Designation: D7664 – 10

Standard Test Methods for Measurement of Hydraulic Conductivity of Unsaturated Soils[1]

This standard is issued under the fixed designation D7664; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 These test methods cover the quantitative measurement of data points suitable for defining the hydraulic conductivity functions (HCF) of unsaturated soils. The HCF is defined as either the relationship between hydraulic conductivity and matric suction or that between hydraulic conductivity and volumetric water content, gravimetric water content, or the degree of saturation. Darcy's law provides the basis for measurement of points on the HCF, in which the hydraulic conductivity of a soil specimen is equal to the coefficient of proportionality between the flow rate of water through the specimen and the hydraulic gradient across the specimen. To define a point on the HCF, a hydraulic gradient is applied across a soil specimen, the corresponding transient or steady-state water flow rate is measured (or vice versa), and the hydraulic conductivity calculated using Darcy's law is paired with independent measurements of matric suction or volumetric water content in the soil specimen.

1.2 These test methods describe a family of test methods that can be used to define points on the HCF for different types of soils. Unfortunately, there is no single test that can be applied to all soils to measure the HCF due to testing times and the need for stress control. It is the responsibility of the requestor of a test to select the method that is most suitable for a given soil type. Guidance is provided in the significance and use section of these test methods.

1.3 Similar to the Soil Water Retention Curve (SWRC), defined as the relationship between volumetric water content and matric suction, the HCF may not be a unique function. Both the SWRC and HCF may follow different paths whether the unsaturated soil is being wetted or dried. A test method should be selected which replicates the flow process occurring in the field.

1.4 These test methods describe three categories of methods (Categories A through C) for direct measurement of the HCF. Category A (column tests) involves methods used to define the HCF using measured one-dimensional profiles of volumetric water content or suction with height in a column of soil compacted into a rigid wall permeameter during imposed transient and steady-state water flow processes. Different means of imposing water flow processes are described in separate methods within Category A. Category B (axis translation tests) involves methods used to define the HCF using outflow measurements from a soil specimen underlain by a saturated high-air entry porous disc in a permeameter during imposed transient water flow processes. The uses of rigid-wall or flexible-wall permeameters are described in separate methods within Category B. Category C (centrifuge permeameter test) includes a method to define the HCF using measured volumetric water content or suction profiles in a column of soil confined in a centrifuge permeameter during imposed steady-state water flow processes. The methods in this standard can be used to measure hydraulic conductivity values ranging from the saturated hydraulic conductivity of the soil to approximately 10^{-11} m/s.

1.5 The methods of data analysis described in these test methods involve measurement of the water flow rate and hydraulic gradient, and calculation of the hydraulic conductivity using Darcy's law (direct methods) (**1**).[2] Alternatively, inverse methods may also be used to define the HCF (**2**). These employ an iterative, regression-based approach to estimate the hydraulic conductivity that a soil specimen would need to have given a measured water flow response. However, as they require specialized engineering analyses, they are excluded from the scope of these test methods.

1.6 These test methods apply to soils that do not change significantly in volume during changes in volumetric water content or suction, or both (that is, expansive clays or collapsing soils). This implies that these methods should be used for sands, silts, and clays of low plasticity.

1.7 The methods apply only to soils containing two pore fluids: a gas and a liquid. The liquid is usually water and the gas is usually air. Other fluids may also be used if requested. Caution shall be exercised if the liquid being used causes shrinkage or swelling of the soil.

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[1] These test methods are under the jurisdiction of ASTM Committee D18 on Soil and Rock and are the direct responsibility of Subcommittee D18.04 on Hydrologic Properties and Hydraulic Barriers.

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

1.8 The units used in reporting shall be SI units in order to be consistent with the literature on water flow analyses in unsaturated soils. The hydraulic conductivity shall be reported in units of [m/s], the matric suction in units of [kPa], the volumetric water content in [m^3/m^3] or [%], and the degree of saturation in [m^3/m^3].

1.9 All observed and calculated values shall conform to the guide for significant digits and rounding established in Practice D6026. The procedures in Practice D6026 that are used to specify how data are collected, recorded, and calculated are regarded as the industry standard. In addition, they are representative of the significant digits that should generally be retained. The procedures do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the objectives of the user. Increasing or reducing the significant digits of reported data to be commensurate with these considerations is common practice. Consideration of the significant digits to be used in analysis methods for engineering design is beyond the scope of these test methods.

1.10 *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]

D422 Test Method for Particle-Size Analysis of Soils
D653 Terminology Relating to Soil, Rock, and Contained Fluids
D854 Test Methods for Specific Gravity of Soil Solids by Water Pycnometer
D1587 Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes
D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
D2487 Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
D4318 Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
D5084 Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter
D5101 Test Method for Measuring the Filtration Compatibility of Soil-Geotextile Systems
D6026 Practice for Using Significant Digits in Geotechnical Data
D6527 Test Method for Determining Unsaturated and Saturated Hydraulic Conductivity in Porous Media by Steady-State Centrifugation
D6836 Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge

3. Terminology

3.1 *Definitions:*

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *air entry suction,* ψ_a*,* (FL^{-1}), *n*—the suction required to introduce air into (and through) the pores of a saturated porous material (soil or porous plate).

3.2.2 *angular velocity, ω, (radians/T), n*—the angular speed of a centrifuge.

3.2.3 *axis translation, n*—the principle stating that a matric suction ψ can be applied to a soil by controlling the pore air pressure u_a and the pore water pressure u_w so that the difference between the pore air and water pressures equals the desired matric suction, that is, $\psi = u_a - u_w$.

3.2.4 *capacitance probe, n*—a tool used to infer the volumetric water content of an unsaturated soil through measurement of the capacitance of a probe embedded within the soil.

3.2.5 *centrifuge permeameter, n*—a system having the purposes of holding a soil specimen in a centrifuge, applying inflow rates to the top of the soil specimen, and collecting outflow from the bottom of the soil specimen.

