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Measurement of the Hydraulic Conductivity of Fine-Grained Soils

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ABSTRACT: The purpose of this paper is to review the state of the art in the measurement of hydraulic conductivity of fine-grained soils. Both field and laboratory tests for saturated and partially saturated soils are considered.

For saturated soils, field tests are to be preferred because they permeate a larger volume of soil, thus taking into account the effects of macrostructure better than laboratory tests. Field tests are generally best performed by using a cylindrical piezometer tip, installed by methods that minimize disturbance, and measuring flow under a constant head. Laboratory tests offer the advantage of economy. Laboratory specimens should be as large as practical and should be oriented to produce flow in the direction of maximum hydraulic conductivity. The permeant should be a fluid similar to that encountered in the field. Without proper experimental technique, the conductivity measured in the laboratory may differ from the field value by several orders of magnitude.

Field tests for unsaturated soils are not well developed and can only be recommended for cases where water will be ponded on the surface of a site. The most versatile laboratory techniques are the instantaneous profile method using tensiometric or psychrometric probes, and the pressure plate outflow method. The best method to use depends on the soil suction expected in the field.

KEY WORDS: permeability, hydraulic conductivity, soils, fine-grained soils, clays, sample preparation, laboratory tests, field tests, suction, unsaturated soils, groundwater

Analyses of water flow in saturated soils are usually based on Darcy's [*1*][2] law which, in turn, is based on the experimental observation of a linear relationship between the rate of flow and the driving forces. The law has been written in many forms depending mainly on the discipline of the user and the date of usage. The form most commonly encountered is

$$q = -kiA \tag{1}$$

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[2]The italic numbers in brackets refer to the list of references appended to this paper.

where q is the flow rate [length^3/time (L^3/T)]; i is the hydraulic gradient (dimensionless); A is the total cross-sectional area of flow (L^2); and k is the constant of proportionality (L/T), which is termed the hydraulic conductivity in most disciplines but is often termed the permeability by civil engineers. In Eq 1, k is dependent on the properties of both the fluid and the porous medium. An alternative form of Darcy's law is

$$q = -K \frac{\gamma_w}{\mu} iA \tag{2}$$

where γ_w [units of mass/length^2 time^2 (M/L^{2}T^2)] and μ (ML/T) are the unit weight and viscosity of the fluid, respectively, and K is the constant of proportionality (L^2). In most disciplines K is termed the coefficient of permeability but is sometimes termed intrinsic permeability [*2*]. A third form of Darcy's law is [*3*]

$$q = -\frac{k}{\mu} \frac{dp}{dx} A \tag{3}$$

where q is the flow rate (cubic centimetres per second), μ is viscosity (centipoises), p is pressure (atmospheres), x is flow distance (centimetres), A is total cross-sectional area (square centimetres), and k is the permeability in units of "darcies." For a permeant of pure water at 20°C the conversions are [*4*]

$$1 \text{ cm/s} = 1.02 \times 10^{-5} \text{ cm}^2 = 1.04 \times 10^3 \text{ darcy}$$

Because of its simplicity and the fact that we are concerned with the flow of a single fluid, water, we prefer to use Eq 1. To conform with general usage we will also term k the hydraulic conductivity, or, where the meaning is clear, simply conductivity. However, when considering general matters not concerned with a specific equation or parameter we will use the term permeability, as, for example, "permeability tests."

Most engineers and geologists are familiar with techniques for measuring k in coarse-grained soils—for example, constant or falling head tests in the laboratory and pump tests from wells in the field—but are less familiar with techniques for measuring k in fine-grained soils. The reason for this, in the case of geologists, is probably that primary interest has traditionally been in development of groundwater supplies, which cannot be extracted economically from fine-grained soils due to their low hydraulic conductivities. In engineering, past practice has frequently been to assume that fine-grained soils are effectively "impervious" and to forgo attempts to measure k. The need for measurements of hydraulic conductivity in fine-grained soils seems to be increasing as a result of recent developments. One such development is in-

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creased concern over the long-term environmental effects associated with burying toxic wastes in the ground. When consideration is given to water and pollutant movements over periods of up to hundreds of thousands of years, the fine-grained soils can no longer be treated as impervious and their conductivities must be measured. The attractiveness of sites in arid regions for disposal of radioactive and other toxic wastes has also created interest in measuring the conductivity of partially saturated soils.

Another area of increased interest involves consolidation problems; evidence now indicates that the accuracy of field predictions may be improved by using either laboratory [*5*] or *in situ* [*6*] measurements of conductivity, as opposed to evaluating the coefficient of consolidation directly by fitting theoretical curves to laboratory time–settlement data [*7*]. Measurements of hydraulic conductivity in fine-grained soils have always been, and will continue to be, of concern in design of earth dams, slurry trenches used as groundwater cutoffs, and compacted clay used to line water-storage reservoirs or waste-disposal pits, as well as in hydrological investigations of groundwater recharge.

