Designation: D5084 – 16a

Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter[1]

1. Scope*

1.1 These test methods cover laboratory measurement of the hydraulic conductivity (also referred to as *coefficient of permeability*) of water-saturated porous materials with a flexible wall permeameter at temperatures between about 15 and 30°C (59 and 86°F). Temperatures outside this range may be used; however, the user would have to determine the specific gravity of mercury and R_T (see 10.3) at those temperatures using data from *Handbook of Chemistry and Physics*. There are six alternate methods or hydraulic systems that may be used to measure the hydraulic conductivity. These hydraulic systems are as follows:

1.1.1 *Method A*—Constant Head

1.1.2 *Method B*—Falling Head, constant tailwater elevation

1.1.3 *Method C*—Falling Head, rising tailwater elevation

1.1.4 *Method D*—Constant Rate of Flow

1.1.5 *Method E*—Constant Volume–Constant Head (by mercury)

1.1.6 *Method F*—Constant Volume–Falling Head (by mercury), rising tailwater elevation

1.2 These test methods use water as the permeant liquid; see 4.3 and Section 6 on Reagents for water requirements.

1.3 These test methods may be utilized on all specimen types (intact, reconstituted, remolded, compacted, etc.) that have a hydraulic conductivity less than about 1×10^{-6} m/s (1×10^{-4} cm/s), providing the head loss requirements of 5.2.3 are met. For the constant-volume methods, the hydraulic conductivity typically has to be less than about 1×10^{-7} m/s.

1.3.1 If the hydraulic conductivity is greater than about 1×10^{-6} m/s, but not more than about 1×10^{-5} m/s; then the size of the hydraulic tubing needs to be increased along with the porosity of the porous end pieces. Other strategies, such as using higher viscosity fluid or properly decreasing the cross-sectional area of the test specimen, or both, may also be possible. The key criterion is that the requirements covered in Section 5 have to be met.

1.3.2 If the hydraulic conductivity is less than about 1×10^{-11} m/s, then standard hydraulic systems and temperature environments will typically not suffice. Strategies that may be possible when dealing with such impervious materials may include the following: *(a)* controlling the temperature more precisely, *(b)* adoption of unsteady state measurements by using high-accuracy equipment along with the rigorous analyses for determining the hydraulic parameters (this approach reduces testing duration according to Zhang et al. (**1**)[2]), and *(c)* shortening the length or enlarging the cross-sectional area, or both, of the test specimen (with consideration to specimen grain size (**2**)). Other approaches, such as use of higher hydraulic gradients, lower viscosity fluid, elimination of any possible chemical gradients and bacterial growth, and strict verification of leakage, may also be considered.

1.4 The hydraulic conductivity of materials with hydraulic conductivities greater than 1×10^{-5} m/s may be determined by Test Method D2434.

1.5 All observed and calculated values shall conform to the guide for significant digits and rounding established in Practice D6026.

1.5.1 The procedures used to specify how data are collected, recorded, and calculated in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that should generally be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analysis methods for engineering design.

1.6 This standard also contains a Hazards section (Section 7).

1.7 The time to perform this test depends on such items as the Method (A, B, C, D, E, or F) used, the initial degree of

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[1] This standard is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.04 on Hydrologic Properties and Hydraulic Barriers.

Current edition approved Aug. 15, 2016. Published August 2016. Originally approved in 1990. Last previous edition approved in 2016 as D5084–16. DOI: 10.1520/D5084-16A.

[2] The boldface numbers in parentheses refer to the list of references appended to this standard.

***A Summary of Changes section appears at the end of this standard**

saturation of the test specimen and the hydraulic conductivity of the test specimen. The constant volume Methods (E and F) and Method D require the shortest period-of-time. Typically a test can be performed using Methods D, E, or F within two to three days. Methods A, B, and C take a longer period-of-time, from a few days to a few weeks depending on the hydraulic conductivity. Typically, about one week is required for hydraulic conductivities on the order of 1×10^{-9} m/s. The testing time is ultimately controlled by meeting the equilibrium criteria for each Method (see 9.5).

1.8 *Units*—The values stated in SI units are to be regarded as the standard. The inch-pound units given in parentheses are mathematical conversions, which are provided for information purposes only and are not considered standard, unless specifically stated as standard, such as 0.5 mm or 0.01 in.

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D698 Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3))

D854 Test Methods for Specific Gravity of Soil Solids by Water Pycnometer

D1140 Test Methods for Determining the Amount of Material Finer than 75-μm (No. 200) Sieve in Soils by Washing

D1557 Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))

D1587 Practice for Thin-Walled Tube Sampling of Fine-Grained Soils for Geotechnical Purposes

D2113 Practice for Rock Core Drilling and Sampling of Rock for Site Exploration

D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

D2434 Test Method for Permeability of Granular Soils (Constant Head) (Withdrawn 2015)[4]

D2435 Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading

D3550 Practice for Thick Wall, Ring-Lined, Split Barrel, Drive Sampling of Soils (Withdrawn 2016)[4]

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D4220 Practices for Preserving and Transporting Soil Samples

D4318 Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils

D4753 Guide for Evaluating, Selecting, and Specifying Balances and Standard Masses for Use in Soil, Rock, and Construction Materials Testing

D4767 Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils

D5079 Practices for Preserving and Transporting Rock Core Samples

D6026 Practice for Using Significant Digits in Geotechnical Data

D6151 Practice for Using Hollow-Stem Augers for Geotechnical Exploration and Soil Sampling

D6169 Guide for Selection of Soil and Rock Sampling Devices Used With Drill Rigs for Environmental Investigations

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

3. Terminology

3.1 *Definitions:*

3.1.1 For common definitions of technical terms in this standard, refer to Terminology D653.

3.1.2 *head loss,* Δh—the change in total head of water across a given distance.

3.1.2.1 *Discussion*—In hydraulic conductivity testing, typically the change in total head is across the influent and effluent lines connected to the permeameter, while the given distance is typically the length of the test specimen.

3.1.3 *permeameter*—the apparatus (cell) containing the test specimen in a hydraulic conductivity test.

3.1.3.1 *Discussion*—The apparatus in this case is typically a triaxial-type cell with all of its components (top and bottom specimen caps, stones, and filter paper; membrane; chamber; top and bottom plates; valves; etc.).

3.1.4 *hydraulic conductivity, k*—the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of porous medium under a unit hydraulic gradient and standard temperature conditions (20°C).

3.1.4.1 *Discussion*—In hydraulic conductivity testing, the term *coefficient of permeability* is often used instead of *hydraulic conductivity*, but *hydraulic conductivity* is used exclusively in this standard. A more complete discussion of the terminology associated with Darcy's law is given in the literature. (**3, 4**)

3.1.5 *pore volume of flow—in hydraulic conductivity testing*, the cumulative quantity of flow into a test specimen divided by the volume of voids in the specimen.

4. Significance and Use

4.1 These test methods apply to one-dimensional, laminar flow of water within porous materials such as soil and rock.

4.2 The hydraulic conductivity of porous materials generally decreases with an increasing amount of air in the pores of

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[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The last approved version of this historical standard is referenced on www.astm.org.

the material. These test methods apply to water-saturated porous materials containing virtually no air.

4.3 These test methods apply to permeation of porous materials with water. Permeation with other liquids, such as chemical wastes, can be accomplished using procedures similar to those described in these test methods. However, these test methods are only intended to be used when water is the permeant liquid. See Section 6.

4.4 Darcy's law is assumed to be valid and the hydraulic conductivity is essentially unaffected by hydraulic gradient.

4.5 These test methods provide a means for determining hydraulic conductivity at a controlled level of effective stress. Hydraulic conductivity varies with varying void ratio, which changes when the effective stress changes. If the void ratio is changed, the hydraulic conductivity of the test specimen will likely change, see Appendix X2. To determine the relationship between hydraulic conductivity and void ratio, the hydraulic conductivity test would have to be repeated at different effective stresses.

4.6 The correlation between results obtained using these test methods and the hydraulic conductivities of in-place field materials has not been fully investigated. Experience has sometimes shown that hydraulic conductivities measured on small test specimens are not necessarily the same as larger-scale values. Therefore, the results should be applied to field situations with caution and by qualified personnel.

4.7 In most cases, when testing high swell potential materials and using a constant-volume hydraulic system, the effective confining stress should be about 1.5 times the swell pressure of the test specimen or a stress which prevents swelling. If the confining stress is less than the swell pressure, anomalous flow conditions my occur; for example, mercury column(s) move in the wrong direction.

NOTE 1—The quality of the result produced by this standard is dependent of the competence of the personnel performing it and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing, sampling, inspection, etc.. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

5. Apparatus

5.1 *Hydraulic System*—Constant head (Method A), falling head (Methods B and C), constant rate of flow (Method D), constant volume-constant head (Method E), or constant volume-falling head (Method F) systems may be utilized provided they meet the following criteria:

5.1.1 *Constant Head*—The system must be capable of maintaining constant hydraulic pressures to ±5 % or better and shall include means to measure the hydraulic pressures to within the prescribed tolerance. In addition, the head loss across the permeameter must be held constant to ±5 % or better and shall be measured with the same accuracy or better. A pressure gage, electronic pressure transducer, or any other device of suitable accuracy shall measure pressures to a minimum of three significant digits. The last digit may be due to estimation, see 5.1.1.1.

5.1.1.1 Practice D6026 discusses the use or application of estimated digits. When the last digit is estimated and that reading is a function of the eye's elevation/location, then a mirror or another device is required to reduce the reading error caused by parallax.

5.1.2 *Falling Head*—The system shall allow for measurement of the applied head loss, thus hydraulic gradient, to ±5 % or better at any time. In addition, the ratio of initial head loss divided by final head loss over an interval of time shall be measured such that this computed ratio is accurate to ±5 % or better. The head loss shall be measured with a pressure gage, electronic pressure transducer, engineer's scale, graduated pipette, or any other device of suitable accuracy to a minimum of three significant digits. The last digit may be due to estimation, see 5.1.1.1. Falling head tests may be performed with either a constant tailwater elevation (Method B) or a rising tailwater elevation (Method C), see Fig. 1. This schematic of a hydraulic system presents the basic components needed to meet the objectives of Method C. Other hydraulic systems or schematics that meet these objectives are acceptable.

5.1.3 *Constant Rate of Flow*—The system must be capable of maintaining a constant rate of flow through the specimen to ±5 % or better. Flow measurement shall be by calibrated syringe, graduated pipette, or other device of suitable accuracy. The head loss across the permeameter shall be measured to a minimum of three significant digits and to an accuracy of ±5 % or better using an electronic pressure transducer(s) or other device(s) of suitable accuracy. The last digit may be due to estimation, see 5.1.1.1. More information on testing with a constant rate of flow is given in the literature (**5**).

5.1.4 *Constant Volume-Constant Head (CVCH)*—The system, with mercury to create the head loss, must be capable of maintaining a constant head loss cross the permeameter to ±5 % or better and shall allow for measurement of the applied head loss to ±5 % or better at any time. The head loss shall be measured to a minimum of three significant digits with an electronic pressure transducer(s) or equivalent device, (**6**) or based upon the pressure head caused by the mercury column, see 10.1.2. The last digit may be due to estimation, see 5.1.1.1.

5.1.4.1 Schematics of two CVCH systems are shown in Fig. 2 and Fig. 3. In each of these systems, the mercury-filled portion of the tubing may be continuous for constant head loss to be maintained. For the system showed in Fig. 2, the head loss remains constant provided the mercury column is vertical and is retained in only one half of the burette system (left burette in Fig. 2). If the mercury spans both columns, a falling head exists. In the system shown in Fig. 3, the head loss remains constant provided the water-mercury interface on the effluent end remains in the upper horizontal tube, and the water-mercury interface on the influent end remains in the lower horizontal tube. These schematics present the basic components needed to meet the objectives of Method E. Other hydraulic systems or schematics that meet these objectives are acceptable.

5.1.4.2 These types of hydraulic systems are typically not used to study the temporal or pore-fluid effect on hydraulic conductivity. The total volume of the specimen is maintained constant using this procedure, thereby significantly reducing

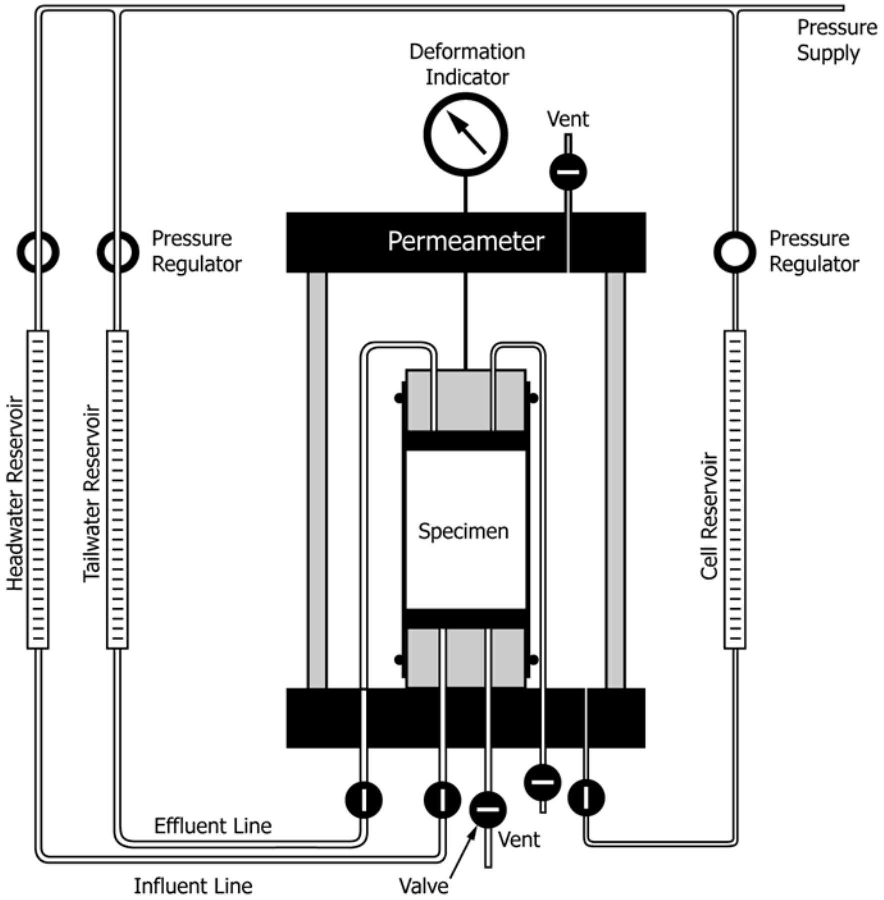

FIG. 1 Falling Head – Rising Tail System, Method C

effects caused by seepage stresses, pore fluid interactions, etc. Rather, these systems are intended for determining the hydraulic conductivity of a material as rapidly as possible.

