate permeability test specimens is to apply vacuum to the specimens for a period of time and then to allow de-aired water to slowly percolate into the sample. This percolation can be done from both ends under the residual vacuum in the sample, or from one end while the vacuum is maintained at the other end. This procedure works best on

relatively pervious air dried soil. At best, it is a tedious procedure, and it may result in an undesirable compaction of the soil. Christiansen (10) reports that for some soils this type of saturation results in a breakdown of the soil structure and a lower permeability value than if the soil had been saturated using the percolation procedure.

Saturation Using Carbon Dioxide

A third method which can be used to saturate soil samples is to displace the air in the voids with carbon dioxide, and then to allow de-aired water to percolate through the soil. Carbon dioxide is 45 times more soluble in water than is air, so its solution, and consequently the saturation of the soil occurs much more rapidly than if air occupied the soil voids. The removal of the air from the soil and its replacement by carbon dioxide are accomplished by allowing the carbon dioxide to flow through the soil for a period of time, for example Chu et. al. (12) report using a flow rate of .03 cubic foot per minute for 15 minutes on an uncompacted air dried sand. The procedure works best on air dried coarse grained material; however, Christiansen et. al. (11) report using it to saturate a clay loam. The lower the permeability of the soil, the longer it will take to saturate the soil with carbon dioxide, and the longer it will take for the water to penetrate the soil and dissolve it.

Christiansen et. al. (11) could find no indication that carbon dioxide produced any chemical reactions in the soil which altered the permeability.

Saturation Using Elevated Permeant Pressures

There is little in the soil mechanics literature concerning permeability testing in which saturation has been produced using elevated pore water pressures. Lowe and Johnson (19) discuss the use of back pressure to produce saturation in triaxial test specimens, while Lowe et. al. (20) discuss the use of back pressure to produce saturation in consolidation testing. Bjerum and Huder (6) and the U. S. Bureau of Reclamation (34) discuss one of the procedures which may be used in permeability testing at elevated permeant pressures.

III. THEORETICAL ANALYSIS

The volume of a gas that will dissolve in a given volume of a particular fluid at a given temperature is a constant regardless of the pressure. This relationship is known as Henry's law and is expressed mathematically as follows,

$$V_g = HV_1 \quad (3)$$

where V_g is the volume of gas that can dissolve in the volume of liquid V_1 , and H is the coefficient of solubility. The value of the coefficient of solubility depends on the gas and liquid involved and on the liquid temperature, its value may be taken as 0.02 for water and air at room temperature (18).

Using Henry's law, the degree of saturation S of a given soil sample, and an assumed initial pore air pressure, it is possible to derive two equations to compute the pressure increment necessary to saturate the soil. The form of the equation derived depends on the conditions assumed to exist in the soil sample following the application of the pressure increment.

Saturation Pressure Equation Based on Constant Water Content

If the pressure increment ΔP_g which produces saturation is applied rapidly and if it is assumed that the soil volume decreases as rapidly as the pore air is compressed and absorbed into the pore

water, then no flow of water into the soil sample is possible, and the volume of the soil sample must decrease by the amount of the volume of air originally present in the soil voids, and the following development applies. The original volume of air in the soil voids, both free and in solution in the pore water, is

$$(1 - S_0) V_v + S_0 V_v H \quad (4)$$

where V_v is the initial volume of the soil voids, S_0 is the initial degree of saturation of the soil sample (the pore water volume divided by V_v) and H is the coefficient of solubility. Since there is no flow of any kind into or out of the soil sample, the amount of air in the system remains constant. Since the temperature may reasonably be assumed to remain constant, the equation of state of an ideal gas may be applied in the form $P_1 V_1 = P_2 V_2$ and the volume of free air V_a at the new pore air pressure P is

$$V_a = \left\{ (1 - S_0) V_v + S_0 V_v H \right\} \times \frac{P_0}{P} - S_0 V_v H, \quad (5)$$

where P_0 is the initial pore air pressure. Since it is desired that the final degree of saturation be 100%, the final volume of free air must be zero, and equation 5 yields

$$\begin{aligned} \frac{P_s}{P_o} &= \frac{(1 - S_o)}{S_o H} + 1, \\ P_s &= P_o + P_o \frac{(1 - S_o)}{S_o H}, \\ \Delta P_s &= P_s - P_o = P_o \frac{(1 - S_o)}{S_o H}, \end{aligned} \quad (6)$$

the equation for the increment of pressure ΔP_s necessary to produce saturation.

The implications of the assumptions made in the derivation of equation 6 should be discussed at this time. The assumption of P and P_o to be the total pressures in the pore air neglects the vapor pressure of water, which is reasonable since the vapor pressure is small at room temperature. Another reasonable assumption in a controlled environment is that the temperature remains constant. The assumption that the soil volume decreases as rapidly as the air is compressed and goes into solution implies that there is no flow into or out of the soil sample, thus the water content w (the weight of water divided by the weight of soil solids) must remain constant. The validity of this assumption is in doubt, since the pressure necessary to reduce the volume of the air to the point where it can dissolve in the pore water present in the soil does not necessarily have to be large enough to overcome the resistance of all the soil grains to motion. In this case, the volume of some of the voids which contain air might reasonably be expected to remain constant, and as the

air in these voids is compressed, water must flow into them, either from neighboring void spaces which are decreasing in volume, or from a point exterior to the soil sample. Thus it would seem reasonable to believe that though the amount of flow will depend on the resistance to consolidation and on the permeability of the soil, some water will flow into or out of a given soil sample when the pressure increment is applied regardless of how rapidly this is done.

Dry Density at Saturation Pressure, Water Content Constant

If it is assumed that the soil volume decreases in the amount of the original volume of air in the soil pores, then it is desirable to be able to compute γ_f the dry unit weight at saturation. The dry density of a soil is the dry weight of a unit volume of the soil in place. The computation of γ_f can be made if the initial water content of the soil w , the specific gravity of solids G_s , and the unit weight of water γ_w are known. It can be shown by basic soil mechanics that, for the assumption made above, the final dry unit weight is

$$\gamma_f = \frac{\gamma_w G_s}{w G_s + 1} \quad (7)$$

Saturation Pressure Equation Based on Constant Soil Volume

If it is assumed that the saturation pressure is applied slowly so that water flows into the soil to replace the air as it is compressed, then the volume of the soil remains constant and the following development applies. If the soil volume is unchanged, the volume of the voids V_v is unchanged, and the total volume of air in the soil after the pressure has been applied is

$$V_f = (1 - S_f) V_v + H S_f V_v , \quad (8)$$

where S_f is the final degree of saturation of the soil sample, $S_f = \left(\frac{V_w}{V_v} \right)_f$. The volume occupied by this air before application of the pressure increment is

$$V_o = (1 - S_o) V_v + H S_o V_v , \quad (9)$$

if the water which flows into the soil is saturated with air. However, if the water which flows into the soil is assumed to be air free equation 9 becomes

$$V_o = (1 - S_o) V_v + H S_o V_v , \quad (10)$$

where S_o is the initial degree of saturation of the soil sample. For isothermal conditions $P_o V_o = P_f V_f$ applies, and the equation for the pressure increment necessary to achieve final saturation S_f when the initial saturation is S_o is

$$\Delta P = P_f - P_o = P_o \left\{ \frac{(1 - S_o) + HS_o}{(1 - S_f) + HS_f} - 1 \right\} \quad (11)$$

Equation 11 is the same equation arrived at by Lowe and Johnson (19), however, in their derivation Lowe and Johnson have ignored any air which might flow into the sample dissolved in the water which enters the sample; this is strictly justified only if the water which flows into the soil sample is initially air free. The saturation pressure increment ΔP_s can be derived from equation 11, since $S_f = 1$,

$$\Delta P_s = \frac{P_o}{H} (1 - H) (1 - S_o) \quad (12)$$

where P_o is the initial pressure in the air voids.

The important assumptions made in the derivation of equation 12 were that the soil volume remained constant, and that air free water flowed into the soil sample. In this investigation, de-aired water was used, so the second assumption is valid. In addition, since the amount of air which can flow in with the entering water is only two percent of the volume of the free air initially present in the soil voids, the magnitude of the error induced by ignoring this extra volume of air might be considered negligible in view of the uncertainties in the other terms in the equation. The validity of the assumption of constant volume is in doubt at any practical pressure application rate, since some volume decrease can be expected even though the pressure gradient from exterior to interior of the soil

sample is very small. The amount of volume decrease for a given soil should depend on the pressure application rate, resistance to consolidation, and the permeability of the given soil.

Water Content at Saturation Pressure, Dry Density Constant

If it is assumed that the soil volume remains constant during the application of the saturation pressure increment, then water must flow into the soil to replace the air as it is compressed and absorbed. If it is desired to compute the final water content in this case, w_f may be computed using the most convenient form of equation 13,

$$w_f = \frac{G_s \gamma_w - \gamma}{G_s \gamma} = \frac{w_o}{S_o} \quad (13)$$

where γ is the dry density, S_o is the initial degree of saturation, and w_o the initial moisture content of the soil sample.

From the discussion pertaining to equations 6 and 12, it can be seen that the pressure increment required for saturation is somewhere between the values given by the two equations. Since the saturation pressure increment given by equation 6 is always larger than that given by equation 12, application of the pressure increment given by equation 6 should always provide saturation. The final dry density will be somewhere between the initial dry density and the dry density value given by equation 7. The more slowly the pressure increment is applied, the more closely will the final dry density approximate the initial dry density.

Before the saturation pressure increment ΔP_s can be found either from equation 6 or equation 12, the initial pore air pressure P_o must be known. In samples of coarse soils, and in clay samples which have been allowed to come to equilibrium while exposed to atmospheric pressure, the initial pore air pressure is atmospheric. In fine soils immediately following compaction, the pore air pressure may be slightly higher than atmospheric. Bishop et. al. (5) cite a boulder clay in which the pore air pressure was about 0.9 psi over atmospheric immediately following compaction. About 150 minutes were required for this excess pore air pressure to dissipate. In permeability testing of finer soils, time should be allowed for this excess pore air pressure to dissipate before pressure application is started in the testing apparatus. Equations 6 and 12 have been plotted in Figure 1 for an atmospheric pressure of 12.2 psi and $H = 0.02$.

The main two equations developed in this section are equation 6 which applies to conditions under which w remains constant, and equation 12 for conditions under which γ remains constant. Equation 7 was developed for the computation of γ_f if the conditions of equation 6 apply, and equation 13 for the computation of w_f if the conditions of equation 12 apply.

IV. EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental work done by the author in the preparation of this study was performed at the U. S. Bureau of Reclamation Soils Engineering Laboratory, Denver Federal Center, Denver, Colorado. The primary objective was to determine the feasibility of using the high pressure permeability test as a standard permeability test, since this type of test can be as much as ten times faster than the standard percolation test currently in use.

Experimental Equipment

In addition to the standard laboratory equipment for the preparation and analysis of soil specimens, a special high pressure permeameter was used in the experimental phase of the preparation of this work. This high pressure permeameter, designed and built by the U. S. Bureau of Reclamation Soils Engineering Laboratory at Denver is illustrated schematically in Figure 2.

Essentially, the high pressure permeameter consists of a lateral pressure chamber A which is connected to the water reservoir B through valve 1. Pressurized air can be applied over the water in reservoir B by the air pressure regulator C, the amount of this pressure is determined by pressure gauge II. Valve 5 is the chamber drain valve. Water can be supplied to the porous brass upper end plate D from either the two inch inner

diameter reservoir E, or the one-half inch inner diameter reservoir F; reservoir selection is controlled by the positions of valves 2 and 3. Valve 4 is the flush valve for the upper end plate. The air pressure over the reservoir water in reservoirs E and F is controlled by regulator I and monitored by gauge III. Similarly, reservoirs G and H hold the water supply for the lower porous brass end plate J, while the air pressure over these reservoirs is controlled by regulator K and monitored by gauge IV. Valve 7 allows water from the lower end plate reservoirs to seek its hydrostatic level in the right branch L of the manometer, while valve 8 performs a similar function for the upper end plate reservoirs and the left branch M of the manometer. Valve 9 allows the pressure over the manometer water to be adjusted to equal that over reservoirs G and H. Valve 10 allows the water to be moved from one reservoir system to another without passing through the soil sample. Air pressure regulator N controls the pressure of the air supplied to the regulators C, I, and K, while gauge I monitors the supply pressure. Valves 11, 12, 13, and 14 make it possible to control the pressure over all the reservoirs using only regulator C, or to control each of the reservoir pressures separately with their respective regulators C, I, and K. Figure 3 shows the high pressure permeability apparatus in operation, Figure 4 shows a soil sample in place in the pressure chamber, and Figure 5 is a close-up of the control panel.