3.2.6 *degree of saturation* S_r*,* (L^3L^{-3}), *n*—the ratio of: *(1)* the volume of water in a given soil or rock mass, to *(2)* the total volume of intergranular space (voids).

3.2.7 *flexible-wall permeameter, n*—a setup used to control/measure the flow and hydraulic gradient across a soil specimen contained within a latex membrane.

3.2.8 *g-level,* $N_{r,mid}$*, (D), n*—the ratio of the acceleration of gravity *g* to the centripetal acceleration, equal to $\omega^2(r_0\text{-}z_{mid})/g$, where r_0 is equal to the radius at the bottom of the centrifuge permeameter, and z_{mid} is the distance from the base of the soil specimen to its mid-height.

3.2.9 *high air-entry porous disc, n*—a disc made of metal, ceramic, or other porous material that can transmit water and has an air entry pressure exceeding the highest matric suction to be applied during a test.

3.2.10 *high air-entry porous membrane, n*—a porous polymeric membrane that transmits water and has an air entry suction greater than the highest suction to be applied during a test.

3.2.11 *hydraulic conductivity, k,* (LT^{-1}) , *n*—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). The hydraulic conductivity is defined as the coefficient of proportionality between the water discharge velocity and the spatial gradient in hydraulic head across a saturated or unsaturated soil specimen, as follows:

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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.

$$k = \frac{v}{i} \tag{1}$$

3.2.12 *hydraulic conductivity function (HCF), n*—relationship between the hydraulic conductivity and the matric suction, volumetric water content, or degree of saturation.

3.2.13 *hydraulic gradient, i, (D), n*—the change in total hydraulic head, Δh, per unit distance L in the direction of fluid flow, or $i = \Delta h/L$.

3.2.14 *infiltration rate,* (LT^{-1}), *n*—the value of the water discharge velocity applied to the surface of a soil specimen to simulate infiltration.

3.2.15 *matric suction, ψ,* (FL^{-2}) , *n*—the difference between the pore gas pressure u_g and the pore water pressure u_w in soil; that is $\psi = u_g - u_w$, which yields a positive value. The pore gas in this test method is assumed to be air under pressure u_a, so $\psi = u_a - u_w$.

3.2.16 *pressure chamber, n*—a setup that involves a rigid-wall oedometer cell contained within a pressure vessel. This chamber is used to independently apply a gas pressure to one side and water pressure to the other side of a soil specimen held within the oedometer in order to impose an average value of matric suction on the specimen.

3.2.17 *soil-water retention curve (SWRC), n*—relationship between matric suction and volumetric water content.

3.2.18 *tensiometer, n*—a tool used to measure the matric suction in soil by measuring the negative water pressure in a water reservoir in equilibrium with a soil via a saturated porous disc.

3.2.19 *time domain reflectometer (TDR), n*—a tool used to infer the volumetric water content of an unsaturated soil through measurement of the travel time of an electromagnetic pulse through a metallic, shielded rod embedded within the soil.

3.2.20 *total hydraulic head, h, n*—the sum of three components at a point: *(1)* elevation head, h_e, which is equal to the elevation of the point above a datum; *(2)* pressure head, h_p, which is the height of a column of static water that can be supported by the static pressure at the point; and *(3)* velocity head, h_v, which is the height the kinetic energy of the liquid is capable of lifting the liquid. In tests run using this standard, h_v is negligible compared with the other components.

3.2.21 *volumetric water content, θ,* (L^3L^{-3} or %), *n*—the ratio of the volume of water contained in the pore spaces of soil or rock to the total volume of soil or rock.

3.2.22 *water discharge velocity, v,* (LT^{-1}), *n*—rate of discharge of water through a porous medium per unit of total area perpendicular to the direction of flow.

3.2.23 *water flow rate, Q, n*—the volumetric rate of flow of water through a soil specimen.

4. Summary of Test Method

4.1 *Method A—Column Tests:*

4.1.1 Category A includes four methods (Methods A1 to A4) which involve measurement of changes in volumetric water content and suction over space and time in a soil specimen held within a horizontally- or vertically-oriented column during one-dimensional water flow.

4.1.2 Method A1 involves downward infiltration of water onto the surface of an initially unsaturated soil specimen, Method A2 involves upward imbibition of water from the base of an initially unsaturated soil specimen, Method A3 involves downward drainage of water from an initially saturated soil specimen, and Method A4 involves evaporation of water from an initially saturated soil specimen.

4.1.3 Methods A1 to A4 can be used for a wide range of soil types, but their practical application will depend on the time required to impose water flow through the soil specimen. Methods A1 through A4 shall not be used for soils with high plasticity because of prohibitive testing times, potential for soil cracking, side-wall leakage, and prohibitive column lengths to avoid outflow boundary effects. Methods A1 and A2 shall be used for fine-grained sands and for low-plasticity silts. In the case of Method A1, coarse-grained soils may be subject to flow through preferential pathways, while in the case of Method A2, coarse-grained soils may not have sufficient capillary rise. Methods A1 and A2 can be used to measure *k* values corresponding to matric suction values ranging from 0 to 80 kPa (12 psi) the upper limit on common matric suction instrumentation). Method A3 shall be used with fine- or coarse-grained sands. Method A3 shall not be used for silts or clays because of difficulties in saturating the soil specimen and the long time required for gravity drainage to occur. Method A3 can be used to measure *k* values corresponding to matric suction values from 0 to 200 kPa (29 psi). Method A4 shall be used for any soil with the exception of clays of high plasticity that show significant cracking during drying. Method A4 can be used to measure *k* values corresponding to matric suction values from 0 to 1000 kPa (145 psi) (or higher). Method A4 shall not be used for silts or clays because of the potential for formation of low permeability surface crusts. The best-suited soils for Methods A1 through A4 are summarized in Table 1.

4.2 *Category B—Axis Translation Tests:*

4.2.1 Category B includes two methods (Methods B1 and B2), which both involve measurement of outflow from a soil specimen during an axis translation test (a test commonly used to measure the SWRC—see Test Methods D6836). An axis translation test involves placing a soil specimen on a water-saturated high air-entry porous disc or membrane, then applying a matric suction to the soil specimen by imposing an air pressure on the top side of the specimen and a water pressure on bottom side of the high air-entry porous disc.

