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STEP
Strategies for Today's
Environmental Partnership

OVERVIEW OF SOIL PERMEABILITY TEST METHODS

REGULATORY AFFAIRS DEPARTMENT
PUBLICATION NUMBER 351
APRIL 1999

American Petroleum Institute

STEP Strategies for Today's Environmental Partnership

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Overview of Soil Permeability Test Methods

Regulatory Affairs Department

API PUBLICATION NUMBER 351

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EXECUTIVE SUMMARY

This report presents some of the available test methods for determining the coefficient of permeability for earthen secondary containment systems at aboveground storage tank facilities. It provides the guidance necessary for operators of an aboveground storage tank facility to select an appropriate test method to determine soil permeability.

The presented permeability test methods are categorized into laboratory or field methods. A brief overview and applicable equations are provided for each method. The report contains two main tables (Table 2-1 and Table 3-1), which the reader can use to compare and contrast the presented test methods. The information in these tables includes the test method name, technical references, applicability of the test to specific soil types, advantages, disadvantages, overview of the test procedures and typical costs.

The document is intended to provide information for facility operators and engineers to understand the basic requirements of each method and to provide guidance for selection of an appropriate test method. This report is not intended to be used as a "how to manual" for each test. Nor is the report to be construed as stipulating permeability requirements for earthen secondary containment systems.

Section 1
INTRODUCTION

The determination of soil permeability is one of the most important items in assessing aboveground storage tank facilities' secondary containment areas. This report outlines the available methods for determining soil permeability both in the laboratory and in the field. This publication is intended for use by facility operators, engineers and other parties interested in the evaluation of soil permeability.

SCOPE OF REPORT

This publication outlines various methods to test the permeability of soil. It is intended to serve only as a general guideline in the selection of a suitable test method for determining soil permeability. The final selection of the method and its implementation should be the responsibility of an experienced hydrologist or geotechnical engineer. The methods listed here are not an exhaustive list of all available permeability methods. The report distinguishes between laboratory and field methods. They are identified according to their applicability to particular soil types. The methods presented in this report are applicable to fine-grained soils (silts and clays) and coarse-grained soils (sands and gravels), but may not be appropriate to organic soils, such as peat, or to materials such as construction and demolition debris.

The laboratory test methods covered in this report include the following:

- Constant head test
- Falling head test
- Flexible wall permeameter test (triaxial test)
- Grain size analysis (sieve analysis)

The field methods covered in this report include the following:

- Slug test (Hvorslev's Method)
- Infiltrometer tests
- Double tube test method

- Air-entry permeameter test
- Borehole test
- Gulf Oil Field Test method
- Well pumping test
- Piezometer method

ORGANIZATION OF REPORT

Sections 2 and 3 provide detailed information on the cited laboratory and field permeability test methods. These sections each contain a table that summarizes the test procedures, presents the advantages/disadvantages for the procedures and provides typical costs for conducting the procedures. Preceding the tables are more detailed narratives of the tests including schematics of the test methods. For detailed specifications on how to perform each test, the reader is directed to consult the cited references.

The tables provide an indication of the relative costs of sampling and analysis for each test method. These costs are intended to be used only as a basis for comparing the various test methods. Actual sampling and analytical costs will vary depending on site conditions, geographical location, access into the facility and other conditions that will vary from site to site.

A NOTE OF CAUTION

Numerous test methods exist to determine soil permeability. The API does not endorse or recommend any one method, nor can API represent or defend the accuracy of a particular method. The reader is cautioned to fully investigate the appropriateness of a test method and to determine its suitability to a particular situation.

Application of the methods cited in this report should be based on sound engineering judgment and in accordance with relevant codes and standards. Results of the tests depend on sampling analytical methods, experience and expertise of the technical staff, and the site conditions. The more complex tests should be performed only by personnel experienced in soil permeability test methods. This publication is not meant to be a guide for using these methods.

RECOMMENDATIONS FOR METHOD SELECTION

Permeability test methods often are suitable for certain types of soils (e.g., fine grained soils, such as silts and clays, or coarse grained soils, such as sands and gravels). The soil conditions at the test site determine the selection of the most suitable test method or methods. The following guidelines are presented for information only, and may serve as a basis to assist the reader in the proper selection and use of the various methods presented in this report.

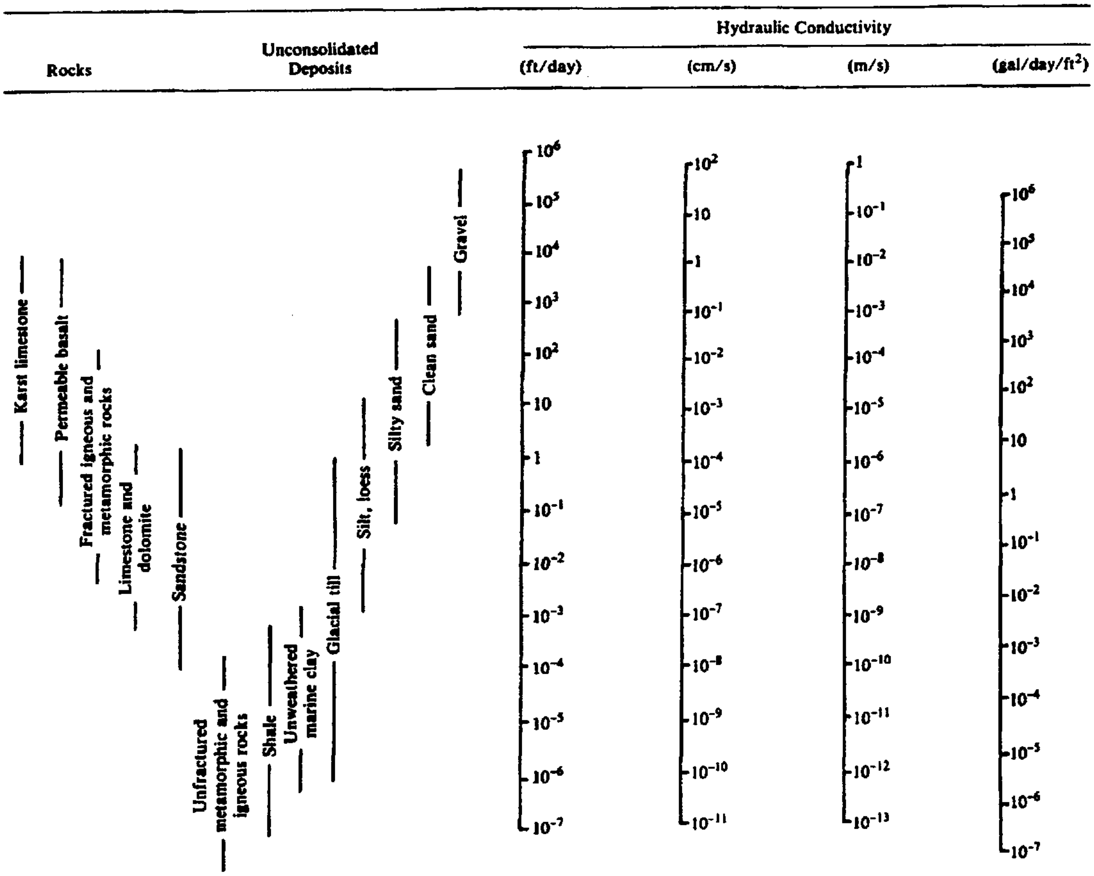
- Determine the approximate soil type via hand excavated test pits. The soil type should be determined using the Unified Soil Classification System (USCS) (U.S. Army Engineer Waterways Experiment Station, 1953). Typically, soil types can be divided into granular soils, including sands and gravels, or fine grained soils, such as silts and clays. Other types of soil deposits may include organic soils, such as peat, or fill materials consisting of construction and demolition debris.
- After the soil type is determined, the most appropriate test method(s) can be selected from the tables provided in this document.
- For granular soils, such as sands, gravels, silty sands or sandy silts, many of the field methods and several of the lab methods are suitable for determining permeability. These methods are relatively inexpensive and provide good correlation to actual field conditions.
- Impermeable cohesive clays represent a challenge for field test methods. For silty clays and heavy clay soils, the majority of the readily available field methods cannot be performed within a reasonable timeframe or they may report inaccurate results. The laboratory flexible wall permeameter (triaxial) test will provide accurate results for a moderate cost. This method usually requires obtaining an undisturbed tube (Shelby tube) sample. The use of field methods, such as the air entry permeameter and the various infiltrometer methods, would be substantially more expensive, require expert soil technicians familiar with the methods, and would not necessarily provide more accuracy.

The reader should note that several of the referenced field methods were developed for *in situ* permeability testing of very-low-permeability (less than $1x10^{-7}$ cm/sec) clay liner soils, such as clay soils or clay liners encountered at hazardous waste sites or landfills. These methods are more rigorous than are needed for most tank farms. Furthermore, these methods require very specialized equipment and training that may not be readily available.

HYDRAULIC CONDUCTIVITY VS. PERMEABILITY

Any material with voids is porous, and if the voids are interconnected, the material possesses permeability (Bowles, 1984). More specifically, the permeability of a material is a measure of its ability to transmit fluid, and is a property of the material itself. The hydraulic conductivity is also a measure of the ability of a material to transmit fluid, but is dependent on the type of fluid passing through the material. Although the two terms are often used interchangeably, the term *permeability* will be used throughout this publication. Table 1-1 shows the range of permeabilities for various materials.

Table 1-1.: Range of Values of Hydraulic Conductivity



Note: ft/day = feet per day; cm/s = centimeters per second; m/s = meters per second; gal/day/ft^2 = gallons per day per square foot.
[a]Source: Modified from Freeze and Cherry, 1979.

The relationship between hydraulic conductivity and permeability is as follows:

$$K = \frac{kg}{\nu}$$

(Equation 1-1)

where:

K = hydraulic conductivity

k = specific or intrinsic permeability

ν = kinematic viscosity

g = gravitational constant

To calculate the actual hydraulic conductivity, corrections need to be made for fluid density and viscosity. Since the kinematic viscosity already accounts for density, the hydraulic conductivity is found using Equation 1-1. Typical kinematic viscosities for various fluids can be found in Table 1-2.

Table 1-2: Viscosities of Selected Fluids

FLUID	VISCOSITY (CENTIPOISE), AT 15°C
Water	1.14
Automotive gasoline	0.62
Automotive diesel fuel	2.70
Kerosene	2.30
No. 2 fuel oil	4.04[a]
No. 6 fuel oil	3180[b]

Note: C = Celsius

[a] Data reported were determined at 20°C

[b] Data reported were determined at 25°C

Source: Modified from American Petroleum Institute, 1989.

