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MEASUREMENT AND ESTIMATION OF PERMEABILITY OF SOILS FOR ANIMAL WASTE STORAGE FACILITY DESIGN

I. INTRODUCTION

This technical note is intended for use by area engineers and state personnel in planning and preliminary evaluation of conservation practices that store water or other liquids including animal wastes. Such practices include, but are not limited to; grade stabilization structures, waste storage ponds, sewage lagoons, and ponds. The improper evaluation of the permeability of in situ and compacted soils can result in the practice not fulfilling its intended purpose, contamination of surface and ground water, and, thus, the failure of the structure.

This document describes the primary factors affecting permeability of soils, and the importance of each factor affecting the potential for seepage from the boundaries of the impoundment. These factors should be evaluated and documented in investigating the suitability of planned or existing sites where SCS technical assistance is given.

Guidelines for preliminary estimates of permeability, both qualitative and quantitative, are given. On critical projects, sampling and testing in the planning stage will assist in locating most suitable sites. Final designs may require field testing, sampling, and laboratory testing. This note provides information on the field and laboratory permeability tests that are available and their applicability. Permeability rates, along with the procedures given in Soil Mechanics Note 7, may be used to calculate quantities of seepage from water impoundment sites.

Many federal and state agencies have established guidelines for leakage from animal waste sites. These minimums are usually stated in terms of allowable permeability or the physical properties of the soils involved. This note includes a variety of considerations that are important at a successful site and that can be documented for future reference.

SNTC Technical Note 716 describes methods for determining required thickness of compacted clay liners in agricultural waste storage ponds and treatment lagoons. Approximate estimates for compacted liner permeability are given. This note provides means for more precise estimation as well as methods for field and laboratory measurement of the permeability of clay liners. SNTC Technical Note 716 used together with this note should give excellent planning estimates for required minimum thickness of clay liners.

II. FACTORS AFFECTING PERMEABILITY

A. Introduction.

The coefficient of permeability is defined as the quantity of flow through a unit cross-sectional area of a porous media under a unit hydraulic gradient. The units are in $L^3/L^2/Time$. Because water flows only through the pores in a soil mass, it is important to understand that the velocity of seepage water is higher than the value of the coefficient of permeability. The seepage velocity is related to the value of coefficient of permeability by the equation:

$$\text{Seepage Velocity} = \frac{\text{Coefficient of Permeability}}{\text{Porosity (\%)/100}}$$

For instance, in a soil that has a coefficient of permeability of 1×10^{-7} centimeters per second and a porosity of 60 percent, water would flow through the soil at an average velocity of 1.67×10^{-7} centimeters per second, and flow through a 1 foot thick layer would take about 5.8 years.

In discussing the permeability of a soil mass, it is helpful to define permeability in two ways. These two definitions of permeability are sometimes referred to as macro-permeability and micro-permeability. Alternative terminology is to discuss the soil material characteristics and the soil mass characteristics. Macro-permeability refers to the overall permeability of a large soil mass. Micro-permeability refers to the permeability of a soil element within a larger mass of soil. Soil material characteristics are mainly a function of the gradation and classification of the soil. Soil mass characteristics include structure in the soil, cracks, root holes, and other discontinuities in the soil mass.

To illustrate this concept, consider a compacted, highly plastic clay that has been allowed to dry out at some time. Such a clay may have a very low permeability on a micro-permeability basis (soil material characteristics), but the compacted mass could have a higher macro-permeability because of drying cracks (soil mass characteristics). The soil material characteristics are slowly permeable; the higher than expected permeability is because of the soil mass characteristics.

Soil material characteristics affecting permeability are discussed in parts B, C, and E of this section. Soil mass characteristics are discussed in part D.

B. Soil Classification.

Often, preliminary estimates of soils' permeabilities are based on soil classification. The Unified Soil Classification System (USCS) is based upon several soil properties that directly influence permeability. Consequently, the USCS class does give a good preliminary indication of permeability. Because the USCS is based on soils' material characteristics, permeability estimates based solely on classification don't consider soil mass characteristics that can strongly affect the permeability of a soil mass. Permeability estimates based solely on soil material characteristics, such as gradation and plasticity, apply best to compacted soils. Compacted soils do not have some of the structural or mass characteristics of undisturbed soils.

As covered in following sections, the percentage of fines (percentage finer than the # 200 sieve) and the character of those fines are very important. The USCS divides soils into groups on the basis of fines contents of: less than 5 percent; 5 to 12 percent; more than 12 percent but less than 50 percent; and 50 percent or more fines. The character of fines is expressed in the USCS by defining where the liquid limit and plasticity index plot on a plasticity chart. Plastic fines plot on or above the "A-line," slightly plastic fines and nonplastic fines plot below the

"A-line," and hatched-zone fines plot on or above the "A-line" in the range of PI values between 4 and 7, with liquid limits less than 30.

1. Usually, the less permeable soil groups are the fine-grained soils, those with 50 percent or more passing the #200 sieve. A general ranking of the five USCS classes of fine-grained soils is given below. This grouping, however, does not consider many other important factors covered in following sections. For instance, an ML soil may have a lower permeability than a CL-ML soil if the ML soil has 95 percent fines as opposed to 55 percent fines for the CL-ML soil. In order of increasing permeability, the fine grained USCS classes are:

CH CL MH CL-ML ML

2. Another group of usually slowly permeable soils are the silty and clayey coarse-grained soils. These soils may have from 13 percent to 49 percent fines. These soils may be as slowly permeable or even less permeable than some of the fine-grained groups, such as ML, listed above. The soils in this category listed in general order of increasing permeability are:

SC GC SC-SM GC-GM SM GM

One must be especially careful in evaluating these soil types to determine whether cleaner sand and gravel lenses occur within a profile. Field logging and sampling procedures may obscure this possibility if layers of different soil types are mixed.

3. The next most permeable soil groups are the sands and gravels that have between 5 and 12 percent fines (inclusive). These soil groups are listed in order of increasing permeability as follows:

SW-SC	SW-SM	SP-SC	SP-SM
GW-GC	GP-GC	GW-GM	GP-GM

The permeability of these soils may be estimated from the D_{10} of the soil. The term D_{10} is defined in following section II.C.3. The classes that have plastic fines are less permeable than those that have nonplastic or slightly plastic fines, other factors being equal.

4. The most permeable soil classifications are those that have less than 5 percent fines. The soil groups are listed in order of increasing permeability as follows:

SW GW SP GP

The permeability of these soils is largely determined by the D_{10} size. Other factors being equal, soils that have a wide assortment of particle sizes (well-graded) are less permeable than soils that have a narrow range of particle sizes (poorly graded).

Figure 1 gives a general description of various soil types and general permeability information. This information is very general and does not specifically apply to either undisturbed or compacted soils. It does not consider many important factors that can drastically affect these generalized values of

PERMEABILITY CHARACTERISTICS OF SOILS

Cm/Sec.	10^{1}	1.0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}
Ft/Day	10^{5}	10^{4}	10^{3}	10^{2}	10^{1}	1.0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
Relat. Perm.	Extremely High	Very High	High	Medium	Low	V. Low	Practically Impervious				
Soil Types	Clean Gravel (GP)	Clean sands, clean sand and gravel mixtues (GW, GP, SW, SP, SM)	Very fine sands, organic and inorganic silts, mixtures of sand silt and clay, glacial till, stratified clay deposits, etc. (GM, SM, ML, GC, CL)	"Impervious" soils. Homogeneous clays below zone of weathering (CL, CH)							
			"Impervious" soils. Modified by effects of vegetation and weathering (MH, ML, CL)								
Direct determination of K	Field tests. Reliable if properly conducted. Considerable experience required	Well permeameter test. Considerable experience required									
	Constant head permeameter. Little experience required										
Indirect determination of K		Falling-head permeameter. Reliable. Little experience required	Falling-head permeameter. Unreliable. Much experience required	Falling-head permeameter. Fairly reliable. Considerable experience necessary							
	Computation from grain size distribution Applicable only to clean, cohesionless sands and gravels (less than 10% fines)		Computation based on results of consolidation tests. Reliable. Considerable experience required								

After Casagrande and Fadum, 1940, with SCS evaluation of relative permeability

Figure 1. Permeability Characteristics of Soils

permeability. It should not be used as the only documentation of assumed permeability values.

C. Gradation.

1. Introduction.

A soil's permeability (soil material characteristics) is influenced strongly by its gradation characteristics. Gradation affects permeability as discussed below:

2. Percentage of fines.

Guidelines sometimes require a minimum percentage of fines for soils at grade at a proposed waste storage site, or for soils to be used in a blanket or lining around its boundary. One regulatory agency specifies a minimum fines percentage of 30%.

The following permeability test results were obtained in a series of tests on fine sands to which varying amounts of silty fines had been added. The test results illustrate that the influence of the percentage of material finer than the # 100 sieve is dramatic. (Reference 7):

Percentage Finer Than #100 Sieve	Coefficient of Permeability (feet per day)	(centimeters per second)
0	80-300	2.8×10^{-2} - 1.1×10^{-1}
2	10-100	3.5×10^{-4} - 3.5×10^{-3}
4	2-50	7.1×10^{-4} - 1.8×10^{-2}
6	0.5-20	1.8×10^{-4} - 7.1×10^{-3}
7	0.2-3	7.1×10^{-5} - 1.1×10^{-3}

For soils that have a low percentage of fines (less than about 10 percent), the D_{10} size is the most important indicator of the soils' permeability. For soils that have a high percentage of fines (more than 30 percent), the plasticity characteristics of the fines are probably equally important.

Figure 2 shows how the presence of fines drastically reduces the permeability of coarse-grained soils. Permeabilities shown on the chart are for a coarse sand to which various amounts of clay and silt type fines have been added. The chart shows that clay fines reduce permeability more than silty fines (Reference 34). The chart is not useful as a design tool, but it does demonstrate quantitatively how the percentage of fines and the character of those fines affects the permeability of coarse-grained soils.

3. Effective grain size (D_{10})

The D_{10} size of a soil is the diameter of the particle size such that 10 percent of the total sample, by dry weight, is smaller than this size particle. The value is obtained from a soil gradation curve plotted as percent finer versus sieve size or log of grain size as shown in figure 3. The data for plotting such curves is obtained from a gradation analysis, or mechanical analysis of a soil sample.