5.1.4.3 *Hazards*—Since this hydraulic system contains mercury, special health and safety precautions have to be considered. See Section 7.

5.1.4.4 *Caution*—For these types of hydraulic systems to function properly, the separation of the mercury column has to be prevented. To prevent separation, the mercury and "constant head" tube have to remain relatively clean, and the inside diameter of this tube cannot be too large; typically a capillary tube is used. The larger diameter flushing tube (Fig. 2) is added to enable flushing clean water through the system without excessive mercury displacement. Traps to prevent the accidental flow of mercury out of the "Constant Head" tube or flushing tube are not shown in Fig. 2 and Fig. 3.

5.1.5 *Constant Volume-Falling Head (CVFH)*—The system, with mercury to create the head loss, shall meet the criteria given in 5.1.2. The head loss shall be measured to a minimum of three significant digits with an electronic pressure transducer(s) or equivalent device(s), (**6**) or based upon the differential elevation between the top surfaces of the mercury level in the headwater and tailwater tubes. The last digit may be due to estimation, see 5.1.1.1.

5.1.5.1 A schematic drawing of a typical CVFH hydraulic system is shown in Fig. 4 (**6**). Typically, the tailwater tube has a smaller area than the headwater tube to increase the sensitivity of flow measurements, and to enable flushing clean water through the system without excessive mercury displacement in the headwater tube. The schematic of the hydraulic system in Fig. 4 presents the basic components needed to meet the objectives of Method F. Other hydraulic systems or schematics that meet these objectives are acceptable. The development of the hydraulic conductivity equation for this type of system is given in Appendix X1.

5.1.5.2 See 5.1.4.2.

5.1.5.3 *Hazards*—Since this hydraulic system contains mercury, special health and safety precautions have to be considered. See Section 7.

5.1.5.4 *Caution*—For these types of hydraulic systems to function properly, the separation of the mercury column and entrapment of water within the mercury column have to be prevented. To prevent such problems, the mercury and tubes have to remain relatively clean. In addition, if different size headwater and tailwater tubes are used, capillary head might have to be accounted for, see Appendix X1, X1.2.3.2, and X1.4. Traps to prevent the accidental flow of mercury out of the tubes are not shown in Fig. 4.

5.1.6 *System De-airing*—The hydraulic system shall be designed to facilitate rapid and complete removal of free air bubbles from flow lines; for example, using properly sized tubing and ball valves and fittings without pipe threads. Properly sized tubing, etc., means they are small enough to

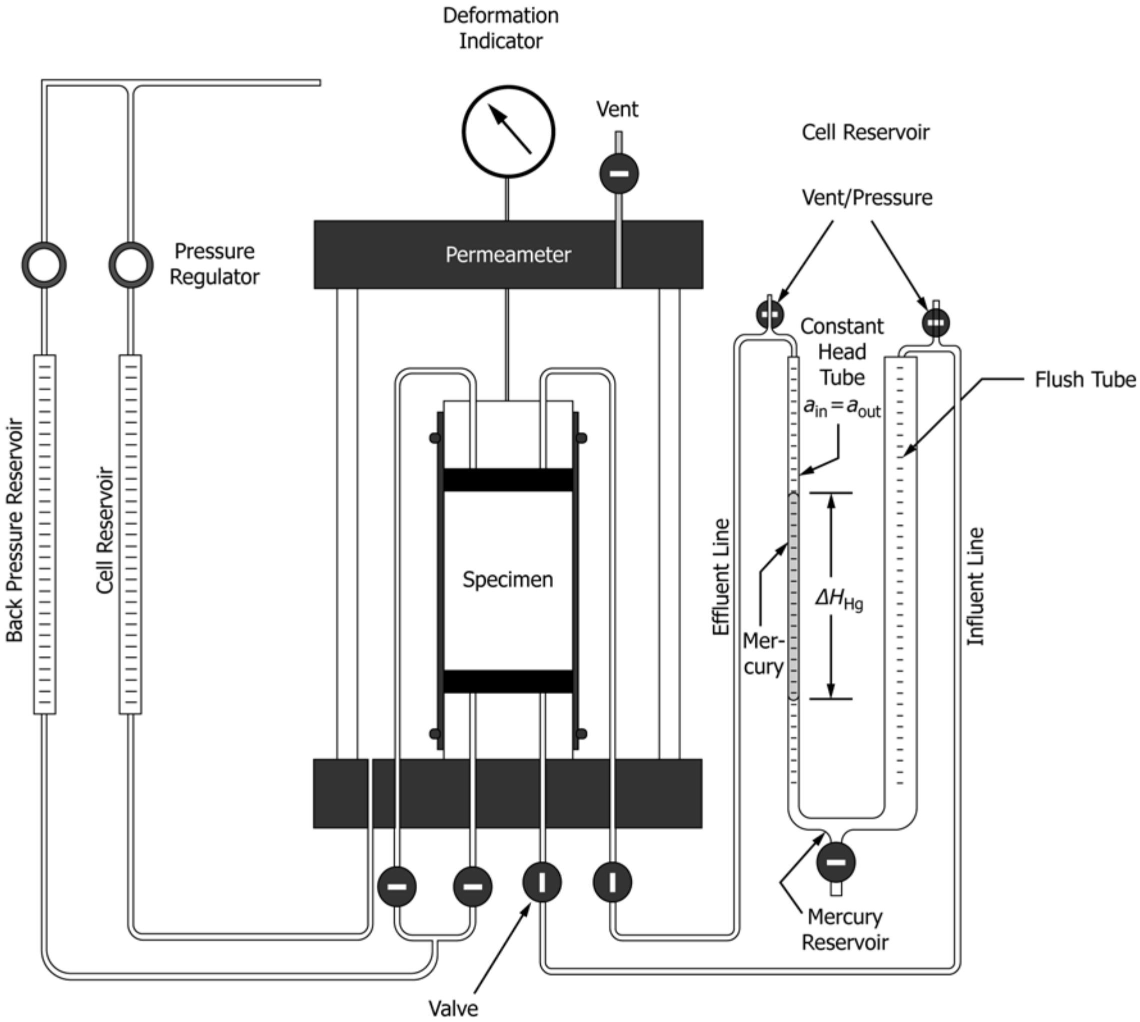

FIG. 2 Constant Volume – Constant or Falling Head System, Method E or F (6)

prevent entrapment of air bubbles, but not so small that the requirements of 5.2.3 cannot be met.

5.1.7 *Back Pressure System*—The hydraulic system shall have the capability to apply back pressure to the specimen to facilitate saturation. The system shall be capable of maintaining the applied back pressure throughout the duration of hydraulic conductivity measurements. The back pressure system shall be capable of applying, controlling, and measuring the back pressure to ±5 % or better of the applied pressure. The back pressure may be provided by a compressed gas supply, a deadweight acting on a piston, or any other method capable of applying and controlling the back pressure to the tolerance prescribed in this paragraph.

NOTE 2—Application of gas pressure directly to a fluid will dissolve gas in the fluid. A variety of techniques are available to minimize dissolution of gas in the back pressure fluid, including separation of gas and liquid phases with a bladder and frequent replacement of the liquid with de-aired water.

5.2 *Flow Measurement System*—Both inflow and outflow volumes shall be measured unless the lack of leakage, continuity of flow, and cessation of consolidation or swelling can be verified by other means. Flow volumes shall be measured by a graduated accumulator, graduated pipette, vertical standpipe in conjunction with an electronic pressure transducer, or other volume-measuring device of suitable accuracy.

5.2.1 *Flow Accuracy*—Required accuracy for the quantity of flow measured over an interval of time is ±5 % or better.

5.2.2 *De-airing and Compliance of the System*—The flow-measurement system shall contain a minimum of dead space and be capable of complete and rapid de-airing. Compliance of the system in response to changes in pressure shall be minimized by using a stiff flow measurement system. Rigid tubing, such as metallic or rigid thermoplastic tubing, or glass shall be used.

5.2.3 *Head Losses*—Head losses in the tubes, valves, porous end pieces, and filter paper may lead to error. To guard against such errors, the permeameter shall be assembled with no specimen inside and then the hydraulic system filled.

5.2.3.1 *Constant or Falling Head*—If a constant or falling head test is to be used, the hydraulic pressures or heads that will be used in testing a specimen shall be applied, and the rate of flow measured with an accuracy of ±5 % or better. This rate of flow shall be at least ten times greater than the rate of flow that is measured when a specimen is placed inside the permeameter and the same hydraulic pressures or heads are applied.

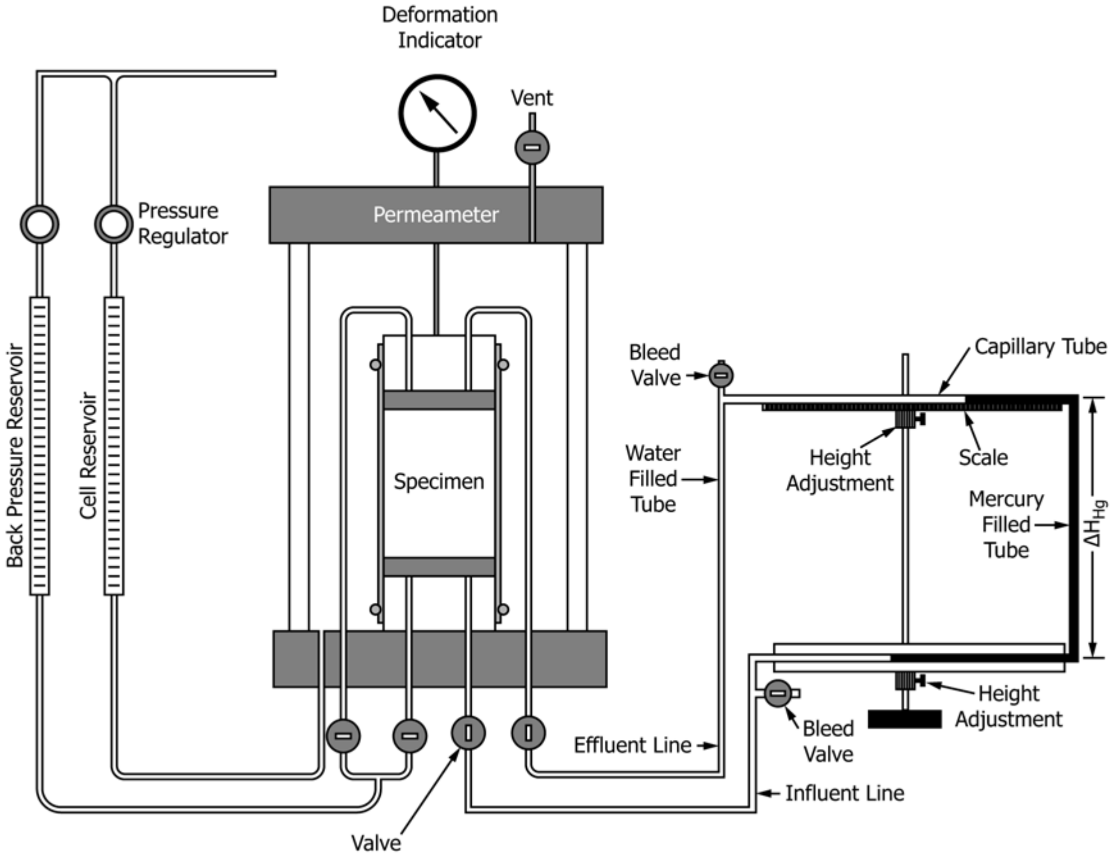

FIG. 3 Constant Volume—Constant Head System, Method E

5.2.3.2 *Constant Rate of Flow*—If a constant rate of flow test is to be used, the rate of flow to be used in testing a specimen shall be supplied to the permeameter and the head loss measured. The head loss without a specimen shall be less than 0.1 times the head loss when a specimen is present.

5.3 *Permeameter Cell Pressure System*—The system for pressurizing the permeameter cell shall be capable of applying and controlling the cell pressure to ±5 % or better of the applied pressure. However, the effective stress on the test specimen (which is the difference between the cell pressure and the pore water pressure) shall be maintained to the desired value with an accuracy of ±10 % or better. The device for pressurizing the cell may consist of a reservoir connected to the permeameter cell and partially filled with de-aired water, with the upper part of the reservoir connected to a compressed gas supply or other source of pressure (see Note 3). The gas pressure shall be controlled by a pressure regulator and measured by a pressure gage, electronic pressure transducer, or any other device capable of measuring to the prescribed tolerance. A hydraulic system pressurized by deadweight acting on a piston or any other pressure device capable of applying and controlling the permeameter cell pressure within the tolerance prescribed in this paragraph may be used.

NOTE 3—De-aired water is commonly used for the cell fluid to minimize potential for diffusion of air through the membrane into the specimen. Other fluids that have low gas solubilities such as oils, are also acceptable, provided they do not react with components of the permeameter. Also, use of a long (approximately 5 to 7 m) tube connecting the pressurized cell liquid to the cell helps to delay the appearance of air in the cell fluid and to reduce the flow of dissolved air into the cell.

5.4 *Permeameter Cell*—An apparatus shall be provided in which the specimen and porous end pieces, enclosed by a membrane sealed to the cap and base, are subjected to controlled fluid pressures. A schematic diagram of a typical permeameter cell and falling head (raising tailwater) hydraulic system is shown in Fig. 1.

5.4.1 The permeameter cell may allow for observation of changes in height of the specimen, either by observation through the cell wall using a cathetometer or other instrument, or by monitoring of either a loading piston or an extensometer extending through the top plate of the cell bearing on the top cap and attached to a dial indicator or other measuring device. The piston or extensometer should pass through a bushing and seal incorporated into the top plate and shall be loaded with sufficient force to compensate for the cell pressure acting over the cross-sectional area of the piston where it passes through the seal. If deformations are measured, the deformation indicator shall be a dial indicator or cathetometer graduated to 0.5 mm or 0.01 in. or better and having an adequate travel range. Any other measuring device meeting these requirements is acceptable.