The information provided in this report is based on the permeability of soil using water as the test fluid. Further adjustments or considerations are required when a fluid other than water is used, or when evaluating the suitability of a particular soil to inhibit the transmission of a stored fluid. If the permeability using water is known, the permeability of other fluids can be calculated by using the fluids viscosity ratio with water as follows (Toso, 1994):

$$k_f = \frac{1}{VR} * k_w$$

(Equation 1-2)

where:

k_f = permeability using the fluid

VR = viscosity ratio of the fluid compared to water

k_w = permeability using water

COLLECTION AND HANDLING OF SOIL SAMPLES

The preparation, gathering and date of collection of soil samples for use in permeability testing have a significant effect on the integrity of the test results. Sample collection and preparation should be done using good engineering practices. For further information on sampling, preservation and transportation of soil samples, refer to ASTM 1587 and ASTM 4220.

HORIZONTAL AND VERTICAL PERMEABILITY

There is often a difference in the horizontal and vertical permeability of a soil. The difference between horizontal and vertical permeability is due to soil stratification. In general, the horizontal permeability is often greater than the vertical permeability. For example, the horizontal permeability of sands can be 10 to 1000 times the vertical permeability. For sands, the field soil structure is invariably lost in the laboratory because an undisturbed sample cannot be tested, since it would have to be transferred from the recovery device to the permeameter (Bowles, 1984). For horizontal flow, the flow is dominated by the layer with the highest permeability, while for vertical flow, the flow is limited by the layer with the lowest permeability.

SATURATED VS UNSATURATED SOIL

The degree of saturation of a particular soil can greatly affect permeability results. Entrapped air bubbles can cause the permeability of unsaturated soil to be lower then that of saturated soil. The permeability of an unsaturated soil increases with increasing moisture content (Freeze, 1979). The degree of saturation of a soil can be found as follows (Holtz, 1981):

$$S = \frac{V_w}{V_v} * 100$$

(Equation 1-3)

where:

S = degree of saturation (percentage)

V_w = volume of water

V_v = volume of voids

The degree of saturation tells what percentage of the total volume of voids contains water. If the soil is completely dry, then $S = 0\%$, and if the soil is completely saturated, then $S = 100\%$ (Holtz, 1981). The amount of saturation is important in permeability testing. For laboratory tests, the sample must be saturated for accurate results. In the field, the saturation depth (depth to the wetting front) may or may not have to be determined. Field methods that do not require determination of the saturation depth may underpredict the permeability. Field tests that do require determination of the depth to the wetting front may yield more accurate results.

OTHER PROPERTIES OF SOILS

Additional properties of soils that affect the passage of fluid are porosity, void ratio, and density. Porosity is defined as follows (Holtz, 1981):

$$n = \frac{V_v}{V_t} * 100$$

(Equation 1-4)

where:

n = porosity (percentage)

V_v = volume of voids

V_t = total volume of soil sample

The maximum range of n is between 0 and 100%.

The void ratio is normally expressed as a decimal as follows (Holtz, 1981):

$$e = \frac{V_v}{V_s}$$

(Equation 1-5)

where:

e = void ratio

V_v = volume of voids

V_s = volume of the solids

The dry density and saturated density are defined as follows (Holtz, 1981):

$$\rho_d = \frac{M_s}{V_t}$$

(Equation 1-6)

$$\rho_{sat} = \frac{M_s + M_w}{V_t} (for V_a = 0, S = 100\%)$$

(Equation 1-7)

where:

ρ_d = dry density

ρ_{sat} = saturated density

M_s = mass of soil solids

M_w = mass of water

V_t = total volume of soil sample

V_a = volume of air

S = degree of saturation

Section 2
LABORATORY METHODS

INTRODUCTION

Laboratory tests result in permeability values measured under closely controlled conditions. However, laboratory methods often represent only a small sample of the actual field conditions. In addition, laboratory results depend upon the quality of the soil sample obtained from the field. By removing soil samples for examination in the laboratory, these natural conditions can be destroyed. This is especially true for sands, silty soils and certain clays. The field sampling method, the conditions resulting from transfer to the lab, or sample disturbance at the lab may compromise the sample integrity. Furthermore, some laboratory tests may rely on the use of remolded soil samples, which may not be representative of the actual field conditions.

This section outlines the methods available for determining permeability in the laboratory. It summarizes the test procedures, and outlines the advantages and disadvantages of the presented methods. The laboratory methods described here apply only to saturated soils. The samples are saturated in the lab prior to testing.

CONSTANT HEAD TEST

The constant head test is a laboratory test performed on saturated, permeable, coarse-grained soils in accordance with ASTM Standard D-2434, *Standard Test Method for Permeability of Granular Soils (Constant Head).* This method is limited to disturbed granular soils containing not more than 10 percent soil passing the No. 200 sieve. Throughout the constant head test, the hydraulic head is held at the same value through use of a constant head permeameter. The soil sample is placed in the permeameter and a constant flow of water is passed through the sample. The water passing through the sample is collected over a period of time and measured. The permeability is then calculated as follows (ASTM, 1985):

$$k = \frac{QL}{Ath}$$

(Equation 2-1)

where:

k = permeability (cm./second)

Q = quantity of water discharged (cm.^{3})

L = distance between manometers (cm.)

A = cross-sectional area of sample specimen (cm.^{2})

t = total time of discharge (seconds)

h = difference in head on manometers (cm.)

If the test is performed at a temperature other than 20°C, permeability (k) needs to be corrected by multiplying by the ratio of the viscosity of water at the test temperature to the viscosity of water at 20°C (ASTM, 1985).

Precautions should be taken to ensure the quality of the soil sample is as representative of field conditions as possible. Avoid segregation of the sample during placement in the permeameter (Cedergren, 1989) and eliminate air present in the pores. Distilled water, warmer than the sample, should be passed through the sample for a considerable amount of time before performing the test (Spangler, 1973). This test should not be used on saturated soils with low-permeability (less than 1×10^{-3} cm./second); the falling head test is more suitable for low-permeability soils (Cedergren, 1989). An illustration of a constant head permeameter can be seen in Figure 2-1 below (Cedergren, 1989).

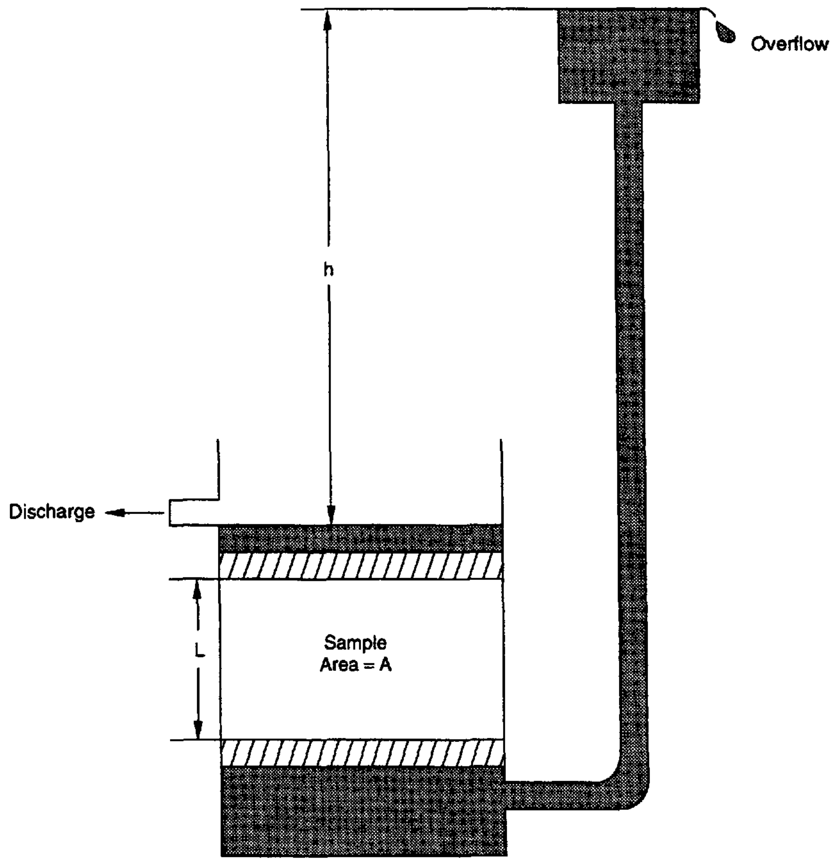


Figure 2-1—Constant Head Test

FALLING HEAD TEST

The falling head test is a laboratory test performed on saturated, fine-grained soils and can be used for lower permeability soils (1×10^{-3} to 1×10^{-5} cm/sec). Water is passed through the sample by a small-diameter standpipe attached to the top of the permeameter. The water in the standpipe is filled to a recorded level and the time for the water level to drop to a new, lower level is recorded (Cedergren, 1989). The permeability is calculated as follows:

$$k = \frac{2.3aL}{Adt}\log_{10}\frac{h_1}{h_2}$$

(Equation 2-2)

where:

k = permeability (cm./second)

a = area of the standpipe (cm.^{2})

A = cross-sectional area of the sample (cm.^{2})

L = sample length (cm.)

h_1 = initial height in the standpipe (cm.)

h_2 = final height in the standpipe (cm.)

dt = change in time for the water to fall from h_1 to h_2 (seconds)

Reverse flow can be used in the falling head test to prevent clogging. The same precautions should be used with this test as for the constant head test. An example of a falling head permeameter can be seen in Figure 2-2 below (Cedergren, 1989).