Figure 2. Effect of Fines on Permeability

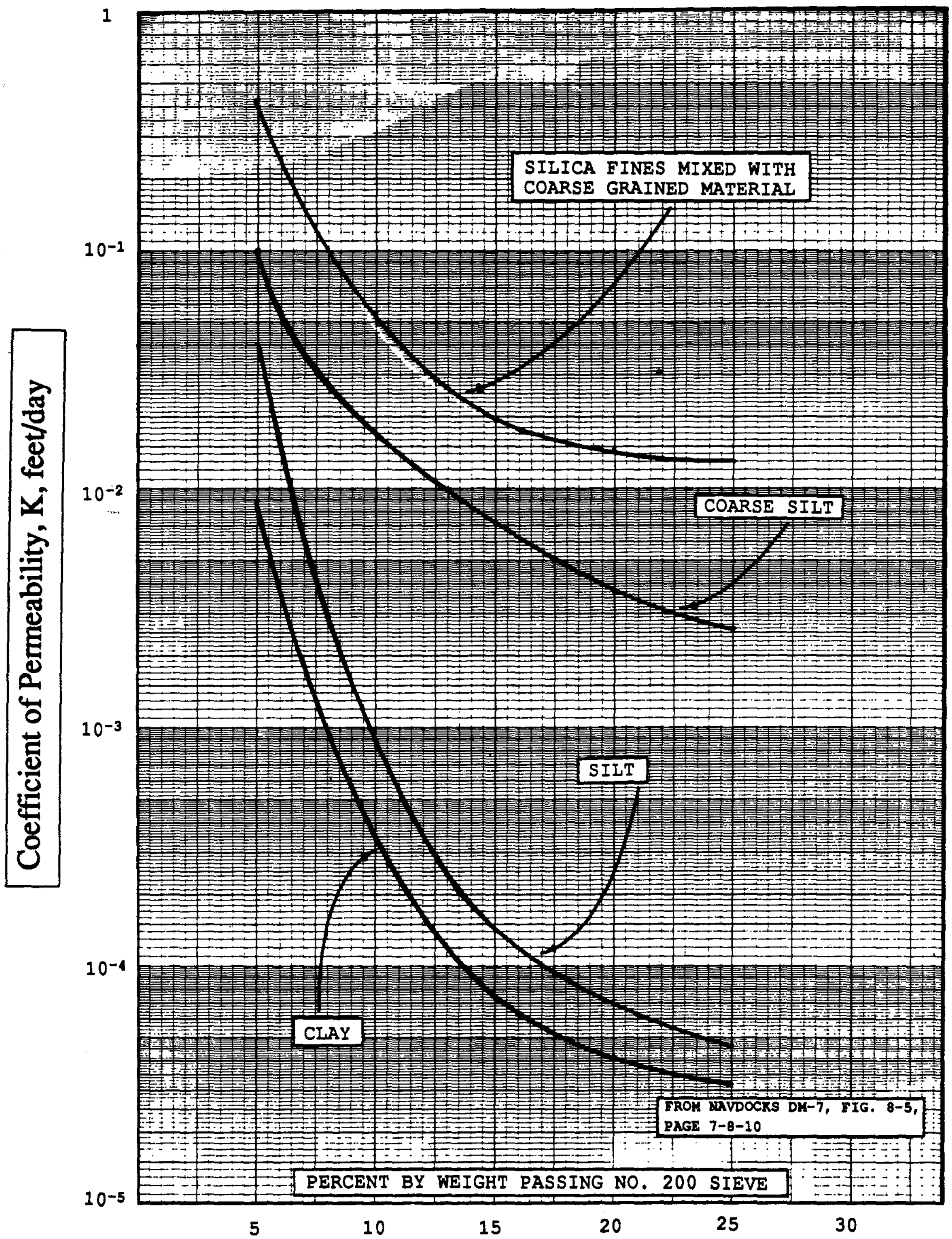

Figure 3

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Soil Conservation Service

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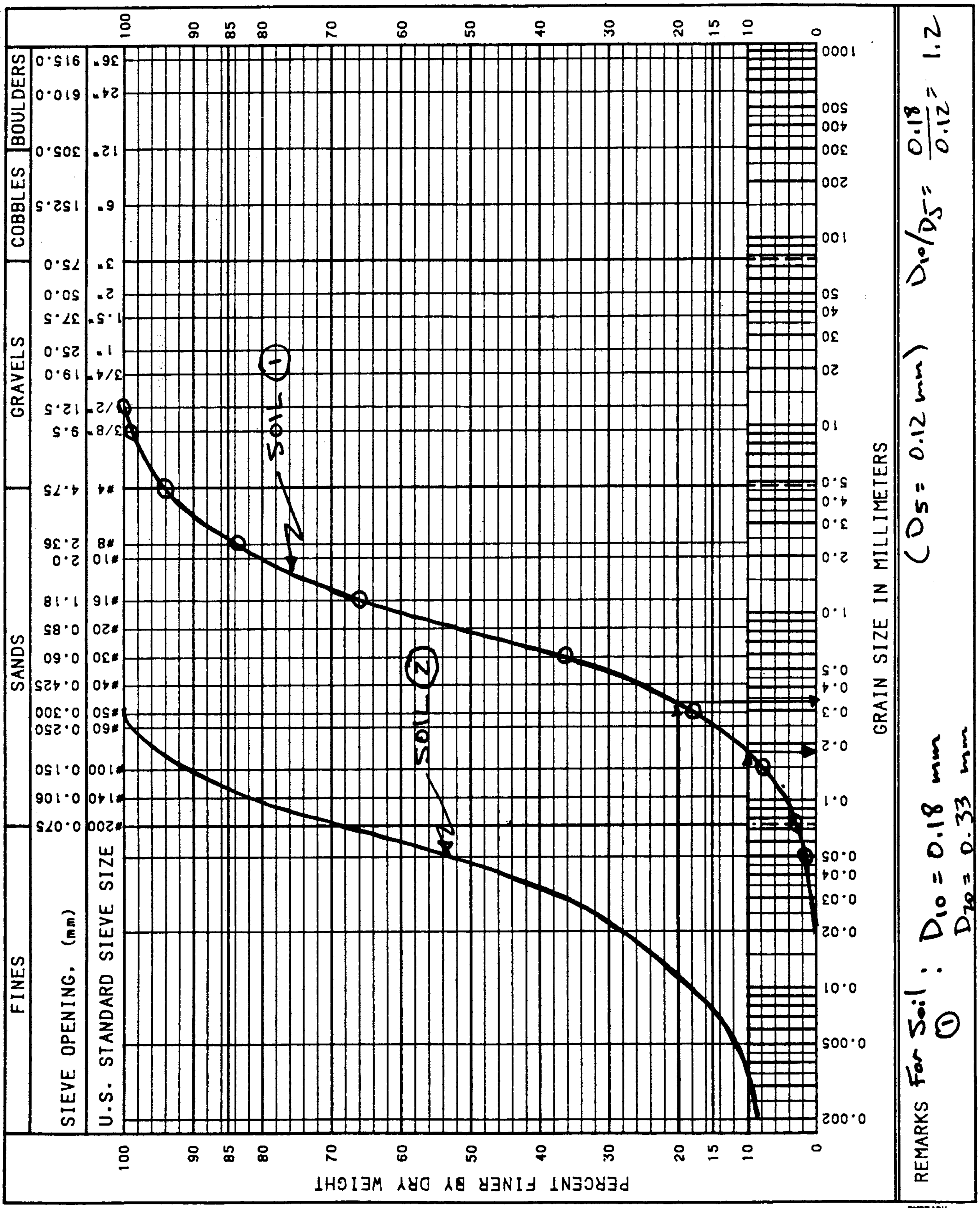
GRAIN SIZE ANALYSIS FOR

____
(Specify)

Project and state Permeability Estimating Procedures

Designed at SML Ft Worth By [signature] Date 6/90



In figure 3, read horizontally from 10 percent to intersect the gradation curve, read downwards to the scale at the bottom of the curve the D_{10} size for the soil using the scale in millimeters. For the example soil number 1 shown in figure 3, read a D_{10} size of 0.18 millimeters.

Several empirical estimates have been developed based on correlations of permeability measurements and gradations of tested soils. These are discussed as follows.

a. Hazen's equation.

The following equation is based on experiments on relatively clean filter sands in a loose state. This chart is applicable only to soils that have a D_{10} size between 0.1 and 3 millimeters. USCS classes can include SP, SP-SM, SW, and SW-SM. If the ratio of the D_{10} size to the D_5 size of the sample is greater than 1.4, the estimate given by the equation will be too high.

Assumes a well-graded sample.

$$k, (\text{fpd}) = 2{,}835 \times D_{10}^2$$

Where,

k is the coefficient of permeability, in feet per day
D_{10} is effective grain size, in mm.

For the example soil number 1 shown on figure 3 with a D_{10} of 0.18 millimeter, calculate an estimated permeability of 92 feet per day (3.25×10^{-2} cm/sec). For this soil, the ratio of D_{10} to D_5 is 1.5. Since this ratio is above the maximum guideline given of 1.4, the estimate for this soil is probably high.

b. Slichter's chart.

These charts are developed for undisturbed soils. The charts, shown on figures 4A and 4B, correlate the permeability of soils with two factors; the D_{10} of the soil, and its dry unit weight. The ordinates of the charts are the dry density of the soil, in grams per cubic centimeter. The abscissas are the permeability, in feet per day. The charts have a series of curves for various D_{10} sizes of soils. Figure 4A is useful for soils that have a D_{10} size between 0.01 and 0.4 millimeters, while figure 4B is for soils that have a D_{10} size between 0.5 and 5.0 millimeters.

Using example soil number 1 in figure 3, estimate the permeability of the soil assuming a dry density of 1.60 grams per cubic centimeter. With a D_{10} size of 0.18 millimeters, read a permeability estimate of about 40 feet per day (1.41×10^{-2} cm/sec).

4. Estimates based on D_{20} size of soil.

The chart shown in figure 5 correlates the D_{20} size, in millimeters, of soils with the coefficient of permeability, in feet per day. The chart is specifically for undisturbed, water deposited soils. To estimate the permeability of a soil using this chart, determine the D_{20} size of a soil from its gradation curve, read vertically in figure 5 to the diagonal line, and read the left scale value for the coefficient of permeability. For example, using soil 1 in figure 3, with a D_{20} of 0.33 millimeters, read a coefficient of permeability of 80 feet per day (2.82×10^{-2} cm/sec) using figure 5 .

Because this chart is based on the D_{20} size and does not adequately consider the importance of the presence of any silt or clay fines in the soil, permeability estimates of the chart can be high. Permeability estimates should be regarded as probably high if the coefficient of uniformity (C_u) of the soil is greater than 5. C_u is defined as the D_{60} size, in millimeters, divided by the D_{10} size, in millimeters. Soils that have low C_u values are poorly graded, and usually more permeable than soils that have higher C_u values.

For the soil 1 in figure 3, the calculated value of C_u is 5.6, and, therefore, the estimate obtained is probably slightly high.

5. Additional Permeability Estimation Tools

Fine-grained soils have gradations such that many of the estimates discussed above are not applicable. The D_{10} or even D_{20} sizes of these soils may be so fine that they cannot be measured in ordinary laboratory tests. Usually, the percentage of a sample finer than 0.002 millimeters is the smallest particle size analyzed. For these soil types, the chart shown in figure 6 may be useful in obtaining a rough estimate of permeability. This figure is based on correlations of several hundred permeability tests by the SCS soil mechanics laboratories. The chart relates the coefficient of permeability versus the percent of a sample that is finer than 0.005 millimeters, for various dry densities.

Although the chart is based on data from tests on compacted soils, it could be used to obtain estimates for foundation soils that do not have other significant features discussed in section D below. Estimates made for natural or in situ soils using this chart are lower limit estimates because the mass characteristics of natural soils are not considered. Mass characteristics, such as drying cracks, generally increase the mass permeability of natural deposits.

To illustrate the use of figure 6, examine soil 2 in figure 3, with a percentage finer than 0.005 millimeters of 12 percent, assuming a dry unit weight of 115 pounds per cubic feet, read a k estimate of 0.008 feet per day (2.82×10^{-6} cm/sec).

D. Structure.

1. Stratification.

Stratified soils have alternating lenses of different gradations and are difficult to sample and analyze. Laboratory tests on soil samples obtained using destructive techniques, such as augers or backhoes, measure the characteristics of the soil after mixing the layers. Properties, such as gradation and plasticity, represent the average of the mixed materials. Often, the permeability of a stratified deposit is largely determined by the permeability of a few lenses. Figure 7 shows of how clean gravel lenses can affect the permeability properties of an alluvial soil deposit.