5.4.2 In order to facilitate gas removal, and thus saturation of the hydraulic system, four drainage lines leading to the specimen, two each to the base and top cap, are recommended. The drainage lines shall be controlled by no-volume-change

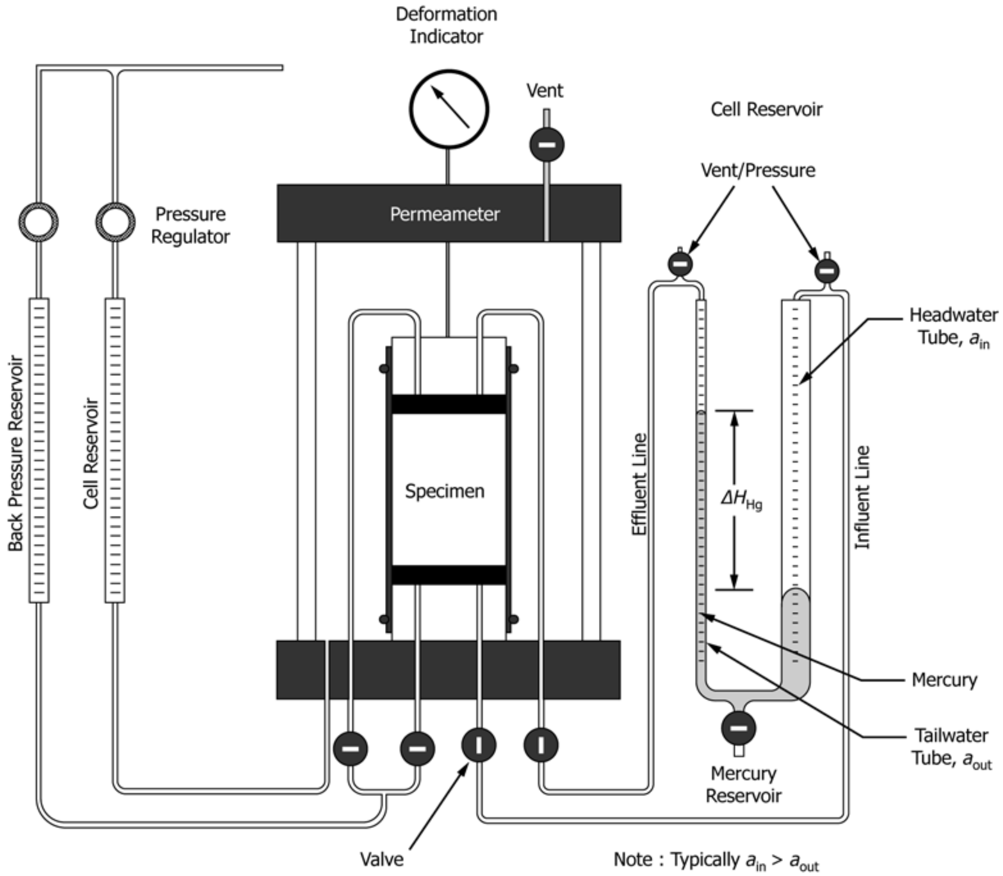

FIG. 4 Constant Volume – Falling Head System, Method F (6)

valves, such as ball valves, and shall be designed to minimize dead space in the lines.

5.4.3 *Top Cap and Base*—An impermeable, rigid top cap and base shall be used to support the specimen and provide for transmission of permeant liquid to and from the specimen. The diameter or width of the top cap and base shall be equal to the diameter or width of the specimen to ±5 % or better. The base shall prevent leakage, lateral motion, or tilting, and the top cap shall be designed to receive the piston or extensometer, if used, such that the piston-to-top cap contact area is concentric with the cap. The surface of the base and top cap that contacts the membrane to form a seal shall be smooth and free of scratches.

5.4.4 *Flexible Membranes*—The flexible membrane used to encase the specimen shall provide reliable protection against leakage. The membrane shall be carefully inspected prior to use. If any flaws or pinholes are evident, the membrane shall be discarded. To minimize restraint to the specimen, the diameter or width of the non-stretched membrane shall be between 90 and 95 % of that of the specimen. The membrane shall be sealed to the specimen base and cap with rubber O-rings for which the unstressed, inside diameter or width is less than 90 % of the diameter or width of the base and cap, or by any other method that will produce an adequate seal.

NOTE 4—Membranes may be tested for flaws by placing them around a form sealed at both ends with rubber O-rings, subjecting them to a small air pressure on the inside, and then dipping them into water. If air bubbles come up from any point on the membrane, or if any visible flaws are observed, the membrane shall be discarded.

5.4.5 *Porous End Pieces*—The porous end pieces shall be of silicon carbide, aluminum oxide, or other material that is not attacked by the specimen or permeant liquid. The end pieces shall have plane and smooth surfaces and be free of cracks, chips, and discontinuities. They shall be checked regularly to ensure that they are not clogged.

5.4.5.1 The porous end pieces shall be the same diameter or width (±5 % or better) as the specimen, and the thickness shall be sufficient to prevent breaking.

5.4.5.2 The hydraulic conductivity of the porous end pieces shall be significantly greater than that of the specimen to be tested. The requirements outlined in 5.2.3 ensure this criterion is met.

5.4.6 *Filter Paper*—If necessary to prevent intrusion of material into the pores of the porous end pieces, one or more sheets of filter paper shall be placed between the top and bottom porous end pieces and the specimen. The paper shall have a negligibly small hydraulic impedance. The requirements outlined in 5.2.3 ensure that the impedance is small.

5.5 *Equipment for Compacting a Specimen*—Equipment (including compactor and mold) suitable for the method of compaction specified by the requester shall be used.

5.6 *Sample Extruder*—When the material being tested is a soil core, the soil core shall usually be removed from the sampler with an extruder. The sample extruder shall be capable of extruding the soil core from the sampling tube in the same direction of travel in which the sample entered the tube and with minimum disturbance of the sample. If the soil core is not extruded vertically, care should be taken to avoid bending stresses on the core due to gravity. Conditions at the time of sample extrusion may dictate the direction of removal, but the principal concern is to keep the degree of disturbance minimal.

5.7 *Trimming Equipment*—Specific equipment for trimming the specimen to the desired dimensions will vary depending on quality and characteristics of the sample (material). However, the following items listed may be used: lathe, wire saw with a wire about 0.3 mm (0.01 in.) in diameter, spatulas, knives, steel rasp for very hard clay specimens, cradle or split mold for trimming specimen ends, and steel straight edge for final trimming of specimen ends.

5.8 *Devices for Measuring the Dimensions of the Specimen*—Devices used to measure the dimensions of the specimen shall be capable of measuring to the nearest 0.5 mm or 0.01 in. or better (see 8.1.1) and shall be constructed such that their use will not disturb the specimen.

5.9 *Balances*—The balance shall be suitable for determining the mass of the specimen and shall be selected as discussed in Specification D4753. The mass of specimens less than 100 g shall be determined to the nearest 0.01 g. The mass of specimens between 100 g and 999 g shall be determined to the nearest 0.1 g. The mass of specimens equal to or greater than 1000 g shall be determined to the nearest gram.

5.10 *Equipment for Mounting the Specimen*—Equipment for mounting the specimen in the permeameter cell shall include a membrane stretcher or cylinder, and ring for expanding and placing O-rings on the base and top cap to seal the membrane.

5.11 *Vacuum Pump*—To assist with de-airing of permeant liquid (water) and saturation of specimens.

NOTE 5—For guidance or avoiding excessive consolidation in the use of vacuum for specimen saturation, consult 8.2 of Test Method D4767.

5.12 *Temperature Maintaining Device*—The temperature of the permeameter, test specimen, and reservoir of permeant liquid shall not vary more than ±3°C or ±6°F or better. Normally, this is accomplished by performing the test in a room with a relatively constant temperature. If such a room is not available, the apparatus shall be placed in a water bath, insulated chamber, or other device that maintains a temperature within the tolerance specified above. The temperature shall be periodically measured and recorded.

5.13 *Water Content Containers*—The containers shall be in accordance with Method D2216.

5.14 *Drying Oven*—The oven shall be in accordance with Test Method D2216.

5.15 *Time Measuring Device(s)*—Devices to measure the duration of each permeation trial, such as either a clock with a second hand or a stopwatch (or equivalent), or both.

6. Reagents

6.1 *Permeant Water:*

6.1.1 The permeant water is the liquid used to permeate the test specimen and is also the liquid used in backpressuring the specimen.

6.1.2 The type of permeant water should be specified by the requestor. If no specification is made, one of the following shall be used: (*i*) potable tap water, (*ii*) a mixture of 0.0013 molar NaCl and 0.0010 molar $CaCl_2$, or (*iii*) 0.01 molar $CaCl_2$. The NaCl-$CaCl_2$ solution is representative of both typical tap waters and soil pore waters (**7**). The $CaCl_2$ solution has been used historically in areas with extremely hard or soft waters. The type of water used shall be indicated in the report.

6.1.2.1 The NaCl-$CaCl_2$ solution can be prepared by dissolving 0.76 g of reagent-grade NaCl and 1.11 g of reagent-grade $CaCl_2$ in 10 L of de-aired Type II deionized water.

6.1.2.2 The 0.01 $CaCl_2$ solution can be prepared by dissolving 11.1 g of reagent-grade $CaCl_2$ in 10 L of de-aired Type II deionized water.

6.1.2.3 Chemical interactions between a permeant liquid and the porous material may lead to variations in hydraulic conductivity. Distilled water can significantly lower the hydraulic conductivity of clayey soils (**3**). For this reason, distilled water is not usually recommended as a permeant liquid.

6.1.3 *Deaired Water*—To aid in removing as much air from the test specimen as possible, deaired water shall be used. The water is usually deaired by boiling, by spraying a fine mist of water into an evacuated vessel attached to a vacuum source, or by forceful agitation of water in a container attached to a vacuum source. If boiling is used, care shall be taken not to evaporate an excessive amount of water, which can lead to a larger salt concentration in the permeant water than desired. To prevent dissolution of air back into the water, deaired water shall not be exposed to air for prolonged periods.

7. Hazards

7.1 *Warning*—Mercury has been designated by many regulatory agencies as a hazardous material that can cause serious medical issues. Mercury, or its vapor, may be hazardous to health and corrosive to materials. Caution should be taken when handling mercury containing products. See the applicable product Safety Data Sheet (SDS) for additional information. Users should be aware that selling mercury or mercury containing products into your state or country may be prohibited by law.

7.1.1 Tubing composed of glass or other brittle materials may explode/shatter when under pressure, especially air. Therefore, such tubing should be enclosed. Establish allowable working pressures and make sure they are not exceeded.

7.2 *Precaution*—In addition to other precautions, store mercury in sealed shatterproof containers to control evaporation. When adding/subtracting mercury to/from the hydraulic system used in Method E or F, work in a well-ventilated area (preferably under a fume hood), and avoid contact with skin. Rubber gloves should be worn at all times when contact with mercury is possible.

7.2.1 Minimize uncontrolled flow of mercury out of the specialized hydraulic system by installing mercury traps or an inline check-valve mechanism. Minimize uncontrolled spills by using shatterproof materials or protective shields, or both.

7.2.2 If mercury comes into contact with brass/copper fittings, valves, etc., such items may rapidly become leaky. Therefore, where-ever practical use stainless steel fittings, etc.

7.2.3 Clean up spills immediately using a recommended procedure explicitly for mercury.

7.2.4 Dispose of contaminated waste materials containing mercury in a safe and environmentally acceptable manner.

8. Test Specimens

8.1 *Size*—Specimens shall have a minimum diameter of 25 mm (1.0 in.) and a minimum height of 25 mm. The height and diameter of the specimen shall be measured to three significant digits or better (see 8.1.1). The length shall vary by no more than ±5 %. The diameter shall vary by no more than ±5 %. The surface of the test specimen may be uneven, but indentations must not be so deep that the length or diameter vary by more than ±5 %. The diameter and height of the specimen shall each be at least 6 times greater than the largest particle size within the specimen. If, after completion of a test, it is found based on visual observation that oversized particles are present, that information shall be indicated on the data sheet(s)/form(s).

8.1.1 If the density or unit weight needs to be determined/recorded to four significant digits, or the void ratio to three significant digits; then the test specimens dimensions need to have four significant digits; that is, typically measured to the nearest 0.01 mm or 0.001 in.

8.1.2 Specimens of soil-cement and mixtures of cement, bentonite, and soils often have more irregular surfaces than specimens of soil. Thus, for these specimens the length and the diameter may vary by no more than ±10 %.

NOTE 6—Most hydraulic conductivity tests are performed on cylindrical test specimens. It is possible to utilize special equipment for testing prismatic test specimens, in which case reference to “diameter” in 8.1 applies to the least width of the prismatic test specimen.

8.2 *Intact Specimens*—Intact test specimens shall be prepared from a representative portion of intact samples secured in accordance with Practice D1587, Practice D3550, Practice D6151, or Practice D2113. In addition, intact samples may be obtained by “block sampling” (**8**). Additional guidance on other drilling and sampling methods is given in Guide D6169. Samples shall be preserved and transported in accordance with these requirements; for soils follow Group C in Practice D4220, while for rock follow either “special care” or “soil-like care,” as appropriate in Practice D5079. Specimens obtained by tube sampling or coring may be tested without trimming except for cutting the end surfaces plane and perpendicular to the longitudinal axis of the specimen, provided soil characteristics are such that no significant disturbance results from sampling. Where the sampling operation has caused disturbance of the soil, the disturbed material shall be trimmed. Where removal of pebbles or crumbling resulting from trimming causes voids on the surface of the specimen that cause the length or diameter to vary by more than ±5 %, the voids shall be filled with remolded material obtained from the trimmings. The ends of the test specimen shall be cut and not troweled (troweling can seal off cracks, slickensides, or other secondary features that might conduct water flow). Specimens shall be trimmed, whenever possible, in an environment where changes in water content are minimized. A controlled high-humidity room is usually used for this purpose. The mass and dimensions of the test specimen shall be determined to the tolerances given in 5.8 and 5.9. The test specimen shall be mounted immediately in the permeameter. The water content of the trimmings shall be determined in accordance with Method D2216, to the nearest 0.1 % or better.