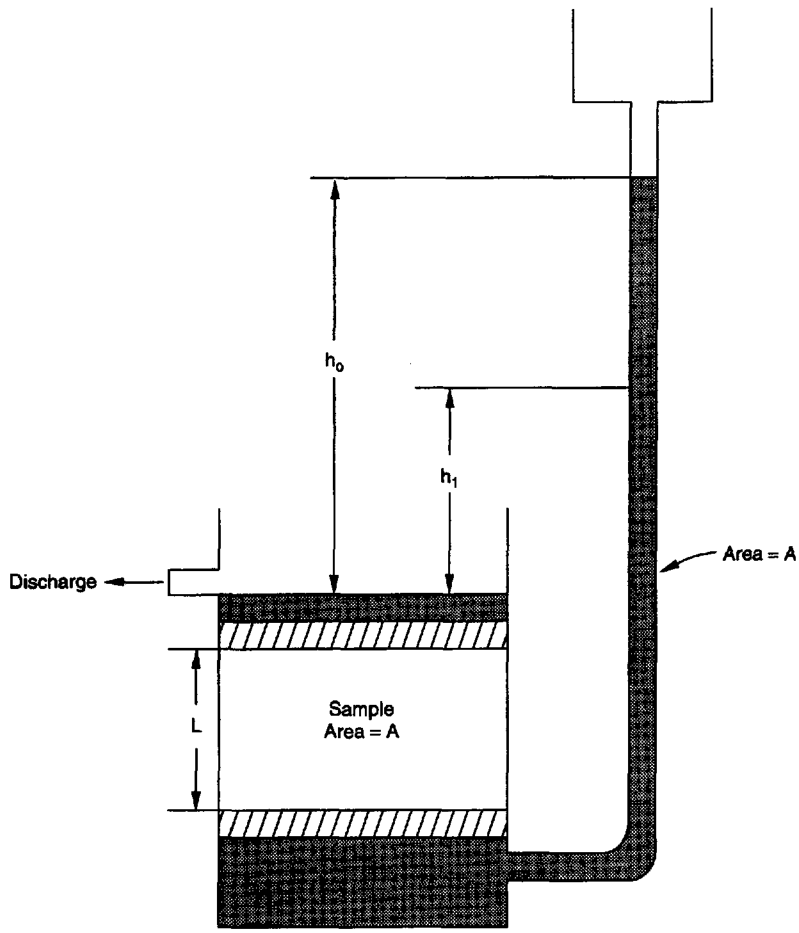


Figure 2-2—Falling Head Test

FLEXIBLE WALL PERMEAMETER (TRIAXIAL TEST)

The flexible wall permeameter test is a laboratory test performed on mostly saturated fine-grained low-permeability soils. The test is used to determine soil permeability for soils with permeability less than or equal to $1x\ 10^{-3}$ cm./second, and accurately determines the soil permeability of clay soils with permeabilities less than $1x\ 10^{-7}$ cm./second. An undisturbed soil sample is extracted, trimmed, and placed in a flexible wall membrane. The sample is placed in a triaxial cell chamber, saturated, and a cell pressure applied. The constant head, falling head, or constant rate of flow methods are used to determine the permeability of the soil in accordance with ASTM Standard D-5084, *Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.* This test method is superior to the constant and falling head methods due to the simulation of in-place conditions by applying pressures and vertical loads. The membrane prevents leakage and sideflow between the wall and soil. The apparatus to be used for the triaxial test is shown in Figure 2-3 below (ASTM, 1990). The triaxial test is most suitable for determining the permeability of silts and clays.

GRAIN SIZE ANALYSIS

The grain size analysis for determining permeability is not very accurate, and should be used only when very little knowledge of the situation exists. All that is needed for this method is knowledge of an average grain size or a grain size distribution (Shepherd, 1989). There are several alternatives to determining permeability from grain size data. One alternative is from the following equation (Shepherd, 1989):

$$k = cd^{a} \qquad \text{(Equation 2-3)}$$

where:

k = permeability (gallons per day/ft^2)

c = a dimensionless constant found through regression analysis

d = mean pore throat or particle diameter (in millimeters)

a = exponent usually ranging from 1.65 to 1.85

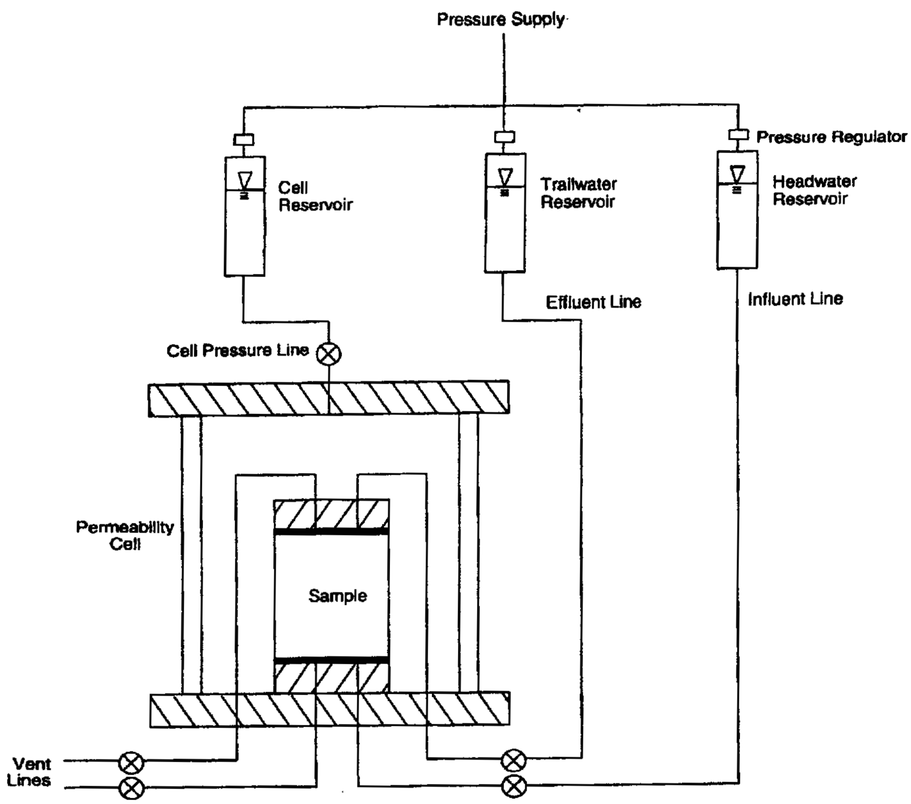


Figure 2-3—Triaxial Test

The analysis required is lengthy and relies on statistical estimation. Other alternatives for grain size analysis can be found in Shepherd (1989).

Holtz (1991developed an empirical equation for clean sands which correlates the permeability to D_{10}.

$$k = C(D_{10})^2$$

(Equation 2-4)

where:

k = permeability (cm./s)

C = a dimensionless constant that varies from 0.4 to 1.2 with an average value of 1.0

D_{10} = the effective grain size for the 10 percent size in the grain-size curve when the particle diameter is between 0.1 to 3.0 millimeters (otherwise the equation is not valid).

Table 2-1 Laboratory Methods for Testing Permeability

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Constant Head Test	ASTM D-2434 Cedergren, 1989.	Laboratory test for coarse grained soils	• Simple test and inexpensive to perform. • Accurate for soils with permeabilities greater than $1x10^{-3}$ cm./sec. • Typically use a field bulk sample, no special drilling or sampling method. • Provides accurate estimate of permeability for coarse grained soils. • Proven track record of use. • Provides good correlation data for well sorted soils. • Equipment readily available and can be performed by persons with basic knowledge of the method.	• Remolded sample or non-uniform soils may cause a large variation in results. • Flow must be in one direction. • Results are dependent on small soil sample size, which may not be representative of the field conditions.	• The soil sample is placed into the appropriate setup and a continuous supply of water is passed through it. • The water that passes through the sample, in a specified time, is collected. • The permeability is calculated.	Lab Test • $80 to $150/ sample Collect Field Bulk sample • $60 to $100 / sample

[1] These costs represent estimates based on 1998 dollars and may vary by locality.

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Falling Head Test	ASTM D-5084 Lambe, 1969. Stephens, 1988	Laboratory test for coarse grained soils and some fine-grained soils	• Simple test and inexpensive to perform. • For lower permeability soils ($1x10^{-3}$ to $1x10^{-5}$ cm./sec). • Typically use a field bulk sample only, no special drilling or sampling method. • Provides accurate estimate of permeability for coarse grained soils and *some* fine grained soils. • Proven track record of use. • Equipment readily available and can be performed by persons with basic knowledge of the method	• If permeability of soil is low, evaporation of water may introduce an error in the measured results. • There can be large variation in results. • Flow must be in one direction. • Dependent on soil sample size and quality of sample, which may not be representative of field conditions.	• The soil sample is placed into the appropriate setup, with a standpipe connected to the top. • The standpipe is filled with water and the time required for the water level to drop to a lower point is recorded. • The permeability is calculated.	Lab Test • $80 to $150 / sample Collect Field Bulk sample • $60 to $100 / sample
Flexible Wall Permeameter (Triaxial Test)	ASTM D-5084 New York State Department of Environmental Conservation, 1988.	Laboratory Test for Fine-grained Soils	• Is representative of undisturbed conditions. • Prevents leaks and sideflow between wall and soil. • Prevents movement of fines, which can lead to clogging or flushing which will provide inaccurate results. • Can measure permeability rates less than $1x10^{-7}$ cm./s. • Most appropriate for silty clay soils.	• Dependent on quality of sample, which may not be representative of field conditions. • Test requires obtaining undisturbed tube samples for clay soils. These samples may be difficult or expensive to obtain. • Use of remolded or disturbed samples may provide less accurate results. • Requires specialized laboratory equipment and training.	• The undisturbed sample is placed in the flexible wall chamber. • The seepage rate through the soil is calculated through drainage holes on the two ends of the chamber.	Lab Test • $200 to $450 / sample Collect Field Bulk sample • $250-$1,000 / sample

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Grain Size Analysis	ASTM D-5126 Lambe, 1969. Shepherd, 1989.	Laboratory Test for some silts and sands	• Little knowledge of the soil sample is needed. • Simple and inexpensive. • Requires a field bulk sample only, no special drilling or sampling method. • Provides accurate estimate of permeability for sand and *some* silt soils.	• Only approximate results are obtained. • Method provides a large variation in results depending on soil sample and degree of sorting of particles. • Involves extensiveemperical solutions. • Very poor correlation to actual field conditions for most soil groups.	• The soil sample is sorted (sieve analysis) to obtain an average grain size or grain size distribution. • Statistical analysis is used to determine the relationship between size and permeability.	Lab Test • $45 to $100 / sample Collect Field Bulk sample • $60 to $100 / sample

Section 3
FIELD METHODS

INTRODUCTION

Field methods are particularly useful when determining flow through native soils. Field tests are generally more representative of the actual field conditions than are laboratory tests. However, field methods have several shortcomings, including the effects of localized site conditions, such as the presence of fine grained soil particles and organics, the presence of large size particles (stones, rubble, etc.) or void spaces present at the test site. These localized conditions can affect the measured permeability. Other factors impacting the permeability results include the limits of the test methodology, field disturbance effects, and exaggerated local conditions.