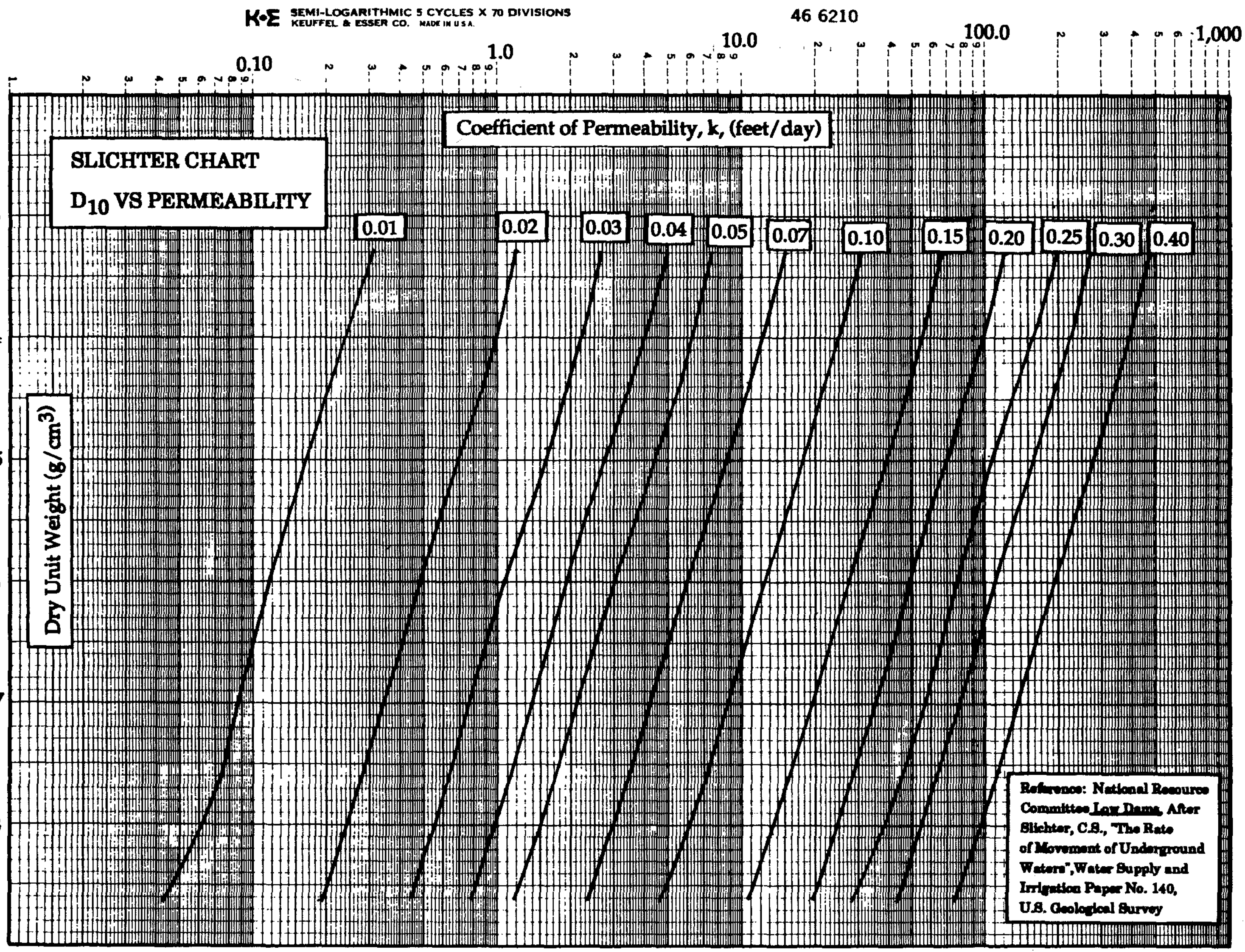


Figure 4A. Slichter Permeability Chart

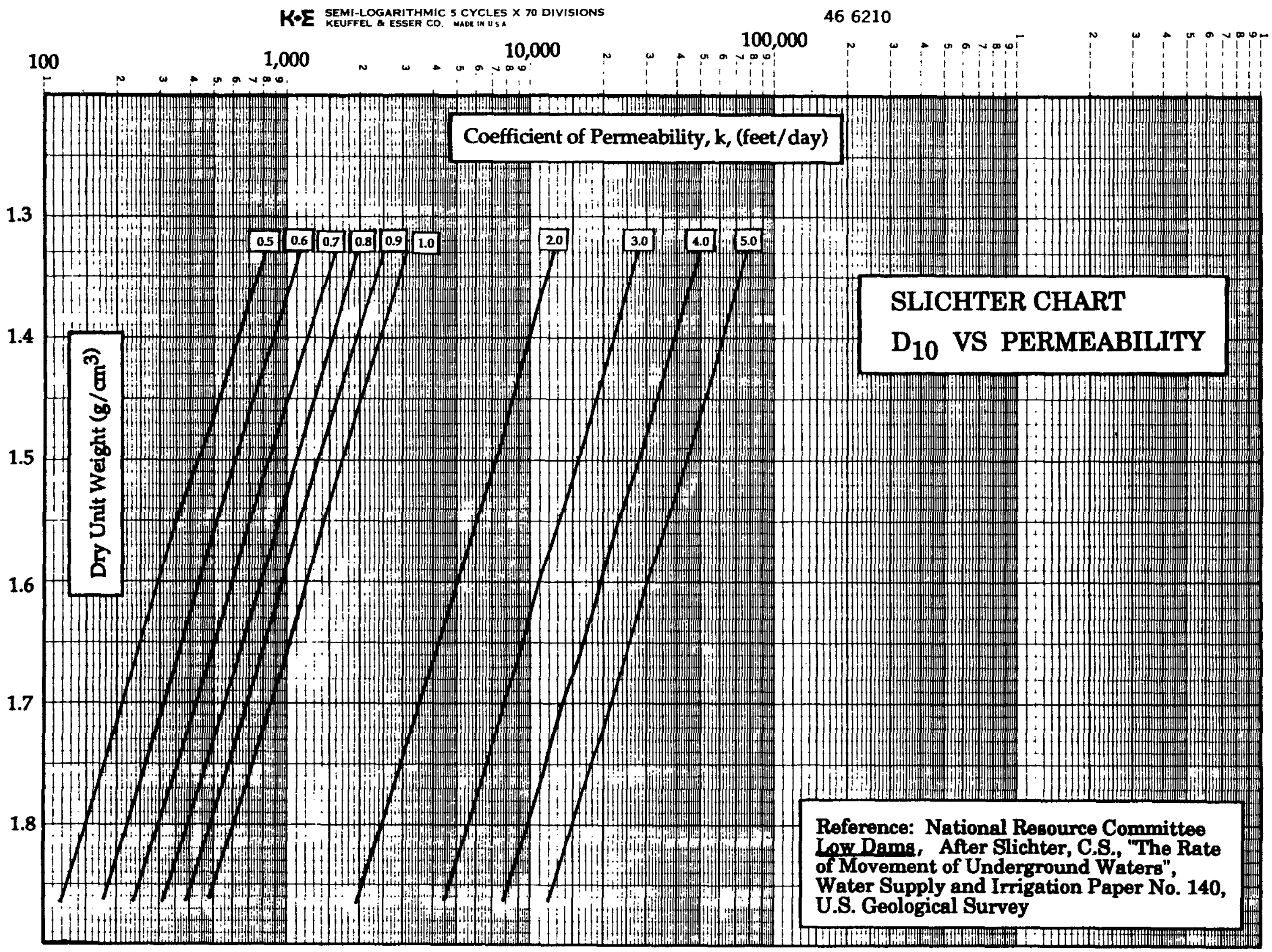
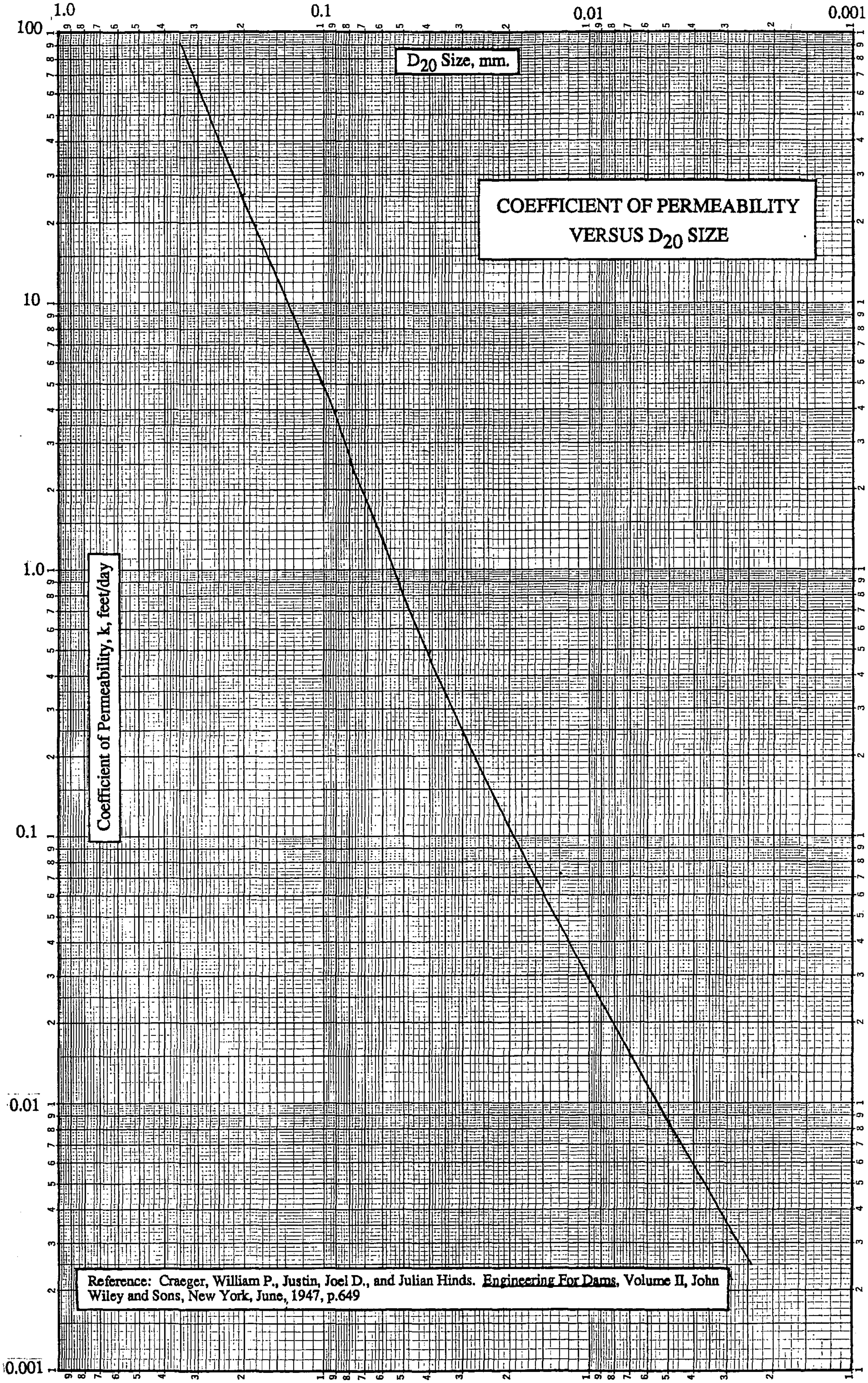


Figure 4B. Slichter Permeability Chart



D20 Size, mm.
1.0
0.1
0.01
0.001
COEFFICIENT OF PERMEABILITY VERSUS D20 SIZE
100
10
1.0
0.1
0.01
0.001
Coefficient of Permeability, k, feet/day
Reference: Craeger, William P., Justin, Joel D., and Julian Hinds. Engineering For Dams, Volume II, John Wiley and Sons, New York, June, 1947, p.649