Permeability Test Equations

The two types of test which can be run in the high-pressure permeability apparatus are the constant head and the falling head permeability tests. In both test types, it is necessary to have the lateral chamber pressure slightly (2 to 5 psi) higher than the permeant water pressure to keep the flexible membrane which encloses the sample tight against the soil sample to prevent flow along the edge of the soil sample between the soil and the membrane.

When a soil with a high permeability is being tested, large quantities of water are necessary, so the small reservoirs F and H are cut out of the system and a constant head test is conducted using the larger reservoirs G and E. It is possible to run a constant head test using reservoirs E and G even though the water level falls in one and rises in the other as the water flows from one reservoir to the other because the air pressures over the water in the two reservoirs can be controlled independently of each other by closing valve 12, and using regulators I and K. This independent control of these two air pressures and the fact that the true head difference between the two reservoirs can be monitored at the manometer LM makes it possible to run a constant head test even though the inlet and the outlet water elevations change constantly.

The equation which applies to the determination of the coefficient of permeability in the constant head test is

$$k = \frac{l \Delta \bar{y} a}{h A \Delta t} \quad (14)$$

where l , h , and A are as defined previously, and a and $\Delta \bar{y}$ are respectively area and average change in water level of the volume tubes in the time interval Δt .

In testing a soil with a low permeability, only a small quantity of water is required, so reservoirs F and H are used, and a falling head test is conducted. In the falling head test, the pressures over the two reservoirs must be the same, so valve 12 is open, valve 14 is closed, and only regulator I is necessary to control the pressure over the permeant. If the pressures over the two reservoirs are the same, then the heads can be read directly from the water levels in the reservoirs. Both the large and the small reservoirs have scales lengthwise along them so volume determinations can be made by noting the initial and final reservoir water levels.

A consideration of the differential form of Darcy's law will show that the equation applicable to the falling head test with rising tail water is

$$k = 1.152 \frac{a l}{A \Delta t} \log_{10} \frac{h_1}{h_2} \quad (15)$$

where h_1 is the head at the start of the time period and h_2 is the head at the end of the elapsed time Δt . Equations 14 and 15 are

simply forms of Darcy's law, and thus are strictly applicable only to laminar flow in saturated porous media.

Experimental Procedure

Prior to a permeability test using the high pressure permeability apparatus the soil sample was prepared and placed in a flexible cylindrical rubber membrane the open ends of which were tied to the porous brass end plates J and D as shown in Figure 3. Next the lateral pressure chamber A and reservoir B were filled with water, the appropriate permeant reservoirs were run approximately half full of de-aired water, and the end plates D and J were flushed. Following this, the pressure in all the reservoirs was raised to the desired lateral chamber operating pressure using regulator C, and the test was conducted using the appropriate permeability testing procedure.

In the experimental program, it was decided to test two soils with widely different permeabilities. These were two standard experimental soils which the USBR Soils Engineering Laboratory had on hand in quantity. The first soil tested was a South Platte Supply Canal sand, laboratory sample number 29B-436, its unified soil classification system classification is silty sand, and its grain size distribution curve is given in Figure 6. The low permeability soil tested was loess from Bonny Dam, laboratory sample number 23J-1,

which classifies as a low plasticity silt, its grain size distribution curve is given in Figure 7.

All permeability test runs were made on remolded samples, and all runs on a given soil were made with the same initial dry density. The initial dry density for the sand was 95% of Proctor maximum, or 109.5 lb/ft^3 . The initial dry density of the silt was 90% of Proctor maximum, or 99.9 lb/ft^3 . All permeability tests were conducted on cylindrical soil samples with a diameter of 3.25 inches and length of 4.0 inches. The initial degree of saturation and water content of the various test series as well as the corresponding final conditions as computed by equations 7 and 13 have been displayed in Table I.

Variation of Final Dry Density

To determine the dry density of a soil sample at saturation pressure, the volume of the sample at this pressure must be known. To determine the volume of a soil sample at pressure, it is necessary to know the initial volume of the soil sample, the change in volume of the soil sample and permeameter as the pressure is raised from atmospheric to saturation pressure, and to know the change in volume of the permeameter itself as the pressure increment is applied. The first two are easily determined, and an attempt was made to determine the volume of the permeameter as a function

of pressure, but it was found to vary not only with pressure but also with time. Due to this creep in the volume of the permeameter, it was impossible to determine the volume of the soil samples at pressures other than atmospheric, thus the dry densities of the soil samples could not be determined at saturation pressure.

It was possible, however, to obtain qualitative information about the variation of γ and the effect of this variation on permeability values by a comparison of the results of the series I and II tests on the sand with the series III results for that soil, and from consideration of the final water content of several of the silt samples. The series I and II sand samples were tested according to the assumption of equation 12 with a pressure application rate of one psi per minute, and thus can be assumed to have negligible change in dry density when compared with the series III samples on which the entire saturation pressure increment was applied in a span of approximately 30 seconds. According to Figure 5 of Lambe (17), the variation of permeability of a sand with compaction water content at water contents above Proctor optimum is small. Since the compaction moisture contents of all the sand samples were above Proctor optimum, the variation of permeability with compaction moisture content may be assumed to be negligible, and the variations in permeability values between the two groups of tests may be assumed to have been caused by variations in dry density. If it is assumed that

a soil sample is saturated before the removal of pressure, and if no water flows from the sample before it is removed from the testing apparatus, the dry density at pressure can be computed using a modified form of equation 7

$$\gamma_f = \frac{G_s \gamma_w}{G_s w_f + 1} , \quad (7a)$$

where w_f is the water content of the soil at saturation pressure.

The assumption of negligible drainage of the soil sample before its removal from the testing apparatus limited the application of equation 7a to the silt samples.

Effect of Sample Preparation Method

To determine if sample preparation method had any effect on the permeability test results, two different compaction procedures were used. In the first method, the soil was placed in the mold shown in Figure 8 in four one-inch layers. Each layer was rodded twenty-five times with the one-half inch diameter rod shown in Figure 8, then tamped to the one-inch thickness with the two-inch diameter tamper. The surface of each layer was scarified before the following layer was placed. Throughout this work, this compaction method has been called the "D" compaction method. In the second compaction method, all of the soil was placed in the mold at once and the sample was consolidated to four inches in length in a single layer using the hydraulic testing machine shown in Figure 9. That is the sample was

compacted by a steady load rather than by impact as in the first method. Throughout this work, this has been called the "S" compaction method.

Restrictions due to the workability of the soil and to the maximum allowable pressure on the testing equipment limited the water contents of the soils to ranges of 13.6% to 15.6% for the sand, and 17.4% to 22.4% for the silt. These water contents are well wet of Proctor optimum water content for both soils.

Adequacy of Computed Saturation Pressure in Producing Saturation

For many of the soil samples, upon conclusion of the series of permeability determinations at the computed saturation pressure, the pressure was increased and further tests conducted. The purpose of this permeability testing at pressures in excess of the theoretical saturation pressure was to determine whether or not the computed saturation pressure increment was sufficient to produce saturation in the soil. The question of whether or not the computed saturation pressure increment is sufficient to produce saturation in a given soil is particularly important in the consideration of permeability data from tests conducted using the saturation pressure increment computed from equation 12 because this is theoretically the smallest pressure increment which can saturate the soil at a given initial degree of saturation. The test was conducted as described above because if after being held at the saturation pressure for some

time, the soil voids still contained air, an increase in pressure should compress this air and cause an increase in permeability. Thus, if a soil sample were not saturated, an increase in pressure should cause an increase in permeability which could be observed if a test were conducted at the higher pressure. It should be noted also that this increase in pressure might cause an increase in dry density which would cause a decrease in permeability that could balance out or even exceed the increase in permeability due to the removal of the air. Also, this is not really a test of whether the applied pressure was producing the saturation, but rather of whether the applied pressure plus percolation to equilibrium flow was producing saturation. That is, in these tests, the saturation pressure was applied, then percolation was started but no permeability determinations were made until it was observed that equal amounts of water were entering and leaving the soil sample, that is until equilibrium flow conditions were established. Following this, the saturation pressure permeability determinations were made, the pressure raised, and the process repeated to ascertain whether or not saturation had been achieved.

In addition, to determine if it might be possible to produce saturation in some soils by using a combination of percolation and a pressure increment smaller than the computed saturation pressure increment, several permeability determinations were made after

percolation for a time at pressures lower than the computed saturation pressure.

Time Required for Saturation

The amount of time required to saturate a given soil sample has been taken to be the length of time from the application of the saturation pressure increment to the establishment of equilibrium flow conditions in the soil sample. This was done because at saturation the fact that water is an incompressible fluid requires equilibrium flow conditions be established, and because it was observed that after equilibrium flow had been established at a given pressure, the soil permeability value changed very little. For soil samples on which the computed saturation pressure was not applied, the time to flow equilibrium was observed and if the permeability approximated the permeability at the saturation pressure, this was taken as the time to saturation. If the permeability did not approach the saturation pressure permeability, it was assumed that saturation had not been reached.

It should be noted that if the assumptions of either of equations 6 or 12 were strictly met in the performance of a given soil test, no time would be required for flow equilibrium to be established. The important assumption in the derivation of equation 6 is that the soil volume decreases as rapidly as the air is compressed, which means, if this condition is to be met, that the pressure must be applied

instantaneously, and the decrease of soil volume must take place instantaneously. If this were not the case, the water columns in the soil pores could instantaneously transmit the "information" about the pressure increase to the soil voids, which contain air, compression of the air would occur, and flow of water would follow. Thus if the assumptions of equation 6 are met, the soil should be saturated immediately following pressure application, which, of course, means that flow equilibrium should occur immediately. In the derivation of equation 12, it is assumed that the pressure is applied so slowly that no volume change can take place, thus water must flow into the soil voids as the pressure is applied, so that at the close of pressure application period, the soil should be saturated, and the conditions for equilibrium flow established. Thus if in the performance of a high pressure permeability test the operator notices that equilibrium flow conditions are not established immediately upon application of pressure, he can conclude that saturation has not been reached, and that the test has not met the assumptions used in the derivation of the equation used to compute the saturation pressure increment. If equation 6 has been used, there is no remedy, however if equation 12 is applicable, a slower pressure application rate is required.

Reproducibility of Test Results

To check the reproducibility of test results from the high pressure permeability apparatus, two tests were run for each compaction method and water content series. Every effort was made to insure that the two tests for the given compaction method and water content would be identical. Thus the variation in the results of the various pairs of identical tests should give a measure of the reproducibility of the test results.

The Standard Permeability Test

As a basis for comparison, U. S. B. R. standard permeability tests were performed on each of the test soils. The initial moisture contents were approximately the average of the values of the initial moisture contents of the experimental high-pressure permeability soil samples ($w = 14.4\%$ for the sand and $w = 20.9\%$ for the silt). The dry densities were the same as the initial dry densities of the experimental soil samples. The U. S. B. R. standard permeability test is a percolation-saturation test. A discussion of the test is found in reference 33 appendix E-13.

V. DISCUSSION OF EXPERIMENTAL RESULTS

As has been mentioned previously, Darcy's law is valid only for laminar flow in saturated porous media. Before this relationship can be applied to permeability test data, the validity of the assumption of laminar flow must be established. A relationship for flow in porous media which includes the effect of turbulence is the following (30):

$$\frac{h}{l} = e X + f X^2 \quad (16)$$

where e and f are constants of the medium and X is the superficial velocity of flow (Q/A). If X is small enough, the magnitude of the second term is negligible when compared with the magnitude of the first; equation 16 is identical to Darcy's law, and laminar flow exists. If $\log h/l$ is plotted versus $\log X$, and the plot has a slope of one, the second term of equation 16 is negligible, and laminar flow exists. This plot has been made for three representative samples of the silt in Figure 10. In this figure, it is seen that the slopes are one, or slightly less than one. Thus laminar flow conditions exist, since the slope would be greater than one for transition or fully developed turbulent flow.

Since the sand samples were tested at only one gradient, it is impossible to apply the above method to determine the condition of flow, however, Sunada (30) has plotted h/l versus X for a number of porous media with a wide range of permeabilities. From this plot

it may be deduced that the flow conditions for the sand were also well within the laminar flow range. Thus Darcy's law is applicable to all the permeability test data taken in this investigation.

Table II lists the important variables and the average coefficient of permeability for all tests considered in this work.

Effect of Variation of Dry Density

As mentioned in Chapter IV, it was possible to obtain qualitative information about the variation of γ and its effect on permeability test results by a comparison of the results of the series I and II tests on the sand with the series III test results for that soil and from a consideration of the final water content of certain of the silt samples.