There is a distinction between saturated and field-saturated permeability for field test methods performed in the vadose zone. The vadose zone refers to the portion of the soil that is unsaturated. True saturated conditions normally do not exist in this zone because of entrapped air. Most tank farms will have unsaturated soil conditions. The entrapped air present in the vadose zone may reduce the permeability measured in the field by as much as a factor of two compared to when there is no air present (ASTM, 1990). The field methods presented can refer to either saturated or unsaturated soils. The correction to field saturated conditions for a specific test measure may be required.

This section outlines the methods available for determining permeability in the field. It outlines the advantages and disadvantages of the methods, and summarizes the test procedures.

SLUG TEST (HVORSLEV'S METHOD)

The slug test is a field test that can be used on homogeneous and non-homogeneous soils. The test utilizes a well that is installed into the groundwater table. A mass or slug is submerged into the well and removed when the water level comes to equilibrium in the casing. By removing the slug, the water level drops an amount equal to the displacement weight of the slug. At this time, water begins entering the casing and the time necessary for the water level to reach equilibrium is recorded. This period of time is called the time lag. The permeability of the soil is determined from a graph of time lag versus permeability. Field procedures for Slug Tests are described in ASTM D-4044.

Sources of error in this method include:

- the inaccuracy of the electronic pressure-sensing device or other device used to measure the water elevation difference during the time lag;
- leakage along the well casing and around the packers;
- clogging of the screen or formation due to intrusion of fines and sediment in the water;
- air entrapment from gas in the soil or water; and
- water flow into the cracks that are opened by excessive head in the test holes.

An illustration of the slug test can be seen in Figure 3-1 below (Cedergren, 1989).

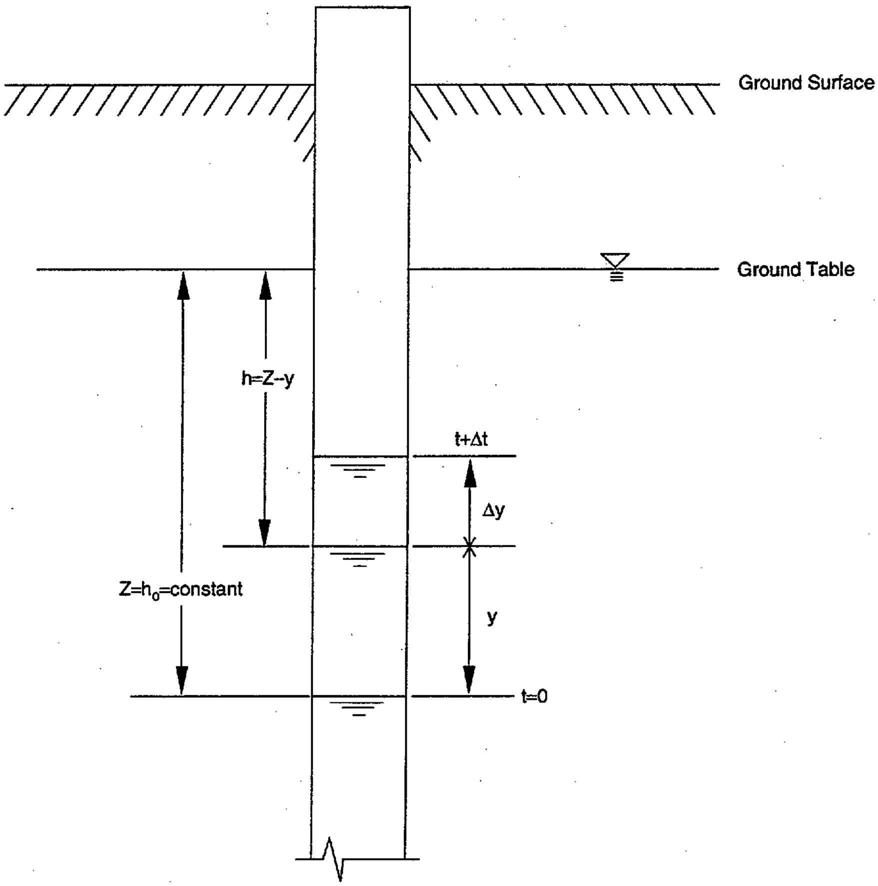


Figure 3–1—Slug Test (Hvorslev's Method)

BOREHOLE TEST

Many variations of the borehole test exist and can be used to determine permeability of soils within the vadose zone. In general, borehole tests consist of pumping into or out of drill holes in order to estimate the permeability of moderate volumes of soil. The “pumping-in” form of the test should be used when the soil sample is above the water table, and either the “pumping-in” or “pumping-out” test methods can be used when the soil is below the water table (Cedergren, 1989). Borehole tests are useful because they can measure the permeability of soils in the unsaturated zone. They also account for flow in all three dimensions. The test can be adjusted to account for capillary effects.

Usually, the borehole test is of the constant head type where the water level needed to maintain a constant level in the hole is measured. Water is introduced into the borehole and kept at a constant level. The flow rate into the hole that is required to maintain this constant level is periodically recorded. The flow rate at the steady state condition, the dimensions and geometry of the borehole, and the depths of the water table are needed to calculate the permeability (ASTM, 1990).

There are numerous options available for calculating permeability from a borehole test. The Bureau of Reclamation expresses permeability in feet per year as follows (Cedergren, 1989):

$$k = C_1(\frac{q}{h})$$

(Equation 3-1)

where:

k = permeability (feet/year)

C_1 = constant, varies with the size of the hole casing

q = constant rate of flow into the hole (gallons/minute)

h = difference in feet between groundwater level and elevation of water level in hole if the test is below the water table, or the depth of water in the hole for tests above the water table

To convert from feet/year to cm/sec, multiply the result by 0.508. See Appendix C for other available conversion factors. For other options for calculating permeability from a borehole test, refer to the ASTM Standard D-5126, *Standard Guide for Comparison of Field Methods for Determining Hydraulic Conductivity in the Vadose Zone.* Two ways to perform the borehole test are shown in Figure 3-2 below (Cedergren, 1989).

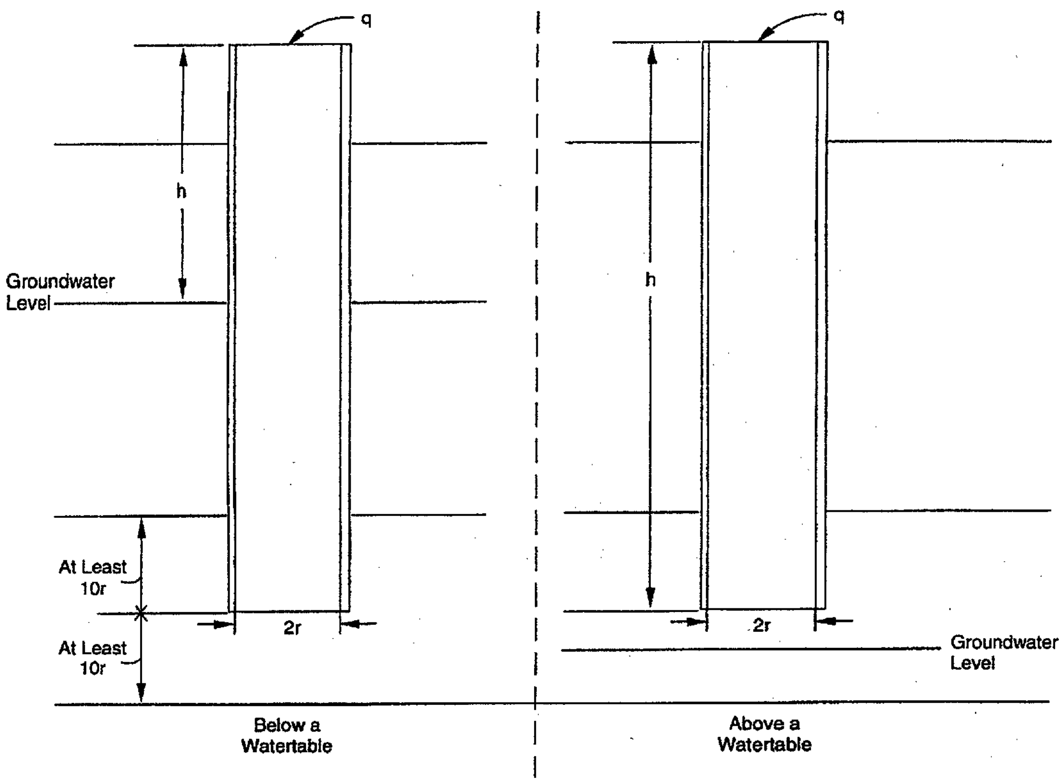


Figure 3–2—Borehole Test

GULF OIL FIELD TEST

The Gulf Oil Field Test is a simple method for determining permeability. A six-inch pipe is placed in the soil and filled to two feet above the bottom edge. A falling head test is performed inside the pipe to determine the soil permeability. Measurements are taken at 30-minute time intervals of the water drop in the pipe. The number obtained is plotted on a graph of water level drop versus permeability, for either unsaturated or saturated soil. For this method, unsaturated soil refers to a groundwater level more than twelve inches below the bottom of the pipe, and saturated soil refers to groundwater less than twelve inches below (PACE, 1979).

Before performing the test, it is necessary to determine the subsoil and groundwater conditions by using excavation test pits for every 3,000 square feet of area, or at least two test pits. In addition, this test should be performed at the driest time of the year (PACE, 1979). An illustration of the Gulf Oil Field Test is shown below in Figure 3-3 (PACE, 1979).