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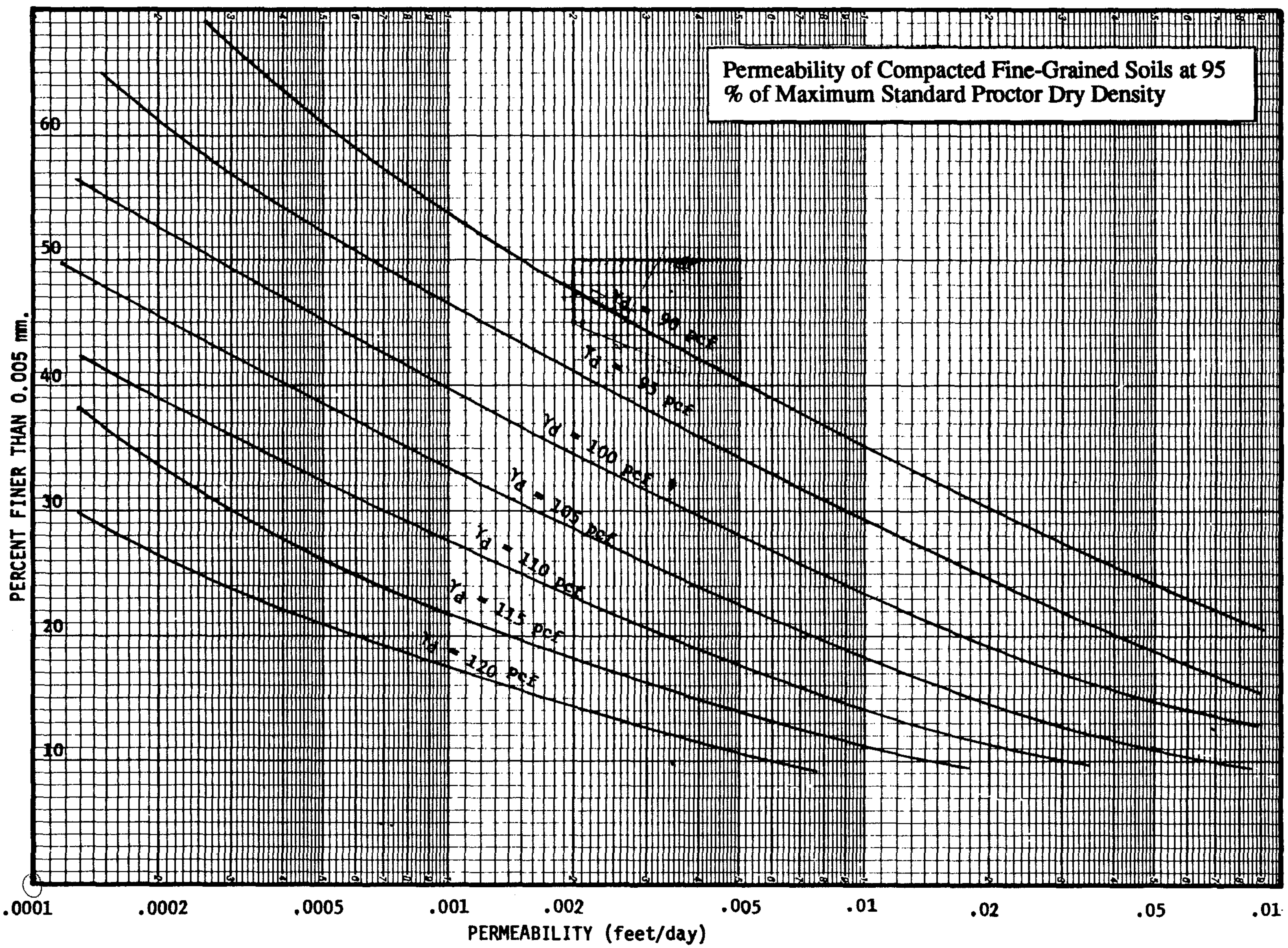


Figure 6. Permeability of Compacted Fine-Grained Soils

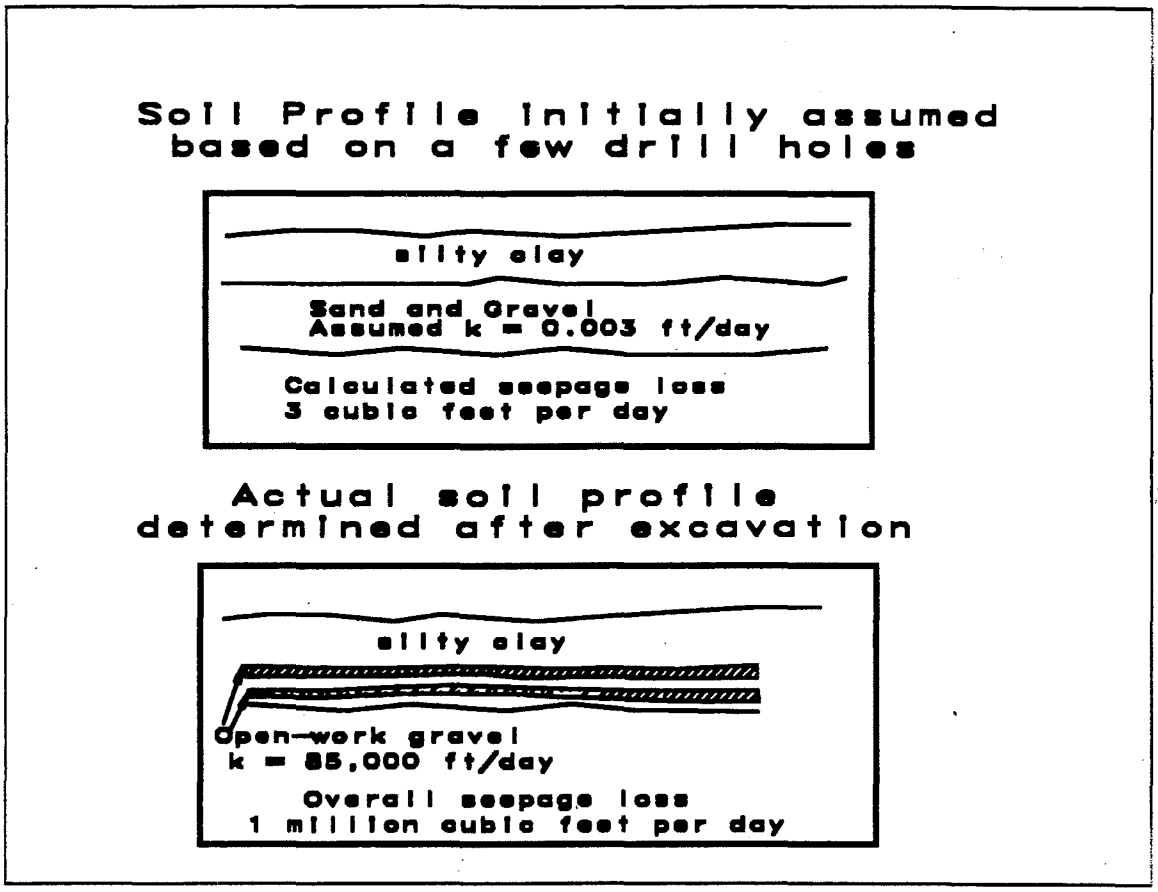


Figure 7. Effect of open-work gravel on permeability.

When lenses or stratified deposits are present at a site, discrete samples of each horizon are important. Alluvial soils are often stratified. These soils usually have a much higher lateral, or horizontal, permeability than vertical permeability. The ratio of horizontal to vertical permeability usually varies from a low of about 9 to as high as 100 or more in alluvial deposits. In stratified deposits, seepage could extend laterally further than in normal deposits.

2. Macro-features

Water may move through discontinuities in a soil deposit even when the intact soil matrix is very slowly permeable. Examples of avenues for water passage include rodent holes, insect and worm holes, crawfish holes, decayed vegetation holes, drying cracks, and a blocky structure that is not healed. Residual features such as joints and fractures in parent material may be present in residual soils developed from weathering of the rock.

An example of such features that is often overlooked is the blocky structure often found in very plastic clay soils, usually CH classifications. On the basis of percentage of fines and plasticity index, the permeability of these soils would be estimated to be very low. However, these soils readily develop numerous interconnected cracks when subject to cycles of wetting and extreme drying. Even when subsequently wetted, the cracks in the soil do not completely heal. Consequently, water can flow through the crack system rather than through intact pods of the clay, and a rather high seepage loss results. This has been observed in several field installations. Field investigations should be watchful for these features.

It is not possible to quantify the effect of such features on the permeability of soil deposits. In some instances, the permeability of soils affected by such features has been found to be at least 1,000 times greater than originally estimated on the basis of assuming no discontinuities in the soil. It is important to note all such features in the site investigation. Designers can then consider remedial measures appropriate for the size, continuity, and intensity of the features in the soil. Often, discing of the boundary soils of the lagoon, followed by compaction, will effectively destroy such features and provide a treated blanket of less permeable soils.

3. Soil Origin

The mode of deposition of soils is important. As previously mentioned, alluvial soils often have a higher lateral than vertical permeability. Soils of other depositional origin may also have features that significantly affect their permeability properties.

Loess is a windblown deposit of silt-sized particles common in the Midwest and Southeast. Loess soils often classify as ML, CL-ML, or CL in the Unified System. The soils typically have 90 percent or more finer than the #200 sieve and have a plasticity index less than 10. On the basis of gradation and the presence of at least some clay fines in the soils, if other factors were not considered, these soils would be estimated to be slowly permeable. However, these soils have a structure caused by their mode of deposition that results in a vertical permeability several orders of magnitude higher than one would expect on the basis of gradation.

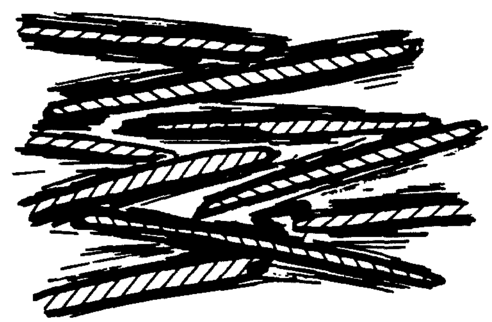
Weathered residual soils often retain the structural characteristics of the parent rocks. Soils weathered from jointed, fractured sandstones, shales, and limestones may have macro-features through which water can flow more easily than through the mass of the soil.

E. Chemical Effects.

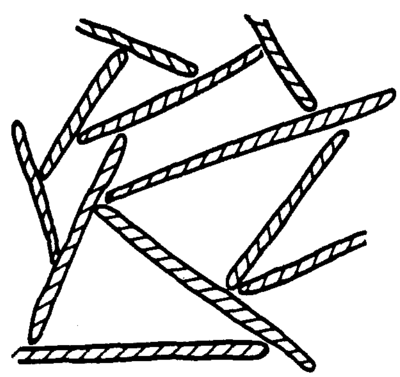
The electrochemical properties of some clay soils may drastically affect their permeability. Often, the usual index tests, such as gradation and Atterberg limits, may not reveal any differences between affected clays and "normal" clays. Examples of clays that have unusual electrochemical composition are dispersive clays and flocculated clays.

Dispersive clays have lower permeability than expected because of the orientation of clay particles. In a dispersive clay, the particles are not strongly attracted to one another, and a structure as shown in figure 8 results. Dispersive clays' have predominantly sodium cations in their pore water. Special field and laboratory tests are required to identify dispersive clays.

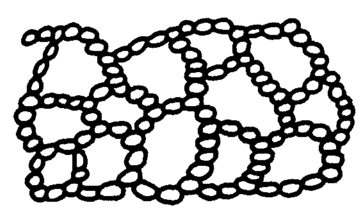
Figure 8. Soil Structure Affecting Permeability



DISPERSED STRUCTURE OF COMPACTED CLAY



FLOCCULENT STRUCTURE OF CLAY



HONEYCOMB STRUCTURE

PHYSICAL PROPERTIES OF SOILS
Means and Parcher, 1963

Flocculated clays usually have predominantly calcium or magnesium cations in the pore water. Higher than normal amounts of calcium in a clay soil causes the clay particles to aggregate and act in a manner similar to a sand. The soils consequently have a much higher permeability than expected on the basis of their clay content. Figure 8 illustrates the structure of a flocculated clay.