8.3 *Laboratory-Compacted Specimens*—The material to be tested shall be prepared and compacted inside a mold in a manner specified by the requester. If the specimen is placed and compacted in layers, the surface of each previously-compacted layer shall be lightly scarified (roughened) with a fork, ice pick, or other suitable object, unless the requester specifically states that scarification is not to be performed. Test Methods D698 and D1557 describe two methods of compaction, but any other method specified by the requester may be used as long as the method is described in the report. Large clods of material should not be broken down prior to compaction unless it is known that they will be broken in field construction, as well, or the requester specifically requests that the clod size be reduced. Neither hard clods nor individual particles of the material shall exceed ⅙ of either the height or diameter of the specimen. After compaction, the test specimen shall be removed from the mold, the ends scarified, and the dimensions and weight determined within the tolerances given in 5.8 and 5.9. After the dimensions and mass are determined, the test specimen shall be immediately mounted in the permeameter. The water content of the trimmings shall be determined in accordance with Method D2216 to the nearest 0.1 % or better.

8.4 *Other Preparation Methods*—Other methods of preparation of a test specimen are permitted if specifically requested. The method of specimen preparation shall be identified in the data sheet(s)/form(s).

8.5 After the height, diameter, mass, and water content of the test specimen have been determined, the dry unit weight shall be calculated. Also, the initial degree of saturation shall be estimated (this information may be used later in the back-pressure stage).

8.6 In some cases, the horizontal hydraulic conductivity of a sample needs to be determined. In that case, the specimen may be trimmed such that its longitudinal axis is perpendicular to the longitudinal axis of the sample. Obtaining a specimen having a diameter of 36 mm (1.4 in.) typically requires a cylindrical sample with a diameter equal to or greater than about 70 mm (2.8 in.) or a rectangular sample with a minimum dimension of about 40 mm (1.6 in.).

9. Procedure

9.1 *Specimen Setup:*

9.1.1 Cut two filter paper sheets to approximately the same shape as the cross section of the test specimen. Soak the two porous end pieces and filter paper sheets, if used, in a container of permeant water.

9.1.2 Place the membrane on the membrane expander. Apply a thin coat of silicon high-vacuum grease to the sides of the end caps. Place one porous end piece on the base and place one filter paper sheet, if used, on the porous end piece, followed by the test specimen. Place the second filter paper sheet, if used, on top of the specimen followed by the second porous end piece and the top cap. Place the membrane around the specimen, and using the membrane expander or other suitable O-ring expander, place one or more O-rings to seal the membrane to the base and one or more additional O-rings to seal the membrane to the top cap.

9.1.3 Attach flow tubing to the top cap, if not already attached, assemble the permeameter cell, and fill it with de-aired water or other cell fluid. Attach the cell pressure reservoir to the permeameter cell line and the hydraulic system to the influent and effluent lines. Fill the cell pressure reservoir with deaired water, or other suitable liquid, and the hydraulic system with deaired permeant water. Apply a small confining pressure of 7 to 35 kPa (1 to 5 psi) to the cell and apply a pressure less than the confining pressure to both the influent and effluent systems, and flush permeant water through the flow system. After all visible air has been removed from the flow lines, close the control valves. At no time during saturation of the system and specimen or hydraulic conductivity measurements shall the maximum applied effective stress be allowed to exceed that to which the specimen is to be consolidated.

9.2 *Specimen Soaking (Optional)*—To aid in saturation, specimens may be soaked under partial vacuum applied to the top of the specimen. Water under atmospheric pressure shall be applied to the specimen base through the influent lines, and the magnitude of the vacuum set to generate a hydraulic gradient across the specimen less than that which will be used during hydraulic conductivity measurements.

NOTE 7—Soaking under vacuum is applicable when there are continuous air voids in the specimen for example, specimens having a degree of saturation of less than about 85%. The specimen may swell when exposed to water; the effective stress will tend to counteract the swelling. However, for materials that tend to swell, unless the applied effective stress is greater than or equal to the swell pressure, the specimen will swell. In addition, see Note 5.

9.3 *Back-Pressure Saturation*—To saturate the specimen, back pressuring is usually necessary. Fig. 5 (**9**) provides guidance on back pressure required to attain saturation. Additional guidance on the back-pressure process is given by Black and Lee (**10**) and Head (**11**).

NOTE 8—The relationships presented in Fig. 5 are based on the assumption that the water used for back pressuring is deaired and that the only source for air to dissolve into the water is air from the test specimen. If air pressure is used to control the back pressure, pressurized air will dissolve into the water, thus reducing the capacity of the water used for back pressure to dissolve air located in the pores of the test specimen. The problem is minimized by using a long (>5 m) tube that is impermeable to air between the air-water interface and test specimen, by separating the back-pressure water from the air by a material or fluid that is relatively impermeable to air, by periodically replacing the back-pressure water with deaired water, or by other means.

9.3.1 During the saturation process, any change in the volume (swelling or compression of the void ratio, density, etc.) of the test specimen should be minimized. The easiest way to verify that volume changes are minor is to measure the height of the specimen during the back-pressuring process. Volume changes are considered minor if the resulting change in hydraulic conductivity is less than about one-half the acceptable error of 25 % given in 9.5.4, unless more stringent control on density or hydraulic conductivity, or both, is required. For this to occur the axial strain should be less than about 0.4 % for normally consolidated soils, or about 0.1 % for overconsolidated soils. See Appendix X2.

9.3.2 Take and record an initial reading of specimen height, if being monitored. Open the flow line valves and flush out of the system any free air bubbles using the procedure outlined in 9.1.3. If an electronic pressure transducer or other measuring device is to be used during the test to measure pore pressures or applied hydraulic gradient, bleed any trapped air from the device.

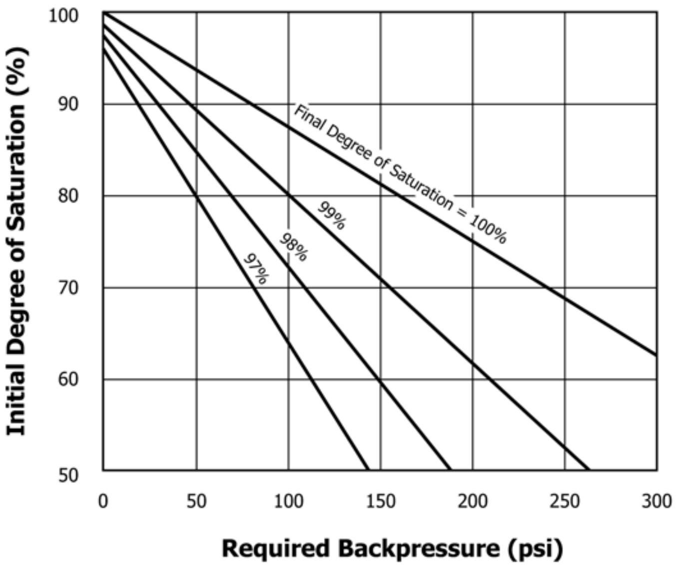

FIG. 5 Back Pressure to Attain Various Degrees of Saturation (9)

9.3.3 Adjust the applied confining pressure to the value to be used during saturation of the specimen. Apply back pressure by simultaneously increasing the cell pressure and the influent and effluent pressures in increments. The maximum value of an increment in back pressure shall be sufficiently low such that no point in the specimen is exposed to an effective stress in excess of that to which the specimen will be subsequently consolidated. At no time shall a head be applied such that the effective confining stress is <7 kPa (1 psi) because of the danger of separation of the membrane from the test specimen. Maintain each increment of pressure for a period of a few minutes to a few hours, depending upon the characteristics of the specimen. To assist in removal of trapped air, a small hydraulic gradient may be applied across the specimen to induce flow.

9.3.4 Saturation shall be verified with one of the three following techniques:

9.3.4.1 Saturation may be verified by measuring the *B* coefficient as described in Test Method D4767 (see Note 9). The test specimen shall be considered to be adequately saturated if the *B* value is ≥0.95, or for relatively incompressible materials, for example, rock, if the *B* value remains unchanged with application of larger values of back pressure. The *B* value may be measured prior to or after completion of the consolidation phase (see 9.4). An accurate *B*-value determination can only be made if no gradient is acting on the specimen and all pore-water pressure induced by consolidation has dissipated. That is, conform completion of primary consolidation before this determination; see Test Method D2435 or D4767 on how to confirm completion of primary consolidation.

NOTE 9—The *B* coefficient is defined for this type of test as the change in pore-water pressure in the porous material divided by the change in confining pressure. Compressible materials that are fully saturated with water will have a *B* value of 1.0. Relatively incompressible, saturated materials have *B* values that are somewhat less than 1.0 (**12**).

9.3.4.2 Saturation of the test specimen may be confirmed at the completion of the test by calculation of the final degree of saturation. The final degree of saturation shall be 100 ± 5 %. However, measurement of the *B* coefficient as described in 9.3.4.1 or use of some other technique (9.3.4.3) is strongly recommended because it is much better to confirm saturation prior to permeation than to wait until after the test to determine if the test was valid.

9.3.4.3 Other means for verifying saturation, such as observing the flow of water into the specimen when the back pressure is increased, can be used for verifying saturation provided data are available for similar materials to establish that the procedure used confirms saturation as required in 9.3.4.1 or 9.3.4.2.

9.4 *Consolidation*—The specimen shall be consolidated to the effective stress specified by the requester. Consolidation shall be accomplished in stages, with the increase in cell pressure minus back pressure (effective stress) in each new stage equal to or less than the effective stress in the previous stage that is, consolidation increment ratio of one or less.

NOTE 10—The test specimen may be consolidated prior to application of back pressure. Also, the back pressure and consolidation phases may be completed concurrently if back pressures are applied sufficiently slowly to minimize potential for overconsolidation of the specimen.

9.4.1 Record the specimen height, if being monitored, prior to application of consolidation pressure and periodically during consolidation.

9.4.2 Increase the cell pressure to the level necessary to develop the desired effective stress, and begin consolidation. Drainage may be allowed from the base or top of the specimen, or simultaneously from both ends.

9.4.3 (Optional) Record outflow volumes to confirm that primary consolidation has been completed prior to initiation of the hydraulic conductivity test. Alternatively, measurements of the change in height of the test specimen can be used to confirm completion of consolidation.

NOTE 11—The procedure in 9.4.3 is optional because the requirements of 9.5 ensure that the test specimen is adequately consolidated during permeation because if it is not, inflow and outflow volumes will differ significantly. However, for accurate *B*-value determination, saturation should be confirmed at the completion of consolidation (see 9.3.4.1). Recording outflow volumes or height changes is recommended as a means for verifying the completion of consolidation prior to initialization of permeation. Also, measurements in the change in height of the test specimen, coupled with knowledge of the initial height, provide a means for checking the final height of the specimen.

9.5 *Permeation:*

9.5.1 *Hydraulic Gradient*—When possible, the hydraulic gradient ($i = \Delta h/L$, for definitions of notation see 10.1) used for hydraulic conductivity measurements should be similar to that expected to occur in the field. In general, hydraulic gradients from <1 to 5 cover most field conditions. However, the use of small hydraulic gradients can lead to very long testing times for materials having low hydraulic conductivity (less than about 1×10^{-8} m/s). Somewhat larger hydraulic gradients are usually used in the laboratory to accelerate testing, but excessive gradients must be avoided because high seepage pressures may consolidate the material, material may be washed from the specimen, or fine particles may be washed downstream and plug the effluent end of the test specimen. These effects could increase or decrease hydraulic conductivity. If no gradient is specified by the requestor, the following guidelines may be followed:

Hydraulic Conductivity, m/s	Recommended Maximum Hydraulic Gradient
1×10^{-5} to 1×10^{-6}	2
1×10^{-6} to 1×10^{-7}	5
1×10^{-7} to 1×10^{-8}	10
1×10^{-8} to 1×10^{-9}	20
less than 1×10^{-9}	30

9.5.1.1 A higher gradient than given above may be used if the higher gradient can be shown not to change the hydraulic conductivity. For example, on a representative specimen, perform a hydraulic conductivity determination at $i = 30$ than at $i = 50$ or 100, or more. Determine which, if any, of the hydraulic conductivities (*k*) determined at these gradients are similar (that is, within the acceptable steady-state range given for the Method (A, B, C, D, E, or F). Any gradient equal to or less than the highest gradient yielding a similar hydraulic conductivity may be used for testing.

NOTE 12—Seepage pressures associated with large hydraulic gradients can consolidate soft, compressible specimens and reduce their hydraulic conductivity. Smaller hydraulic gradients (<10) may be necessary for such specimens.

9.5.2 *Initialization*—Initiate permeation of the specimen by increasing the influent (headwater) pressure (see 9.3.3). The effluent (tailwater) pressure shall not be decreased because air bubbles that were dissolved by the specimen water during backpressuring may come out of solution if the pressure is decreased. The back pressure shall be maintained throughout the permeation phase.

9.5.2.1 The maximum increase in headwater pressure cannot exceed 95 % of the effective consolidation stress. Alternatively, the difference between the cell pressure and the total headwater pressure cannot be less than 5 % of the effective consolidation stress.

9.5.2.2 At the start and end of each permeation trial, at t_1 and t_2, read and record the test temperature to the nearest 0.1°C. See Section 10. If the number of significant digits in the calculation of hydraulic conductivity at 20°C can be one, then the test temperature can be measured to the nearest degree Celsius.

9.5.3 *Time Measurements*—Measure and record the time at the start and end of each permeation trial (or its interval) to two or more significant digits. That is the time interval has to be greater than 9 s unless the time is recorded to the nearest 0.1 s.

9.5.4 *Constant Head Tests:*

9.5.4.1 *(Method A)*—Measure and record the required head loss across the tolerances and significant digits stated in 5.1.1 and 5.2.3 at the start and end of each permeation trial (as a minimum). The head loss across the permeameter shall be kept constant to ±5 % or better. Measure and record periodically the quantity of inflow as well as the quantity of outflow to a minimum of three significant digits. Also measure and record any changes in height of the test specimen, if being monitored (see Note 12). Continue permeation until at least four values of hydraulic conductivity are obtained over an interval of time in which: (*1*) the ratio of outflow to inflow rate is between 0.75 and 1.25, and (*2*) the hydraulic conductivity is steady. The hydraulic conductivity shall be considered steady if four or more consecutive hydraulic conductivity determinations fall within ±25 % or better of the mean value for $k \geq 1 \times 10^{-10}$ m/s or within ±50 % or better for $k < 1 \times 10^{-10}$ m/s, and a plot or tabulation of the hydraulic conductivity versus time shows no significant upward or downward trend.