In Table III the maximum permeability values at saturation pressure have been tabulated for all tests conducted. From an examination of the series I and II portion of the sand section of Table III it is seen that the permeability values of three of the four tests in both the D and S sections of the table are nearly the same. This supports the assumption made in Chapter III of negligible effect on permeability of initial moisture content and dry density variations for these two test series. When the average values for the series I and II tests are compared with the average values for the series III tests on the sand as has been done in Table IV, it is seen that for the D compaction method the average series III permeability is 45% of

the series I and II averages. While for the S compaction method, the series III S-1 value is 46% of the series I and II averages. Thus if for the sand tested the two assumptions are valid, then for an initial saturation of 80% the reduction in permeability due to the increase in γ is approximately 50%.

In Table V are listed the water contents of some of the test specimens on their removal from the testing apparatus. Also in Table V are the final dry densities as computed from these final water contents by equation 7a for those silt samples which were tested only at the computed saturation pressure increment. All silt samples were tested according to the assumptions of equation 6. It is seen from a comparison of Table V with Table I that none of the γ values obtained from a consideration of the final water contents (by equation 7a) are as large as predicted from initial water content considerations (by equation 7). In only one case does the computed density increase exceed 50% of the predicted increase and in all other cases the computed density increase is less than 25% of the predicted increase. The maximum computed increase was 3.4% of the original density. A further consideration of Table III points out that the permeability value of the silt decreases with increasing initial moisture content. From the second and third factors discussed above, it is concluded that, contrary to the prediction of equation 6, the saturation pressure dry density of the silt increased with increasing initial water content.

This was probably due to the fact that the silt with the low initial water content was stiffer than the soil with the high initial water content, the drier soil then had more resistance to the deformation caused by the applied pressure increment and consequently less volume change.

Conclusions which may be made regarding increases in γ and consequent decreases in permeability due to testing based on the assumptions of equation 6 are: a) for a sand at approximately 80% saturation the reduction in permeability due to an increase in γ is approximately 50%; b) for a silt, final water content considerations yield smaller increases in dry density than do initial moisture content considerations; and c) for a silt, final moisture content and permeability considerations indicate that the saturation pressure dry density increases with increasing initial water content, which contradicts the prediction of equation 7.

Effect of Variation of Compaction Method

In Figures 11 and 12 are drawn curves of maximum permeability at saturation pressure versus initial degree of saturation. Figure 11 contains the curves for the sand and Figure 12 contains those for the silt. In these figures, separate curves have been drawn for the two compaction methods and it can be seen that in both cases the curve which represents the S compaction method plots considerably higher than that for the D compaction method. This leads to

the conclusion that there is a close relationship between the method of soil compaction and soil permeability. An idea of the magnitude of the effect of compaction procedure on permeability can be obtained by comparing the average of all the permeability values for a given soil and compaction type with the average of all permeability values for that soil but for the other compaction type. These averages are tabulated in Table VI. For the sand, the S compaction method average is 2.76 times the D compaction method average, while for the silt this value is 5.83. It is seen that the method of compaction of a soil can have a very large effect on its permeability.

The large permeability differences observed between the two compaction methods used in this investigation can be explained in part by the inevitable nonuniformity of density of soil samples compacted in any manner. It will be remembered that the D type compaction method utilized compaction in four different layers. This type of preparation would lead to the soil sample having at least four and possibly five high-density lenses at each of the layer separation points where each layer was compacted before the next layer was placed. There might also be a high density lense at the lower end of the soil sample, where the soil was rodded against the bottom of the mold as the first layer was being compacted. It will also be remembered, that in the S compaction method the soil was placed in a single layer and then consolidated to four inches in length by a steady load.

This type of compaction should lead to the soil sample having only two high density lenses, one at either end. Another explanation for the lower permeability of the soil samples compacted using the D compaction method might be that since such high initial moisture contents had to be used, that when the tamper blows fell upon the soil layer, a temporary quick condition might have ensued with the coarser particles settling slightly and the fines concentrating at the top of the layer being compacted. Thus four low permeability zones might have been set up in the soil samples compacted using the D compaction method. Since no sudden blows were used in the S compaction method, these soil samples would not have been subject to this type of fine segregation and thus would have no low permeability zones. Whatever the cause, an important factor to remember in any type of permeability testing is that the compaction method used on the soil sample being tested can have a considerable influence on the permeability test results.

Adequacy of the Computed Saturation Pressure in Producing Saturation

To determine if the computed saturation pressure increment were sufficient to produce saturation several tests were performed at the computed saturation pressure, then the pressure was increased, and further permeability determinations made (on the premise that if air remained in the soil voids at the lower pressure, then upon the

increase in pressure some of this air should go into solution in the soil water, and an increase in permeability should be noted).

The results of the series of tests described above have been plotted in the right half of Figure 13. In this figure, the ratio of the permeability at the given pressure to the permeability at the saturation pressure has been plotted versus the deviation of the given pressure from the saturation pressure in percent of the saturation pressure. From this figure, it is seen that for 57% of the observed cases in which equation 12 was used to compute the saturation pressure increment, and for 62% of the cases for which equation 6 was used, an increase in pressure brought an increase in permeability, thus indicating that saturation had not been achieved in over 50% of the selected permeability tests. For all but two of the remainder of the cases, it is seen that the permeability remained essentially constant, for these cases it is suspected that saturation had not been achieved, but that any increase in permeability due to the increase in pressure was canceled by the decrease in permeability due to an increase in dry density. For the remaining two cases it is suspected that saturation had been achieved but that the increased pressure caused an increase in dry density and a consequent decrease in permeability. In addition it is seen that the largest increase in permeability obtained by any increase in pressure is nineteen percent, and that the two largest increases are for series I or II tests on the sand in which equation 12 was used to compute the saturation pressure

increment. The largest increase in permeability obtained by an increase in pressure for soil samples originally tested with a saturation pressure increment computed using equation 6 is 13%. Also, for two of the five silt samples tested in this fashion the pressure increase caused a permeability decrease with the maximum decrease being 23%. From Figure 13 it can be concluded that saturation was, in general, not achieved using the saturation pressure increment as computed by either equation 6 or equation 12. This was probably due to insufficient time allowed for dissipation of compaction excess pore air pressures.

Several permeability tests were conducted at pressures less than the computed saturation pressure. The purpose of this type of testing was to determine whether it was possible to achieve saturation using a combination of percolation and a pressure less than the computed saturation pressure. The results of these tests have been plotted in the left half of Figure 13. From this figure it is seen that only about 29% of the tests conducted yielded conductivity values of more than 90% of the saturation pressure permeability, that 47% were within 80% of the saturation pressure permeability value, and that 24% yielded conductivity values of less than 50% of the saturation pressure permeability. Furthermore, there is no apparent relationship between the conductivity value obtained and the amount of deviation of the test pressure from the computed saturation pressure.

Thus it would appear that this is not a reliable method for obtaining the saturated permeability of a soil.

From the discussion of Figure 13 it is seen that a) neither the saturation pressure increment computed by equation 12 nor the one computed by equation 6 always produced saturation, b) when lower pressures were used, the conductivity was almost always considerably below the saturation pressure permeability, and c) the effect of a pressure higher than the computed saturation pressure increment was unpredictable.

Time Required to Achieve Saturation

As mentioned in Chapter IV, if after the application of the computed saturation pressure increment an amount of time elapses before equilibrium flow conditions develop, then the assumption made in the derivation of the saturation pressure equations have not been met. The time required for the establishment of equilibrium flow conditions has been called the time to saturation.

In the testing program, it was noted that some percolation time was, in fact, required before flow equilibrium was established. The amount of time is, of course, a function of the particular soil being tested, and thus will vary from test to test, but some idea of what is to be expected can be obtained from the author's experience. First, it was found that as soon after the cessation of pressure application as the head could be established in the series I and II

tests on the sand that flow equilibrium was established. It is recalled that these tests were conducted using the saturation pressure increment computed by equation 12 and a one psi per minute pressure application rate. Thus it would appear that for a sand, with a relatively slow pressure application rate, the assumptions of equation 12 are valid. Second, in the sand series III tests which were conducted using the saturation pressure increment computed by equation 6 and a pressure application rate as fast as the testing equipment would allow, it was found that two to five minutes of percolation were required to establish equilibrium of flow, while under the same conditions for all series of the silt testing program, about sixteen hours of percolation were required before flow equilibrium was established. Thus it is seen that for permeability testing using a rapid pressure application rate, the time to flow equilibrium is a variable which increases as the soil permeability decreases. Since no attempt was made to test any of the silt samples according to the assumptions of equation 12, no conclusions can be drawn pertaining to its application to a more impervious soil such as a silt, but it is felt that an extremely slow pressure application rate would be required if flow equilibrium were to be achieved at the end of the pressure application period.

Reproducibility of Test Results

If the high-pressure permeability test data are to be of any value in design, the permeability test results must be reproducible. To determine reproducibility of the permeability data as obtained from the high-pressure permeability test, the testing program was conducted so that the testing procedures in the two D compaction type tests for a given soil moisture series were as nearly identical as possible, similarly for the testing procedures in the two S compaction type tests for a given moisture series.

In Figure 14, permeability values for the first test of a given pair of identical tests have been plotted against comparable permeability values for the second test in the pair. This figure gives a comparison between the various pairs of values in terms of their actual physical magnitudes. In Figure 15, the ratio of the permeability at a given point in the first test to the permeability for the same conditions in the second test has been plotted versus the initial degree of saturation of the various soil samples. These ratios have been computed to bring these various pairs of values, which differ considerably in magnitude, to a common base for statistical evaluation. The average μ and the standard deviation σ of these ratios for the various test groups have been listed in Table VII. The standard deviation was computed by the equation

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (R_i - \mu)^2}{n}}$$

where R_i represents the value of the i th individual ratio from Figure 14, n is the number of ratios used, and μ is the mean value of the n ratios.

Upon consideration of Table VII it is noted that all except one of the tabulated averages are less than one. This indicates that there was a systematic error in the preparation of the test specimens which caused the test results to be larger for the second test of a pair than for the first. That is, as experience was gained in the preparation of the soil samples for testing, slight unnoticed variations in sample preparation procedure caused the second sample of a given pair to have a higher permeability value than the first. This variation in permeability due to the systematic error in soil sample preparation also contributed to the size of the standard deviation. It is further noticed in Table VII that the S compaction procedure had a μ very near one, and the lowest standard deviation obtained. Thus this sample preparation method produces more uniform samples than the D compaction method.

Chu et. al. (12) report testing two different methods of placing sand samples in a permeameter. The average value of the permeability of the samples placed by the recommended procedure was 29.4 ft/day, while the standard deviation for this procedure was

1.1ft/day. The average for the samples placed using another procedure was 18.4ft/day, while the standard deviation for this procedure was 4.7ft/day. The standard deviation in the first case was 3.7% of the average, while that in the second case was 25.6% of the average. The values listed in column three of Table VII are considerably in excess of these values. Therefore the standard deviation of permeability tests using the high-pressure permeability apparatus should be considered excessive. As mentioned previously, these excessive standard deviations were caused in part by the undetected change in sample preparation method as the testing proceeded. A further contributor to these excessive standard deviations was probably a variation in final dry density between the two members of the various pairs of tests (see Table V).

Standard Percolation-Saturation Permeability Test Results

In conjunction with the high pressure permeability testing program, U. S. B. R. standard permeability tests were run on the sand and the silt. The testing procedure is described in appendix E-13 of reference 33. The test is of the percolation-saturation type and the sample is compacted in three one-inch layers in a fashion very similar to the D compaction procedure described above. The permeability values obtained, the day on which these values occurred, and the pressure gradient at that time have been shown in Table VIII. The initial water content for the sand was 14.4% and for the silt 20.0%.

These values roughly compare with the series II samples for the two soils. Comparison has only been made between the standard test values and the results of the D compaction method high-pressure permeability tests because the compaction method makes such a difference in the permeability values obtained, and because the preparation methods were so similar for the standard tests and the D compaction tests.

In Table IX are tabulated the maximum permeability values obtained from the standard test and from the series II D compaction method tests. Also listed are the days on which these maximums were obtained. This table shows that the permeability values from the high pressure test are considerably in excess of those from the standard test for the coarse soil, while the reverse is true for the silt. This indicates that dry density variations are not as large in the high pressure permeability testing of coarse soils as in silts, or that the sand never reached saturation in the standard test. Table IX also illustrates the main advantage of the high pressure permeability test, the considerably shorter time required to achieve maximum permeability values.