The permeability of flocculated clays may be reduced by adding chemicals, such as TSPP (tetra-sodium pyro-phosphate), soda ash (sodium carbonate), and sodium chloride. The National Handbook of Conservation Practices, Practice Standards 521-B, covers this type of treatment. Laboratory tests and field observations are helpful in identifying these types of soils at a planned site.

Conductivity measurements often reveal the presence of high soluble salt content soils, many of which are flocculated. However, some soils that have a high salt content, such as saline or alkali soils, may have a dispersive structure. Therefore, conductivity measurements alone are not useful in assessing this property.

III. PERMEABILITY TESTS

A. Laboratory Tests

1. Advantages. The advantages of laboratory testing for measuring the permeability of soils are:

    a. The water content and density of the soil to be tested can be carefully controlled.

    b. Samples can be saturated prior to testing more readily in laboratory tests.

    c. High hydraulic gradients may be employed, which permits measurement of lower permeabilities in a shorter time.

    d. Laboratory methods are usually much more economical than field methods, especially for slowly permeable soils where long testing times are required to measure low volumes of flow.

2. Disadvantages. The disadvantages of laboratory testing are:

    a. Important macro-features of natural soil deposits, such as drying cracks and alluvial soil stratification, are difficult to model with small laboratory scale specimens. Laboratory specimens are limited in size.

    b. To test undisturbed or in situ soils, samples must be obtained, shipped, and handled by the laboratory. Undisturbed samples are expensive to obtain. Sample disturbance may affect test results.

    c. Horizontal permeability is difficult to measure in laboratory specimens. Usually, vertical permeability is measured.

3. Constant Head Laboratory Permeability Tests

a. Fixed Wall Permeameters.

The simplest type of laboratory permeability apparatus is the fixed wall permeameter (figure 9). These permeameters are often constructed of plastic so that the specimen may be observed during the test. Permeameters generally range from 4 to 6 inches in diameter. Several methods are used to apply a constant head. Figure 9 shows the method SCS labs use. ASTM Standard Test Method D2434 is also available.

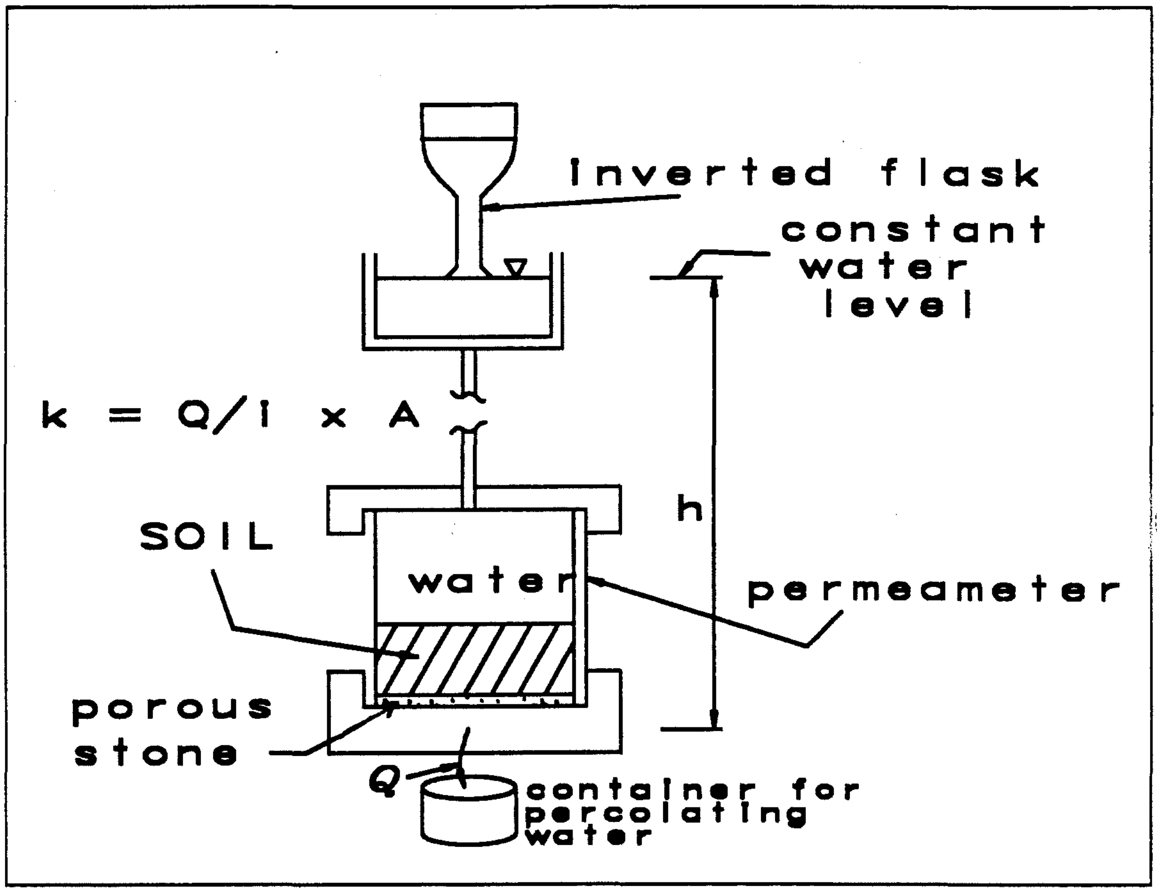


Figure 9. Constant head permeability test.

With the apparatus as shown in figure 9, water flows top to bottom through the specimen. Air pockets that are never removed by the percolating water can be trapped in the sample . The inability to ensure complete saturation of the specimen is one major disadvantage to this type of testing apparatus. The simplicity and economy of the apparatus are advantages. Very low values of permeability cannot be measured very well with this apparatus. Because the calculation of permeability involves physically collecting and measuring effluent, accurate measurements are not possible with very low quantities. This method should not be used to measure k values of less than about 0.01 feet per day (3.5×10^{-6} centimeters per second).

The equation for calculating permeability with the apparatus shown in figure 9 is as follows:

$$k = \frac{Q}{A \times (H/L)}$$

Where,

k = coefficient of permeability, cm/sec
Q = Flow rate through specimen, cm^3/second
A = Cross-sectional area of specimen, cm^2
H = Difference in elevation of water surface between outlet and inlet side of specimen
L = Length of specimen (H and L must have same units of measurement)

H/L is the hydraulic gradient on the sample.

3. Falling Head permeability Tests

a. Fixed Wall Permeameters.

The apparatus shown in figure 10 is often used to measure permeability in conjunction with consolidation tests. The test has all of the disadvantages of any fixed wall permeameter test. The advantage of this test is that it can measure low permeabilities more accurately than a constant head fixed wall permeameter. Permeameters commonly available range from 2.5 inches to 12 inches in diameter, and have allowable specimen thickness from 0.75 to about 4 inches.

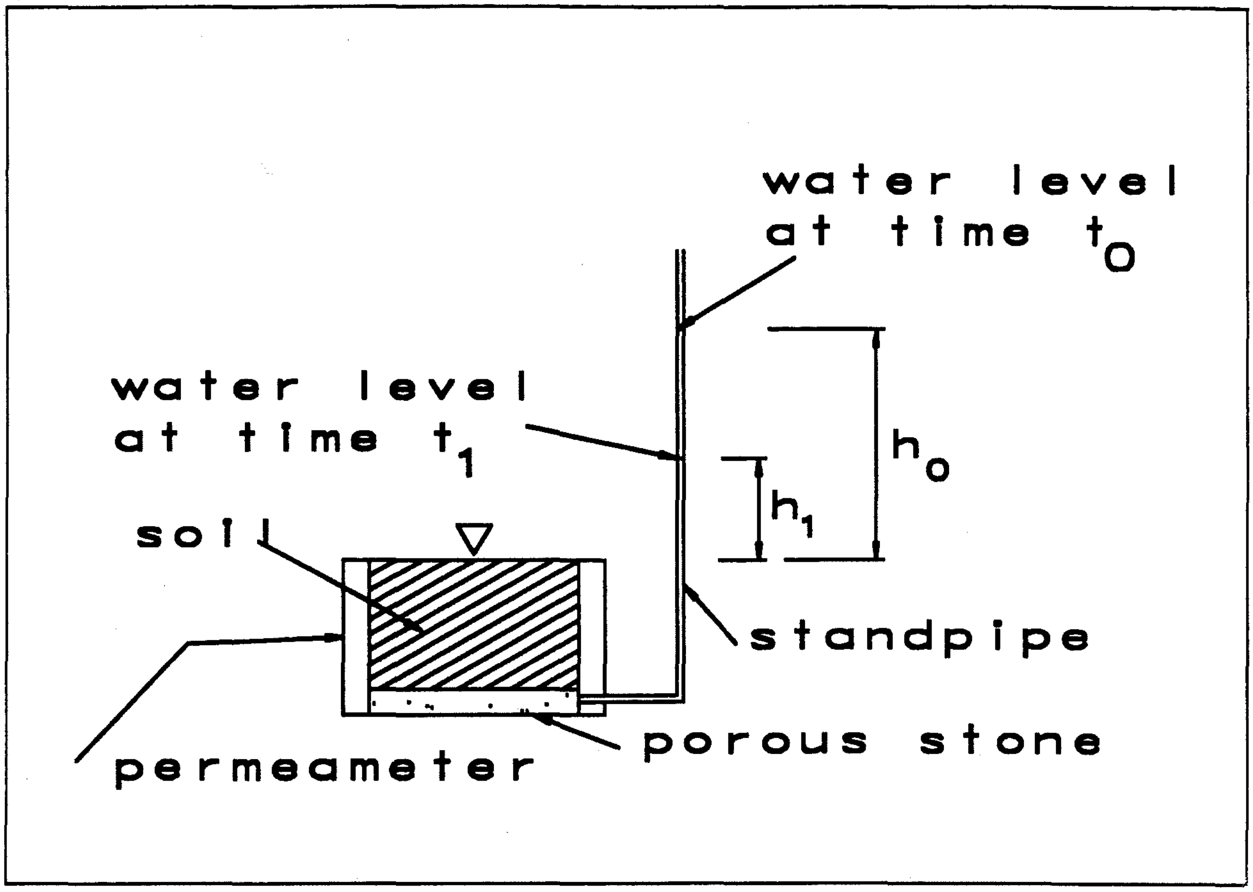


Figure 10. Falling head permeability test.

The equation used to calculate permeability for the apparatus shown in figure 10 is as follows:

$$k = \frac{a \times L \times \ln (h_0/h_1)}{A \times (t_1 - t_0)}$$

Where,

k	=	Coefficient of permeability, cm/sec
a	=	Cross-sectional area of standpipe, cm^2
L	=	Length of flow path through specimen (thickness), cm.
h_0 and h_1	=	Elevation difference between water levels on inlet and outlet side of specimen at times t_0 and t_1
t_0 and t_1	=	Times at which readings h_0 and h_1 are obtained, in seconds.
A	=	Cross-sectional area of sample, cm^2

b. Flexible Wall Permeameters.

Flexible wall permeameters, particularly those which use equipment similar to triaxial shear test equipment, have a number of advantages over fixed wall permeameters. With fixed wall permeameters, leakage up the walls adjacent to the specimen is difficult to prevent and impossible to quantify. With flexible wall permeameters, the problem is almost eliminated. Another advantage to this type of equipment is the ability to saturate specimens using backpressure techniques rather than relying only on percolation and soaking.