9.5.4.2 *Method E (Constant Volume)*—Measure and record the required head loss across the permeameter to the tolerances and significant digits stated in 5.1.4. The head loss across the permeameter shall be kept constant to ±5 % or better. Measure and record, to a minimum of three significant digits, the quantity of either inflow (influent) or outflow (effluent). In this measurement the last digit may be due to estimation, see 5.1.1.1. In addition, measure and record any changes in the height of the test specimen, if being monitored (see Note 12). Continue permeation until at least two or more values of hydraulic conductivity (k) are steady. The hydraulic conductivity shall be considered steady if two or more consecutive k determinations fall within ±15 % or better of the mean value (two or more determinations) for $k \geq 1 \times 10^{-10}$ m/s or within ±50 % or better for $k < 1 \times 10^{-10}$ m/s.

9.5.5 *Falling-Head Tests (Methods B, C, and F)*—Measure and record the required head loss across the permeameter to the tolerances and significant digits stated in 5.1.2. Measure and record these head losses at the start and end of each permeation trial (as a minimum). At no time shall the applied head loss across the specimen be less than 75 % of the initial (maximum) head loss during the hydraulic conductivity determination (see Note 13). At the start and end of each trial, as a minimum, measure and record any changes in the height of the test specimen, if being monitored. To meet these requirements, especially for Method F, the initial head loss in each trial will most likely have to be reset to the same value (±5 %) used in the first trial. In addition, the "75 % criterion" mentioned above has to be adhered to closely.

9.5.5.1 *Methods B and C*—The volumes of outflow and inflow shall be measured and recorded to three significant digits (the last digit may be due to estimation, see 5.1.1.1). Measure and record these volumes at the start and end of each permeation trial (as a minimum). Continue permeation until at least four values of hydraulic conductivity are obtained over an interval of time in which: the ratio of outflow to inflow rate is between 0.75 and 1.25, and the hydraulic conductivity is steady (see 9.5.4.1).

NOTE 13—When the water pressure in a test specimen changes and the applied total stress is constant, the effective stress in the test specimen changes, which can cause volume changes that can invalidate the test results. The requirement that the head loss not decrease very much is intended to keep the effective stress from changing too much. For extremely soft, compressible test specimens, even more restrictive criteria may be needed. Also, when the initial and final head losses across the test specimen do not differ by much, great accuracy is needed to comply with the requirement of 5.1.2 that the ratio of initial to final head loss be determined with an accuracy of ±5 % or better. When the initial and final head loss over an interval of time do not differ very much, it may be possible to comply with the requirements for a constant head test (9.5.4) in which the head loss must not differ by more than ±5 % and to treat the test as a constant head test.

9.5.5.2 *Method F (Constant Volume)*—Continue permeation until at least two or more values of hydraulic conductivity (k) meet the requirements stated in 9.5.4.2.

9.5.6 *Constant Rate of Flow Tests (Method D)*—Initiate permeation of the specimen by imposing a constant flow rate. Choose the flow rate so the hydraulic gradient does not exceed the value specified, or if none is specified, the value recommended in 9.5.1. Periodically measure the rate of inflow, the rate of outflow, and head loss across the test specimen to the tolerances and significant digits given in 5.1.3. Also, measure and record any changes in specimen height, if being monitored. Continue permeation until at least four values of hydraulic conductivity are obtained over an interval of time in which the ratio of inflow to outflow rates is between 0.75 and 1.25, and hydraulic conductivity is steady (see 9.5.4.1).

9.6 *Final Dimensions of the Specimen*—After completion of permeation, reduce the applied confining, influent, and effluent pressures in a manner that does not generate significant volume change of the test specimen. Then carefully disassemble the permeameter cell and remove the specimen. Measure and record the final height, diameter, and total mass of the specimen. Then determine the final water content of the specimen by the procedure of Method D2216. Dimensions and mass of the test specimen shall be measured to the tolerances specified in 5.8 and 5.9.

NOTE 14—The specimen may swell after removal of back pressure as a result of air coming out of solution. A correction may be made for this effect, provided that changes in the length of the specimen are monitored during the test. The strain caused by dismantling the cell is computed from the length of the specimen before and after dismantling the cell. The same strain is assumed to have occurred in the diameter. The corrected diameter and actual length before the back pressure was removed are used to compute the volume of the test specimen prior to dismantling the cell. The volume prior to dismantling the cell is used to determine the final dry density and degree of saturation.

10. Calculation

10.1 *Constant Head and Constant Rate of Flow Tests:*

10.1.1 *Methods A and D*—Calculate the hydraulic conductivity, k, as follows:

$$k = \frac{\Delta Q \cdot L}{A \cdot \Delta h \cdot \Delta t} \tag{1}$$

where:

k = hydraulic conductivity, m/s,
ΔQ = quantity of flow for given time interval Δt, taken as the average of inflow and outflow, m^3,
L = length of specimen, m,
A = cross-sectional area of specimen, m^2,
Δt = interval of time, s, over which the flow ΔQ occurs $(t_2 - t_1)$,
t_1 = time at start of permeation trial, date: hr:min:sec,
t_2 = time at end of permeation trial, date:hr:min:sec,
Δh = average head loss across the permeameter/specimen $((\Delta h_1 + \Delta h_2)/2)$, m of water,
Δh_1 = head loss across the permeameter/specimen at t_1, m of water, and
Δh_2 = head loss across the permeameter/specimen at t_2, m of water.

NOTE 15—The interval of time, Δt, can be measured directly using a stop watch or equivalent device, see 11.5.1. Units other than second(s), meters (m), etc., may be used providing an appropriate unit conversion factor (UCF) is used so k is in m/s or other units, if requested or customary (see Section 11).

10.1.2 *Method E*—Use the above Eq 1. If the height of the mercury column in the "Constant Head" tube is used to determine the head loss, Δh, use the following equation.

$$\Delta h = \Delta H_{Hg} \cdot \left(\frac{\rho_{Hg}}{\rho_w} - 1 \right) = \Delta H_{Hg} \cdot (G_{Hg} - 1) \tag{2}$$

where:

ΔH_{Hg} = the peak to peak height of mercury column (see Fig. 2), m, and
ρ_{Hg} = the density of mercury, g/cm^3,
ρ_{wg} = the density of water, g/cm^3,
G_{Hg} = the ratio of the density of mercury to the density of water (specific gravity of mercury) at the test/trial temperature. See Table 1.

TABLE 1 Specific Gravity of Mercury (G_{Hg})

Temperature (°C)	$G_{Hg} = (\rho_{Hg}/\rho_w)$
15	13.570
16	13.570
17	13.570
18	13.570
19	13.570
20	13.570
21	13.571
22	13.571
23	13.572
24	13.573
25	13.574
26	13.575
27	13.576
28	13.577
29	13.579
30	13.580

NOTE 16—For the constant-volume hydraulic systems, there is no head loss across the permeameter/specimen due to elevation head. Units other than seconds (s), meters (m), etc., may be used providing an appropriate UCF is used so k is in m/s or other units, if requested or customary (see Section 11).

10.2 *Falling-Head Tests:*

10.2.1 *Constant Tailwater Pressure (Method B)*—Calculate the hydraulic conductivity, k, as follows:

$$k = \frac{a \cdot L}{A \cdot \Delta t} ln \left(\frac{\Delta h_1}{\Delta h_2} \right) \tag{3}$$

where:

a = cross-sectional area of the reservoir containing the influent liquid, m^2, and
ln = natural logarithm (base e = 2.71828).

See Note 15.

10.2.2 *Increasing Tailwater Pressure (Method C)*—Calculate the hydraulic conductivity, k, as follows:

$$k = \frac{a_{in} \cdot a_{out} \cdot L}{(a_{in} + a_{out}) \cdot A \cdot \Delta t} ln \left(\frac{\Delta h_1}{\Delta h_2} \right) \tag{4}$$

where:

a_{in} = cross-sectional area of the reservoir containing the influent/inflow liquid, m^2, and
a_{out} = cross-sectional area of the reservoir containing the effluent/outflow liquid, m^2.

See Note 15.

NOTE 17—For the case in which $a_{out} = a_{in} = a$, the equation for calculating k for a falling head test with a rising tailwater level is:

$$k = \frac{a \cdot L}{2 \cdot A \cdot \Delta t} ln \left(\frac{\Delta h_1}{\Delta h_2} \right) \tag{5}$$

where:

a = area of the reservoirs containing either the influent/inflow or effluent/outflow liquid, m^2

10.2.3 *Constant-Volume System (Method F)*—Calculate the hydraulic conductivity, k, as follows:

$$k = \left(\frac{a_{in} \cdot a_{out}}{(a_{out} + a_{in})} \cdot \frac{1}{(G_{Hg} - 1)} \right) \cdot \frac{L}{A} \cdot \frac{1}{\Delta t} \cdot ln \left(\frac{\Delta h_1}{\Delta h_2} \right) \tag{6}$$

10.2.3.1 If the differential elevation between the top surfaces of the mercury level in the headwater and tailwater tubes is used to determine the head loss, Δh, use the following equations.

a) For the head loss at the start of the permeation trial, h_1:

$$h_1 = (\Delta H_{Hg,1} + \Delta H_{Hg,c}) \cdot \left(\frac{\rho_{Hg}}{\rho_w} - 1 \right) = (\Delta H_{Hg,1} + \Delta H_{Hg,c}) \cdot (G_{Hg} - 1) \tag{7}$$

where:

$\Delta H_{Hg,1}$ = difference in elevation between the top surfaces of the mercury level in the tailwater and headwater tubes at the start of the permeation trial, t_1 (see Fig. 3), m, and

$\Delta H_{Hg,c}$ = difference in elevation of mercury in the headwater and tailwater tubes of the manometer with equal pressures applied to both tubes, m. This value is positive if the inside diameter (ID) of the headwater tube is larger than the ID of the tailwater tube, and negative if the opposite is true. A discussion on capillary head is given in Appendix X1, X1.2.3.2 and X1.4. See Note 16.

b) For the head loss at the end of the permeation trial, Δh_2,:

$$\Delta h_2 = \Delta h_1 + \left(\left(-\Delta Hg_{\text{tail}} \right) \cdot \left(\frac{a_{\text{out}}}{a_{\text{in}}} + 1 \right) \cdot \left(G_{\text{Hg}} - 1 \right) \right) \tag{8}$$

where:

$-\Delta Hg_{\text{tail}}$ = the negative change in elevation of the mercury levels in the tailwater tube during the permeation trial, m.

The reason why ΔHg_{tail} is used instead of $\Delta Hg_{\text{Hg,2}}$ (difference in mercury levels at end of trial) is explained in Appendix X1, X1.3.2.1.

10.3 *Hydraulic Conductivity at Standard Temperature*—Correct the hydraulic conductivity to that for 20°C (68°F), k_{20}, by multiplying k by the ratio of the viscosity of water at test temperature to the viscosity of water at 20°C (68°F), R_T:

$$k_{20} = R_T \cdot K \tag{9}$$

with

$$R_T = 2.2902 \left(0.9842^{\,T} \right) / T^{\,0.1702} \tag{10}$$

where:

k_{20} = hydraulic conductivity corrected to 20°C, m/s

R_T = ratio of the viscosity of water at test temperature to the viscosity of water at 20°C

T = average test temperature during the permeation trial $((T_1 + T_2)/2)$, to the nearest 0.1°C.

T_1 = test temperature at start of permeation trial, to nearest 0.1°C, and

T_2 = test temperature at end of permeation trial, to nearest 0.1°C

10.3.1 The equation for R_T is only accurate to three significant digits between 5 and 50°C (41 and 122°F), see 1.1.

10.3.2 If the number of significant digits in the calculation of hydraulic conductivity at 20°C can be one, then the test temperature can be measured to the nearest °C.

11. Report: Test Data Sheet(s)/Form(s)

11.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s), as given below, is covered in 1.5.

11.2 Record as a minimum the following general information (data):

11.2.1 Sample/specimen identifying information, such as Project No., Boring No., Sample No., Depth, etc.

11.2.2 Any special selection and preparation process, such as removal of gravel or other materials, or identification of their presence, if "intact" specimen.

11.2.3 If the specimen is reconstituted, remolded or trimmed in a specialized manner (determine horizontal hydraulic conductivity, see 8.6), provide information on method of reconstitution, remolding, etc.

11.2.4 Name or initials of the person performing the test.

11.3 Record as a minimum the following test specimen data:

11.3.1 The measured specific gravity test (Test Method D854) or assumed value.

11.3.2 The initial mass, dimensions (length and diameter), area, and volume of the specimen, to either three or four significant digits (see 8.1 and 8.1.1).

11.3.3 The initial water content (nearest 0.1 percent), dry unit weight (three or four significant digits, see 8.1.1) and saturation (nearest percent) of the test specimen.

11.3.4 The final mass, dimensions (length and diameter), area, and volume of the specimen, to either three or four significant digits (see 8.1 and 8.1.1).

11.3.5 The final water content (nearest 0.1 percent), dry unit weight (three or four significant digits, see 8.1.1) and saturation (nearest percent) of the test specimen.

11.4 Record as a minimum the following test boundary conditions:

11.4.1 The type of permeant liquid used.

11.4.2 The magnitude of total back pressure (two significant digits or three if used in the head loss determination).

11.4.3 The effective consolidation stress (two or more significant digits).

11.4.4 The area of the headwater and tailwater tubes (such as burettes, reservoirs, U-tube manometers, etc.), as applicable (three or more significant digits).

11.4.5 The length (L) and area (A) of the test specimen during permeation (minimum of three significant digits).

11.4.5.1 These values can be determined based on either *a)* the initial dimensions of specimen plus any length/height and volume changes occurring during saturation and consolidation; or *b)* final dimensions of the test specimen, see 11.3.4.