4.2.2 Method B1 involves performing an axis translation test in a pressure chamber with the soil specimen held within a rigid-wall oedometer. Method B2 involves performing an axis translation test in a flexible-wall permeameter with the soil specimen held within a flexible latex membrane. Methods B1 and B2 are best suited for fine-grained soils. Methods B1 and B2 can be used to measure *k* values corresponding to suctions ranging from 0 to 1000 kPa (145 psi).

4.2.3 The HCF may be defined with the axis translation technique by measuring the outflow when a hydraulic gradient is applied to an unsaturated soil specimen (that is, by applying

TABLE 1 Guide for Selection of HCF Test Methods

Test Method	Description	Best-Suited Soils	Equipment	Field Application	Advantages	Disadvantages	Testing Time for Silty Clays (1, 3, 4, 5, 6, 7)
A1	Infiltration column	Fine sands and low plasticity silts (4, 7)	Column, flow control, water content and suction instrumentation	Infiltration	Straightforward analysis	Long testing time, preferential pathways, no stress control	Several weeks
A2	Imbibition column	Fine sands and low plasticity silts	Column, manometer, Instrumentation	Rising of a water table	Straightforward analysis	Long testing time for fine grained soils, nonuniform wetting	Several weeks
A3	Drainage column	Fine- or coarse-grained sands	Column, manometer, instrumentation	Lowering of a water table	Straightforward analysis	Nonuniform drainage	1-2 weeks
A4	Evaporation column	All soils except clays of high plasticity (6)	Column, heat lamp, fan, Instrumentation	Evaporation from soil surface	Straightforward analysis	Varying boundary conditions, desiccation may cause nonuniform drying	1-2 weeks
B1	Axis translation with rigid wall permeameter	Fine-grained soils (3, 8, 7)	Oedometer with high air entry porous disc, outflow measurement	Wetting and drying with continuous water phase	Oedometric stress control, volume change measurements	Impedance of porous stone	1-2 weeks
B2	Axis translation with flexible wall permeameter	Fine-grained soils (8)	Permeameter with high air entry porous disc, outflow control	Wetting and drying with continuous water phase	Isotropic stress control, volume change measurements	Impedance of porous stone	1-2 weeks
C	Centrifuge permeameter	Coarse-grained soils and low plasticity fine grained soils (7)	Centrifuge permeameter, instrumentation	Similar to column tests, but better suited for wetting/ drying	Fast testing time, best for hysteresis	Equipment requirements	Less than 1 week

an air pressure to one side of the soil specimen and a water pressure to the opposite side).

4.2.4 The axis-translation technique can only be used to provide, at best, an approximation of the HCF of an unsaturated soil. The nonuniformity in suction across the height of the soil specimen (zero at the boundary with the high-air entry porous disc, and greater than zero at the top of the specimen) implies that the matric suction corresponding to the measured hydraulic conductivity is approximate. Also, the impedance to flow due to the high-air entry porous disc affects the measured hydraulic conductivity. Finally, air diffusion through the high air-entry porous disc or membrane complicates accurate measurement of outflow volumes. Nevertheless, the technique provides a means to measure the HCF using commonly available equipment.

4.3 *Category C—Centrifuge Permeameter Test:*

4.3.1 Category C includes one test method (Method C) which involves infiltration of water through a soil specimen within a permeameter spinning in a centrifuge. The centrifuge is used to impose hydraulic gradients by increasing the effect of the elevation head, which reduces the time required to reach steady-state water flow through the soil specimen when compared with column infiltration tests (Method A1). Method C shall be used for coarse-grained soils and low-plasticity fine-grained soils. Method C can be used to measure k values corresponding to suction values between 0 and 200 kPa (29 psi).

5. Significance and Use

5.1 The hydraulic conductivity function (HCF) is fundamental to hydrological characterization of unsaturated soils and is required for most analyses of water movement in unsaturated soils. For instance, the HCF is a critical parameter to analyze the movement of water during infiltration or evaporation from soil specimens. This is relevant to the evaluation of water movement in landfill cover systems, stiffness changes in pavements due to water movement, recharge of water into aquifers, and extraction of pore water from soils for sampling.

5.2 Examples of HCFs reported in the technical literature are shown in Fig. 1(*a*), Fig. 1(*b*), and Fig. 1(*c*), for clays, silts, and sands, respectively. The decision to report a HCF in terms of suction or volumetric water content depends on the test method and instruments used to measure the HCF. The methods in Categories A and C will provide a HCF in terms of either suction or volumetric water content, while the methods in Category B will provide a HCF in terms of suction.

5.3 A major assumption involved in measurement of the hydraulic conductivity is that it is used to quantify movement of water in liquid form through unsaturated soils (that is, it is the coefficient of proportionality between liquid water flow and hydraulic gradient). Water can also move through soil in vapor form, but different mechanisms govern impedance of a soil to water vapor flow (diffusion). Accordingly, the HCF is only applicable in engineering practice for degrees of saturation in which the water phase is continuous (that is, no pockets of "unconnected" water). Although this depends on the soil type and texture, this approximately corresponds to degrees of saturation greater than 50 to 60 %.