Some general observations made during the execution of the testing program are as follows: a) there was a tendency for some fines to be washed from several of the sand samples during percolation; this tendency was stronger for soil samples compacted by the

S compaction procedure; b) it was noted that several of the sand samples tested had slumped slightly during the testing period; and c) a glance at Table III shows that there was generally a difference in permeability values obtained for a given soil sample depending on the direction of water flow through the soil sample; the occurrence of this phenomenon is not unique to the author's data, it occurred also in the data of reference 34.

VI. CONCLUSIONS AND RECOMMENDATIONS

From the discussion of data in the preceding chapter, conclusions can be drawn, and recommendations made.

Conclusions

1. In the high-pressure permeability test, it is possible to determine only a range of final dry densities for a given test situation. The reduction in permeability due to an increase in dry density was about 50% for both soils tested.

2. The method of compaction of a soil specimen considerably influences the permeability value obtained from the high pressure permeability test. The S compaction method produced more uniform samples with higher permeabilities than the D compaction method.

3. Saturation is in general not achieved using the saturation pressure increment as computed by either equation 6 or equation 12, but the effect of increasing the increment beyond the value given by these equations was uncertain.

4. More reliable results can be obtained by using the saturation pressure increment as computed by equation 6 or equation 12 than by using percolation and a lower pressure increment in an attempt to produce saturation.

5. The time required after application of the saturation pressure increment to the achievement of equilibrium of flow conditions is

a variable which depends on test operation procedure and on the permeability of the test soil.

6. The reproducibility of tests results in the testing program was poor. This should be considered in the designation of a safety factor for the use of high-pressure permeability test data in design.

7. From a comparison of high-pressure permeability test data with standard permeability test data it can be seen that, for sands, the high-pressure permeability test gave considerably higher permeability values than the standard test, while for the silt the reverse is true.

8. The main advantage of the high-pressure permeability test is the rapidity with which the maximum permeability values can be obtained. If the problem of determining the dry density at pressure can be solved, it should become a useful permeability test.

Recommendations

If the high-pressure permeability test is to be used as a standard test, it is recommended that provisions be made for determining the volume of the soil samples at test pressure. This will remove the uncertainties due to the variation of dry density.

More accurate results would probably be obtained if the manometer taps were placed at the ends of the soil sample rather than at the bases of the volume tubes, and if better support were provided for samples, such as the test sand, which tend to slump during testing.

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APPENDIX A

Table I. Test Soil Initial Conditions and the Corresponding Computed Final Conditions.

Soil		29B-436	23J-1
Initial Dry Density		109.5 lb/f ³	99.9 lb/f ³
Initial Water Content	Series I	13.94%	20.35%
	Series II	14.79%	21.22%
	Series III	15.48%	22.12%
Initial Degree of Saturation	Series I	71.30%	81.69%
	Series II	75.65%	85.19%
	Series III	79.18%	88.80%
Final Dry Density from Equation 7	Series I	121.3 lb/f ³	107.7 lb/f ³
	Series II	119.3 lb/f ³	106.0 lb/f ³
	Series III	117.9 lb/f ³	104.4 lb/f ³
Final Water Content from Equation 13		19.40%	24.90%

Table II. Average Permeability Values for All Tests

Soil	Series	Sample Number	Computed Saturation Pres. (psi)	Day Obtained	Flow Direction	Actual Pressure (psi)	$\frac{h}{l}$ or $\frac{h}{l}$ Range	Elapsed Time (min)	Average Permeability (ft/year)
29B-436	I	D-1	171*	1	D	171	1.5	40	517.0
					U	171	1.5	120	639.2
		D-2		1	U	171	1.5	110	397.1
					U	171	1.5	60	455.2
				2	U	171	1.5	100	544.1
					U	190	1.5	40	648.3
					U	171	1.5	40	673.2
					U	171	1.5	40	673.2
		S-1		1	U	171	1.0	30	1672.5
					U	171	.75	40	1490.1
				2	D	171	.75	40	1246.8
					D	171	.5	60	1296.6
					D	171	.5	110	1412.9
					D	171	.5	40	1132.1
					D	171	.5	40	1488.7
					D	171	.5	30	1470.7
	D		50		.5	30	1581.3		
	D		50		.5	30	1647.6		
	S-2	1	U	171	.5	30	1680.8		
			D	171	.25	40	1617.2		
		2	U	171	.5	50	1751.6		
			U	171	.5	90	1684.5		
			D	171	.5	50	1350.2		
			D	120	.5	30	1210.9		
			D	120	.5	30	1122.4		
			U	120	.5	30	1697.4		
	II	D-1	1	U	50	1.5	30	219.3	
				U	100	1.5	30	248.8	
				U	145	1.5	30	270.9	
				U	145	1.5	60	305.0	
				2	U	145	1.5	130	464.0
					U	145	1.0	30	627.5
U			145		1.0	30	738.1		
U			175		1.0	30	790.7		
D-2			1	U	50	1.0	30	243.3	
				D	100	1.0	30	301.3	
				U	145	1.0	40	389.8	
				D	145	1.0	40	323.4	
		U		145	1.0	60	309.6		
		2		U	145	1.0	80	308.9	
U			145	1.0	50	303.5			
U			175	1.0	40	377.4			
U			145	1.0	50	345.0			
S-1			1	U	50	.5	30	1780.3	
				D	100	.5	40	1194.3	
		U		145	.5	40	1729.2		
		D		145	.5	40	1455.5		
		U		145	.5	40	1455.5		
		D		145	.5	40	1455.5		

Table II. Average Permeability Values for All Tests (Continued)

Soil	Series	Sample Number	Computed Saturation Pres. (psi)	Day Obtained	Flow Direction	Actual Pressure (psi)	$\frac{h}{l}$ or $\frac{h}{L}$ Range	Elapsed Time (min)	Average Permeability (ft/year)			
29B-436	II	S-1	145*	2	U	145	.5	90	1629.2			
					U	145	.5	30	1658.7			
					D	145	.5	40	1434.8			
					U	145	.5	35	1668.2			
		S-2	145*	1	U	50	.5	30	1315.9			
					U	100	.5	30	1183.2			
					U	145	.5	40	1190.1			
					D	145	.5	30	917.8			
					U	145	.5	30	1177.7			
					2	U	145	.5	100	1114.8		
				U	145	.5	40	1169.4				
				D	175	.5	30	1028.4				
				D	175	.5	30	1067.1				
				U	175	.5	30	1266.1				
	III	D-1	160	1	D	50	1.5	40	59.4			
					D	100	1.5	40	105.0			
					D	160	1.5	60	100.4			
					2**	D	50	1.5	40	85.7		
					U	100	1.5	60	118.0			
					U	160	1.5	60	174.2			
					U	160	1.5	120	191.7			
					U	175	1.5	40	214.2			
					D-2	160	1	U	50	1.5	40	59.4
								U	100	1.5	40	82.9
		U	124	1.5				40	106.4			
		U	124	1.5				32	131.2			
		U	160	1.5				45	165.9			
		2**	U	50				1.5	30	158.5		
		U	100	1.5	30	217.5						
		U	124	1.5	30	254.3						
U	124	1.5	30	274.6								
U	160	1.5	60	305.0								
U	160	1.5	90	329.3								
U	175	1.5	30	361.2								
S-1	160	1	U	50	.75	40	193.5					
			U	100	.75	30	368.6					
			U	100	.75	30	339.1					
			U	124	.75	30	434.9					
			U	160	.75	30	589.8					
			D	160	.75	100	456.1					
			U	160	.50	30	646.9					
			2**	U	50	.50	30	497.6				
			U	100	.50	30	696.7					
			U	124	.50	30	724.3					
			D	124	.50	30	613.7					
			D	160	.50	40	659.3					
			U	160	.50	60	727.2					
			U	175	.50	30	779.6					

Table II. Average Permeability Values for All Tests (Continued)

Soil	Series	Sample Number	Computed Saturation Pres. (psi)	Day Obtained	Flow Direction	Actual Pressure (psi)	$\frac{h}{l}$ or $\frac{h}{l}$ Range	Elapsed Time (min)	Average Permeability (ft/year)	
23J-1	I	D-1	137	0-1	U	137	6.82-4.59	941	.880	
				1	U	137	4.59-3.82	510	.758	
				1-2	U	137	3.82-2.82	929	.688	
				2	U	137	2.82-2.68	150	.661	
			U	137	6.31-5.81	220	.771			
		D-2	137	0-1	U	137	6.39-3.69	940	1.223	
				1	U	137	3.67-2.71	480	1.220	
				1-2	U	137	2.71-1.65	960	1.141	
				2	U	137	1.65-1.50	180	1.109	
			D	137	6.90-6.20	180	1.231			
		S-1	137	0	U	137	7.41-6.84	60	2.736	
				0-1	U	137	6.84-2.71	940	2.062	
				1	U	137	2.71-2.28	180	1.996	
					U	137	7.53-6.33	180	2.023	
					U	177	7.35-6.37	120	2.494	
				1-2	U	177	6.37-2.51	950	2.055	
				U	177	2.51-2.10	180	2.078		
				U	177	7.17-6.93	180	2.228		
	S-2	137	0	U	137	7.19-6.05	60	5.980		
			0-1	U	137	6.05-.97	935	4.114		
			1	U	137	.97-.73	140	4.279		
				U	137	7.21-4.33	240	4.463		
				U	177	7.45-5.97	90	5.152		
			1-2	U	177	5.97-.96	955	4.008		
		U	177	7.45-3.45	360	4.492				
	II	D-1	106	0	U	106	7.20-7.17	30	.264	
				0-1	U	106	7.17-6.75	949	.133	
				1	U	106	6.75-6.55	500	.128	
				1-2	U	106	6.55-6.18	940	.130	
				2	U	106	6.18-6.10	210	.122	
					D	106	7.17-7.08	180	.131	
				D-2	106	0-1	U	106	5.74-5.13	945
1						U	106	5.13-4.85	480	.249
1-2		U	106			4.85-4.33	955	.248		
2		U	106			4.33-4.14	390	.241		
S-1		106	0-1	U	106	5.55-2.15	940	2.110		
			1	U	106	2.15-1.34	480	2.085		
			1-2	U	106	1.34-.51	960	2.079		
			2	U	106	6.50-5.48	180	1.992		
		D	106	7.47-6.16	180	2.258				
S-2		106	0-1	U	106	7.48-6.75	60	3.600		
	1		U	106	6.75-1.73	945	3.014			
			U	106	1.73-1.32	180	3.210			
			U	106	7.27-5.47	180	3.332			
	U	117	7.38-6.04	120	3.533					

Table II. Average Permeability Values for All Tests (Continued)

Soil	Series	Sample Number	Computed Saturation Pres. (psi)	Day Obtained	Flow Direction	Actual Pressure (psi)	$\frac{h}{l}$ or $\frac{h}{l}$ Range	Elapsed Time (min)	Average Permeability (ft/year)
23J-1	II	S-2	106	1-2	U		6.04- .05	3860	2.574
				2	U	117	7.33-5.78	180	2.758
					D	117	6.89-5.32	150	3.615
		S-3	106	0-1	U	0	6.79-3.43	930	1.539
				1	U	0	3.43-3.08	180	1.253
					U	0	7.55-6.28	180	2.150
					U	52	7.27-4.99	120	6.582
				1-2	U	52	4.99- .70	950	4.339
				2	U	52	7.68-3.90	330	4.301
					U	106	7.28-5.70	120	4.266
				2-3	U	106	5.70- .02	3820	3.173
				3	U	106	7.29-3.97	230	5.553
					U	106	7.42-5.50	120	5.207
					U	147	7.48-5.60	120	5.044
				3-4	U	147	5.60- .98	945	3.868
	4	U	147	7.50-5.88	120	4.259			
		U	147	7.69-6.07	120	4.103			
		U	147	7.40-5.90	120	3.957			
	III	D-1	77	1	U	77	6.64-6.50	320	.117
				2**	U	77	7.07-6.99	280	.088
		D-2	77	0-1	U	77	7.10-6.18	3855	.075
				1	U	77	6.18-6.10	360	.073
					U	157	7.36-7.33	120	.096
				1-2	U	157	7.33-7.08	937	.075
				2	U	157	7.08-7.00	300	.077
		S-1	77	0-1	U	77	5.99-3.37	935	1.287
				1	U	77	3.37-2.54	480	1.243
1-2				U	77	2.54- .30	3855	1.160	
		U	77	6.30-5.13	380	1.147			
S-2		77	0-1	U	77	7.00- .96	3829	1.089	
	1		U	77	.96- .87	180	1.052		
			U	77	6.36-5.79	180	1.080		
			D	77	7.45-6.95	110	1.330		
	1-2		D	77	6.95-3.88	940	1.298		
	2		D	77	3.88-3.48	180	1.266		
	D	77	7.61-6.76	180	1.360				

D or U flow direction downward or upward respectively.