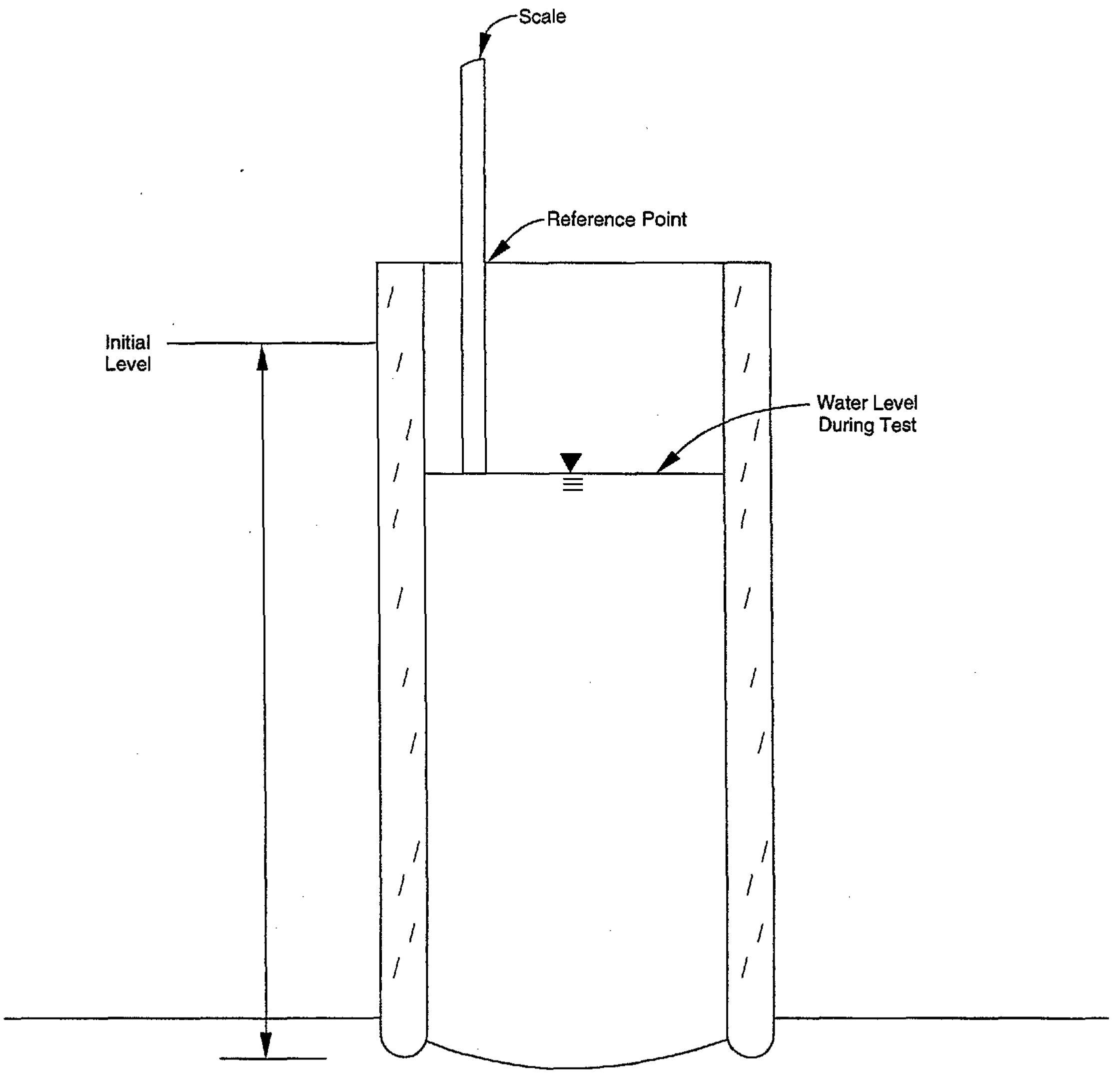


Figure 3–3—Gulf Oil Field Test

WELL PUMPING TEST

The well pumping test consists of a test well and a series of observation wells. A test well is imbedded into an impervious layer, or to a considerable depth below the water table. Observation wells are installed at various radial distances from the test well and initial elevations of the water table are recorded. Pumping at the test well is initiated at a known rate of discharge until a steady state of flow into the well is achieved. The drop in elevation of the water level at the observation wells, the distance to these wells, and the rate of discharge from the test well are used to calculate the permeability using the following equation (Cedergren, 1989):

$$k = \frac{2.3q\log_{10}(r_2 / r_1)}{\pi(h_2^{\,2} - h_1^{\,2})}$$

(Equation 3-2)

where:

k = permeability (feet/day)

q = steady rate of discharge from the test well (ft^3/s)

r_1 = distance to first observation well from center of test well (ft)

r_2 = distance to second observation well from center of test well (ft)

h_1 = elevation above bottom of test well at first observation well (ft)

h_2 = elevation above bottom of test well at second observation well (ft)

The well pumping test is expensive, but accurate at moderate distances from the wells. The reliability of the test depends on the accuracy of the following assumptions inherent in Equation 2-7 (New York State Department of Environmental Conservation, 1988).

- The pumping well penetrates the full thickness of the water-bearing formation;
- A steady-state flow exists;
- The water-bearing formation is homogeneous and isotropic, and extends an infinite distance in all directions; and
- The following Dupuit assumptions are valid (Bedient, 1992):
  - The water table or free surface is only slightly inclined.
  - Streamlines may be considered horizontal and equipotential lines vertical.
  - Slopes of the free surface and hydraulic gradient are equal.

Figure 3-4 below illustrates the well pumping test (Cedergren, 1989).

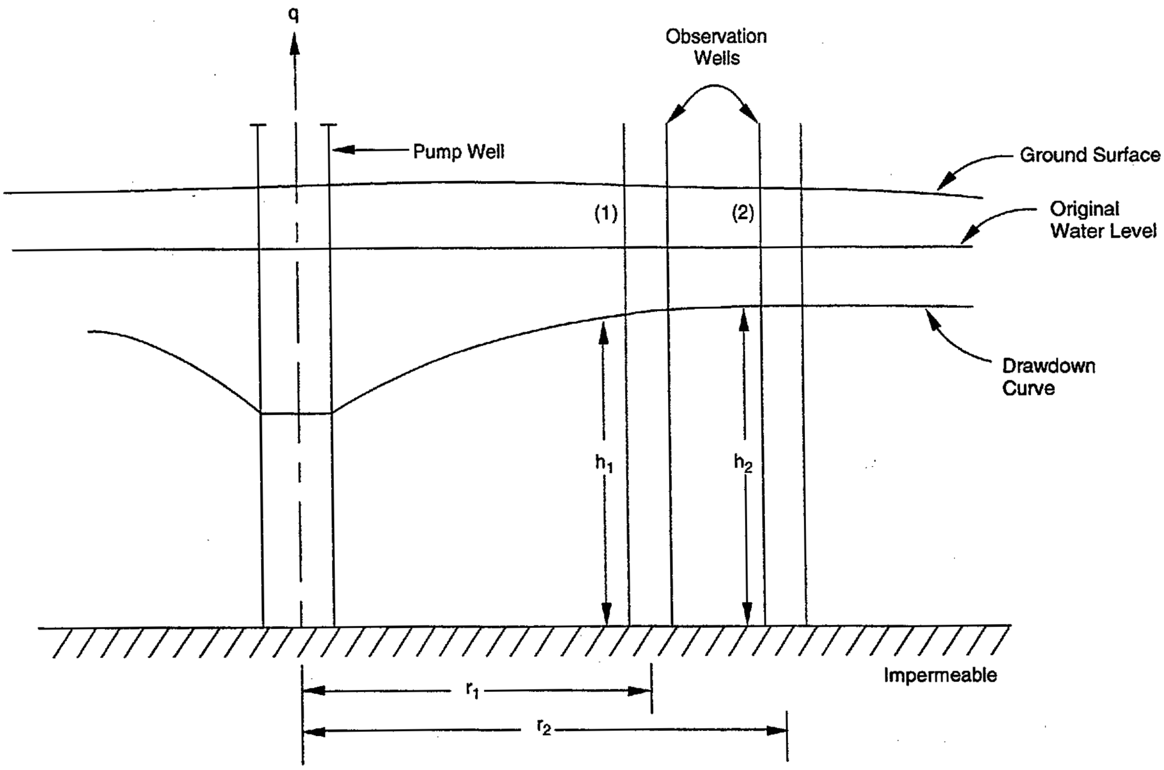


Figure 3-4—Well Pumping Test

PIEZOMETER METHOD

The piezometer method is based upon the measurement of flow into an unlined cavity at the lower end of a lined hole. To perform the piezometer test, a pipe is driven into the soil and a soil auger is bored through the pipe approximately four inches below the bottom of the pipe. The augering is repeated until the pipe is at the desired depth with a space of four inches below the bottom of the pipe remaining open. After the water has been flushed out of the hole several times, the pipe is kept in the hole, and the rise of water in the pipe and the time corresponding to the rise are measured (Spangler, 1973). The permeability can then be calculated using the following equation (Boersma, 1965):

$$k = \frac{\pi R^2}{A\Delta t}\ln\frac{L_1 - E}{L_2 - E}$$

(Equation 3-3)

where:

k = permeability (cm./second)

R = inside radius of the liner (cm.)

E = distance from top of liner to the water table (cm.)

L_1 = distance (cm.) from top of liner to water level in liner at time t_1

L_2 = distance (cm.) from top of liner to water level in liner at time t_2

$\Delta t = t_2 - t_1$, time increment for water to rise from L_1 to L_2 (seconds)

A = geometry factor (cm.)

The liner refers to the casing pipe.

The piezometer method can be adapted to measure horizontal or vertical permeability. If the diameter of the cavity is small and the length is several times the diameter, the horizontal permeability is measured. If the hole is wider and the length of the cavity left unlined is shorter, the measurement becomes closer to the vertical permeability. The piezometer method is shown in Figure 3-5 below (Boersma, 1965).

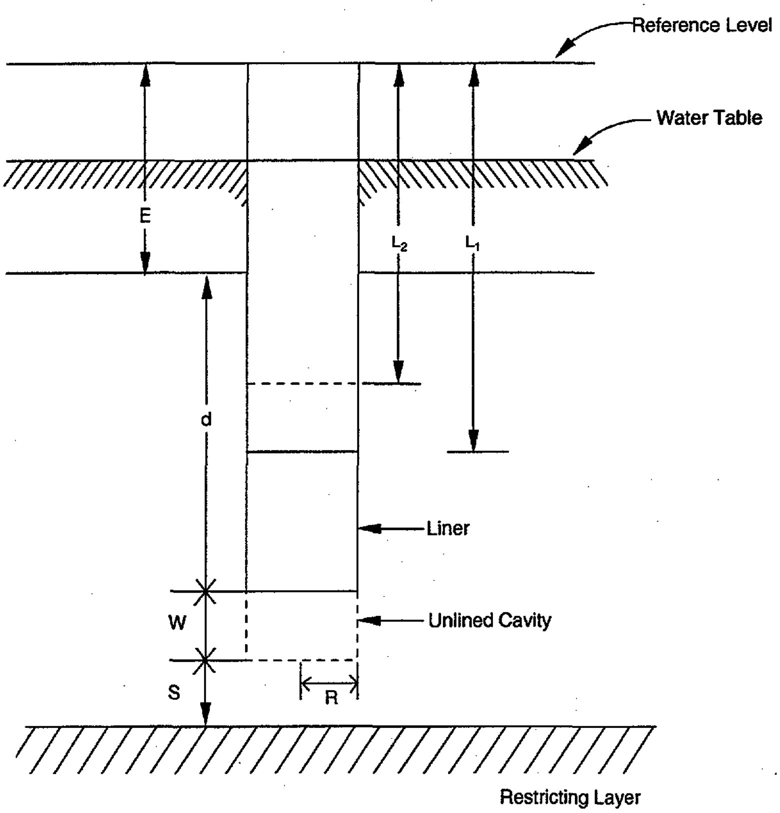


Figure 3-5—Piezometer Method

INFILTROMETERS

Infiltrometers used for permeability tests in the field include single-ring, open double-ring, and sealed double-ring infiltrometers. They should not be used for very coarse soil, heavy clays (except for the sealed double-ring), or in highly fractured ground (ASTM, 1985). Several assumptions apply to the use of infiltrometers including (ASTM, 1990):

- the soil being tested is saturated;
- the water is moving in one direction;
- the wetting front is distinct and easily determined;
- the effects of soil swelling have been taken into account;
- dispersal of clays is insignificant; and
- equipment effects are negligible.