5.4 The HCFs of soils may be sensitive to the porosity, soil structure, compaction (compaction gravimetric water content and dry unit weight), effective stress, temperature, and testing flow path (wetting or drying). However, not all engineering problems need to account for the effects of these variables. Out

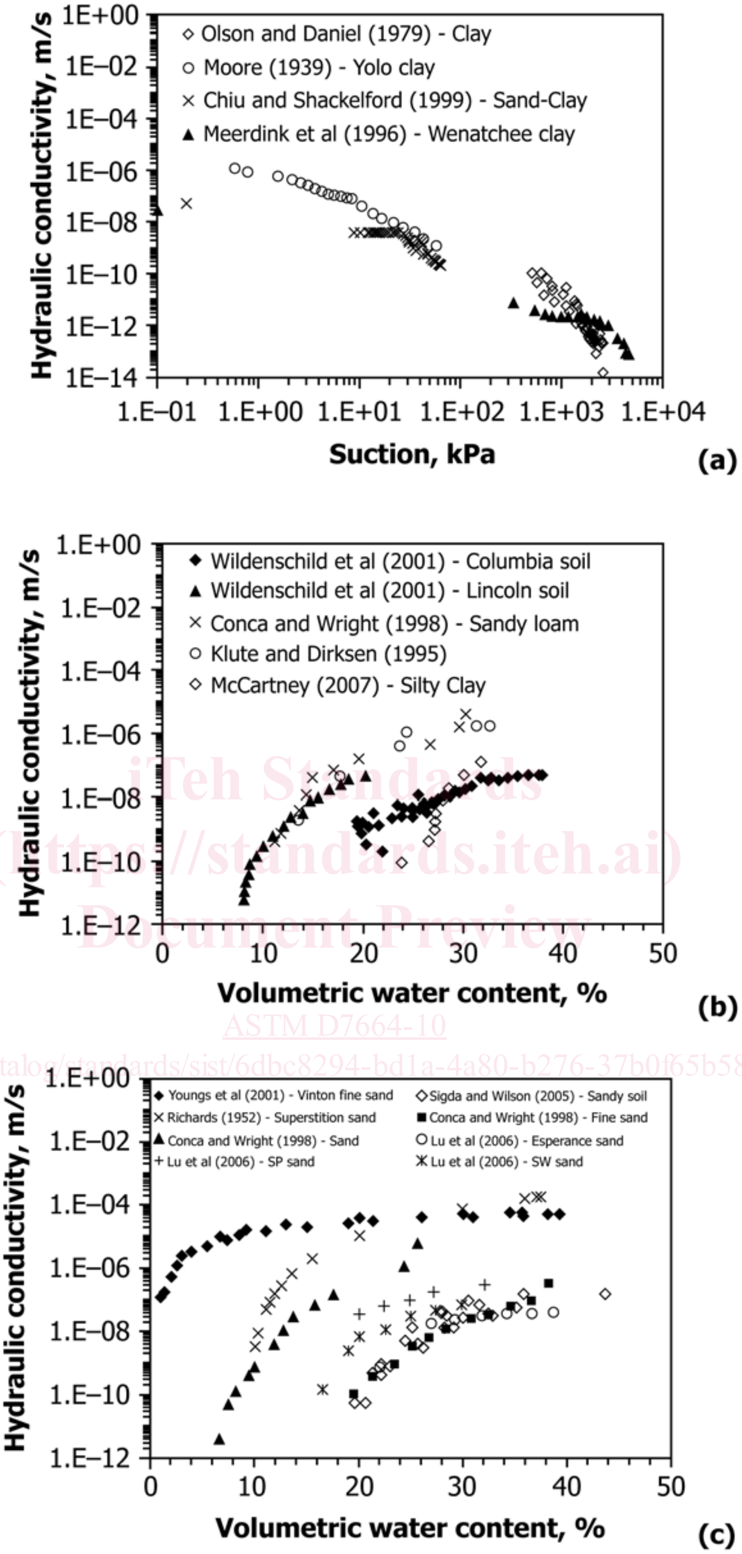

FIG. 1 Experimental HCFs for Different Soils: (*a*) *k*-ψ for Clays; (*b*) *k*-θ for Silts; (*c*) *k*-θ for Sands (3-14)

of the test methods listed in Section 4, there is not a single method that is best suited to measure the effects of all of these variables. In addition, the different tests may have a wide range in testing times. Table 1 is provided as a guide for selection of the best test for a given soil and application. Test times for low plasticity, silty clays are provided as a baseline reference. Testing times for coarse-grained soils are typically on the order of 1 to 2 days.

5.5 A full investigation has not been conducted regarding the correlation between HCFs obtained using the laboratory methods presented herein and HCFs of in-place materials. Thus, results obtained from the test methods should be applied to field situations with caution and by qualified personnel.

NOTE 1—The quality of the result produced by this standard depends on the competence of the personnel performing the test 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 ensure reliable results. Reliable results depend on many factors. Practice D3740 provides a means of evaluating some of these factors.

6. Apparatus

6.1 *Column Apparatus (Category A):*

6.1.1 This apparatus is used to confine the soil specimen during flow processes imposed in Methods A1 through A4. An example column apparatus is shown in Fig. 2.

6.1.2 The column shall be constructed from non-reactive metals, acrylic, or PVC, although it is often advantageous for the column material to be transparent to visualize water movement in the soil specimen. A sturdy working environment shall be provided for the column in the case that the soil specimen is prepared using compaction, wet tamping, or pluviation. A means of affixing the column to the outflow support plate to prevent leakage from the bottom of the column shall be provided. Columns may be attached to a support frame using tensioned wires or rods. If wires are used, they may be attached to eye bolts on the support frame and to hook bolts placed over the top edge of the column (**15**). Turnbuckles have been used to tension the wires.

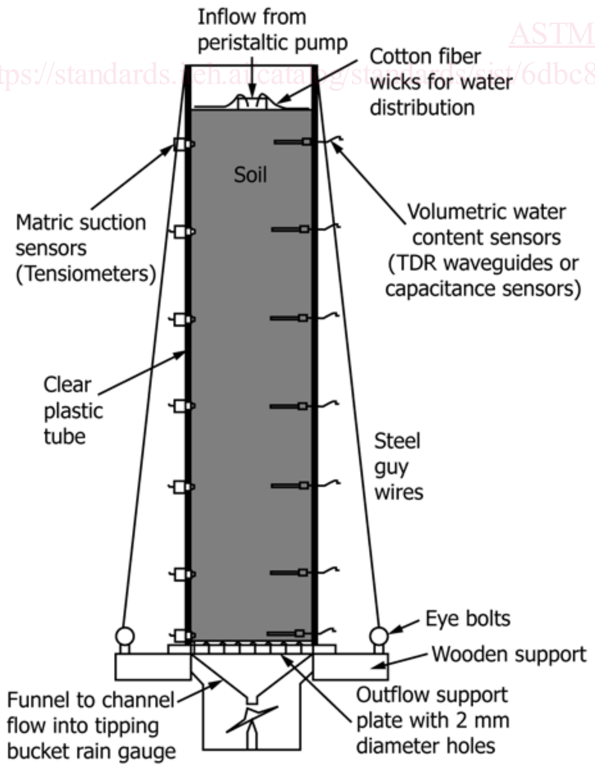

FIG. 2 Typical Column Test Setup (15)