* As computed by equation (23), otherwise equation (17) used.

** Pressure not maintained over interval.

Table III. Maximum Permeability in Feet per Year at Saturation Pressure.

Soil	Series	Compaction type and sample number			
		D-1	D-2	S-1	S-2
298-436	I	639.2U-1	544.1U-2	1672.5U-1 1488.7D-1	1751.6U-1 1617.2D-1
	II	738.1U-2	389.8U-1 323.4D-1	1729.2U-1 1455.5D-1	1190.1U-1 917.8D-1
	III	191.7U-2 100.4D-1	329.3U-1	727.2U-1 659.3D-2	
23J-1	I	.771D-2 .758U-1	1.231D-2 1.220U-1	2.023U-1	4.463U-1
	II	.131D-2 .130U-2	.249U-1	2.258D-2 2.085U-1	3.332U-1
	III		.073U-1	1.243U-1	1.360D-2 1.080U-1

Interpretations:

U - following a number means this permeability value was obtained for upward flow through the soil sample.

D - following a number means this permeability value was obtained for downward flow through the soil sample.

The number following the letter indicates on which day the permeability value was obtained.

Table IV. Comparison of the Series I and II Test Results with the Series III Results for the Sand.

	D compaction method	S compaction method
Series I and II average permeability (ft/year)	577.8	1585.8
Series III average permeability (ft/year)	260.5	727.2
Series III average as a percent of the Series I and II average	45	46

Table V. Final Water Contents and the Saturation Pressure Dry Densities Computed from Them.

		Final Water Content, w in %			
Soil	Series	Compaction type and sample number			
		D-1	D-2	S-1	S-2
29B-436	I			20.09	18.62
	II	18.35	16.86		19.68
	III		17.67	19.16	
23J-1	I	23.76	24.01	25.36*	25.76*
	II	22.70	23.62	24.61	25.58*
	III	22.85	22.55	24.30	24.24
		**Final Dry Density, γ_f in lb/f ³			
23J-1	I	101.8	101.3		
	II	103.3	101.9	100.1	
	III			100.8	100.8

* These values exceed the theoretical maximum of 24.90% given by equation 13.

** Dry density computations have been made only for the tests which were run only at saturation pressure.

Table VI. Average Permeability Values in Feet per Year for the two Compaction Procedures.

Compaction method	D	S
Soil number		
29B-436	472	1300
23J-1	0.421	2.450

Table VII. The Average and Standard Deviation of the Various Groups of Ratios of Figure 15.

Test group	Average μ	Standard deviation σ	σ as a percent of μ
All tests	0.93	0.39	42.0
D compaction method	0.83	0.39	47.0
S compaction method	1.01	0.35	34.7
Maximum permeability at saturation pressure	0.93	0.44	47.3

Table VIII. Permeability Values from U. S. B. R. Standard Permeability Tests.

Soil	Day	h/l	Permeability (ft/year)
29B-436	1	.92	25.5
	2	.92	88.7
	3	.36	90.3
	4	.36	92.2
	4	2.00	82.2
	7	2.00	61.5
	7	4.00	125.6
	8	4.00	117.1
23J-1	1	7.56	.23
	2	7.56	.25
	3	4.84	.28
	4	3.12	.34
	7	2.08	.26
	9	1.12	.33
	10	.76	.55
	11	.76	.43
	14	1.56	.29
	15	2.32	.25
	16	4.36	.25
17	5.72	.24	

Table IX. Comparison of the Standard Test Results with the Series II type D Compaction Results.

Soil number		29B-436	23J-1
Maximum permeability in (ft/year)	Standard test	125.6	.55
	Series II at saturation pressure	738.1	.249
Day Obtained	Standard test	7	10
	Series II at saturation pressure	1	1

APPENDIX B

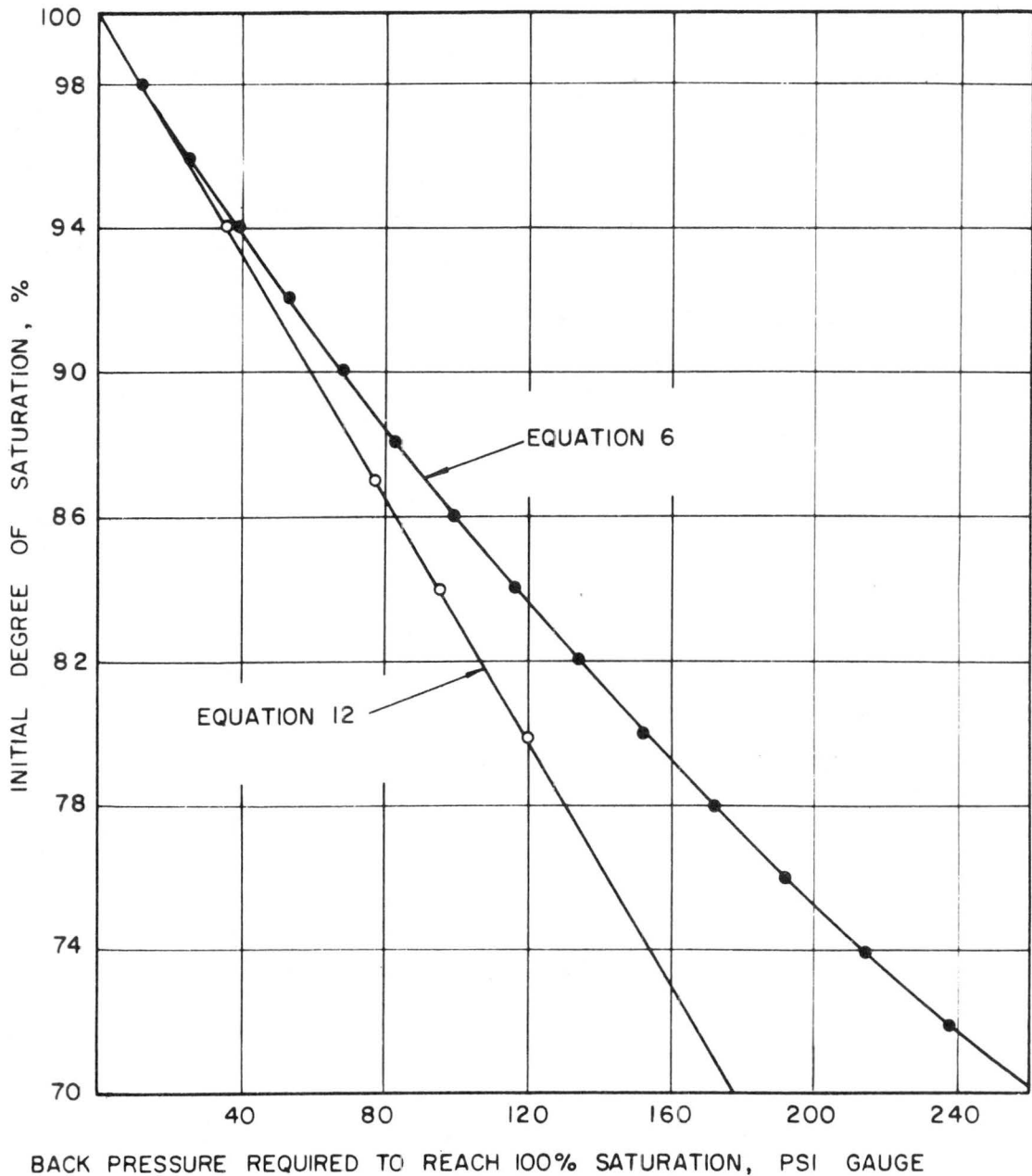
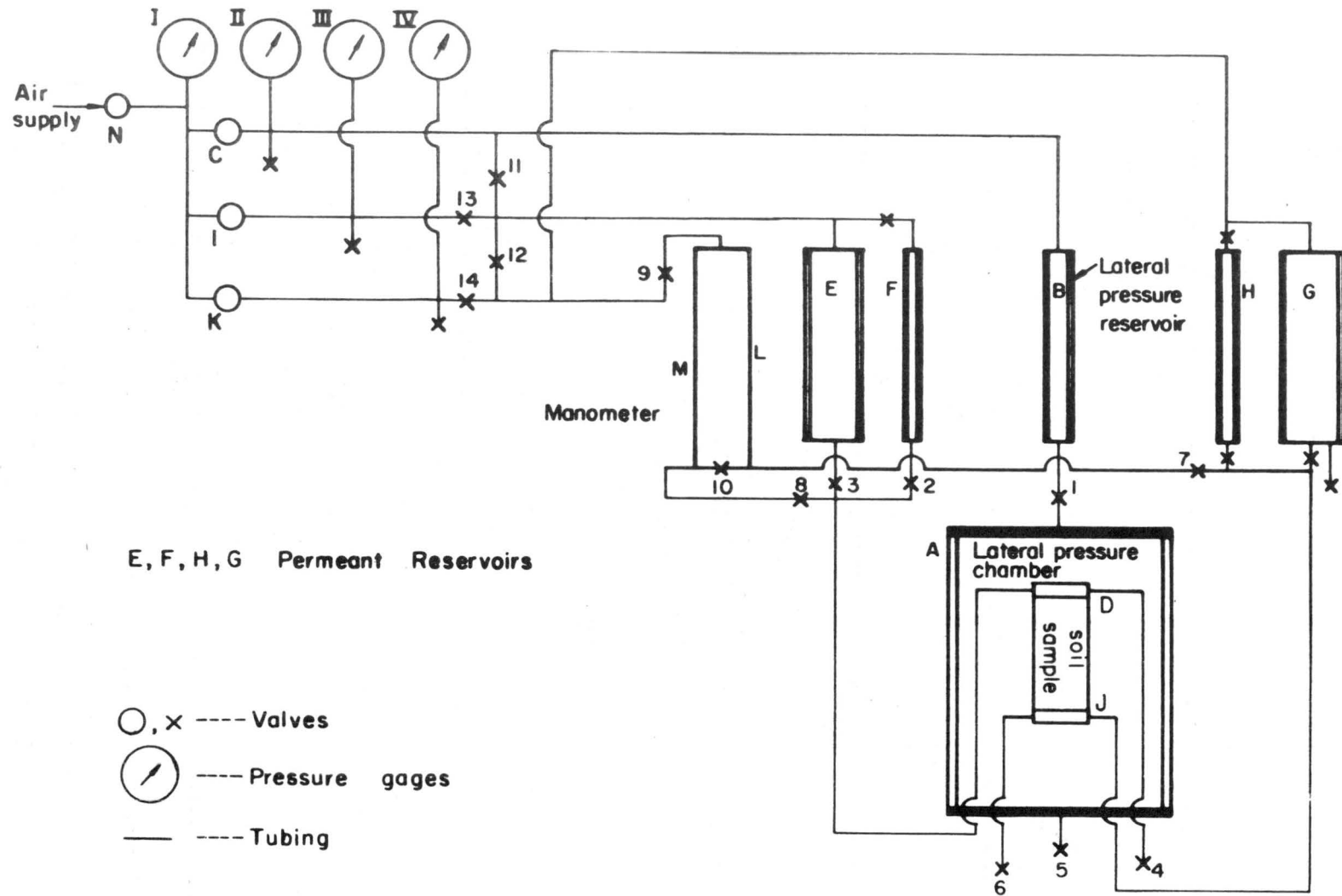


FIG. 1 BACK PRESSURE REQUIRED TO REACH 100 % SATURATION FOR A GIVEN INITIAL SATURATION.



E, F, H, G Permeant Reservoirs

- , x ---- Valves
- ⊙ ---- Pressure gages
- ---- Tubing

FIG. 2 SCHEMATIC OF THE HIGH PRESSURE PERMEAMETER.

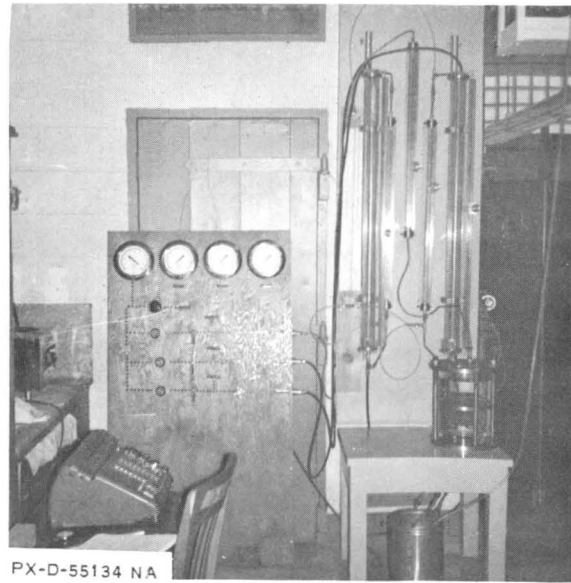


Fig. 3. High pressure permeameter in operation.