Infiltrometers are useful because they can test large amounts of soil, and seepage can be made one-dimensional. In addition, they can be used to test soils in the vadose zone. The infiltrometer rings can be varied in size depending on the volume of soil being tested. Drawbacks to these tests include inadequate sealing of the ring, large evaporative losses, difficulty in measuring low flow rates, long testing times, and inadequate saturation of the soil (Daniel, 1986). Double-ring infiltrometers are used to ensure flow in one direction. Sealed double-ring infiltrometers can be used to minimize effects of evaporation and temperature, and to measure low-permeability and low flow rates. Depth to the wetting front is determined via excavation or installed transducers.

Single-Ring Infiltrometers

Single-ring infiltrometers are usually 30 cm. or larger in diameter. The ring is driven into the ground several centimeters, and water is ponded in the ring above the ground. The surface of the ring should be covered to minimize evaporation. The rate of water added to the ring surface to maintain constant head within the ring is measured. After the flow has become constant, infiltration is stopped and the depth to the wetting front is determined (ASTM, 1990). Once these measurements are obtained, the permeability can be determined using the following equation (Bouwer, 1986):

$$I = S_i t^{1/2} + At \quad \text{(Equation 3-4)}$$

where:

I = cumulative infiltration (cm of H_2O)

S_i = sorbtivity of soil (determined from plot of cumulative infiltration against $t^{1/2}$)

t = time increment in seconds

A = approximates 0.5 field saturated permeability

Open Double-Ring Infiltrometers

An open double-ring infiltrometer is approximately 50 cm. high with one ring 30 cm. in diameter and the other 60 cm. The smaller ring is placed inside the larger ring and both are partially filled with water. The outer ring is driven in approximately 15 cm., and the inner ring is driven in approximately 5 cm. The water needed to maintain a constant level is measured over timed intervals. The measured amount of water added is assumed to equal the amount of water that infiltrates (ASTM, 1985). These measurements are used to calculate the permeability with the same equation used for single-ring infiltrometers.

Sealed Double-Ring Infiltrometers

Sealed double-ring infiltrometers are similar to open double-ring infiltrometers except that the inner ring is covered to minimize evaporative effects. The flow rate is measured by weighing a sealed flexible bag that is used for storage for the inner ring (ASTM, 1990). Permeability is calculated using the same equation as for the single-ring infiltrometer. A double-ring infiltrometer is shown in Figure 3-6 below (ASTM, 1990).

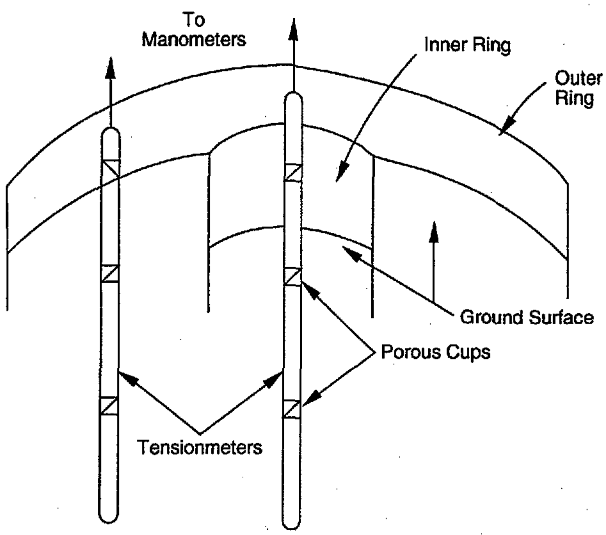


Figure 3–6—Double-Ring Infiltrometer

DOUBLE TUBE TEST METHOD

The double tube test method measures both horizontal and vertical permeability and it can be used to test soil in the vadose zone. To perform this test, an auger hole is excavated to the desired depth for soil measurement. The hole is cleaned, and a 1 to 2 cm. layer of coarse sand is added for protection. A tube is driven into the hole approximately 5 cm. and filled with water. A smaller tube is then driven inside the outer tube. A system of valves and standpipes is installed and water is added to both cylinders (ASTM, 1990). The water level should be kept constant in both standpipes (Boersma, 1965). After approximately one hour, the hole is considered saturated. Next, the water level in the inner tube is allowed to fall while the outer tube stays constant, and the drop in water level is measured over timed intervals through a graduated cylinder. When the first set of measurements is completed, the inner tube is refilled and equilibrium is established by waiting at least ten times as long as the time waited for the first part of the test. The water supply to the inner tube is again allowed to fall, but the level in the outer tube falls simultaneously through use of a valve. The rate of fall of the level in the inner tube is recorded, and both sets of measurements are used to calculate permeability (Boersma, 1965).

The two sets of data collected are first plotted on a graph of time versus the corresponding drop in water level, with time on the X-axis. The permeability is calculated from the following equation (Boersma, 1965):

$$k = \left(\frac{R_v^2}{FR_c}\right)\left(\frac{\Delta H_t}{\int_0^t H dt}\right)$$

(Equation 3-5)

where:

k = permeability (cm./minute)

R_v = radius of the inside-tube standpipe (cm.)

R_c = radius of the inside tube (cm.)

F = dimensionless quantity describing the geometry of the flow system

ΔH_t = vertical distance at time t (minutes) between the two curves of t versus H plotted from the data (cm.)

$\int Hdt$ = area under the curve of t (minutes) versus H (cm), plotted from the data with the water level in the outside tube kept constant up to the time at which ΔH_t is measured

Figure 3-7 below illustrates the set-up for the double tube test method (ASTM, 1990).

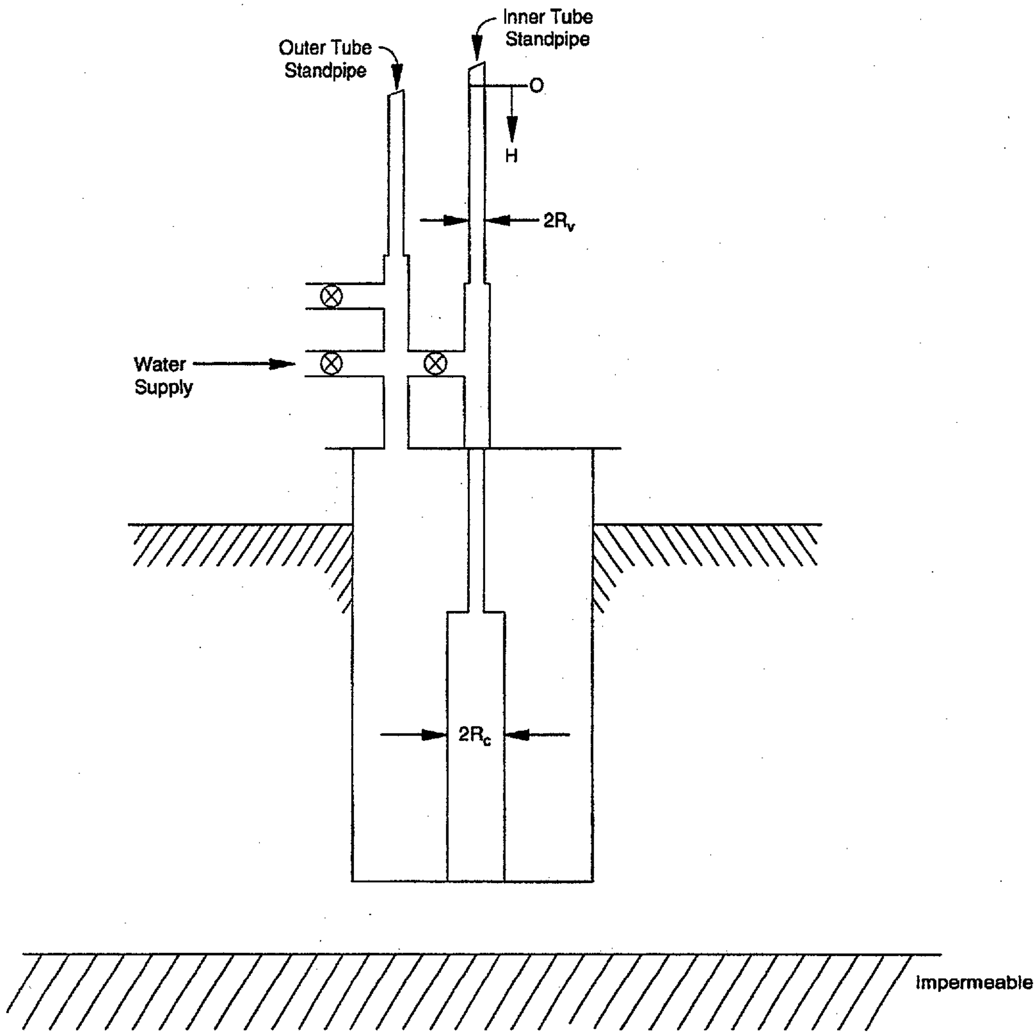


Figure 3-7—Double Tube Method

AIR-ENTRY PERMEAMETER

The air-entry permeameter is similar to the single-ring infiltrometer, except that it enters deeper into the soil and measures the air-entry pressure, which is used to determine the permeability in the vadose zone. A sealed ring approximately 30 cm. in diameter is driven into the soil approximately 15 cm. A water reservoir is attached to a standpipe on top of the permeameter. Water is allowed to infiltrate the soil through the standpipe, and the flow rate is measured from the decline in the water level of the reservoir. When the flow rate has stabilized, and a certain amount of water has infiltrated, the minimum pressure is achieved. The water supply is shut off and the depth to the wetting front is determined (ASTM, 1990).