6.1.3 The column shall have ports at different heights to permit access for auxiliary instrumentation used to measure the volumetric water content and matric suction in the soil specimen. The column shall have at least one port within 10 mm of the soil surface and within 5 mm of the bottom of the soil specimen. At least three additional ports shall be spaced evenly between these upper and lower ports.

6.1.4 A minimum column diameter of 200 mm shall be used to capture the effects of preferential flow paths for water flow that are present in unsaturated soils because of compaction and macro-features (micro-cracks, networks of large pores). A large diameter also helps to minimize boundary effects (side-wall leakage) on flow through the soil specimen.

6.1.5 The height of the soil specimen may have implications on the testing time required to establish water flow through the soil specimen. The distribution of volumetric water content with height in the soil specimen can be influenced by the outflow boundary for infiltration rates less than the saturated hydraulic conductivity of the soil. Accordingly, the height of the column should be large enough that there is a zone of soil that is not influenced by the boundary. A column height of 0.5 m may be used for coarse-grained soils, while a column height greater than 1 m may be used for fine-grained soils (**15**). Other column heights may be used if otherwise specified by the requestor. The required column height may also be determined for a specific test soil using the approach provided in (**16**). However, the approach of (**16**) requires an estimate of the SWRC and HCF for the soil.

NOTE 2—The height of the column shall be large enough that the upper zone of the soil layer has a uniform distribution of volumetric water content and matric suction with height during steady-state infiltration. When the matric suction does not change with height, the total hydraulic head is equal to the elevation head. In this case, the hydraulic gradient is equal to one, a condition referred to as flow under a unit hydraulic gradient. A sufficient column height is needed because the bottom boundary of the column will typically have impedance to water flow different from that of the soil, which will lead to the occurrence of a capillary break. This will prevent water from passing from the soil through the bottom boundary until the soil is nearly water-saturated. This means that the volumetric water content and suction profiles in the soil specimen will change in the vicinity of the boundary, complicating interpretation of results.

6.1.6 *Infiltration Control System (Method A1):*

6.1.6.1 This apparatus is used to control the rate of infiltration in the infiltration column test.

6.1.6.2 A peristaltic or infusion water pump, shown in Fig. 3(*a*), shall be used to supply the constant inflow rate to the upper surface of the soil specimen. Peristaltic pump tubing shall be refreshed at least every 3 weeks to prevent changes in the flow rate due to compression of the tubing during operation of the peristaltic pump. The height of water in a graduated cylinder connected to the inlet of the pump shall be monitored as a backup to the pump velocity setting.

6.1.6.3 Due to the low flow rates used in HCF measurement, a system for distributing the infiltration evenly across the surface of the soil specimen shall be used. A successful approach used in practice involves placing the inflow line from the peristaltic pump into a small cup at the center of the soil area, from which a series of cotton fiber wicks can be draped across the soil surface, as shown in Fig. 3(*b*).

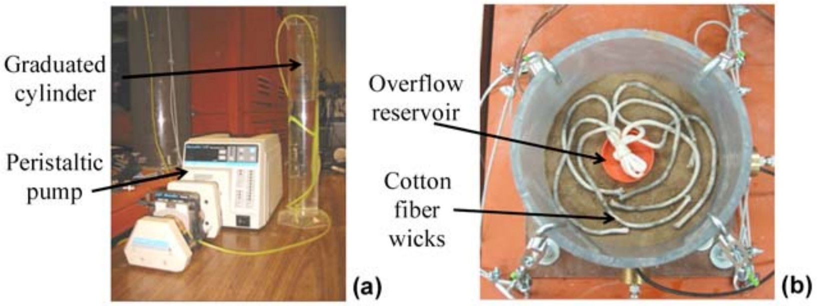

FIG. 3 Infiltration Control System: (*a*) Peristaltic Pump; (*b*) Fluid Distribution System

6.1.7 *Evaporation Control System (Method A4):*

6.1.7.1 This apparatus is used to control the infiltration rate in the evaporation column test.

6.1.7.2 A means of applying a constant relative humidity and temperature to the soil surface shall be used in Method A4. An example of such a setup is shown in Fig. 4. An infrared lamp may be used to provide a constant temperature to the soil surface, and an electric fan may be used to provide air circulation to the soil surface. If this approach is followed, a layer of insulation shall be used to prevent heating of the column sides.

6.1.8 *Base Support System (Category A):*

6.1.8.1 The base of the column shall rest on a permeable support plate, made from metal or acrylic. The purposes of this plate are to permit water drainage from the base of the soil specimen and to support the weight of the soil specimen.

6.1.8.2 The permeable support plate shall serve as a freely-draining lower boundary to the soil specimen, having similar hydraulic impedance to the overlying soil in order to prevent the occurrence of a capillary break and prevent loss of soil particles. A honey-comb pattern of 2 mm holes overlain by a piece of filter paper, shown in Fig. 5(*a*), has been used successfully in column tests on silts (**15**). The filter material shall be selected to have a porosity similar to the test soil.

6.1.8.3 The column shall be sealed to the permeable support plate to prevent leakage from the base of the column. An "O"-ring may be placed within a groove in the base of the column to provide a hydraulic seal with the porous plate, as shown in Fig. 5(*b*).