11.5 Record as a minimum the following permeation data:

11.5.1 The date, time (or start and elapsed time), temperature (nearest 0.1°C see 10.3.2), head loss reading(s), flow reading(s) (if applicable), and deformation gage (if applicable) at the start and end of each trial/determination. Applicable measurements/readings and any averages/differences calculated using measurements/readings obtained shall have two or more significant digits, unless specified differently in Section 9.

11.5.2 The calculated initial hydraulic gradient and ending value if falling head Method B, C, or F is being used, and the hydraulic conductivity to two or more significant digits.

11.5.3 The average corrected hydraulic conductivity (k_{20}, see 10.3) for the values meeting the applicable requirements in 9.5.4 to 9.5.6. Record this value to two or three significant digits in units of m/s or other units, if requested or customary, for example, 7.1×10^{-10} or 7.13×10^{-10}m/s.

11.5.4 A graph or table of hydraulic conductivity versus time or pore volumes of flow is recommended, unless a constant-volume hydraulic system is used.

12. Precision and Bias

12.1 *Precision*—The precision of this test method is based on an interlaboratory study of D5084, Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter, conducted in 2008. Each of twelve laboratories tested three different soil types:

ML-1: Vicksburg silt (ASTM Reference Soil ML-1)
CH-1: Vicksburg clay (ASTM Reference Soil CH-1)
CL-1: Annapolis clay (ASTM Reference Soil CL-1)

All three soils are from the D18 ISR Reference Soils and Testing Program. Index properties for the soils are shown in Table 2. These properties are from the ASTM Reference Soils and Testing Program.

Every "test result" represents an individual determination. Each laboratory reported three replicate test results for the analyses. Practice E691 was followed for the design and analysis of the data; the details are given in ASTM Research Report RR:D18-D1018.[5]

12.1.1 *Repeatability Limit (r)*—Two test results obtained within one laboratory shall be judged not equivalent if they differ by more than the "r" value for that material; "r" is the interval representing the critical difference between two test results for the same material, obtained by the same operator using the same equipment on the same day in the same laboratory.

12.1.1.1 Repeatability limits are listed in Table 3.

12.1.2 *Reproducibility Limit (R)*—Two test results shall be judged not equivalent if they differ by more than the "R" value for that material; "R" is the interval representing the critical difference between two test results for the same material, obtained by different operators using different equipment in different laboratories.

12.1.2.1 Reproducibility limits are listed in Table 3.

12.1.3 The above terms (repeatability limit and reproducibility limit) are used as specified in Practice E177.

12.1.4 Any judgment in accordance with statements 12.1.1 and 12.1.2 would have an approximately 95 % probability of being correct.

12.2 *Bias*—At the time of the study, there was no accepted reference material suitable for determining the bias for this test method. Therefore no statement on bias is being made.

12.3 The precision statement was determined through statistical examination of 104 results, from twelve laboratories, on the three soils described in 12.1.

13. Keywords

13.1 coefficient of permeability; constant head; constant rate of flow; constant volume; falling head; hydraulic barriers; hydraulic conductivity; liner; permeability; permeameter

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[5] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:D18-1018.

TABLE 2 Index Properties for ASTM Reference Soils Used in Interlaboratory Study on Saturated Hydraulic Conductivity

ASTM Reference Soil ID	Liquid Limit per D4318 (%)	Plasticity Index per D4318 (%)	Specific Gravity of Soils per D854 (-)	Percent Finer than No. 200 Sieve per D1140 (%)
ML-1	27.3 ± 2.5	3.9 ± 4.5	2.725 ± 0.043	99.0 ± 0.3
CL-1	33.2 ± 1.4	13.4 ± 3.7	2.675 ± 0.030	88.5 ± 0.8
CH-1	59.7 ± 2.8	39.3 ± 7.0	2.726 ± 0.032	98.8 ± 0.4

TABLE 3 Hydraulic Conductivity Statistics from ILS Report RR:D18-D1018 (All Units in cm/s)

ILS Soil	Average $\bar{\chi}$	Repeatability Standard Deviation s_r	Reproducibility Standard Deviation s_R	Repeatability Limit r	Reproducibility Limit R
ML-1	1.2 x 10^{-6}	3.3 x 10^{-7}	4.4 x 10^{-7}	9.3 x 10^{-7}	1.2 x 10^{-6}
CL-1	3.8 x 10^{-8}	4.4 x 10^{-9}	6.2 x 10^{-9}	1.2 x 10^{-8}	1.8 x 10^{-8}
CH-1	3.6 x 10^{-9}	2.9 x 10^{-9}	4.7 x 10^{-9}	8.2 x 10^{-9}	1.3 x 10^{-8}

APPENDIXES

(Nonmandatory Information)

X1. DEVELOPMENT OF HYDRAULIC CONDUCTIVITY EQUATION FOR THE MERCURY CONSTANT VOLUME-FALLING HEAD HYDRAULIC SYSTEM

X1.1 *Introduction*—A schematic of a mercury constant volume-falling head hydraulic system is given in Fig. 4. In this figure, the falling head is applied by the difference in elevation between the mercury levels in the tailwater and headwater tubes of the mercury U-tube manometer. In designing this type of hydraulic system, the area of the tailwater tube (a_{out}) is made significantly smaller than that of the headwater tube (a_{in}). This is done for three reasons:

First, to increase the sensitivity of the flow/volume measurement;

Second, to decrease the time required to measure the hydraulic conductivity; and,

Third, so one can clean the hydraulic system by flushing water through the tailwater tube and out the headwater tube of the mercury U-tube manometer without loosing mercury.

X1.1.1 The tubing lines leading from the test specimen to mercury U-tube manometer are filled with water, as well as the spaces above the mercury in the manometer. Therefore, the volume of the saturated test specimen remains constant during permeation. This occurs because the components (water, tubing, and manometer) of the hydraulic system are relatively incompressible compared to soil. In addition, there is continuity of inflow and outflow of permeant water during permeation.

X1.1.2 The presentation of determining heads and head losses in a mercury constant volume-falling head hydraulic system is presented before the development of the hydraulic conductivity equation. This allows one to become familiar with the notation and required parameters before addressing that relatively complicated equation development process. The heads involved are the total head (H), pressure head (H_p), elevation head (H_e), capillary head (H_c), velocity head (H_v), and total head loss (Δh).

X1.2 *Determination of Total Head and Total Head Loss*

X1.2.1 *Total Head*—The total head is equal to the sum of the pressure head (H_p), elevation head (H_e), velocity head (H_v), and capillary head (H_c). Usually it is expressed in height of water, such as m or cm of water. In addition, the velocity head is assumed to be zero/insignificant providing the conditions specified in 4.4 through 5.2.3.2 are met. The pressure head is the height of a vertical column of static water that can be supported by the static pressure (p) at a given point. It may be expressed as

$$H_p = \mathrm{UCF} \cdot \frac{p}{\rho_w \cdot g} \tag{X1.1}$$

where:

H_p = the pressure head at given point (units of vertical height of water column, m),

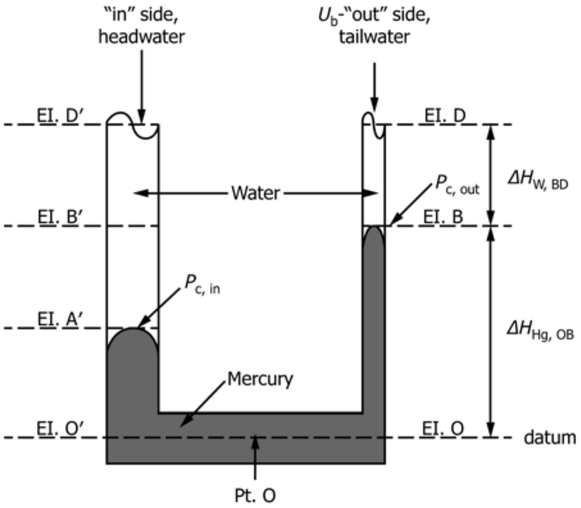
UCF = a unit conversion factor,

p = the static pressure at a given point (units of force per unit area, kPa),

ρ_w = the density of the water (units of mass per unit volume, Mg/m^3), and

g = the acceleration of gravity, convert mass to force ($9.80665\ m/s^2$ or $980.665\ cm/s^2$).

X1.2.2 The static pressure at any point within a confined fluid may be calculated as shown in Fig. X1.1, assuming there



Mercury U-tube Manometer

Determination of pressure for Pt. O at EL. O on the "out" or tailwater side, $p_{o,\ out}$.

$$p_{o,\ out} = \mathrm{UCF} \cdot (OB \cdot \rho_{Hg} \cdot g + \Delta P_{c,\ out} + BD \cdot \rho_W \cdot g + U_b)$$

or

$$= \mathrm{UCF} \cdot (\Delta H_{Hg,\ OB} \cdot \rho_{Hg} \cdot g + \Delta P_{c,\ out} + \Delta H_{W,\ BD} \cdot \rho_W \cdot g + U_b)$$

where:

UCF = a unit conversion factor,

ρ_{Hg} = the density of mercury, g/cm^3 or Mg/m^3,

ρ_W = the density of water, g/cm^3 or Mg/m^3,

g = the acceleration of gravity, m/s^2 or cm/s^2,

$\Delta P_{c,\ out}$ = the change in pressure due to capillarity at the tube-water-mercury interface in the outflow or tailwater tube, and

U_b = the applied back pressure, kPa or kN/m^2

FIG. X1.1 Static Pressure Calculations

is no drop in pressure due to velocity head loss. This figure shows that fluid pressure for Point O at elevation El. O on the "out" or tailwater side may be expressed as:

$$p_{o,\ out} \approx \mathrm{UCF}\cdot\left(\Delta H_{Hg,OB}\cdot\rho_{Hg}\cdot g+\Delta p_{c,out}+\Delta H_{w,BD}\cdot\rho_{w}\cdot g+U_{b}\right) \tag{X1.2}$$

or

$$p \approx \mathrm{UCF}\cdot\left(\Delta H_{Hg}\cdot\rho_{Hg}\cdot g+\Delta p_{c}+\Delta H_{w}\cdot\rho_{w}\cdot g+U_{b}\right)$$

where:

ΔH_{Hg} = the differential height of the mercury column, m,
ρ_{Hg} = the density of the mercury, Mg/m^3,
ΔH_{w} = the differential height of the water column, m,
Δp_{c} = the change in pressure due to capillarity at the tube-water-mercury interface, kPa, and
U_{b} = the applied back pressure, kPa.

X1.2.3 For the above case, the pressure head (in height of water) is

$$H_{p} \approx \mathrm{UCF}\cdot\left(H_{Hg}\times\frac{\rho_{Hg}\cdot g}{\rho_{w}\cdot g}+H_{w}\times\frac{\rho_{w}\cdot g}{\rho_{w}\cdot g}+\frac{\Delta p_{c}}{\rho_{w}\cdot g}+\frac{U_{b}}{\rho_{w}\cdot g}\right) \tag{X1.3}$$

or

$$H_{p} \approx \mathrm{UCF}\cdot\left(H_{Hg}\times G_{Hg}+\Delta H_{w}+\Delta H_{c}+\frac{U_{b}}{\rho_{w}\cdot g}\right)$$

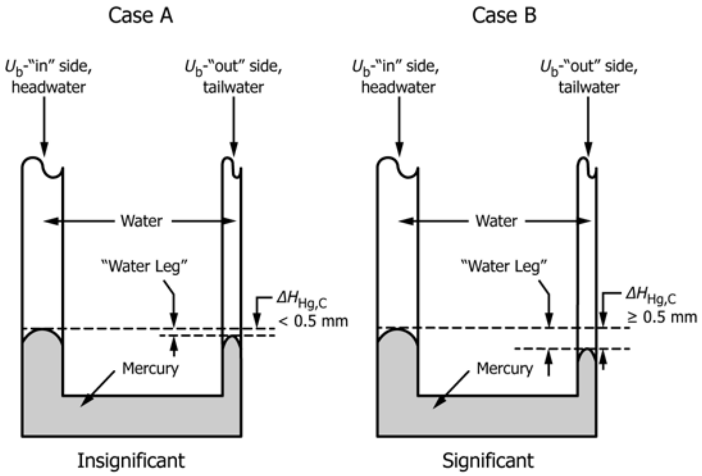
where:

G_{Hg} = the specific gravity of mercury at a given temperature, and
ΔH_{c} = the change in head due to capillarity, m of water, see X1.2.3.2

X1.2.3.1 *Velocity Head*—In most cases, the velocity head or velocity head loss is assumed equal to zero or insignificant, providing the requirements specified in 5.2.3 are met.

X1.2.3.2 *Capillary Head*—In most cases, the capillary head or capillary head loss is assumed equal to zero. However, in some mercury U-tube manometers, the difference in capillary head between the headwater and tailwater tubes; that is, the capillary head loss, ΔH_{c} is significant. Therefore, it has to be accounted for as shown in Fig. X1.2. To help one understand the derivation of ΔH_{c} in this figure, one has to remember to account for the "water leg" in the mercury U-tube manometer containing water instead of air. Subtracting away the "water leg" pressure does this. Also, the pressure difference measured

Capillary Head for
Mercury U-tube Manometer at No Flow or Equilibrium



$$\text{Capillary Head} = \Delta H_{c} = \mathrm{UCF}\cdot\left(\frac{\Delta H_{Hg,c}\cdot\rho_{Hg}\cdot g-\Delta H_{Hg,c}\cdot\rho_{w}\cdot g}{\rho_{w}\cdot g}\right)$$

or

$$\Delta H_{c} = \mathrm{UCF}\cdot\Delta H_{Hg,c}\cdot\left(\frac{\rho_{Hg}}{\rho_{w}}-1\right) = \mathrm{UCF}\cdot\Delta H_{Hg,c}\cdot(G_{Hg}-1)$$

Notes:
1) For definitions of notation, see X1.2.1 through X1.2.3.2.
2) For this case, the capillary head loss is a positive value since the total head on the headwater side would have to be increased to make the mercury levels equal.

NOTE 1—For this case capillary head loss is a positive value since the total head on the head water side would have to be increased to make the mercury levels equal.