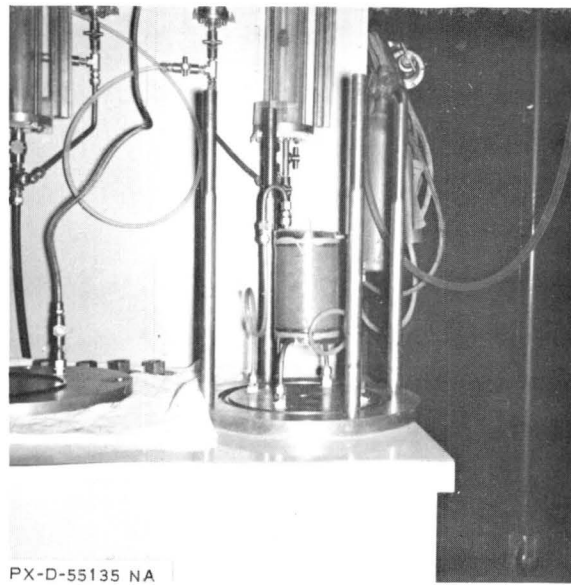


Fig. 4. Sample installed in the permeameter.

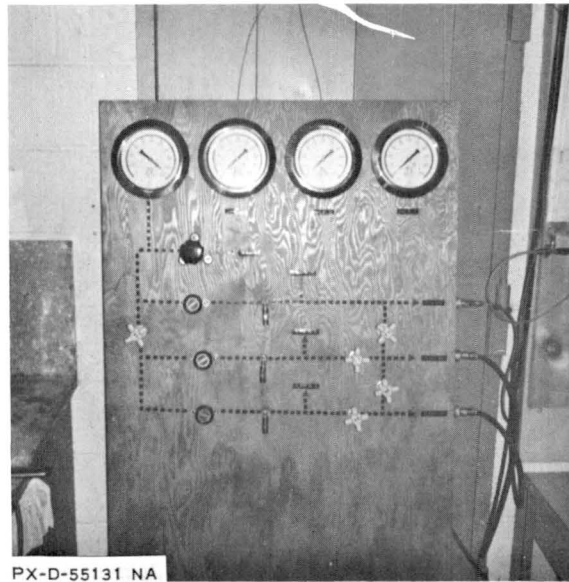


Fig. 5. Close-up of the permeameter control panel.

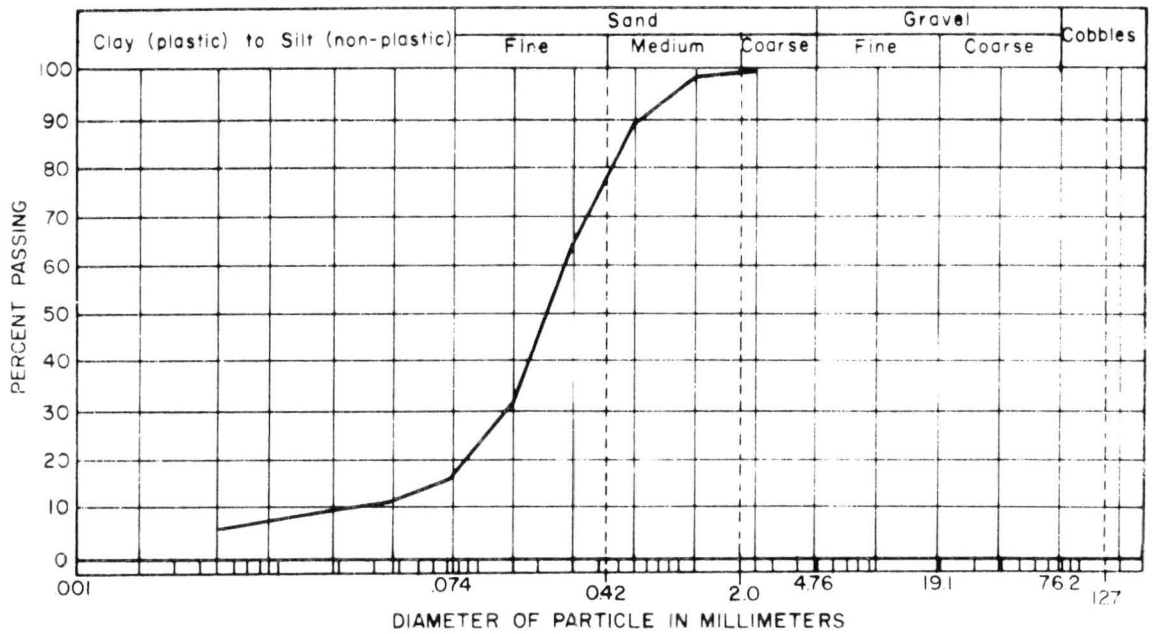


FIG. 6 GRAIN SIZE DISTRIBUTION OF THE SAND

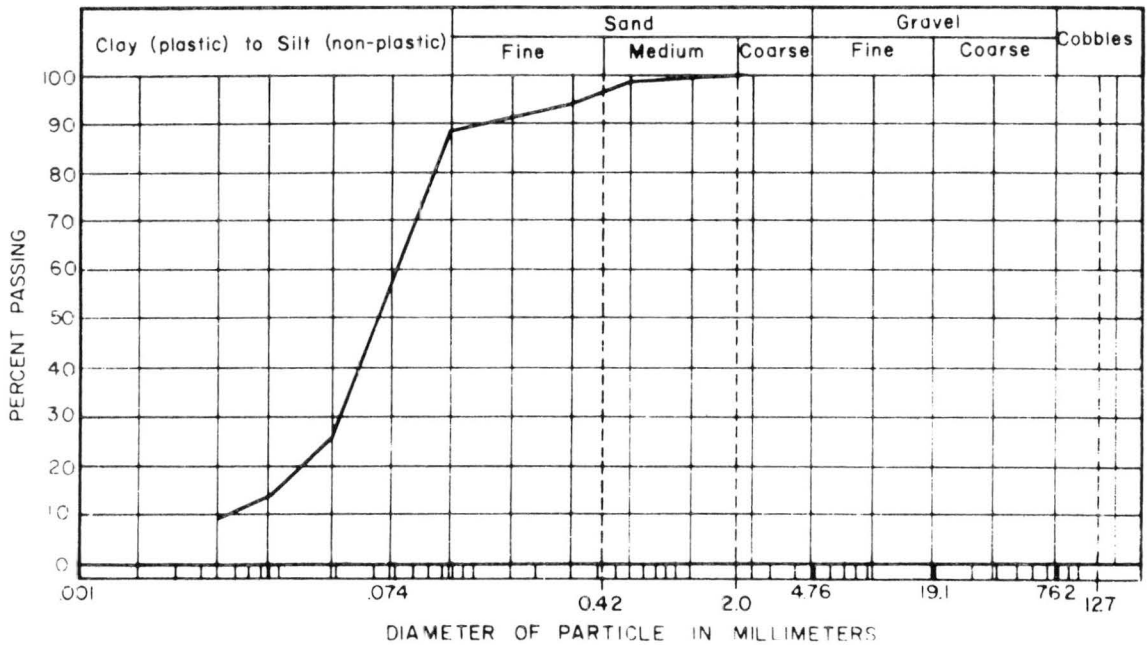


FIG. 7 GRAIN SIZE DISTRIBUTION OF THE SILT

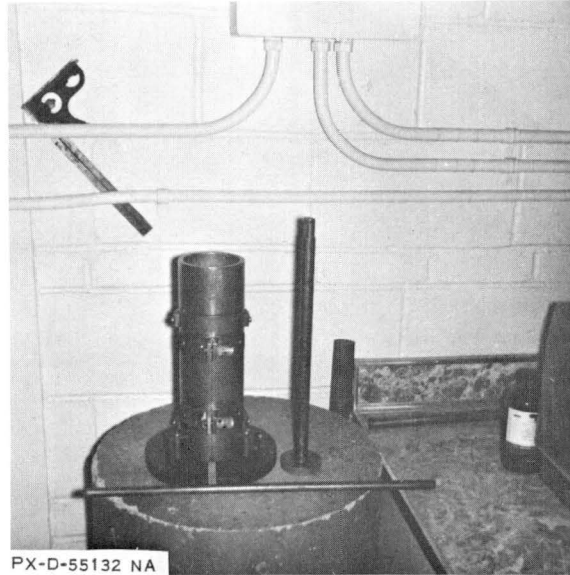


Fig. 8. Sample molding tools.

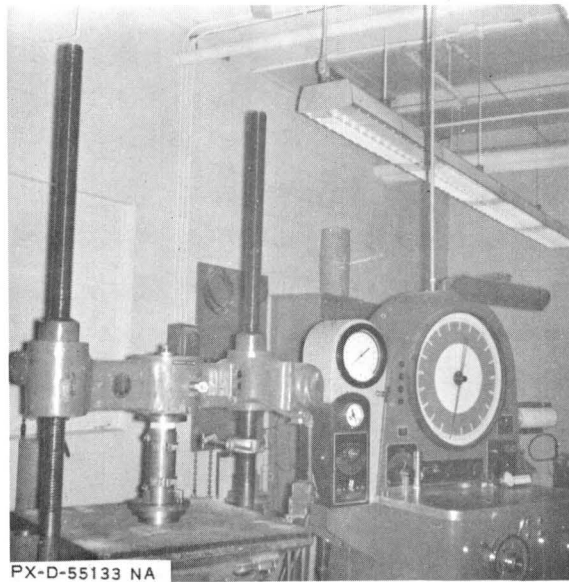


Fig. 9. "S" compaction device.