6.1.9 *Outflow Measurement Systems (Category A):*

6.1.9.1 For Method A1, a tipping bucket [Fig. 6(*a*)] may be used to provide an electronic record of the volume of water collected from the base of the column. The funnel of the tipping bucket shall be placed beneath the permeable support plate so that it captures all water exiting from the base of the column. A graduated cylinder may also be used to provide a back-up measurement of the water that passes out of the tipping bucket [Fig. 6(*b*)].

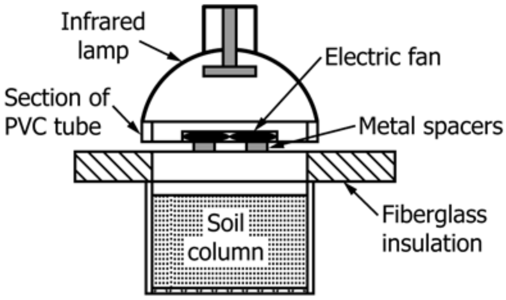

FIG. 4 Heat Lamp and Fan for Evaporation Column Test

6.1.9.2 For Methods A2, A3, and A4, a manometer system shall be used to control water flow from the bottom of the soil specimen. Specifically, a water-filled manometer tube is useful to measure outflow during downward gravity drainage, to provide a source of water imbibition from the base, or to help initially saturate the soil specimen for a surface evaporation test. In general, the manometer system may be used to impose water table at any height in the soil specimen. However, in order to measure the volume of water flow from or into the base of the soil specimen, a Mariotte bottle must be attached to maintain a constant head. An example sealing approach for the manometer control system to the column and permeable support plate is shown in Fig. 6(*c*). The manometer tube shall also be fitted with valves that can be used to stop water flow into or out of the base of the column.

6.2 *Axis Translation Apparatus (Category B):*

6.2.1 This test setup is used for measurement of the hydraulic conductivity of unsaturated soils using the axis translation technique. A pressure chamber (Method B1) or a flexible wall permeameter (Method B2) may be included in this setup.

6.2.2 *Regulated Pressure and Water Supply Source (Pressure Panel) (Category B):*

6.2.2.1 A regulated pressure source (an air compressor or bottled gas) shall be used to supply gas pressures up to 700 kPa (100 psi).

6.2.2.2 The pressure source and associated regulators shall be capable of maintaining the desired pressure with an accuracy of 0.25 % or better.

6.2.2.3 The pressure source shall be connected to graduated burettes, which can be filled with either water or air. The graduations on the burettes shall be sufficient to measure water volumes of at least 1 mL, and shall have a volume of at least 25 mL.

6.2.2.4 The pressure source shall use incompressible tubing (with a stiffness equal or greater than HDPE plastic) to connect the bottom of the burettes to the cell or bottom of the pressure chamber or to the cell, top, and bottom of the flexible-wall permeameter.

6.2.3 *Pressure Indicators (Category B):*

6.2.3.1 Bourdon gages or pressure transducers shall be used to measure the water and air pressures applied to the soil

FIG. 5 Column Test Base: (*a*) Base Support System; (*b*) Hydraulic Sealing System

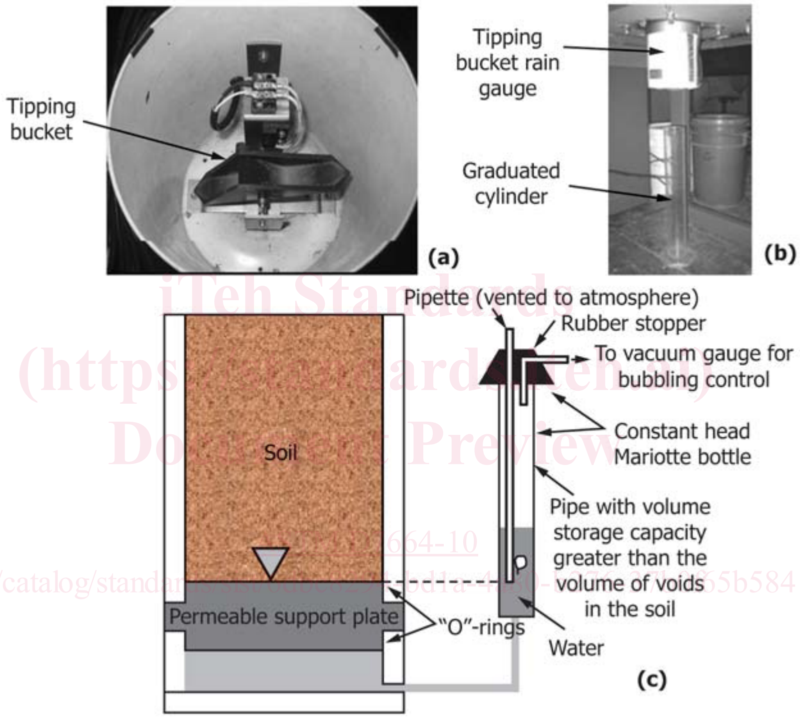

FIG. 6 Outflow Monitoring Systems: (*a*) Tipping Bucket (Inside); (*b*) Tipping Bucket (Outside) with Graduated Cylinder; (c) Manometer Outflow System

specimen confined within the pressure chamber or flexible wall permeameter in the axis translation test.

6.2.3.2 The accuracy of the measuring device shall be within 0.25 % of the water or air pressure being applied.

6.2.4 *Vacuum Pump and De-Airing Reservoir (Category B):*

6.2.4.1 A vacuum pump capable of applying a vacuum of at least –80 kPa (–12 psi) shall be used to de-air water contained within a closed de-airing reservoir. A valve shall be included such that the de-airing reservoir may be used to fill the burettes in the pressure panel, or to apply vacuum directly to the pressure chamber or flexible wall permeameter.

6.2.5 *Porous Disc or Membrane (Category B):*

6.2.5.1 A porous disc shall be to provide a water-saturated interface between the pore water in the soil and the water in the volume measuring system. When the porous disc is water-saturated, air cannot pass through the disc. Porous discs shall be fabricated from material that is hydrophilic and has an air-entry pressure greater than the maximum matric suction to be applied during the test. Porous ceramic is the most commonly used material.