FIG. X1.2 Difference in Capillary Head in Mercury U-tube Manometer

by the manometer has to be converted to a pressure head by dividing it by $\rho_w \cdot g$. As shown in Fig. X1.2, the capillary head loss is

$$\Delta H_c = \Delta H_{Hg,c} \cdot (G_{Hg} - 1) \qquad (X1.4)$$

where:

ΔH_c = capillary head loss in hydraulic system, m of water,

$\Delta H_{Hg,c}$ = differential height of mercury in the tailwater/outflow and headwater/inflow tubes of the manometer with equal pressure applied to each tube, m of mercury, and

G_{Hg} = specific gravity of mercury at test/trial temperature, see Table 1.

X1.2.3.2.1 As shown in Fig. X1.2, the application of either ΔH_c or $\Delta H_{Hg,c}$ is only necessary when $\Delta H_{Hg,c}$ is equal to or greater than 0.0005 m or 0.5 mm (0.02 in.). An explanation of how to measure ΔH_c is given in X1.4.

X1.2.4 *Total Head*—As stated above, the total head equals the sum of the pressure, elevation, velocity, and capillary heads. Since the change in velocity head is assumed to be zero and the change in capillary head is included in the pressure head calculation given above (Eq X1.3), the total head relationships at various points/elevations, as shown in Fig. X1.3, may be expressed as follows.

X1.2.4.1 Assuming there are no head losses in the tubing, the pressure head at Point Z ($H_{p,Z}$) equals the pressure head just above Point B ($H_{p,B}$), before the effect of capillary head; therefore

$$H_{p,Z} = H_{p,B} \textit{ and } H_{p,X} = H_{p,B'}$$

X1.2.4.2 By definition, the total head just above Point B equals the pressure plus elevation heads at that point, therefore

$$H_B = H_{p,B} + H_{e,OB} = \frac{U_b}{\rho_w \cdot g} + H_{e,OB}$$

and

$$H_{B'} = H_{p,B'} + H_{e,O'B'}$$

Assuming continuity in hydraulics, the pressure head at Point B' equals

$$H_{p,B'} = \frac{U_b}{\rho_w \cdot g} + \Delta H_{p,c,B} + H_{p,BA} + H_{p,AO} - H_{p,O'A'} - \Delta H_{p,c,A'} - H_{p,A'B'}$$

where:

$\Delta H_{p,c,B}$ = the change in capillary pressure head going from just above Point B to just below it, and

$\Delta H_{p,c,A'}$ = the change in capillary pressure head going from just below Point A' to just above it.

X1.3 *Total Head Loss*—Based on a detailed review of the hydraulic systems shown in Fig. X1.1, Fig. X1.2, and Fig. X1.3, one can come to the conclusion that the flow of fluid (permeant) will only occur when the difference in the mercury heights in the U-tube manometer is greater then equilibrium value, as shown in Fig. X1.2.

X1.3.1 *Initial Head Loss*—Using the total head discussion given above and the notation given in Fig. X1.3; the initial total-head loss (Δh_1) across the specimen is:

$$\Delta h_1 = H_X - H_Z = H_{B'} - H_B \qquad (X1.5)$$

or

$$\Delta h_1 = H_{p,B'} - H_{p,B} =$$

$$= \frac{U_b}{\rho_w \cdot g} + \Delta H_{p,c,B} + H_{p,BA} + H_{p,AO}$$

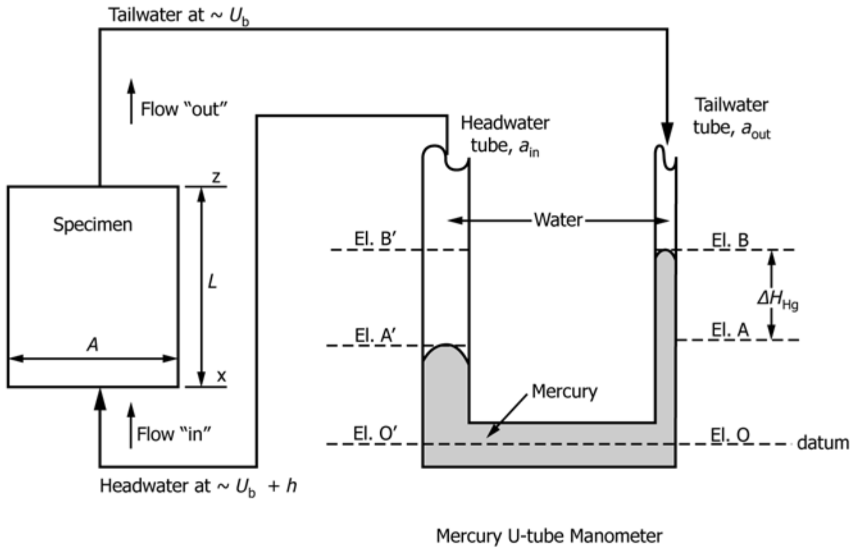


FIG. X1.3 Schematic of Mercury Constant Volume – Falling Head Hydraulic System for Head and Head Loss Equations

$$-H_{p,O'A'}-\Delta H_{p,c,A'}-H_{p,A'B'}-H_{p,B}$$

Since

$$H_{p,b}=\frac{U_b}{\rho_w\cdot g}, \qquad (X1.6)$$

$$H_{p,AO}=H_{p,O'A',}, \text{ and}$$

$$\Delta H_c=\Delta H_{p,c,B}-\Delta H,$$

therefore

$$\Delta h_1=H_{p,BA}-H_{p,A'B'}+\Delta H_c \qquad (X1.7)$$

Using generic notation instead of specific notation as given in Fig. X1.1 to Fig. X1.4, therefore

$$\Delta h_1=\frac{\Delta H_{Hg,1}\cdot g}{\rho_W}-\Delta H_{Hg,1}+\Delta H_{Hg,c}\times\left(\frac{\rho_{Hg}}{\rho_W}-1\right) \qquad (X1.8)$$

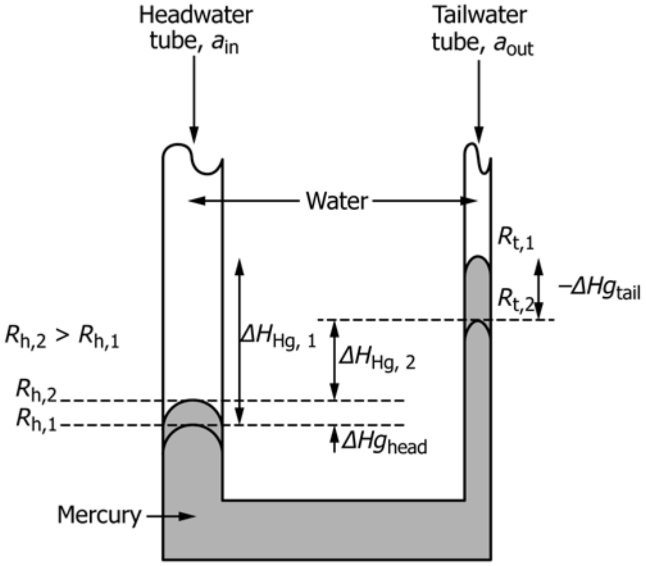
and rearranging, therefore

$$\Delta h_1=(\Delta H_{Hg}+\Delta H_{Hg,c})\cdot\left(\frac{\rho_{Hg}}{\rho_w}-1\right) \qquad (X1.9)$$

$$\Delta h_1=(\Delta H_{Hg,1}+\Delta H_{Hg,c})\cdot(G_{Hg}-1)$$

where:

Δh_{Hg} = the initial total-head loss at the start (t_1) of a given permeation trial, in m of water,



"Flow" Functions:

Flow "in" = $\Delta Q_{in} = \Delta Hg_{head}\cdot a_{in}$

Flow "out" = $-\Delta Q_{out} = -\Delta Hg_{tail}\cdot a_{out}$

Based on continuity, $\Delta Q_{in} = -\Delta Q_{out}$

Therefore, $\Delta Hg_{head}\cdot a_{in} = -\Delta Hg_{tail}\cdot a_{out}$

or

$$\Delta Hg_{head} = -\Delta Hg_{tail}\cdot\frac{a_{out}}{a_{in}}$$

"Head" Functions:

$$\Delta H_{Hg,2} = \Delta H_{Hg,1} + (-\Delta Hg_{tail}) - \Delta Hg_{head}$$

Substituting for ΔHg_{head},

$$\Delta H_{Hg,2} = \Delta H_{Hg,1} + (-\Delta Hg_{tail}) + \left(-\Delta Hg_{tail}\cdot\frac{a_{out}}{a_{in}}\right)$$

$$\Delta H_{Hg,2} = \Delta H_{Hg,1} + (-\Delta Hg_{tail})\cdot\left(\frac{a_{out}}{a_{in}}+1\right)$$

Substituting for $\Delta H_{Hg,2}$ in the final head loss equation (X1.10) and rearranging,

$$\Delta h_2 = \left(\Delta H_{Hg,1} + \Delta H_{Hg,c} + (-\Delta Hg_{tail})\cdot\left(\frac{a_{out}}{a_{in}}+1\right)\right)\cdot(G_{Hg}-1)$$

or

$$\Delta h_2 = \Delta h_1 + \left((-\Delta Hg_{tail})\cdot\left(\frac{a_{out}}{a_{in}}+1\right)\cdot(G_{Hg}-1)\right)$$

FIG. X1.4 Relationship Between Change in Flow and Total Head Loss

ΔH_{Hg} = the initial differential height of mercury in the tailwater and headwater tubes of the manometer at the start (t_1) of a given permeation trial, in m,

$\Delta H_{Hg,c}$ = the positive differential height of mercury in the tailwater and headwater tubes of the manometer with equal pressures applied to both tubes, in m. This height differential is caused by the difference in capillary pressure heads within the two tubes making up the mercury U-tube manometer, see X1.2.3.2 and X1.4

ΔH

X1.3.2 *Final Head Loss*—The final total-head loss (Δh_2) across the specimen is

$$\Delta h_2 = (\Delta H_{Hg,2} + \Delta H_{Hg,c})\cdot(G_{Hg} - 1) \quad (X1.10)$$

where:

Δh_2 = the final total-head loss at the end (t_2) Of a given permeation trial, in m of water,

$\Delta H_{Hg,2}$ = the final differential height of mercury in the tailwater and headwater tubes of the manometer at the end (t_2) of a given permeation trial, in m.

X1.3.2.1 The determination of $\Delta H_{Hg,2}$ requires two readings; that is, the elevation of the top surfaces of the mercury (meniscus) in the tailwater and headwater tubes. Each of these readings will have some error, especially the headwater reading. In addition, the change in the headwater readings between t_1 and t_2 is typically very small and at about the sensitivity to which readings can be made/estimated. Because of these factors, it is assumed that the accuracy of Δh_2 can increased by just measuring the change in elevation of the top surface mercury level in the tailwater tube and calculating what $\Delta H_{Hg,2}$ should be based on the area relationships between the tailwater and headwater tubes. As shown in Fig. X1.4, the following flow relationships can be established.

$$\Delta Q_{in} = \Delta Hg_{head}\cdot a_{in}$$

,

$$-\Delta Q_{out} = -\Delta Hg_{tail}\cdot a_{out}$$

NOTE X1.1—the symbol for height (H) has been omitted to keep the notation simpler, and

ΔQ_{in} = inflow of permeant water for given time interval (positive units of volume),

$-\Delta Q_{out}$ = outflow of permeant water for given time interval (negative units of volume),

ΔHg_{head} = positive change in elevation of the mercury level (top of meniscus) in the headwater tube (units of distance)

$-\Delta Hg_{tail}$ = negative change in elevation of the mercury level (top of meniscus) in the tailwater tube (units of distance),

a_{in} = area of the headwater/inflow tube containing mercury (units of area), and

a_{out} = area of the tailwater/outflow tube containing mercury (units of area)

Based on continuity of flow in a saturated specimen at constant volume,

$$\Delta Qin = -\Delta Qout$$

therefore,

$$\Delta Hg_{head}\cdot a_{in} = -\Delta Hg_{tail}\cdot a_{out} \quad (X1.11)$$

or

$$\Delta Hg_{head} = -\Delta Hg_{tail}\cdot\frac{a_{out}}{a_{in}}$$

therefore,

$$\Delta H_{Hg,2} = \Delta H_{Hg,1} + (-\Delta Hg_{tail}) + \left(\Delta Hg_{tail}\cdot\frac{a_{out}}{a_{in}}\right) \quad (X1.12)$$

or

$$\Delta H_{Hg,2} = \Delta H_{Hg,1} + (-\Delta Hg_{tail})\cdot\left(\frac{a_{out}}{a_{in}} + 1\right)$$

Substituting for $\Delta H_{Hg,2}$ and rearranging

$$\Delta h_2 = \left(\Delta H_{Hg,1} + \Delta H_{Hg,c} + (-\Delta Hg_{tail})\cdot\left(\frac{a_{out}}{a_{in}} + 1\right)\right)\cdot(G_{Hg} - 1) \quad (X1.13)$$

or

$$\Delta h_2 = \Delta h_1 + \left((-\Delta Hg_{tail})\cdot\left(\frac{a_{out}}{a_{in}} + 1\right)\cdot(G_{Hg} - 1)\right)$$

X1.4 *Capillary Head Measurements*—The key to measuring the difference in capillary head (ΔH_c) between the headwater and tailwater tubes of the mercury U-tube manometer is to ensure that an equal water pressure is applied to both tubes. In addition, flow of water can occur under that equal water pressure. This can be accomplished by individually connecting the tailwater and headwater tubing lines to clean burettes containing water at equal elevation. These lines can not have any air bubbles in them. Then, apply the same air pressure to these two burettes. This air pressure should be similar to the back pressure applied during testing. Finally, adjust the height of one burette (typically the one connected to the headwater line) so the water level within each burette is equal. In making this height adjustment, make sure the water level in the headwater burette starts out below that of the tailwater burette. This simulates the direction of fluid flow during the test.

X1.4.1 Once the water level in the two burettes are level, determine the difference in elevation of the two mercury columns at the tops of their meniscuses. The mercury level in the tailwater tube (one with a smaller ID) should be below that in the headwater tube. If it is not, there is an error in applying equal pressures to the two tubes of the U-tube manometer, check for air in the lines, external pressure source, etc..

