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# OVERVIEW OF SOIL PERMEABILITY TEST METHODS

REGULATORY AFFAIRS DEPARTMENT  
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# Overview of Soil Permeability Test Methods

**Regulatory Affairs Department**

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PREPARED UNDER CONTRACT BY:

GIANNA AIEZZA AND JOSEPH BURKE  
SPEC CONSULTING SERVICES  
427 CLIFTON CORPORATE PARK  
CLIFTON PARK, NEW YORK 12065

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### API STAFF CONTACT

F. Dee Gavora, Regulatory Affairs Department

### MEMBERS OF THE STORAGE TANK TASK FORCE SUBCOMMITTEE

Don Gilson, Product Chairman, Chevron Products Company

Jerry Engelhardt, Santa Fe Pacific Pipeline Company

Jerry Garteiser, Exxon Company, USA

George Lloyd, Shell Oil Company

William Martin, ARCO Products Company

Gene Milunec, Mobil Oil Corporation

James Moore, Amoco Oil Company

Philip Myers, Chevron Research and Technology

Randall Steele, BP Oil Company

James Stevenson, Phillips Pipeline Company

John Thomas, Shell Oil Company

Alan Wolf, Exxon Research and Engineering Company

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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  $1 \times 10^{-7}$  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**

| Rocks | Unconsolidated Deposits | Hydraulic Conductivity |        |       |                            |
|-------|-------------------------|------------------------|--------|-------|----------------------------|
|       |                         | (ft/day)               | (cm/s) | (m/s) | (gal/day/ft <sup>2</sup> ) |

  

Note: ft/day = feet per day; cm/s = centimeters per second; m/s = meters per second; gal/day/ft<sup>2</sup> = gallons per day per square foot.  
 \*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

$\nu$  = 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 <sup>a</sup>               |
| No. 6 fuel oil         | 3180 <sup>b</sup>               |

Note: C = Celsius

<sup>a</sup> Data reported were determined at 20°C

<sup>b</sup> 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 than 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)

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

(Equation 1-7)

where:

$\rho_d$  = dry density

$\rho_{sat}$  = 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.<sup>3</sup>)

$L$  = distance between manometers (cm.)

$A$  = cross-sectional area of sample specimen (cm.<sup>2</sup>)

$t$  = 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  $1 \times 10^{-3}$  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).