6.2.5.2 A cellulose membrane may also be used in the flexible wall permeameter approach to provide a lower impedance to water flow due to their smaller thickness. Cellulose membranes shall not be used in the pressure chamber because of difficulties in sealing.

6.2.6 *Pressure Chamber (Method B1):*

6.2.6.1 A pressure chamber, such as that shown in Fig. 7, may be used in axis-translation testing to apply a gas pressure (typically air pressure) to a specimen resting on a water-saturated, high-air entry porous disc (as specified in 6.2.4.1).

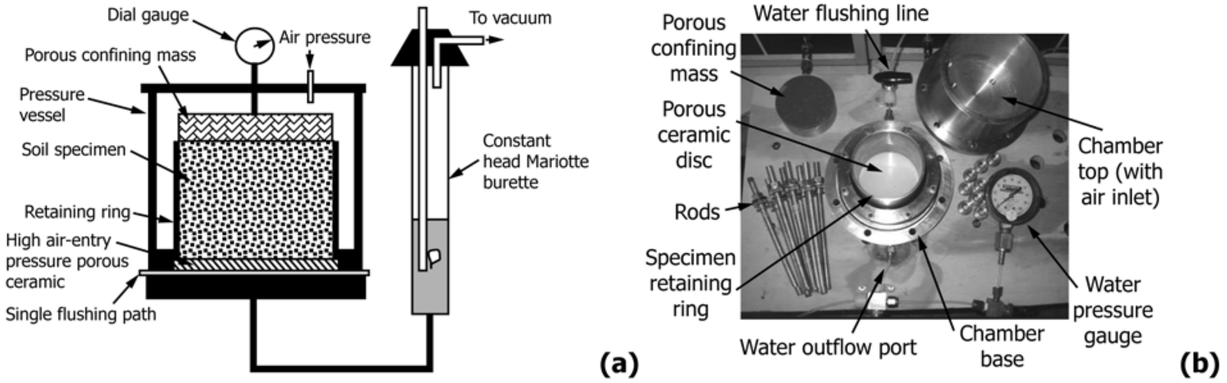

FIG. 7 Pressure Chamber Setup: (*a*) Schematic; (*b*) Picture of Disassembled Setup

6.2.7 The pressure chamber shall be a metallic vessel that shall be pressure-rated, at the very least, for 3 times the maximum pressure to be applied to the vessel during the test.

6.2.8 In some cases, the effects of overburden pressure may be simulated for a test. For these cases, the pressure vessel may be equipped with a piston and dial gauge for height measurement during testing. A coarse porous confining mass that permits free flow of air shall be placed above the specimen.

6.2.9 The pressure chamber shall have a sealed, noncollapsing outflow tube that connects the atmospheric pressure side of the porous plate (or membrane) to the outside of the pressure chamber. Schematics and photographs of an example pressure chamber are shown in Fig. 7(*a*) and Fig. 7(*b*), respectively.

6.2.10 The soil specimen shall be contained within a retaining ring, which may have similar dimensions to a standard oedometer test ring (inside diameter of 6.35 cm, height of 2.54 cm). This height is suitable to balance the uncertainty due to the difference in matric suction across the thickness of the specimen during testing, with the need to have sufficient water storage in the specimen to provide measurable outflow values during testing.