X1.4.2 If the mercury U-tube manometer being used is the version in which the tailwater tube is contained within the headwater tube, a different approach has to be used. A different approach is required since the mercury level in the tailwater tube is not visible at equilibrium. One approach would be to raise the headwater burette until the mercury levels (top of menisci) in the U-tube manometer (headwater and tailwater columns) are equal. Then determine the difference in elevation of the water levels in the headwater and tailwater burettes in m of water,

Next, convert ΔH_c to $\Delta H_{Hg,c}$ with

$\Delta H_{Hg,c} = \Delta H_c/(G_{Hg} - 1) = \Delta H_c/12.74$, in m of mercury. The value of 12.57 is good for temperatures ranging between 15°C and 25°C.

X1.5 *Falling-Head Hydraulic Conductivity Equation*—Darcy's law for hydraulic conductivity in a saturated medium requires that:

$$q = k \cdot i \cdot A = k \cdot \frac{\Delta h}{L} \cdot A \qquad \text{(X1.14)}$$

or

$$\Delta Q = k \cdot \frac{\Delta h}{L} \cdot A \cdot \Delta t$$

where:

q = rate of flow of the fluid (units of volume over time, m^3/s),

k = hydraulic conductivity or coefficient of permeability (units of length over time, m/s),

i = hydraulic gradient (no unit),

Δh = total head loss across a given length/test specimen (unit of height of water, m),

L = given length (test specimen) over which the total head loss occurs (unit of distance, m),

ΔQ = volume of flow for a given time interval (unit of volume, m^3), and

Δt = time interval (unit of time, s).

X1.5.1 For a differential volume of flow and time period, this equation becomes

$$d\Delta Q = k \cdot \frac{\Delta h}{L} \cdot A \cdot d\Delta t \qquad \text{(X1.15)}$$

where:

$d\Delta Q$ = differential volume of flow in a differential time period, and

$d\Delta t$ = differential time period.

X1.5.2 It can be demonstrated that the differential volume of flow is a function of the differential head loss, as shown below. From Fig. X1.4 or X1.3.2.1;

$$-\Delta Q = -\Delta Hg_{\text{tail}} \cdot a_{\text{out}} \qquad \text{(X1.16)}$$

or

$$-d\Delta Q = -d\Delta Hg_{\text{tail}} \cdot a_{\text{out}}$$

and from Fig. X1.4,

$$-d\Delta Hg_{\text{tail}} = \frac{dh}{1} \cdot \frac{a_{\text{in}}}{a_{\text{out}} + a_{\text{in}}} \cdot \frac{1}{(G_{\text{Hg}} - 1)} \qquad \text{(X1.17)}$$

By substituting for $-d\Delta Q$ and $-d\Delta Hg_{\text{tail}}$ from the above equations in Eq X1.15 we get,

$$-\frac{dh}{1} \cdot \frac{a_{\text{in}} \cdot a_{\text{out}}}{a_{\text{out}} + a_{\text{in}}} \cdot \frac{1}{(G_{\text{Hg}} - 1)} = k \cdot \frac{\Delta h}{L} \cdot A \cdot d\Delta t \qquad \text{(X1.18)}$$

or

$$d\Delta t = -\frac{L}{A} \cdot \frac{1}{k} \cdot \frac{1}{\Delta h} \cdot \frac{1}{(G_{\text{Hg}} - 1)} \cdot \frac{a_{\text{in}} \cdot a_{\text{out}}}{a_{\text{out}} + a_{\text{in}}} \cdot dh$$

By integrating between times t_1 and t_2 and h_1 and h_2 we get,

$$\int_{t_1}^{t_2} d\Delta t = \int_{\Delta h_1}^{\Delta h_2} -\frac{L}{A} \cdot \frac{1}{k} \cdot \frac{1}{\Delta h} \cdot \frac{1}{(G_{\text{Hg}} - 1)} \cdot \frac{a_{\text{in}} \cdot a}{a_{out} + a_{in}} \cdot dh$$

which yields the general constant volume-falling head equation,

$$\Delta t = -\frac{L}{A} \cdot \frac{1}{k} \cdot \frac{1}{(G_{\text{Hg}} - 1)} \cdot \frac{a_{\text{in}} \cdot a_{out}}{a_{\text{out}} + a_{\text{in}}} ln\left(\frac{\Delta h_2}{\Delta h_1}\right) \qquad \text{(X1.19)}$$

or

$$k = -\frac{L}{A} \cdot \frac{1}{\Delta t} \cdot \frac{1}{(G_{\text{Hg}} - 1)} \cdot \frac{a_{\text{in}} \cdot a_{\text{out}}}{a_{\text{out}} + a_{\text{in}}} ln\left(\frac{\Delta h_2}{\Delta h_1}\right)$$

Noting that,

$$-ln\frac{\Delta h_2}{\Delta h_1} = ln\frac{\Delta h_1}{\Delta h_2}$$

the equation becomes,

$$k = \left(\frac{a_{\text{in}} \cdot a_{\text{out}}}{(a_{\text{out}} + a_{\text{in}})} \cdot \frac{1}{(G_{\text{Hg}} - 1)}\right) \cdot \frac{L}{A} \cdot \frac{1}{\Delta t} \cdot ln\left(\frac{\Delta h_1}{\Delta h_2}\right) \qquad \text{(X1.20)}$$

where:

k = hydraulic conductivity of the test specimen at the test temperature, m/s,

Δh_1 = total head loss across length L at the start of a permeation trial; that is, initial total head loss, m of water,

Δh_2 = final total head loss across length L at the end of a permeation trial; that is, final total head loss, m of water,

Δt = elapsed time during a permeation trial; that is, $\Delta t = t_2 - t_1$, s,

a_{out} = area of the tailwater tube (tube with smaller ID), m^2,

a_{in} = area of the headwater tube, in m^2,

G_{Hg} = specific gravity of mercury (ρ_{Hg}/ρ_w) at the test temperature,

ρ_{Hg} = density of mercury at the test temperature, in Mg/m^3,

ρ_W = density of water at the test temperature, Mg/m^3,

$(G_{Hg}-1)$ = constant equal to 12.57 between 15 and 25°C,

L = length/height of the test specimen, in m,

A = area of the test specimen, in m^2,

ln = natural logarithm (base e),

and head loss equations from X1.3.1 and X1.3.2 are

$$\Delta h_1 = (\Delta H_{\text{Hg},1} + \Delta H_{\text{Hg,c}}) \cdot (G_{\text{Hg}} - 1) \qquad \text{(X1.21)}$$

$$\Delta h_2 = \Delta h_1 + \left((-\Delta Hg_{\text{tail}}) \cdot \left(\frac{a_{\text{out}}}{a_{\text{in}}} + 1\right) \cdot (G_{\text{Hg}} - 1)\right) \qquad \text{(X1.22)}$$

where for Δh_1 and Δh_2:

$\Delta H_{Hg,1}$ = the initial difference in height of mercury in the tailwater and headwater tubes of the manometer at the start (t_1) of a given permeation trial, m;

$\Delta H_{Hg,c}$ = the positive difference in height of mercury in the tailwater and headwater tubes of the manometer with equal pressure applied to both tubes, m, (This height differential is caused by the difference in capillary pressure of the two tubes making up the mercury U-tube manometer); and,

$-\Delta Hg_{tail}$ = the negative change in height of the mercury level in the tailwater tube of the manometer during a given permeation trial, m.

X2. RELATIONSHIP BETWEEN CHANGE IN AXIAL STRAIN AND HYDRAULIC CONDUCTIVITY OF TEST SPECIMEN

X2.1 *Introduction*—It is important to understand how hydraulic conductivity (k) changes with changes in void ratio, dry unit weight, or volume change of a given test specimen. With this understanding, one can thereby know the accuracy to which volume changes need to be controlled while testing. For instance, if k is very sensitive to volume changes then the effective consolidation stress needs to be accurately controlled; also, any volume changes during the back-pressuring process would have to be minimized.

X2.1.1 The relationships presented in this appendix are for relatively plastic clays, CL or CH, with a plasticity index greater than about 10, but less than about 50.

X2.2 *Change in Void Ratio versus Hydraulic Conductivity*—A graphical representation of how hydraulic conductivity (k) varies with void ratio (e) is presented in Fig. X2.1. This figure graphically shows that the k decreases as e decreases. In addition, for a given change in void ratio (Δe) the rate of change in k is much more dramatic in the overconsolidated range than in the normally consolidated range. The definition for the terms/notation presented in this figure are:

k= given hydraulic conductivity, m/s,
k_L= lower bound k for given percent change in k, m/s,
k_U= upper bound k for given percent change in k, m/s,
Δk_L= lower bound change in k for given percent change (decimal form) in k, m/s/
% Change = the percent change (decimal form) in k,
Δe_L= the compressive change in void ration (decreasing change)
e_U= the swelling change in void ratio (increasing change), and
m = the ratio of Δe to $\Delta log\ k = \Delta e/log\ (k/k_L)$, 1/(m/s).

X2.3 Mathematical Relationship Between e and k—It can be shown that:

$$k_L = k + (-\Delta k_L) = k - \%Change \times k = (1 - \%Change) \times k \quad (X2.1)$$

or

$$k_U = (1 + \%Change) \times k$$
$$-\Delta k_L = log(1 - \%Change) \quad (X2.2)$$

or

$$\Delta k_U = log(1 + \%Change)$$
$$e_L = e + (-\Delta e_L) \quad (X2.3)$$

or

$$e_U = e + \Delta e_U$$
$$-\Delta e_L = m \times -\Delta k_L = m \times log(1 - \%Change), \quad (X2.4)$$

or

$$\Delta e_U = m \times \Delta k_U = m \times log(1 + \%Change)$$

X2.4 Based upon the theory of elasticity, the following relationships between axial strain (ε_a) and volumetric strain (ε_v), and volumetric strain and change in void ratio ($\Delta\varepsilon$) are:

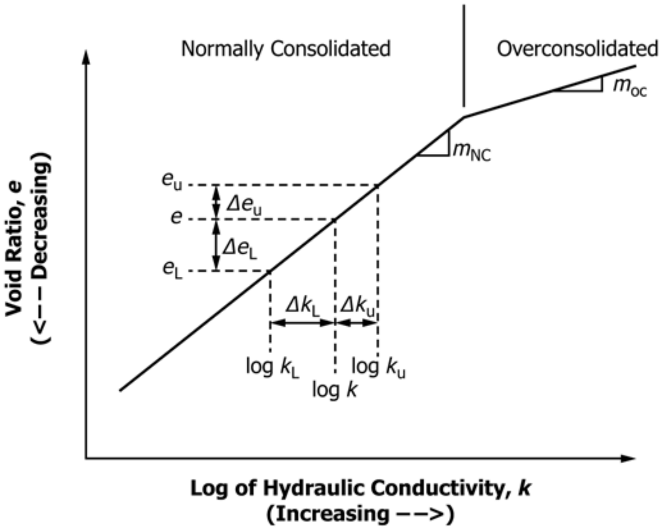


FIG. X2.1 Typical Relationship Between Void Ratio and Logarithm of Hydraulic Conductivity

$$\Delta\varepsilon_a = \frac{1}{3}\cdot E_c\cdot\Delta\varepsilon_v = \left(\frac{1}{3}\cdot E_c\cdot - \Delta\varepsilon_L\right)/(1 - e_o) \qquad (X2.5)$$

$\Delta\varepsilon_a$ = the change in compressive axial strain ($\Delta L/L_o$), m/m.
E_c = a constant to correct for the non-elastic response of hydraulic-conductivity test specimens. For test specimens having a height to diameter ratio of about one, this value is about 0.8 for normally consolidated (NC) specimens and 0.6 for overconsolidated (OC) specimens,
$\Delta\varepsilon_v$ = the change in compressive volumetric strain ($\Delta V/V_o$), m^3/m^3.
$-\Delta e$ = the compressive change in void ratio; that is, decreasing change,
e_o = the initial void ratio.

X2.5 Combining the above equations and rearranging:

$$\Delta\varepsilon_{a,NC} = \frac{-1}{3\cdot E_c}\cdot\frac{m_{NC}}{1+e_o}\cdot log(1 - \%Change) \qquad (X2.6)$$

or

$$\Delta\varepsilon_{a,OC} = \frac{-1}{3\cdot E_c}\cdot\frac{m_{OC}}{1+e_o}\cdot log(1 - \%Change)$$

also

$$-\%Change = 10^{-\left(3\cdot E_c\cdot\left(\frac{1+e_o}{m}\right)\cdot\Delta\varepsilon_{a,L}\right)} \qquad (X2.7)$$

$$+\%Change = 10^{-\left(3\cdot E_c\cdot\left(\frac{1+e_o}{m}\right)\cdot-\Delta\varepsilon_{a,U}\right)}$$

where:

m_{NC} = $m$value in normally consolidated region, 1/[m/s], and
m_{OC} = m value in the overconsolidated region, 1/[m/s].

X2.5.1 Tavenas, et al. (**12**) indicates that m is about (⅓ to ½) × e_o for normally consolidated clays. For overconsolidated clay, it is assumed that m in the overconsolidated range is reduced by the same ratio that the compression index (C) is when going from the normally consolidated region (C_{NC}) to the overconsolidated region (C_{OC}). Therefore,

$$m_{OC}/m_{NC} = C_{OC}/C_{NC} \sim 0.185 + 0.002 \times PI$$

where PI = plasticity index. This assumption is based on limited data, and in some cases, there was not any significant difference in m between the normally consolidated and overconsolidated regions. Based on the above, an initial void ratio of 0.8 and a plasticity index (PI) of 30, m_{NC} is about 0.33; while m_{OC} is about 0.082.

X2.5.2 Using the above m values and equations, and a % Change equal to 12.5 %, one could assume excess axial strains caused by a poor testing protocol should be less than the following values:

For normally consolidated soils:

$$\Delta\varepsilon_{a,NC} = \frac{-1}{3\cdot 0.8}\cdot\frac{0.33}{1.8}\cdot log0.875 = 0.0044 = 0.4\,\%$$

For overconsolidated consolidated soils:

$$\Delta\varepsilon_{a,OC} = \frac{-1}{3\cdot 0.6}\cdot\frac{0.082}{1.8}\cdot log0.875 = 0.00147 = 0.1\,\%$$

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SUMMARY OF CHANGES

In accordance with Committee D18 policy, this section identifies the location of changes to this standard since the last edition (2010) that may impact the use of this standard. (August 1, 2016)

(1) Revised 6.1.2.

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