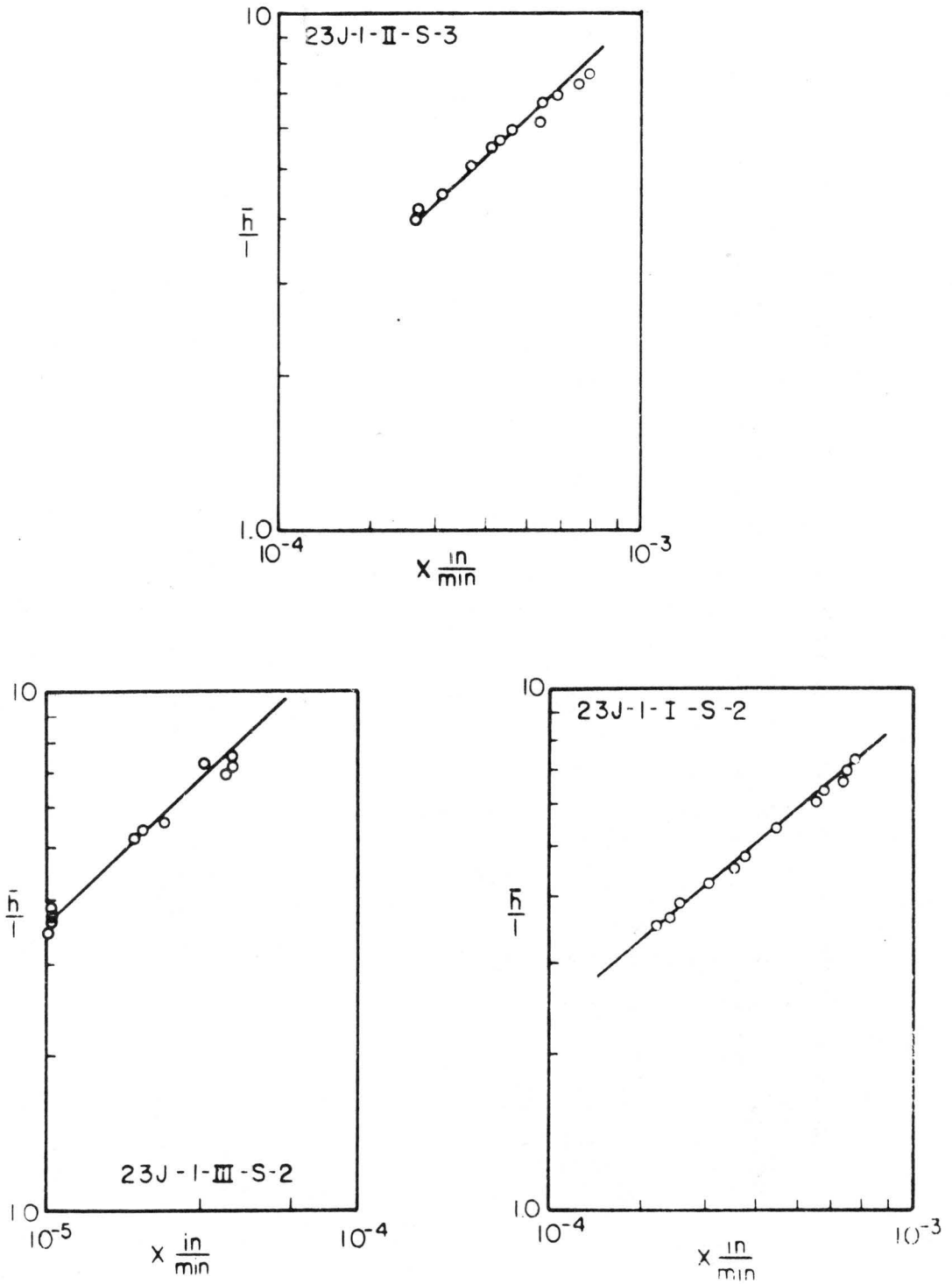


FIG. 10 GRADIENT -VS- VELOCITY FOR SELECTED SILT SAMPLES

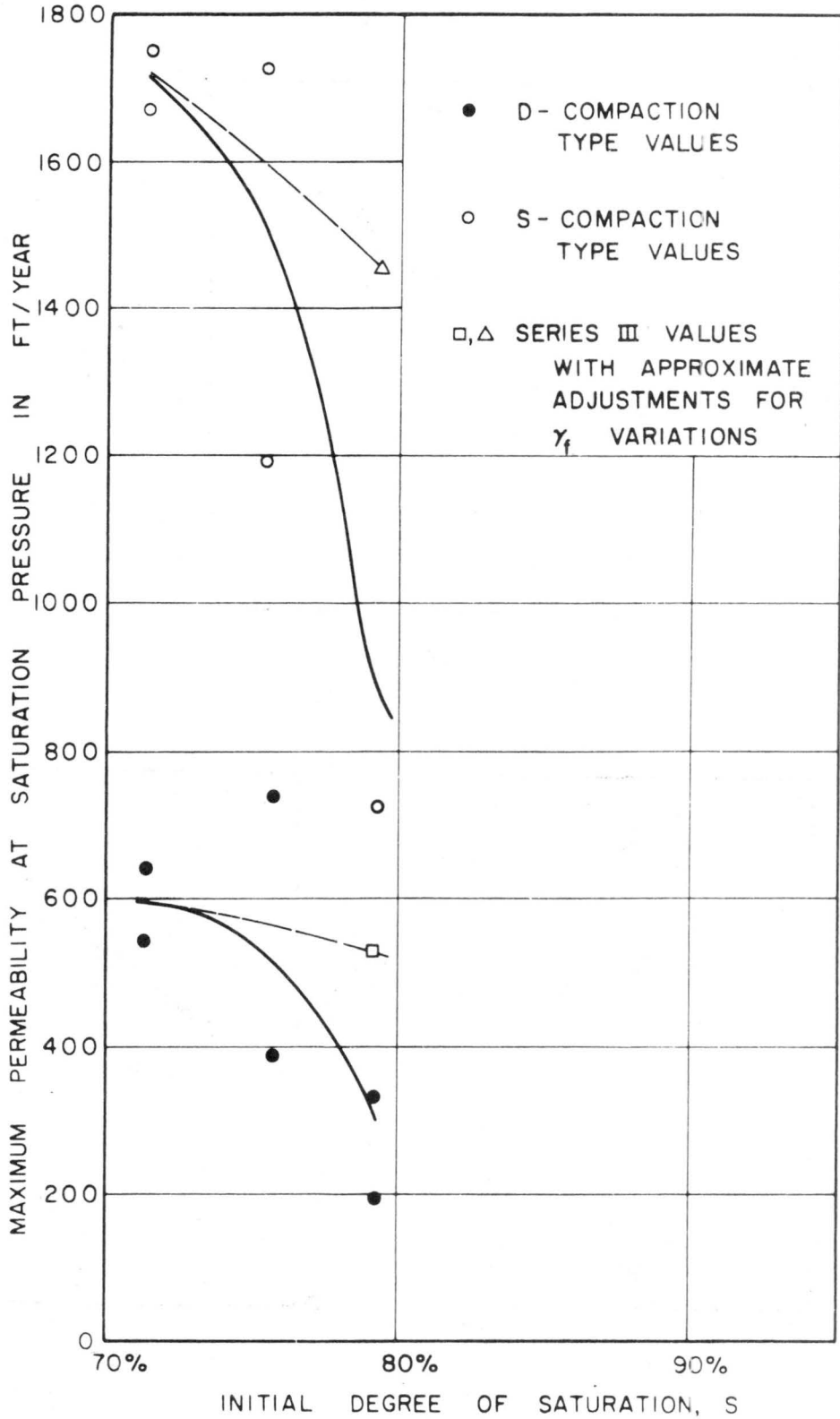


FIG. II MAXIMUM SAND PERMEABILITY AT SATURATION PRESSURE AS A FUNCTION OF INITIAL DEGREE OF SATURATION.

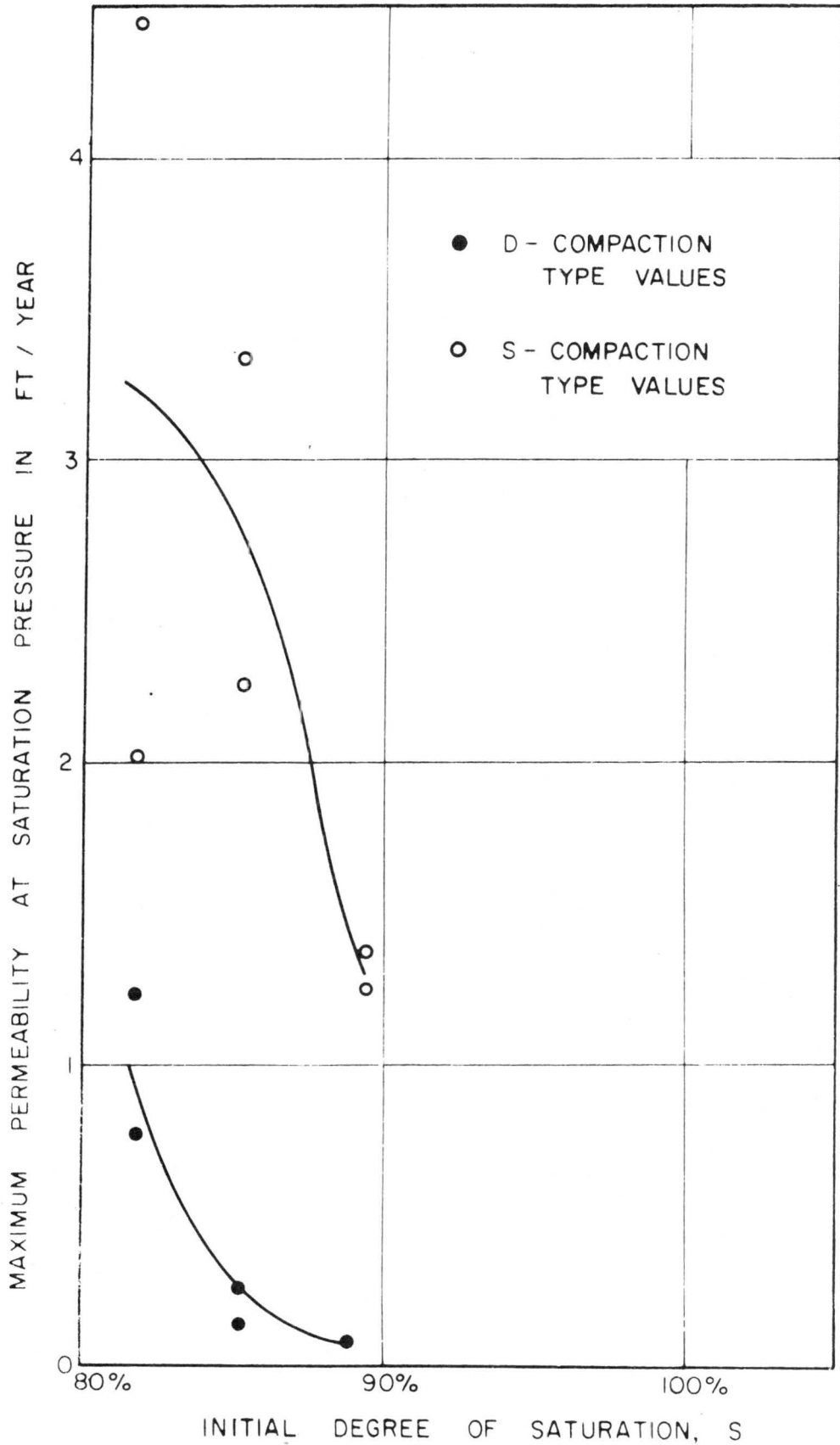


FIG. 12 MAXIMUM SILT PERMEABILITY AT SATURATION PRESSURE AS A FUNCTION OF INITIAL DEGREE OF SATURATION.

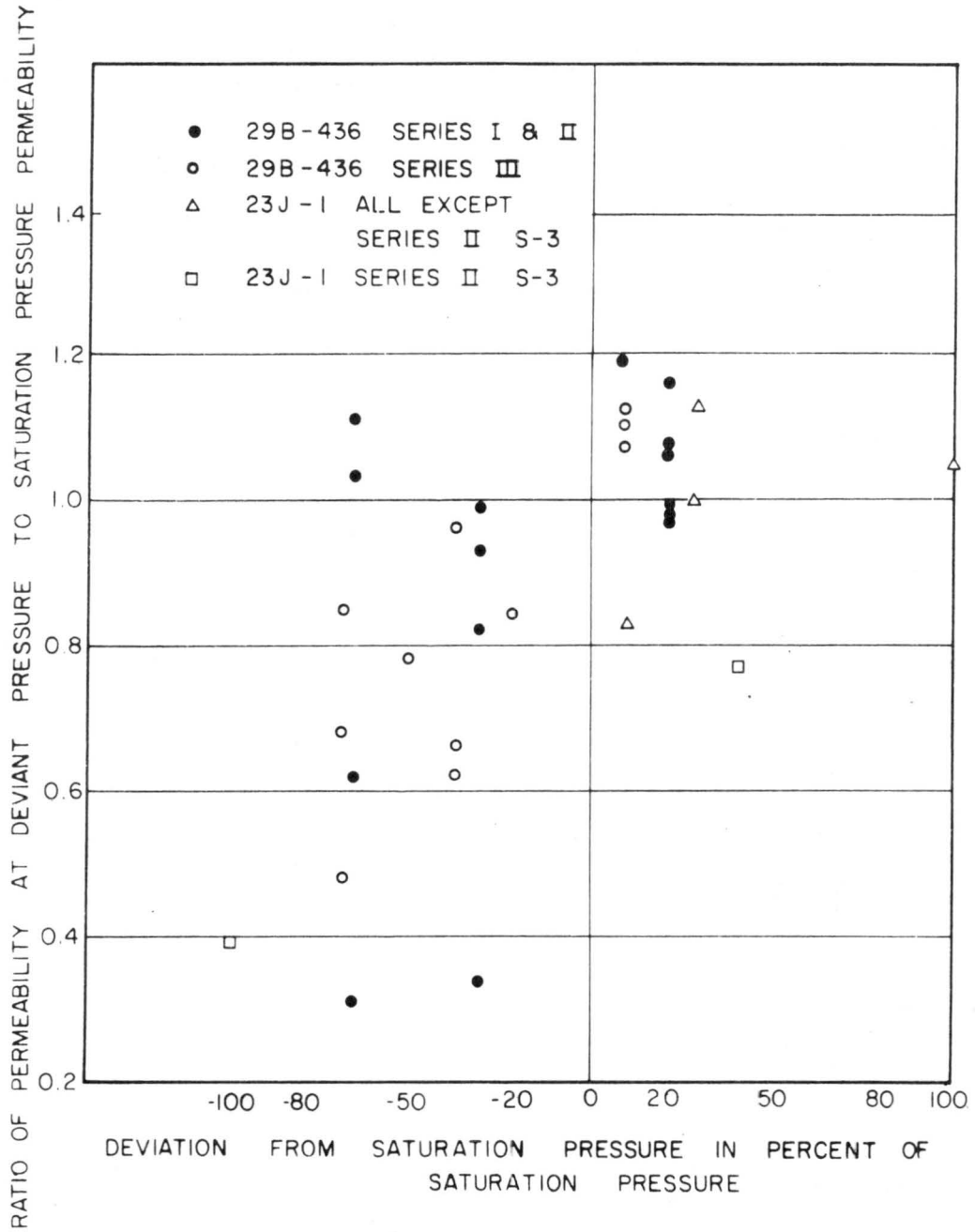


FIG. 13 ADEQUACY OF SATURATION PRESSURE IN PRODUCING SATURATION.