A typical laboratory apparatus for performing permeability tests with this apparatus is shown in figure 11.

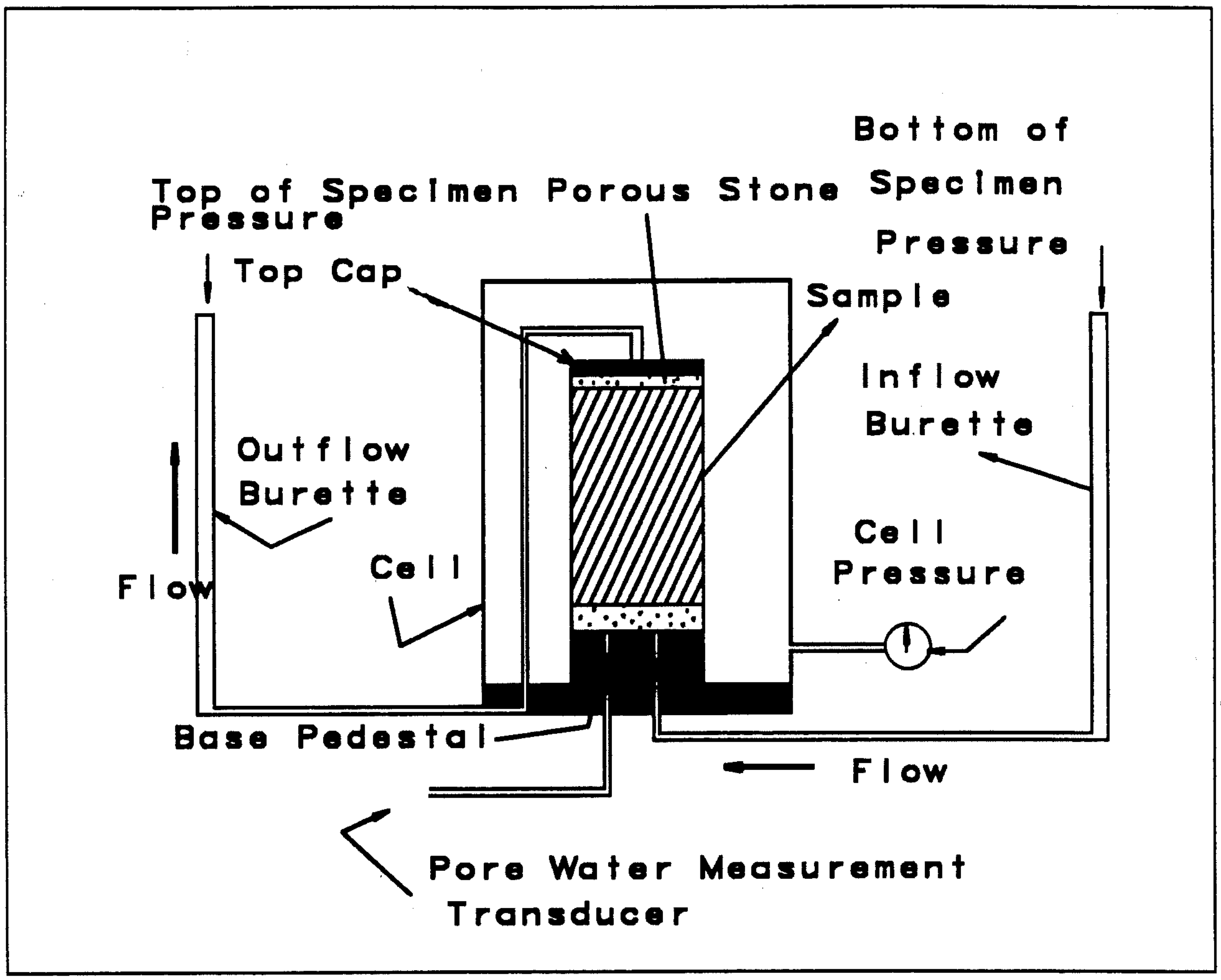


Figure 11. Triaxial permeability test.

Tests may be performed on both undisturbed and remolded samples. Using equipment that accommodates 2.8 inch diameter specimens is convenient because this is a commonly available diameter for undisturbed Shelby tube core samples. Test equipment with 1.4 inch diameter sample sizes is also common, but this size of sample is not as likely to represent structure in undisturbed soils as larger diameter specimens.

This type of apparatus can measure very low permeability rates, because the volume of flow is measured using small diameter burettes rather than collecting the flow and measuring the collected quantity. For instance, a 1 inch (2.54 centimeters) change in a burette that has a 1/8 inch inside diameter represents a flow quantity of 0.2 milliliters, a quantity that would be impossible to measure by collecting the effluent. Another advantage of this type of apparatus is that it is a closed system, and evaporation does not affect the results. If tests are performed for long time intervals, de-aired water should be used for the permeant to prevent buildup of air pockets in the sample.

The coefficient of permeability of the sample is calculated from falling head measurements on the burettes attached to the base and top of the specimen in the apparatus.

B. Field Permeability Tests

1. Advantages

a. A much larger volume of soil can be tested in a field test than is possible with laboratory specimens. The values of permeability obtained are then more representative of field deposits. Field tests also have the ability to include macro-structure in the soil deposit tested.

b. Permeability may be measured in a horizontal direction more easily than with laboratory specimens. For layered deposits, including alluvial soils and compacted fills, the ratio of horizontal to vertical permeability may be on the order of 9:1 to 100:1.

c. Relatively clean, coarse-grained soils cannot be sampled without excessive disturbance, and field tests are the only possible method for measuring their permeabilities.

2. Disadvantages

a. Field permeability tests generally are expensive, time-consuming, and require skilled, experienced personnel to perform reliably.

b. For slowly permeable to very slowly permeable soils, field methods require very long testing times - as much as 2 weeks for very slowly permeable soils.

c. Equipment for performing field permeability tests is not readily available.

3. Types of Field Tests

a. Introduction.

Most normal field permeability tests, such as those used for site investigations, are inadequate to measure accurately the low permeabilities of acceptable in situ soils or compacted liners for sewage lagoons and storage ponds. A number of specialized tests have been developed in the past 10 years to measure very low permeabilities in the field. Daniel (Reference 12) discusses all of the tests and the advantages and disadvantages of each.

For this paper, detailed descriptions are given for three types of tests that can be most easily adopted for SCS purposes.

b. Boutwell Borehole Permeability Test

(1) Introduction.

The apparatus is shown in figure 12. A hole is drilled that is at least 2 inches in diameter larger than the o.d. of the plastic casing used for the test. The hole is carefully cleaned and the bottom smoothed so the casing can be set firmly on the bottom of the hole on undisturbed soil. A bentonite seal at least 6 inches thick is formed around the casing, and the remainder of the annulus between the casing and hole is filled with native soil to the ground surface.

The test is performed in two stages. In the first stage, the casing and standpipe are filled with water. Water runs out the open end of the plastic casing, and thus vertical permeability is largely measured. Permeability is measured using a falling head method. Readings are taken on the standpipe at appropriate time intervals, and a coefficient of permeability is calculated using the applicable equation.

In the second stage of the test, the hole is extended by removing the standpipe apparatus and augering through the casing. An open hole of length L then extends below the bottom of the casing. After cleaning the hole, reassembling the standpipe apparatus, and refilling with clean water, additional measurements of falling head and times are taken. In this second stage, water runs out the sides of the extended hole as well as out the bottom of the hole. In Stage II, the permeability being measured is largely horizontal.

Using the equations for the two different flow cases, both vertical and horizontal permeabilities can be quantified.

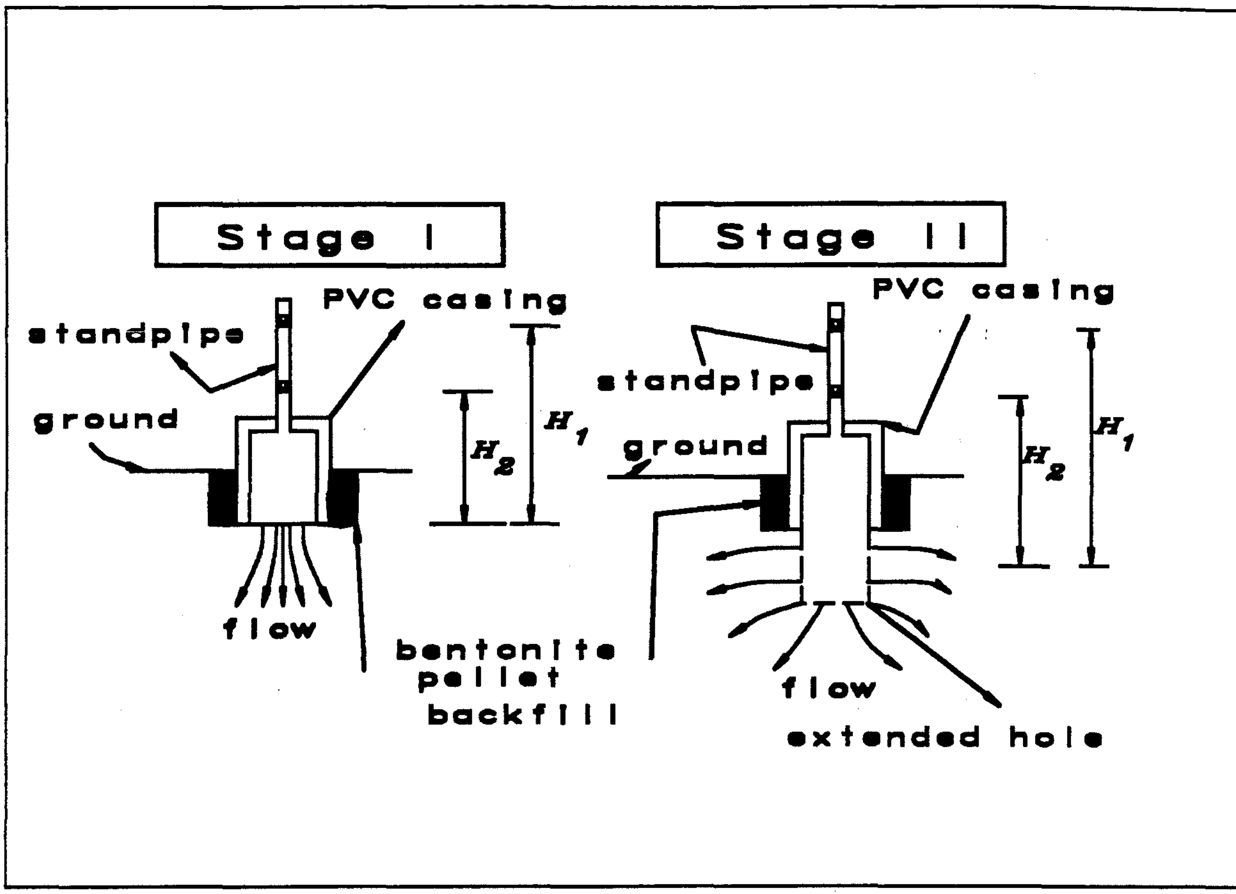


Figure 12. Boutwell permeability test.

(2) It is outside the scope of this paper to include the complete testing procedures and equations for calculating test results. A spread sheet program has been developed by the Soil Mechanics Laboratory, Fort Worth, Texas, for calculating results. A complete explanation of the test, example drawings of the apparatus, its installation and use are also available from the same source.

(3) The test may be used to measure a very low permeability, as low as 10^{-7} cm/sec. However, testing time may be up to 10 days for performing both stages of the test in very slowly permeable soils.