In the pages that follow, we will examine the state of the art for measuring the hydraulic conductivity of both saturated and partially saturated fine-grained soils, including both field and laboratory methods. It is convenient to discuss the relative merits of laboratory versus field tests first. Then laboratory testing for both saturated and unsaturated soils will be considered, followed by a similar discussion of field testing. Finally, laboratory and field values will be compared. Testing techniques and testing errors will be discussed. No attempt will be made to cover in detail all methods that have been used, but references will be made to numerous papers to aid in a more expanded study.

Laboratory Versus Field Measurements

Soils tend to be nonhomogeneous. Fine-grained soils may be stratified on a large scale but may also be nonhomogeneous on a small scale as a result of sand partings, fissures and joints, and root holes. It is desirable, therefore, to test a volume of soil that is large enough to contain a statistically significant distribution of these features. Such volumes are almost always too large to be included in laboratory tests. Further, the results of laboratory tests may be influenced by effects of sampling disturbance, by various laboratory errors to be discussed subsequently, and by a tendency to select the most uniform, intact samples for testing. The soil is also likely to be anisotropic, and laboratory samples are not likely to be oriented so that flow occurs in the direction of highest conductivity. Clearly, field tests will be required in many cases.

There are several cases in which laboratory tests seem appropriate. In the case of compacted soils, permeability tests on soil prepared at various densities and water contents are most readily performed in the laboratory. Comparative tests to determine the effects of different permeants on conductivity are also typically performed in the laboratory.

Two practical reasons may also be advanced for use of laboratory tests. The first is economics. Large numbers of laboratory tests can be performed in a well-equipped laboratory with minimal expense, but field tests can be prohibitively expensive. A second reason for using laboratory tests is ignorance of field testing methods. Essentially all soil mechanics texts mention acceptable laboratory testing methods, but none currently provides a similar treatment for field measurements of the hydraulic conductivity of fine-grained soils.

Laboratory Tests for Saturated Soils

Permeability Cells

The standard laboratory tests for saturated fine-grained soils generally have the soil in the form of a disk with radial boundaries of metal, or occasionally plastic, and with the flow vertically upwards. Consolidation cells work well for undisturbed samples, whereas compaction molds are used directly for compacted soils.

A simple design for a consolidation-cell permeameter is shown in Fig. 1. The ring has a sharpened upper edge to facilitate trimming. With such apparatus and hand trimming, values of k less than 1×10^{-12} cm/s have been measured. Mechanical devices [*8, 9, 10*] may be used to prevent tilting of the ring during trimming and thus minimize the possibility of creating voids between the soil and the ring.

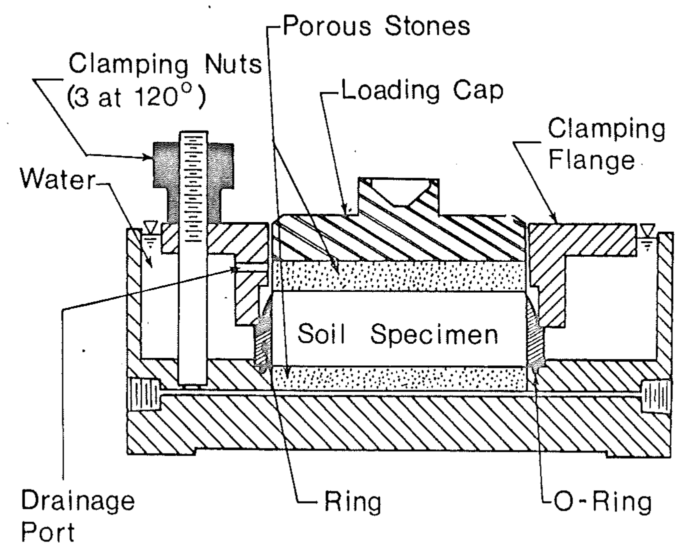

FIG. 1—*Consolidation cell permeameter.*

and found that the thickness of disturbed soil on each face was 0.06 cm (0.025 in.).

To minimize the effects of smear, (1) use a sharp knife for final trimming and cut the soil rather than trowel it; (2) include open root holes and other visible zones of higher conductivity in the specimen to be tested; and (3) use as large a specimen as possible.