An assumption inherent in this model is that the wetting front pressure head is closely approximated by air-entry pressure (Stephens, 1988). Permeability can be determined from the minimum pressure (air-entry value) as follows (Amoozegar, 1986):

$$k_{fs} = \frac{L(\frac{dH}{dt})(\frac{R}{R_c})^2}{H + L - (\frac{P}{2pg})}$$

(Equation 3-6)

where:

k_{fs} = field-saturated permeability (cm./second)

L = depth of wetting front (cm.)

H = ponded height of water above the soil (cm.)

dH/dt = rate of fall just before water supply was shut off (cm./second)

R/R_c = radius of the reservoir divided by the cylinder radius

$P/2pg$ = air-entry value (minimum pressure divided by the unit weight of liquid [cm.])

The field saturated permeability is usually about 0.5 the saturated permeability (k_s), or 0.25 k_s in clayey soils (ASTM, 1990). An air-entry permeameter is shown in Figure 3-8 below (ASTM, 1990).

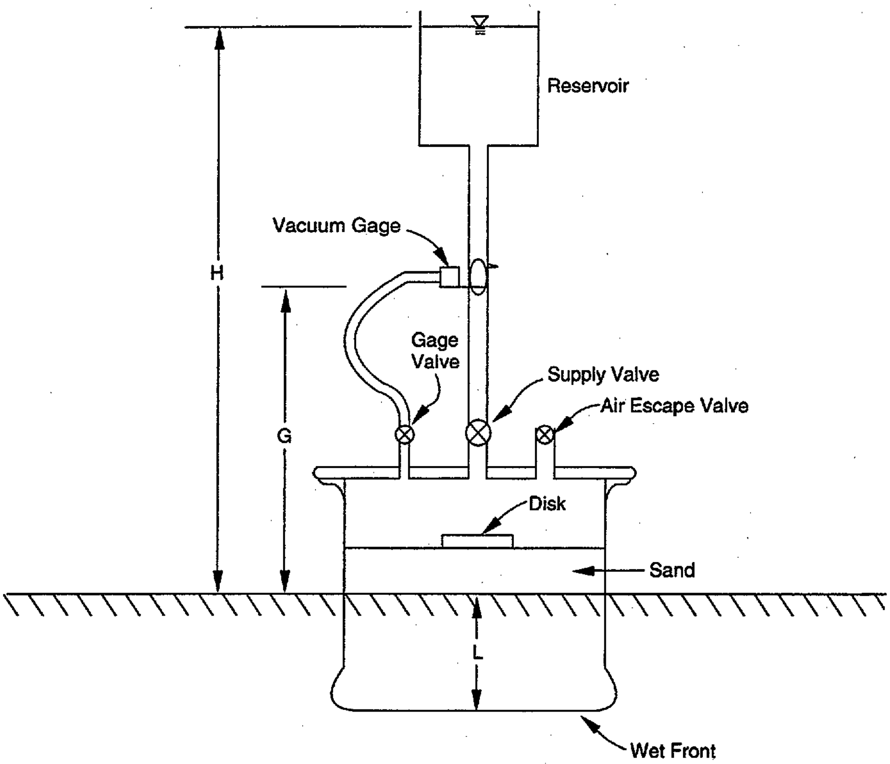


Figure 3-8—Air-Entry Permeameter

Table 3-1. Field Methods for Testing Permeability

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Slug Test (Hvorslev's Method)	Cedergren, 1989	Field Test for Homogeneous and Non-homogeneous Soils	• Simple to perform and inexpensive. • Field results are repeatable. • Provides accurate estimate of permeability for coarse and fine grained soils. • Proven track record of use. • Provides good correlation data for well sorted soils.	• Leakage can occur along casing and around packers. • Clogging can occur due to movement of fines or sediment in water. This will cause recorded results to be lower than actual. • Air locking due to trapped gas bubbles in soil or water can occur. This will cause results to be lower than actual. • Flow of water into cracks that are opened by excessive head in test holes can occur which will cause results to be higher than actual.	• A well is installed into the groundwater table and a mass or slug is submerged into the well casing, raising the water level. • When the level in the well reaches equilibrium, the slug is removed, dropping the water level by a known volume. • As water enters the casing, the amount of time (time lag) is recorded for the water level in the well to reach equilibrium. • The permeability is determined from a graph of time lag versus permeability.	Field Test • $200 to 250 / test Assumes installation of shallow tube or use of existing well without the installation of packers.

[1] These costs represent estimates based on 1998 dollars and may vary by locality.

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Borehole Test	ASTM D-5126 Cedergren, 1989. Daniel, 1986.	Field Test, Generally applicable to all soil conditions.	• Low cost. • Simple and convenient to perform. • Accounts for three-dimensional flow. • Can measure saturated permeability at depths within the unsaturated zone. • Eliminates the need for observation wells. • Can be adapted to account for capillary effects.	• Results depend on accurate measurements of steady-state flow. • Results depend on the quality of the borehole. • Leakage along the casing and around the packers can affect the results. • Clogging due to movement of fines or sediment in water can affect the results. • Air locking from gas bubbles in the soil or water will affect the permeability results. • Flow of water into cracks that are opened by excessive head in test holes will cause permeability results to be higher than actual. • Low flow rates are difficult to measure. • The volume of soil that is permeated is usually very small. • Flow is within, not through, the liner.	• Pumping can be performed "in-to" or "out-of" a drill hole. For above water table testing, "pumping-in" should be used; either method can be used below the water table. • A borehole is drilled to the desired depth and water is added and maintained at a constant level. • The flow rate of the water into the borehole to maintain the level is measured at various times. • The flow rate at steady state conditions is used along with dimensions and geometry of the borehole and the elevation of the water table to calculate the permeability.	Field Test • $200 to 350 / test Assumes installation of shallow borehole with multiple tests performed at each site.

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Gulf Oil Field Test	PACE, 1979.	Field Test, Generally applicable to all soil conditions.	• Equipment and test method are simple. • Method provides a good first pass investigation into soil permeability. • Method has gained wide acceptance in the industry and with some regulators. • Method is similar to a borehole and slug test.	• Method may have some variability in reported results and repeatability of results. • Test pits are required prior to testing to determine subsoil and groundwater conditions. • Method may not accurately predict permeability for soils with permeabilities lower than 10^{-5} cm/s.	• A six-inch diameter pipe is filled to two feet above the bottom edge. • A falling head test is performed inside the pipe with results recorded as inches of water drop in the pipe per 30 minute period. • The result is plotted on a graph to determine permeability.	• $100 to $250 / test Assumes multiple tests performed at each site.
Well Pumping Test	Cedergren, 1989. Spangler, 1973.	Field Test, Generally applicable to all soil conditions.	• Accurate at moderate distances from the wells. • Can be used for level or sloping water tables. • Can be used for sites where shallow groundwater and complex soil conditions exist. • Can provide an accurate estimate of the effective permeability of the soils underlying a large area below the water table. • One of the only methods which provides a large aerial evaluation of the soil permeability.	• Expensive to set up and perform. • The assumptions inherent in the application of this method for measuring permeability may not be true during performance of the test. • Large errors at distances close to the wells. • Not really feasible if the wells are not already in place. • Does not provide information on the soil permeability of the near surface soils. • Can provide conduit for introduction of contaminates	• A test well is installed to the depth of an impervious layer or to a considerable depth below the water table. • Observation wells are installed at various radial distances from the test well. • Initial levels of the water table are recorded and pumping is performed at the test well at a known rate until steady state of flow into the well is achieved. • The drop of water level at the observation wells, the radial distances to the wells, and the rate of discharge from the test well are used to calculate the permeability.	Field Test • $250 to $500 / test Assumes multiple tests performed at each site. Cost does not include test well installation costs.

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Piezometer Method	Boersma, 1965. Spangler, 1973.	Field test for soils consisting of homogeneous layers in stratified soil	• Useful for measurement of permeability at greater depths. • Adaptable to the measurement of horizontal or vertical permeability. • Useful in measuring the permeability of individual layers	• Difficult to use in rocky soils. • Difficult to establish cavities of the correct dimensions.	• A pipe is driven a short distance into the soil. A soil auger is drilled through the pipe to approximately four inches below the bottom of the pipe. • The soil is removed and the process is repeated until the bottom of the pipe is at the desired depth below the water table, with a space of four inches being left open below the bottom pipe. • Water is pumped from the tube several times to flush the soil pores. • The rise of water in the tube and the time corresponding to the rise in water are measured.	• $250 to $1000 / test Assumes multiple tests performed at each site with easy access into the tank farm.

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Single-Ring Infiltrometer	ASTM D-5126 ASTM D-3385 Daniel, 1986.	Field Test, Not to be used for very coarse grained soils, heavy clays, or in highly fractured ground.	• Can permeate a large volume of soil, thus providing a more thorough evaluation of soils than point sampling methods. • Provides accurate measure of vadose zone soil permeability, including measurement of soil permeability variations in the vertical and horizontal direction. • Is suitable for most silty soils and some silty clay soils.	• Lateral flow introduces an error into the calculated permeability which may overstate the vertical permeability. • Will not work for soils with permeability rates less than 1×10^{-6} cm/s due to evaporation losses. • Low flow rates are difficult to measure. • Lengthy time requirements. • The soil may not necessarily be saturated due to trapped air in the soil void space.	• The ring is driven several centimeters into the soil. • Water is ponded in the ring above the soil surface and the ring is covered to prevent evaporation. • The volumetric rate of water added to the ring to maintain a constant head within the ring is measured. • After flow has been stabilized, infiltration is stopped and the depth to the wetting front is determined. • Can be used as falling head type test, refer to ASTM D-5126.	Field Test • $400 to $800/ test Assumes installation of shallow tube or use of existing well without packers.
Open Double-Ring Infiltrometer	ASTM D-3385 ASTM D-5126 Daniel, 1986.	Field Test, Not to be used for very coarse grained soils, heavy clays or in highly fractured ground.	• Seepage is made essentially one-dimensional, isolating the vertical permeability from the horizontal permeability. • Can permeate a large volume of soil, thus providing a more thorough evaluation of soils than point sampling methods. • Provides accurate measure of vadose zone soil permeability.	• Will not work for soils with permeability rates less than 1×10^{-6} cm/s due to evaporation losses. • Low flow rates are difficult to measure. • Lengthy time requirements. • The soil is not necessarily saturated due to trapped air.	• Same as for single-ring infiltrometer, except for the inclusion of the outer ring. • Can be used as falling head type test; refer to ASTM D-5126. • The volumetric rate of water added to the ring to maintain a constant head within the inner ring is measured.	• $400 to $1000 / test Assumes multiple tests performed at each site.