(4) This test could be used to measure the permeability of in situ soils at grade at a proposed storage site. The test could also be used to measure the permeability of a compacted liner; however, it is limited for testing compacted liners less than about 3 feet thick. These limitations are theoretical and apply to the flow equations used to calculate permeability.

c. Single Ring Infiltrometer

(1) Introduction.

The apparatus is shown in figure 13. The test is performed by excavating to the level where permeability is to measured and leveling a surface slightly larger than the ring. Circular rings generally are used, but square rings may also be used. The ring should have a diameter at least equal to the thickness of the liner or horizon being tested.

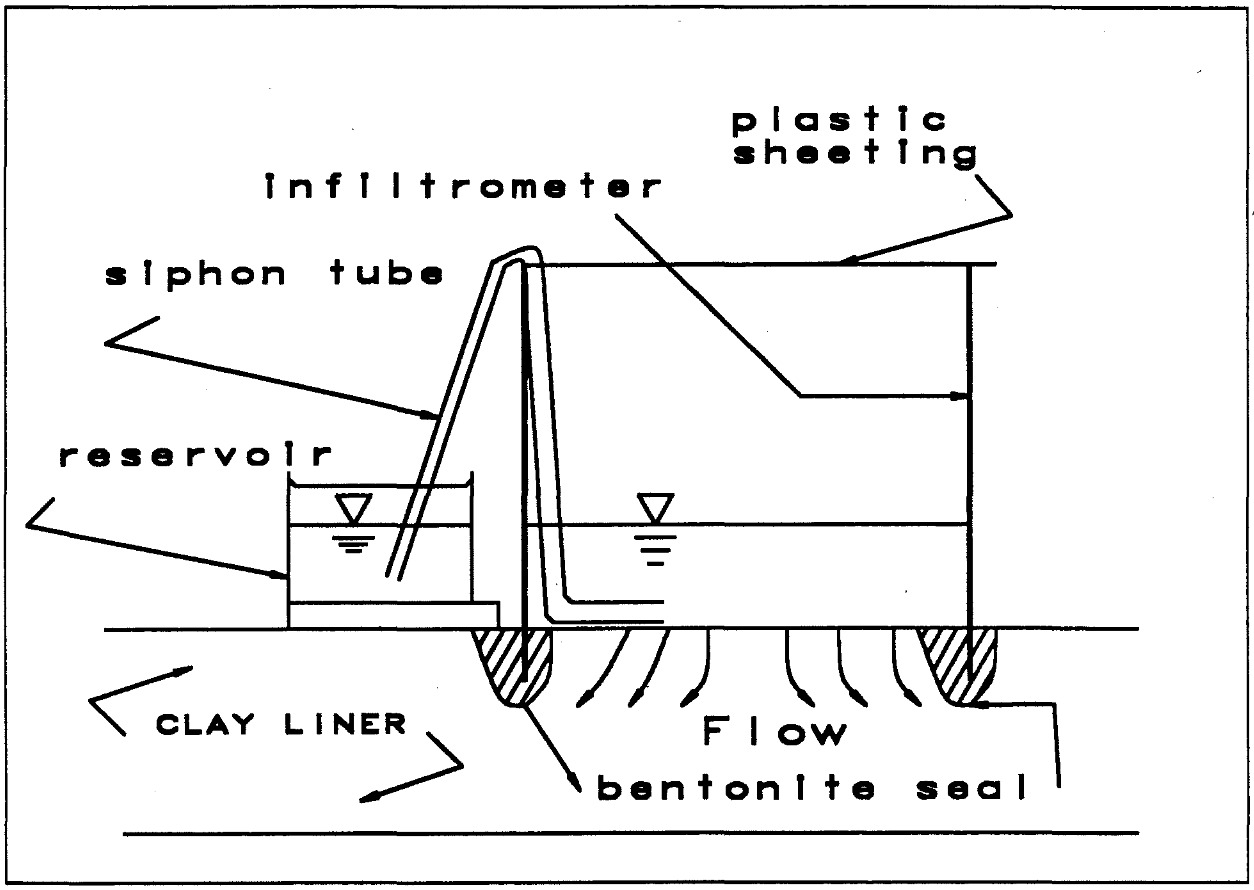


Figure 13. Single ring infiltrometer.

To establish a good seal and prevent water from leaking upwards along the ring/soil interface, the infiltrometer ring is generally partly embedded into the soil to be tested . Usually, a small trench is dug using the ring for a template, embedding the ring in the trench, and then backfilling the trench with a mixture of soil and bentonite. (See figure 13)

The ring is filled with water and kept at a constant elevation using a water supply and siphon device. The ring must be covered with plastic to prevent evaporation, or evaporation must be measured and subtracted from the flow quantity.
The soil should be protected from erosion as the ring is filled with water,

For very low permeability soil, an alternate ring apparatus should be used so that lower quantities of flow can be measured. The device is called a sealed single ring infiltrometer. This apparatus also has the advantage of limiting evaporation and accounting for that complication. Even with this type of device, it is difficult to accurately measure permeabilities less than about 10^{-7} cm/sec.

(2) It is outside the scope of this paper to include the complete testing procedures and equations for calculating test results. A spread sheet program has been developed by the Soil Mechanics Laboratory, Fort Worth, Texas, for calculating results. Example drawings with parts lists for constructing such an apparatus are also available from SML.

(3) The test may be used to measure a low permeability, down to 10^{-7} cm/sec. However, testing time may be up to 10 days when flow quantities are very low. You must have an approximate idea of what the ratio of horizontal to vertical permeability is to assess test results properly. The test measures largely the vertical permeability of the soil tested.

(4) This test could be used to measure the permeability of in situ soils at grade at a proposed storage site. It could also be used to measure the permeability of a compacted liner. Permeability coefficients substantially less than 10^{-7} cm/sec are difficult to measure with this test.

d. Double Ring Sealed Infiltrometer

(1) Introduction.

The apparatus is shown in figure 14. First, soil is excavated to the level where permeability is to measured and leveling a surface slightly larger than the ring to be used. Circular rings generally are used, but square rings may also be used. The inner ring should have a diameter at least equal to the thickness of the liner or horizon being tested.

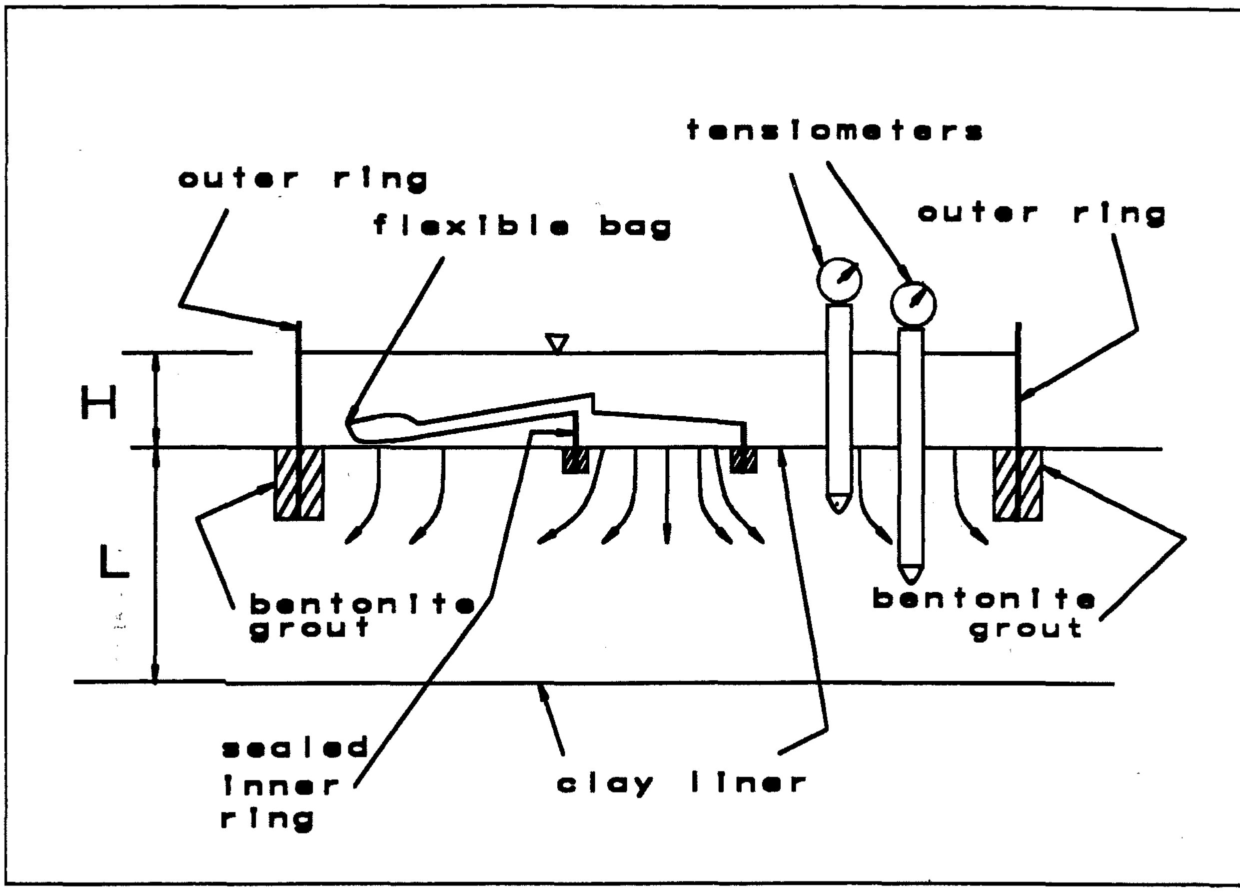


Figure 14. Sealed double ring infiltrometer.

To establish a good seal and prevent water from leaking upwards along the ring/soil interface, the infiltrometer rings are partly embedded into the soil to be tested . Small trenches are generally dug using the rings for a template, embedding the rings in the trench, and then backfilling the trenches with a mixture of soil and bentonite, (figure 14).

The rings are filled with water. The inner ring is sealed, attached to a small, flexible bag that can be weighed to measure water flow. Because the outer ring is filled above the inner sealed ring, there is no head difference and the differential pressure between the inner and outer ring is always zero. Flow from the inner ring is measured by periodically weighing the bag that siphons into the inner ring.

The outer ring is usually covered with plastic to prevent evaporation.

(2) It is outside the scope of this paper to include the complete testing procedures and equations for calculating test results. An ASTM Standard D3385, "Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometers," gives the test details. This ASTM test method does not specifically

cover the sealed ring type of test, but, rather, covers a more simple variation. Also, the small rings traditionally used for this test are not applicable for measuring permeability coefficients less than about 10^{-7} cm/sec. This is because of the very low quantities of flow that must be measured.

Larger rings and double ring devices with sealed systems capable of measuring smaller flow quantities are commercially available for this test. The commercial suppliers furnish detailed test procedures and methods for calculating results. Sources for obtaining suitable commercial devices are available on request from SML.

(3) The test may be used to measure very low permeability, down to 10^{-7} cm/sec. However, testing time may be up to 30 days for very slowly permeable soils, so that a saturated condition may be established and the low quantities of flow are accurately measured.

IV. FACTORS AFFECTING THE PERMEABILITY OF COMPACTED OR TREATED CLAY LINERS

Three primary factors control the resultant permeability of a clay liner. They are: (a) the type of soil used for the liner, (b) the density and water content to which the clay is compacted, and (c) the construction procedures used for spreading, processing, wetting, compacting, and bonding between lifts. The structure of the compacted clay and its resultant permeability are affected strongly by each of these factors. If a clay liner is to have predicted low permeability, all three factors must be carefully controlled.

A. TYPE OF SOIL USED FOR LINER

SNTC Technical Note 716, "Design and Construction Guidelines for Considering Seepage from Agricultural Waste Storage Ponds and Treatment Lagoons," provides guidance on types of soil in relation to compaction and permeability.