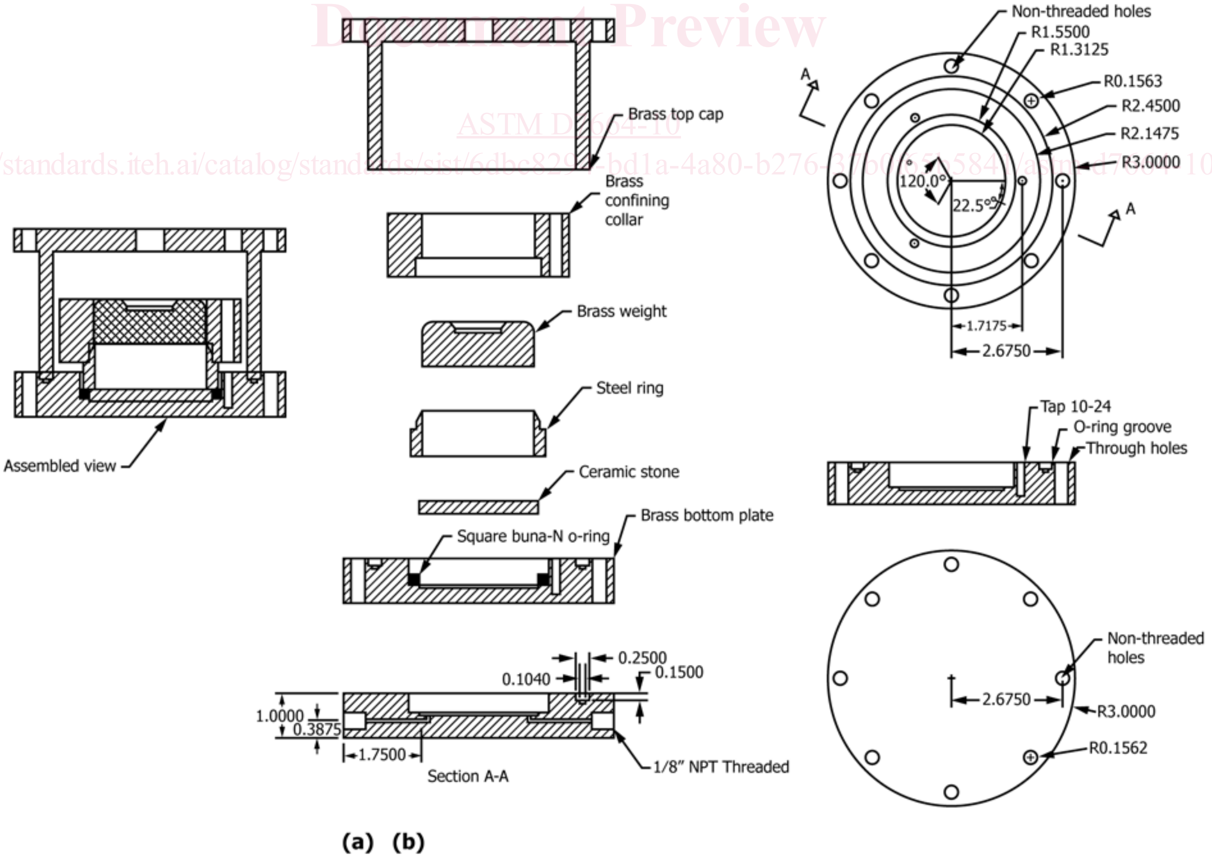

FIG. 8 Pressure Chamber Setup: (*a*) Expanded Cross-Section; (*b*) Base Detail

6.2.11 The pressure chamber shall have a means of providing a hydraulic seal around the porous ceramic disc, in order to prevent air or water from passing around the edges of the disc. A square "O"-ring is used in the detailed drawing in Fig. 8(*a*) and Fig. 8(*b*), which provides a seal between the edges of the porous disc and the bottom of the specimen retaining ring when the retaining ring is compressed onto the "O"-ring with the confining collar. For more information on possible designs of a pressure chamber, see (**17**).

6.2.12 The pressure chamber shall have a method of flushing water beneath the bottom of the porous disc to remove air bubbles, as shown in Fig. 8(*b*). An approach may involve a single, straight groove in the bottom platen which connects two water supply ports, or a network of grooves connected to the two water supply ports (**17**).

6.2.13 *Flexible Wall Permeameter (Method B2):*

6.2.13.1 The axis translation technique can also be incorporated into a flexible wall permeameter. In this approach, a cylindrical soil specimen is placed within a triaxial cell in which the bottom porous stone is replaced with a high-air entry porous disc or membrane. A schematic of the flexible-wall permeameter system for unsaturated soils is shown in Fig. 9. The flexible wall permeameter has the advantage over the pressure chamber in that back-pressure saturation combined with measurement of Skempton's B parameter ($B = \Delta u_w/\Delta\sigma$) can be used to infer if the soil specimen is initially water-saturated or not. The flexible wall permeameter also has the advantage that specimens may either be remolded specimens extruded from a compaction mold or undisturbed samples extruded from a field sampling tube.

6.2.13.2 The specimen in the flexible wall permeameter shall have a diameter which is 1 to 2 cm less than the high air-entry porous disc. This contrast in diameter permits the latex membrane to overlap the sides and part of the upper surface of the porous disc as shown in Fig. 9. This overlap prevents air from passing around the edge of the porous disc. Alternatively, the porous disc may be affixed to a recess within the bottom platen using epoxy suitable for porous materials according to the porous ceramic disc manufacturer specifications.

6.2.13.3 A cellulose porous membrane having a high air-entry suction may also be used in the flexible-wall permeameter. Cellulose membranes have less of an impact on the hydraulic gradient than ceramic porous discs due to their smaller thickness, so they may be desirable when testing soils with higher permeability. They may be used in a flexible wall permeameter without any special modification. Specifically, if the specimen has a diameter that is 1 to 2 cm less than the cellulose porous membrane, the latex membrane will provide a hydraulic seal between the bottom platen of the permeameter and the cellulose membrane (see Fig. 9).

6.2.13.4 Volume changes during de-saturation of a specimen may be evaluated using a force-displacement system involving a piston connected to the top of the specimen, loaded with a pressure equivalent to the hydrostatic pressure in the permeameter.

6.2.13.5 The flexible-wall permeameter shall be equipped with flushing lines for air and water in the top and bottom platens, respectively.

6.3 *Centrifuge Permeameter Apparatus (Category C):*

6.3.1 *Centrifuge (Category C):*

6.3.1.1 The centrifuge used for this method may either be a geotechnical centrifuge or a medical centrifuge in which the angular velocity w can be controlled by the test user.

NOTE 3—Geotechnical centrifuges typically have an outside diameter greater than 2 m, and can spin soil specimens weighing 1 kg or greater at $\omega > 875$ RPM. Geotechnical centrifuges are often equipped with on-board data acquisition systems which can be used to collect data from sensors during centrifugation. Medical centrifuges typically have a smaller outside diameter of up to 0.5 m, and can spin soil specimens weighing less than 100 g at $\omega > 3000$ RPM. Medical centrifuges do not have on-board data acquisition systems so measurements of the flow process cannot be made during centrifugation. Although the use of medical centrifuges to measure the hydraulic conductivity of unsaturated soils is described by Test Method D6527, this method compliments this standard by extending it to centrifuges in general.

6.3.1.2 The centrifuge shall be thermostatically controlled, capable of maintaining a temperature of 20°C.

6.3.1.3 The centrifuge shall have a rotary union which is capable of passing fluids from the stationary environment to the spinning environment without pressurizing the water.

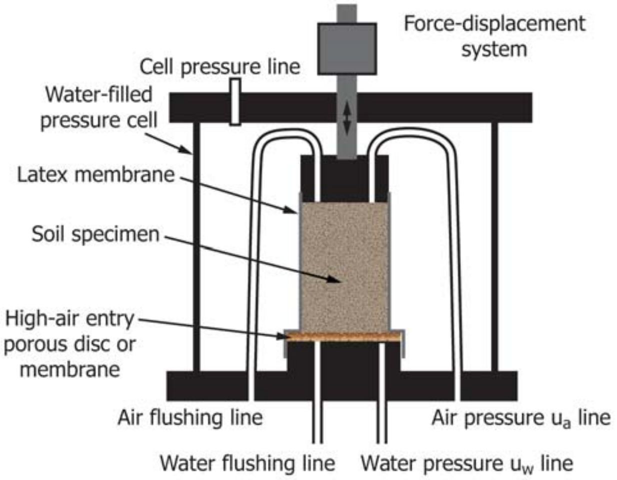

FIG. 9 Flexible Wall Permeameter for Unsaturated Soils Testing