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Sealed Double-Ring Infiltrometer	ASTM D-5126 ASTM D-3385 Daniel, 1986.	Field Test, Not to be used for very coarse grained soils or in highly fractured ground.	• Minimizes evaporation. • Minimizes effects of temperature variations. • Can permeate a large volume of soil, thus providing a more thorough evaluation of soils than point sampling methods. • Provides accurate measure of vadose zone soil permeability, including measurement of soil permeability variations in the vertical and horizontal direction. • Is suitable for most silty soils and some silty clay soils.	• Lengthy time requirements for testing. • The soil is not necessarily saturated due to trapped air. • Test has poorer accuracy for very impermeable clays when compared to a laboratory triaxial permeability test. • Test requires complex set-up and specially trained technicians	• Same as for open double-ring infiltrometer, except inner ring is covered to prevent evaporation. • Flow rate is measured by weighing a sealed flexible bag used as the supply reservoir for the inner ring.	Field Test • $1000 to > $4000 / test Costs very dependent upon site test conditions and setup.

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Double Tube Method	ASTM D-5126 Boersma, 1965.	Field Test, General.	• Allows measurement of soil permeability in the absence of a water table. • Method is free of simplifying assumptions used in the infiltrometer method. • Geometry of the flow paths into the soil is taken into account. • Measures horizontal and vertical permeability.	• Lengthy time requirements for testing. • Not appropriate for rocky soils. • Method is complex requiring specialized equipment and expertise.	• An auger hole is drilled into the soil to the desired depth, the hole is cleaned, and a thin layer of coarse sand is added for protection. • The outer and inner cylinders are installed and water is supplied concurrently to the cylinders to obtain saturation. • The rate of change of the water level in the inner tube is recorded while the level in the outer tube is held constant. • The water levels are returned to the starting point. The supply to the inner tube is sealed and the level of the outer tube is changed to equal the inner tube level through use of a valve. • The rate of change of the level in the inner tube is recorded, then both measurements are plotted and the permeability is calculated.	Field Test • $500 to > $1000 / test Costs very dependent upon site test conditions and setup.

Permeability Test	Reference	Applicability	Advantages	Disadvantages	Procedure	Typical Costs[1]
Air-Entry Permeameter	ASTM D-5126 Stephens, 1988.	Field test, Generally applicable to all soil conditions.	• One-dimensional flow in the vertical direction is attained, so vertical permeability is measured. • Small amounts of water needed. • Short amount of time is required for performing the test.	• Difficult to determine the depth of the wetting front. • Method is complex requiring specialized equipment and expertise.	• The ring is driven into the soil 15 to 25 cm. and water is introduced through a standpipe, which has a water reservoir attached to the top. • Water infiltrates the permeameter ring and the flow rate is measured from the drop of the water level in the reservoir. • After a certain amount of water has infiltrated, the test is stopped and the depth to the wetting front is determined by excavation or installed transducers.	Field Test • $500 to $1500 / test Assumes multiple tests performed at each site.

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Appendix A

DEFINITIONS

Terms within this report are used with the following meaning:

Atterberg Limits Test

A simple laboratory testing method which is used to determine the type and properties of clay and silt soils.

Clay

Clays are fine grained soils with 50% plastic fines passing the No. 200 sieve. Atterberg limits testing are used to determine the type of clay present.

Coarse Grained Soils

Coarse grained soils are those having 50% or more material retained on the No. 200 sieve. Sands and gravels are considered to be coarse grained. The permeability of these soils is typically greater than that of fine grained soils.

Cohesive Soils

Fine grained soils which exhibit plastic properties, including molecular bonding of particles in the presence of water. Clays are considered to be cohesive soils. Not all fine grained soils are cohesive or plastic. For example, silt particles passing the No. 200 sieve are considered to be non-plastic fines. Cohesive soils, such as clay, typically have very low-permeability, if the soils have not been acted on by outside forces, such as desiccation cracking.

Fine Grained Soils

Fine grained soils are those having more than 50% passing the No. 200 sieve. Clays and silts are considered to be fine grained soils. The permeability of these soils is typically less than that of coarse grained soils.

Gravel

Gravels are coarse grained soils with particles ranging from 2.0 millimeters to 64.0 millimeters. They have the greater percentage of the coarse fraction retained on the No. 4 sieve.

Homogeneous

A soil sample that consists of relatively similar soil types and uniform particle sizes.

Non-Homogeneous

A soil sample that consists of differing soil types and non-uniform particle sizes.

Permeability (Hydraulic Conductivity)

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 (20°C).

Permeameter

An apparatus used in the laboratory to measure soil permeability, usually of the falling head or constant head type.

Poorly Graded / Well Sorted

A sample of soil that contains particles of relatively uniform particle size.

Sand

Sands are considered to be coarse grained soils with particles ranging from 0.062 mm. to 2.0 mm. Sand has the greater percentage of the coarse fraction passing the No. 4 sieve.

Saturated

A soil is saturated when the voids in the soil are completely filled with water and it has little, if any, entrained air or air bubbles present. Saturated soils are typically below the groundwater table.

Silt

Silts are fine grained soils with particles ranging from 0.004 mm. to 0.062 mm. Silts consist of soils which have more than 50% passing the No. 200 sieve. Atterberg limits testing is used to determine the type of silt present.

USCS

A system of soil classification which relies upon a sieve analysis and Atterberg limit test to divide soils into coarse grained or fine grained, and to further subdivide soils into various classifications including sand(S), gravel(G), silt(M), clay(C).

Unsaturated

A soil is unsaturated when the voids of the soil contain an amount of air. Unsaturated soils typically are above the groundwater table.

Vadose

The area of the soil that extends from the soil surface to the groundwater table. The vadose zone refers to the area of the soil that is unsaturated.

Well Graded / Poorly Sorted

A sample of soil that contains a wide distribution of different size particles.

Appendix B

LIST OF VARIABLES

A	= cross-sectional area of sample specimen (cm^2) (Equations 2-1, 2-2)
	= geometry factor (cm.) (Equation 3-3)
	= approximates 0.5 field saturated permeability (Equation 3-4)
a	= area of the standpipe (cm^2) (Equation 2-2)
	= exponent usually ranging from 1.65 to 1.85 (Equation 2-3)
c	= a dimensionless constant found through regression analysis (Equation 2-3)
	= a dimensionless constant which varies from 0.4 to 1.2 with an average value of 1.0 (Equation 2-4)
C_1	= constant, varies with the size of the hole casing (Equation 3-1)
D_{10}	= the effective grain size for the 10 percent size in the grain-size curve when the particle diameter is between 0.1 to 3.0 millimeters (otherwise the equation is not valid) (Equation 2-4)
d	= mean pore throat or particle diameter (in millimeters) (Equation 2-3)
E	= distance from top of liner to the water table (cm.) (Equation 3-3)
e	= void ratio (Equation 1-5)
F	= dimensionless quantity describing the geometry of the flow system (Equation 3-5)
g	= gravitational constant (Equation 1-1)
H	= ponded height of water above the soil (cm) (Equation 3-6)
ΔH_t	= vertical distance at time *t* (minutes) between the two curves of *t* versus *H* plotted from the data (cm.) (Equation 3-5)
$\int Hdt$	= area under the curve of *t* (minutes) versus *H* (cm), plotted from the data with the water level in the outside tube kept constant up to the time at which ΔH_t is measured (Equation 3-5)
dH/dt	= rate of fall just before water supply was shut off (cm/second) (Equation 3-6)
h	= difference in head on manometers (cm) (Equation 2-1)
	= difference in feet between groundwater level and elevation of water level in hole if the test is below the water table, or the depth of water in the hole for tests above the water table (Equation 3-1)

h_1 = initial height in the standpipe (cm) (Equation 2-2)

= elevation above bottom of test well at first observation well (ft) (Equation 3-2)

h_2 = final height in the standpipe (cm) (Equation 2-2)

= elevation above bottom of test well at second observation well (ft) (Equation 3-2)

I = cumulative infiltration (cm of H_2O) (Equation 3-4)

K = hydraulic conductivity

k_f = permeability using a fluid other than water (Equation 1-2)

k_w = permeability using water (Equation 1-2)

k = permeability

= specific or intrinsic permeability (Equation 1-1)

k_{fs} = field-saturated coefficient of permeability (cm/second) (Equation 3-6)

L = distance between manometers (cm) (Equation 2-1)

= sample length (cm) (Equation 2-2)

= depth of wetting front (cm) (Equation 3-6)

L_1 = distance (cm.) from top of liner to water level in liner at time t_1 (Equation 3-3)

L_2 = distance (cm.) from top of liner to water level in liner at time t_2 (Equation 3-3)

M_s = mass of soil solids

M_w = mass of water

n = porosity (percentage)

P/2pg = air-entry value (minimum pressure divided by the unit weight of liquid (cm)) (Equation 3-6)

Q = quantity of water discharged (cm^3) (Equation 2-1)

q = constant rate of flow into the hole (gallons/minute) (Equation 3-1)

= steady rate of discharge from the test well (ft^3/s) (Equation 3-2)

R = inside radius of the liner (cm.) (Equation 3-3)

R_v = radius of the inside-tube standpipe (cm.) (Equation 3-5)

R_c = radius of the inside tube (cm.) (Equation 3-5)

R/R_c = radius of the reservoir divided by the cylinder radius (Equation 3-6)

r_1 = distance to first observation well from center of test well (ft) (Equation 3-2)

r_2 = distance to second observation well from center of test well (ft) (Equation 3-2)

S_i = sorbtivity of soil (determined from plot of cumulative infiltration against $t^{1/2}$) (Equation 3-4)

S = degree of saturation (percentage) (Equation 1-3)

t = total time of discharge (seconds) (Equation 2-1)

= time increment in seconds (Equation 3-4)

Δt = $t_2 - t_1$, time increment for water to rise from L_1 to L_2 (seconds) (Equation 3-3)

dt = change in time for the water to fall from h_1 to h_2 (seconds) (Equation 2-2)

V_a = volume of air

V_s = volume of the solids

V_t = total volume of soil sample

V_v = volume of voids

V_w = volume of water

VR = viscosity ratio of a fluid compared to water

ν = kinematic viscosity

ρ_d = dry density

ρ_{sat} = saturated density

Appendix C

CONVERSION FACTORS

To Convert From:	To:	Multiply By:
Centimeters/second	Feet/minute	1.9685
	Feet/year	1034643.6
Centimeters	Feet	0.032808399
	Millimeters	10
Square centimeters	Square feet	1.076387×10^{-3}
Cubic centimeters	Cubic feet	3.5314667×10^{-5}
	Gallons	2.642×10^{-4}

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