The workability of the clay is very important. Highly plastic clays are potentially less permeable than lower plasticity clays, but the more plastic clays can be more difficult to mix, hydrate with added water, and homogenize in a compacted layer. A factor in the compaction of clay soils that is often overlooked is the size of the clay clods in the soil before compaction. Larger clods that have dried surfaces result in a poorer compacted mass permeability because of a secondary structure. Any process that reduces the size of clods before compaction is beneficial. SCS has specified the use of heavy disc plows for its construction projects in some states for many years. The water content of the clay liner soils is important because it determines how well the soil can be processed and homogenized.

B. COMPACTION DENSITY AND WATER CONTENT

In general, increasing the compacted dry density and the degree of saturation at which that density is achieved decreases the permeability of the compacted soil. A given value of permeability may be obtained at an infinite number of combinations of density and water content. Compaction wet of optimum water content is probably more important in reducing permeability than small increases in compacted density. Some field data (Reference 4) have shown that compacting a given soil 1 percent wet of optimum has the same effect on reducing permeability as that caused by increasing the degree of compaction by 5 percent. Compacting a soil to a 100 percent degree of compaction at optimum water content results in about the same permeability as compacting the same soil to a 95 percent degree of compaction at a water content 1 percent wetter.

The type, weight, and number of passes of roller used will affect the permeability of the compacted clay liner. For most clay soils, a tamping or sheepsfoot roller is the preferable type of compaction equipment. Smooth wheel or rubber-tired rollers are inappropriate for the kneading action required to compact clay soils to as high a density as is commonly desired. Use of rubber-tired farm equipment may produce densities equal to 90 percent of maximum Standard Proctor density, but achieving a higher density is difficult without tamping rollers.

Experience with many projects has indicated that from 4 to 6 passes, and seldom more than 8 passes, of a tamping roller generally produces acceptably high compacted densities (greater than 95 percent of maximum Standard Proctor). Using very large rollers is undesirable if compacting soils wet of optimum water content, as is usually specified. Internal shear planes in soil lifts can be caused by the roller pushing the soil ahead of the roller. Operating the rollers at excessive speed may also be contribute to this problem.

C. CONSTRUCTION PROCEDURES

The single most important factor affecting the overall compacted permeability of a clay liner, other than the type of clay used for the liner, is the efficient construction processing of the compacted liner. The sequence of equipment use and the routing of equipment in an established pattern helps assure uniformity in the whole placement and compaction process. This uniformity of process makes any testing and verification of results more reliable and representative of the total work.

Early in construction, a section of the compacted liner should be excavated and inspected to insure that the combination of lift thickness, water content, and roller are resulting in a relatively homogeneous mass relatively free of defects such as unbonded and uncrushed clods in the mass.

The following general guidelines for compaction should be closely followed in construction of a clay liner or any other processed earth fill:

1. Fill should not be placed until the required excavation and foundation preparation have been completed and the foundation has been inspected and approved.

2. Fill should be placed in approximately horizontal layers. The thickness of each layer before compaction should not exceed the maximum thickness specified. Materials placed by dumping in piles or windrows should be spread uniformly to not more than the specified thickness before being compacted.

3. The distribution of materials throughout each layer should be essentially uniform, and the fill should be free from lenses, pockets, streaks, or layers of material differing substantially in texture, moisture content, or gradation from the surrounding material.

4. Rocks, roots, and other oversize or undesirable materials should be raked or otherwise removed from the fill. Discing may be required to break up soil clods into fragments that will compact better and be more receptive to thorough water distribution.

5. During placement and compaction of fill, the moisture content of the materials being placed should be maintained within the specified range.

6. Water should be applied to fill materials at the borrow areas insofar as practicable. Water can be applied by sprinkling the materials after placement on the fill, if necessary. Uniform moisture distribution must be obtained. The most positive way to accomplish this is to require the use of a disc heavy enough to cut through the specified lift thickness.

7. If the surface of any layer becomes too hard and smooth for proper bond with the succeeding layer, it should be scarified parallel to the axis of the fill to a depth of not less than 2 inches before the next layer is placed. This should be standard practice between progressively placed lifts.

D. DISCUSSION OF MACRO-STRUCTURE OF LINERS

Macro-structure in a compacted clay liner can drastically affect the flow direction of permeants. Nearly always, permeability will be greater in a direction parallel to the plane of compaction than in a direction perpendicular to the plane. Field tests have shown the ratio of permeabilities to be on the order of 5 or 10 to 1. Field testing to assess compacted liners should consider this.

Another factor is the thickness of the compacted liner. With thicker liners, defects in adjacent lifts are not as likely to interconnect. Macro-structure in clay liners may be caused by:

1. Joints.

Joints are the area where two adjacent lifts are placed. Borrow soils generally are transported and spread, processed, then compacted. Normal construction procedures result in an area between the dumped loads where compaction is less controlled. When fill is added adjacent to an area that has already been compacted, the existing fill should be battered and scarified before adding adjacent lifts to the liner.

2. Construction Method.

Liners in a pond bottom may be constructed using two techniques, referred to as "stair-step" and "bathtub" construction (figure 15). The "bathtub" type of construction is limited to side slopes of about 3 to 1 or flatter because construction equipment is difficult to operate on steeper slopes. In liners constructed using the "bathtub" construction, flow is generally perpendicular to the plane of compaction, while flow through liners constructed using the "stair-step" construction is more parallel to the direction of compaction. Any substandard lifts have a greater potential to leak excessively in the "stair-step" constructed liner as compared to the "bathtub" constructed liner.

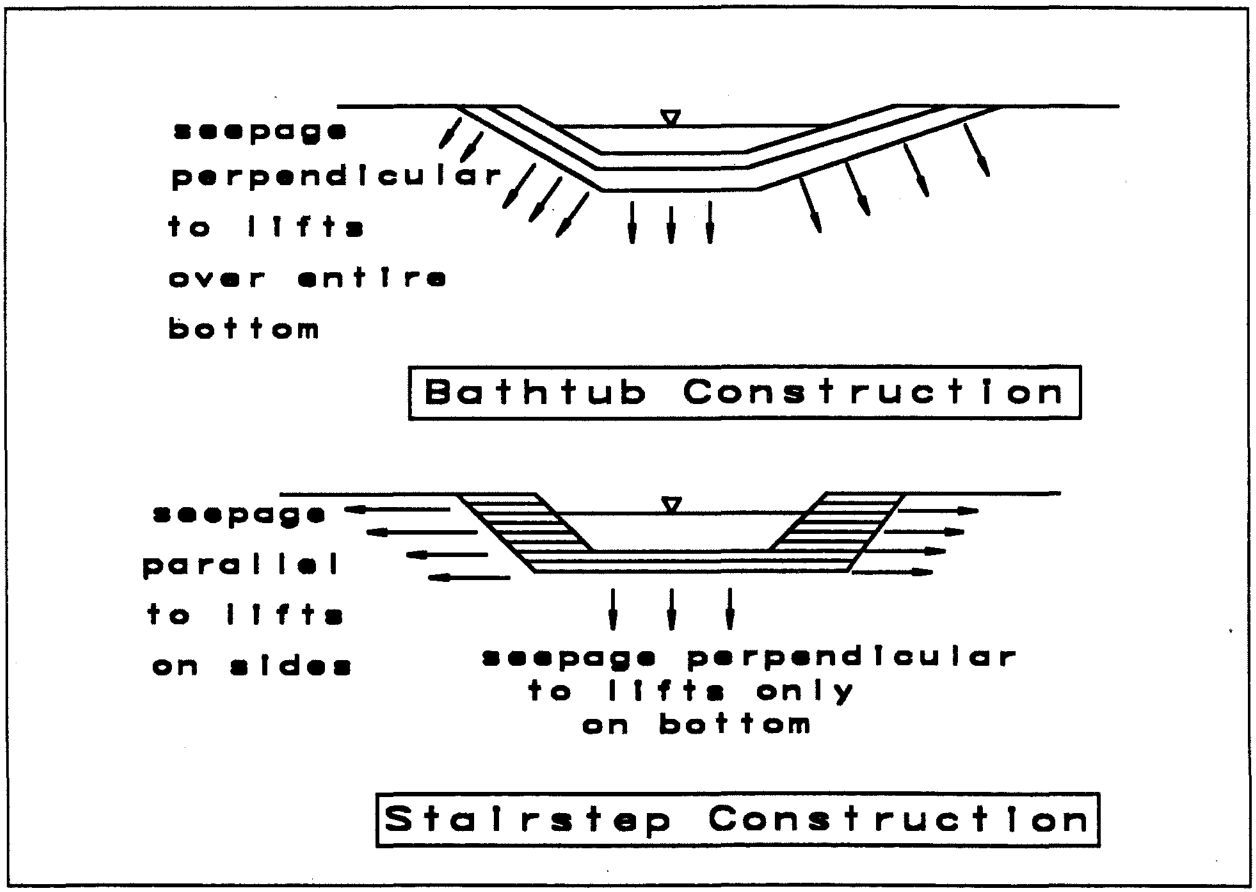


Figure 15. Methods of construction of liners.

V. THE EFFECT OF MAINTENANCE ON PERMEABILITY

Maintenance considerations for liners are minor for ponds that are kept full. Ponds that are periodically emptied to remove waste, or that are pumped out for other reasons may have more problems with liners.

If a clay liner is installed over a permeable sand/gravel material that has a high water table, the liner can heave because artesian head under the liner can be excessive when the pond is emptied. The buoyant weight of the overlying clay blanket or clay horizon in the bottom of the excavation must be greater than the artesian head under the liner.

The clay liner may be subjected to mechanical attack from removal equipment, erosion of the liner when exposed during empty periods, wave action, and any vehicular traffic when exposed. Other mechanical attacks include animals, such as crayfish, and rodents, such as muskrats.

Desiccation of the clay liner while the pond is empty is another serious potential problem. Classical equations indicate that cracks can theoretically extend through clay to a depth of 10 feet. Some documented cases have shown a 100-fold increase in permeability of clay liners because of desiccation cracks. To prevent desiccation cracking during periods the pond is empty, clay liners should be protected by a blanket of several feet of silty sand or periodically sprinkled during empty periods

VI. CONVERSION FOR UNITS OF PERMEABILITY

A. INTRODUCTION

Different units of measurement for permeability are used by various agencies and personnel. The most commonly used English system units of measurement for permeability are feet per day and inches per hour. Units of feet per year are occasionally used. In the metric system, centimeters per second are the most commonly used units.

B. CONVERSION FACTORS

Factors for converting from one unit of permeability to another are given in the following table:

TO CONVERT FROM	TO	MULTIPLY BY
Ft/Day	Cm/Sec	3.53×10^{-4}
	In/Hour	0.5
Cm/Sec	Ft/Day	2,835
	In/Hour	1,417
In/Hour	Ft/Day	2.0
	Cm/Sec	7.06×10^{-4}

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PERMEABILITY ESTIMATES - CLEAN SAND/GRAVEL FILTERS (REFERENCE SOIL MECHANICS NOTE 9

General Equation: $k\ (fpd) = 992 \times D_{15}^{2}$

ASTM GRADATION #	Relative Density	Band	k fpd	Angularity Description
C-33	70 % Minimum	Fine	30 55	rounded
	70 % Minimum		10 90	angular
	70 % Minimum	Coarse	110 145	rounded
	70 % Minimum		75 430	angular
D448 - 78	70 % Minimum	Fine	20,000 35,000	rounded
	70 % Minimum		7,200 47,000	angular
	70 % Minimum	Coarse	47,000 72,000	rounded
	70 % Minimum		43,000 76,000	angular