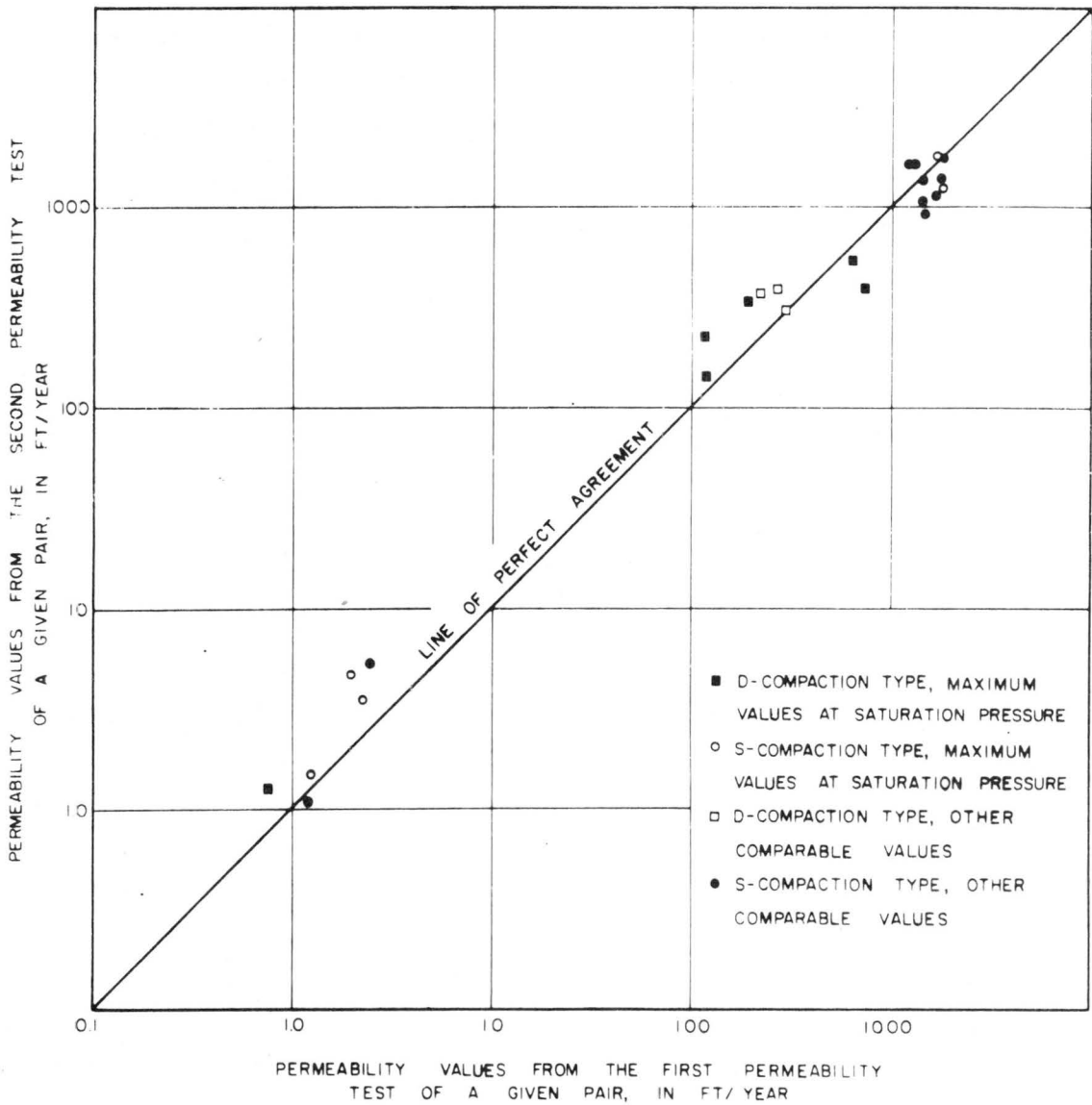


FIG. 14 PERMEABILITY VALUES FROM IDENTICAL HIGH - PRESSURE PERMEABILITY TESTS.

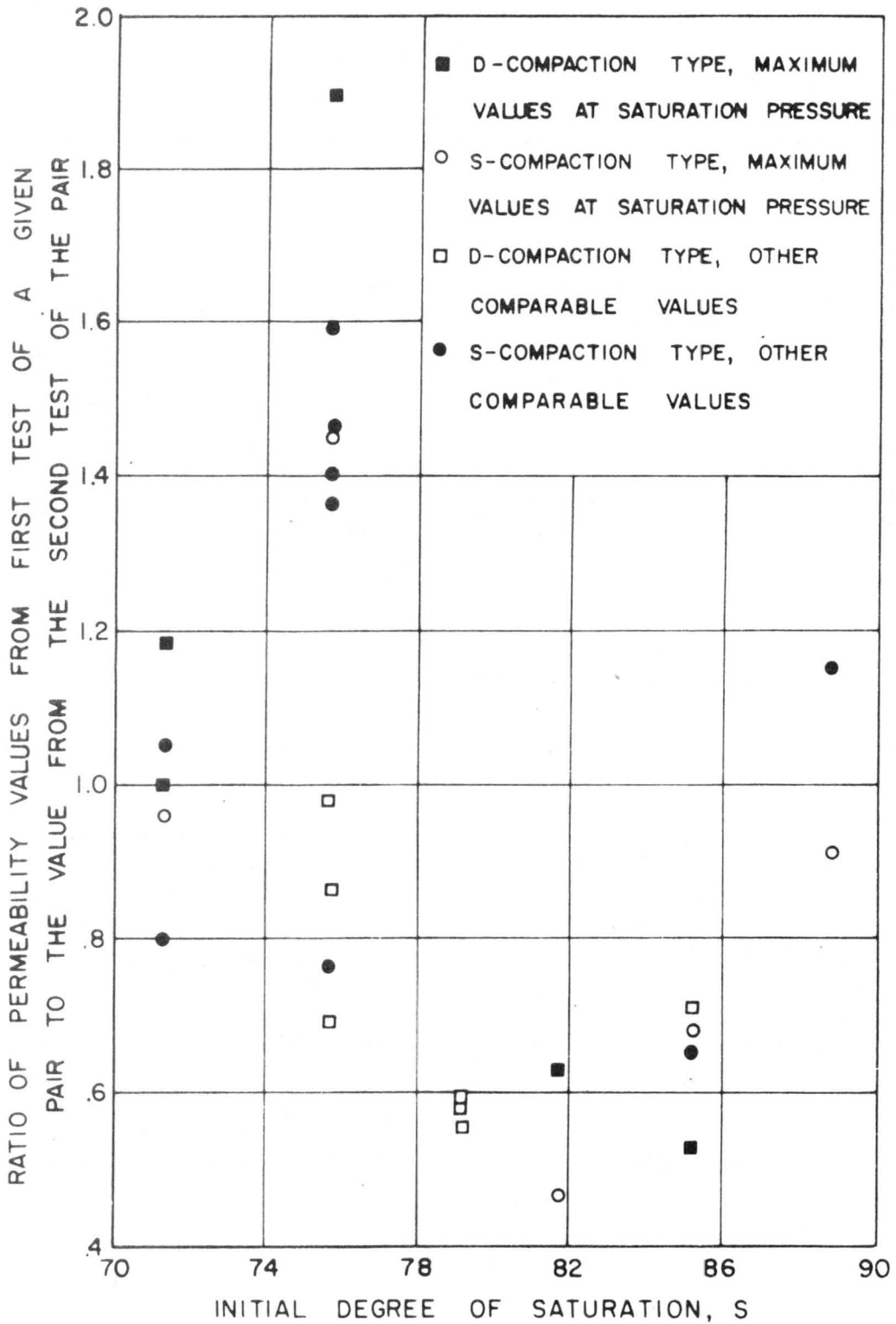


FIG. 15 RATIOS OF PERMEABILITY VALUES FROM IDENTICAL HIGH PRESSURE PERMEABILITY TESTS.

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table 1

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil.	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
.	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
.	0.3048 (exactly)*	Meters
.	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
.	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03 (exactly)*	Square centimeters
.	0.092903 (exactly)	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
.	4,046.9*	Square meters
.	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
.	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
.	0.473166	Liters
Quarts (U.S.)	9,463.58	Cubic centimeters
.	0.946358	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
.	3.78543	Cubic decimeters
.	3.78533	Liters
.	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
.	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
.	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain	Multiply	By	To obtain
MASS			FORCE*		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams	Pounds	0.453592*	Kilograms
Troy ounces (480 grains)	31.1035	Grams		4.4482*	Newtons
Ounces (avdp)	28.3495	Grams		4.4482 x 10 ⁻⁵ *	Dynes
Pounds (avdp)	0.45359237 (exactly)	Kilograms	WORK AND ENERGY*		
Short tons (2,000 lb)	907.185	Kilograms	British thermal units (Btu)	0.252*	Kilogram calories
	0.907185	Metric tons		1,055.06	Joules
Long tons (2,240 lb)	1,016.05	Kilograms	Btu per pound	2.326 (exactly)	Joules per gram
			Foot-pounds	1.35582*	Joules
FORCE/AREA			POWER		
Pounds per square inch	0.070307	Kilograms per square centimeter	Horsepower	745.700	Watts
	0.689476	Newtons per square centimeter	Btu per hour	0.293071	Watts
Pounds per square foot	4.88243	Kilograms per square meter	Foot-pounds per second	1.35582	Watts
	47.8803	Newtons per square meter	HEAT TRANSFER		
MASS/VOLUME (DENSITY)			Btu in./hr ft ² deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
Ounces per cubic inch	1.72999	Grams per cubic centimeter		0.1240	Kg cal/hr m deg C
Pounds per cubic foot	16.0185	Kilograms per cubic meter	Btu ft/hr ft ² deg F (C, thermal conductance)	1.4880*	Kg cal m/hr m ² deg C
	0.0160185	Grams per cubic centimeter		0.568	Milliwatts/cm ² deg C
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter	Deg F hr ft ² /Btu (R, thermal resistance)	4.882	Kg cal/hr m ² deg C
MASS/CAPACITY			Btu/lb deg F (c, heat capacity)	1.761	Deg C cm ² /milliwatt
Ounces per gallon (U.S.)	7.4893	Grams per liter	Btu/lb deg F	4.1868	J/g deg C
Ounces per gallon (U.K.)	6.2362	Grams per liter	Btu/lb deg F	1.000*	Cal/gram deg C
Pounds per gallon (U.S.)	119.829	Grams per liter	Ft ² /hr (thermal diffusivity)	0.2581	Cm ² /sec
Pounds per gallon (U.K.)	99.779	Grams per liter		0.09290*	M ² /hr
BENDING MOMENT OR TORQUE			WATER VAPOR TRANSMISSION		
Inch-pounds	0.011521	Meter-kilograms	Grains/hr ft ² (water vapor transmission)	16.7	Grams/24 hr m ²
	1.12985 x 10 ⁶	Centimeter-dynes	Perms (permeance)	0.659	Metric perms
Foot-pounds	0.138255	Meter-kilograms	Perm-inches (permeability)	1.67	Metric perm-centimeters
	1.35582 x 10 ⁷	Centimeter-dynes	Table III		
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter	OTHER QUANTITIES AND UNITS		
Ounce-inches	72.008	Gram-centimeters	Multiply	By	To obtain
VELOCITY			Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Feet per second	30.48 (exactly)	Centimeters per second	Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
	0.3048 (exactly)*	Meters per second	Square feet per second (viscosity)	0.02903* (exactly)	Square meters per second
Feet per year	0.965873 x 10 ⁻⁶ *	Centimeters per second	Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Miles per hour	1.609344 (exactly)	Kilometers per hour	Volts per mill.	0.03937	Kilovolts per millimeter
	0.44704 (exactly)	Meters per second	Lumens per square foot (foot-candles)	10.764	Lumens per square meter
ACCELERATION*			Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Feet per second ²	0.3048*	Meters per second ²	Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
FLOW			Milliamps per square foot	10.7639*	Milliamps per square meter
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second	Gallons per square yard	4.527219*	Liters per square meter
Cubic feet per minute	0.4719	Liters per second	Pounds per inch	0.17858*	Kilograms per centimeter
Gallons (U.S.) per minute	0.06309	Liters per second			