Alterations in Clay Chemistry—A belief apparently held by some is that the permeability test should be performed using distilled water because such water is inert. Actually, leaching a sample with distilled water may cause expansion of the diffuse cloud of absorbed cations around clay particles and reduce hydraulic conductivity. Further, in some soils the leaching may increase particle mobility, either because of expansion of diffuse double layers or because of removal of cements, and lead to particle migration. An example of these effects is shown in Fig. 6 [*32*]. A solution is to use a permeant of the same chemistry as the original pore water but the time and expense involved in extracting, analyzing, and duplicating the pore water makes this solution impractical. Alternatively, samples of groundwater may be obtained in the field and used as a permeant. Another possible solution is to perform laboratory tests using very small amounts of flow and using sealed permeameters in which the flow can be reversed, thus cycling the same fluid to and fro [*19,33*].

Large changes in conductivity are likely to occur if a permeant is used with a chemistry that is widely different from that of the pore fluid. For example, Fireman [*34*] leached samples of Hesperia sandy loam with various aqueous solutions and found the following conductivities: 4×10^{-3} cm/s (originally), 6×10^{-3} cm/s (800 ppm calcium chloride), 3×10^{-3} cm/s (tap water), 1×10^{-4} cm/s (4500 ppm sodium chloride), and 2×10^{-5} cm/s (distilled water). Numerous studies have shown changes in conductivity for samples originally prepared with different chemistries [*35-38*].

When it is not feasible to determine the chemistry of the natural pore fluid and duplicate it as a permeant, agronomists have often used 0.01 *N* calcium sulfate as the permeant [*39,40*]. Some prefer to use tap water, which, though not ideal, generally seems a much better choice than distilled water.

Air in the Sample—In testing compacted samples, engineers often assume that soaking from the bottom, with the top open to the atmosphere, will lead to saturated samples. Smith and Browning [*41*] used this procedure to "saturate" 200 samples. They found that the average degree of saturation of their samples was 91 percent with the lowest value 78 percent. Because water cannot flow through an air bubble, the bubbles effectively reduce the void space that can be occupied by water and thus reduce hydraulic conductivity. Bjerrum and Huder [*42*] noted that air bubbles may tend to accumulate near the end of the sample where the water emerges, causing a clogging and erroneous measurements. Christianson [*43*] soaked a number of air-dried samples from the bottom up and then ran permeability tests. As flow continued

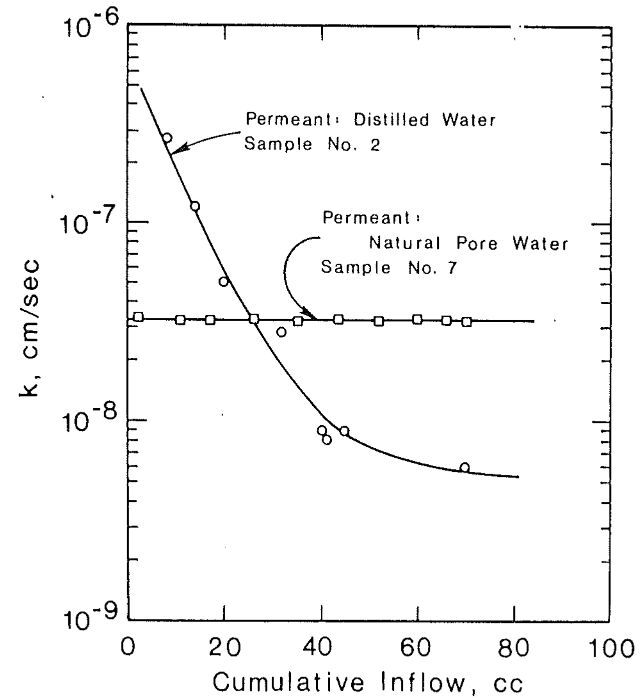

FIG. 6—*Influence of using distilled water (from Wilkinson [32]).*

the entrapped gas bubbles were slowly removed, and the measured hydraulic conductivities went up by factors ranging from 2 to 40 times. A typical range for many soils may be closer to 2 to 5 times [*44*]. When Christianson soaked his samples under vacuum he found no time-dependent increase in conductivity.

If water is forced through the soil using compressed air, the water entering the sample may contain a higher gas concentration than that corresponding to gas saturation at a lower pressure, and thus gas bubbles may form as the pressure in the flowing water decreases.

Growth of Microorganisms—Prolonged performance of permeability tests may result in a substantial reduction in hydraulic conductivity due to clogging of the flow channels by organic matter that grows in the soil during the test. Allison [*45*] reported on tests in which a variety of disinfectants were added to the permeating water to stop such organic growth. He found that phenol (1000 ppm) and formaldehyde (2000 ppm) were the most effective agents in delaying growth of organic matter, but eventually even these soils "sealed up." Finally, he sterilized samples of three soils, including one that was rich in organics and two that contained little organic matter, and used elaborate procedures to keep the permeating fluid sterile. In the sterile samples there was an insignifi-

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