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.

$$k = \frac{v}{i} \quad (1)$$

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

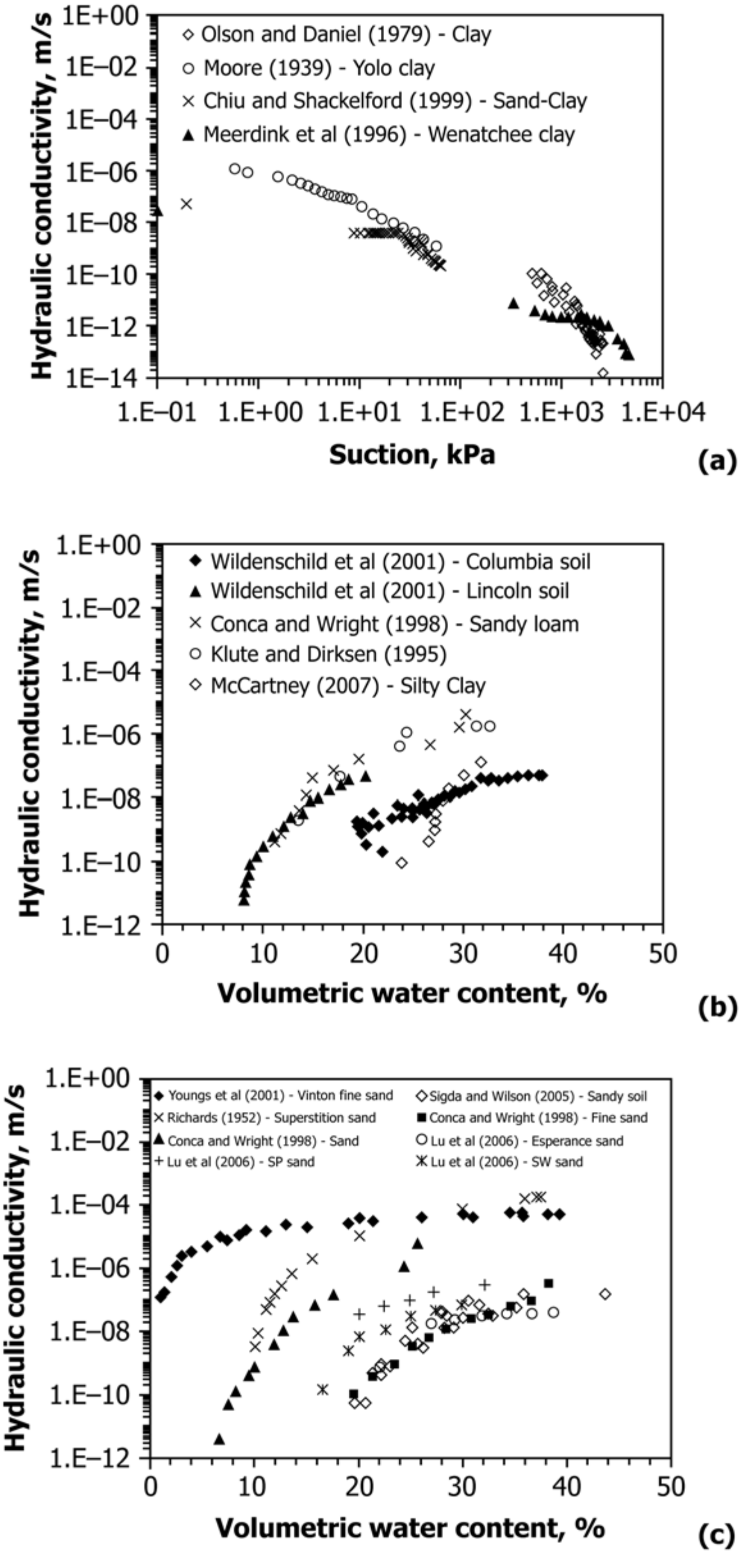

FIG. 1 Experimental HCFs for Different Soils: (*a*) *k*-ψ for Clays; (*b*) *k*-θ for Silts; (*c*) *k*-θ for Sands (3-14)

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.

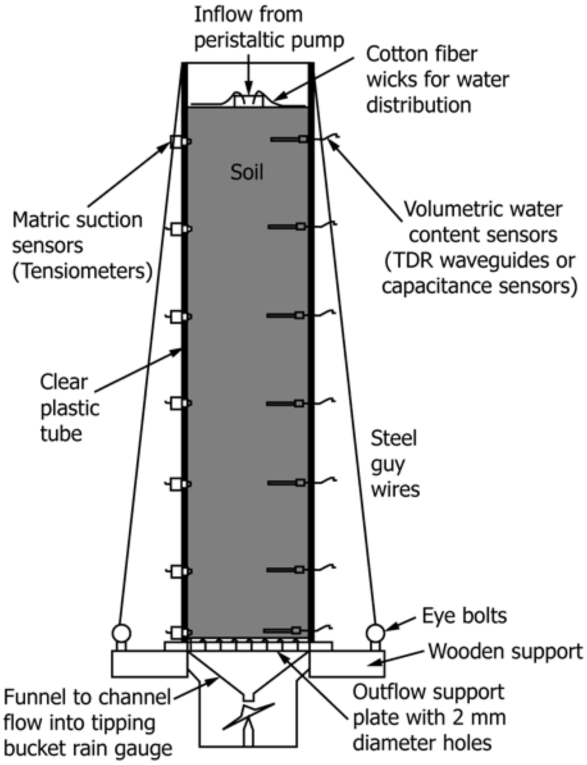

FIG. 2 Typical Column Test Setup (15)

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*).

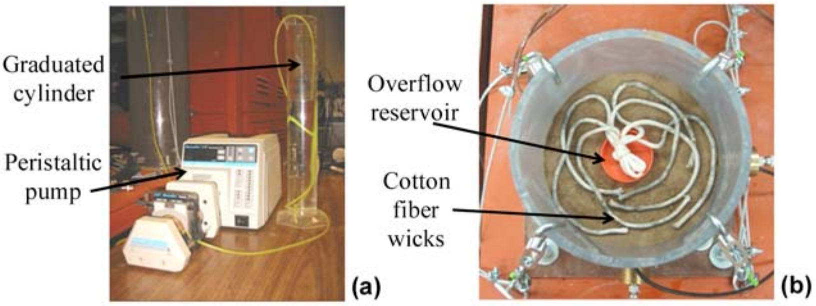

FIG. 3 Infiltration Control System: (*a*) Peristaltic Pump; (*b*) Fluid Distribution System

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*)].

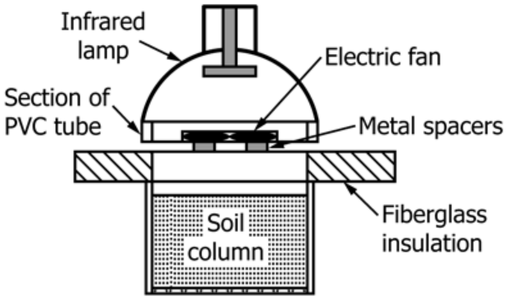

FIG. 4 Heat Lamp and Fan for Evaporation Column Test

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

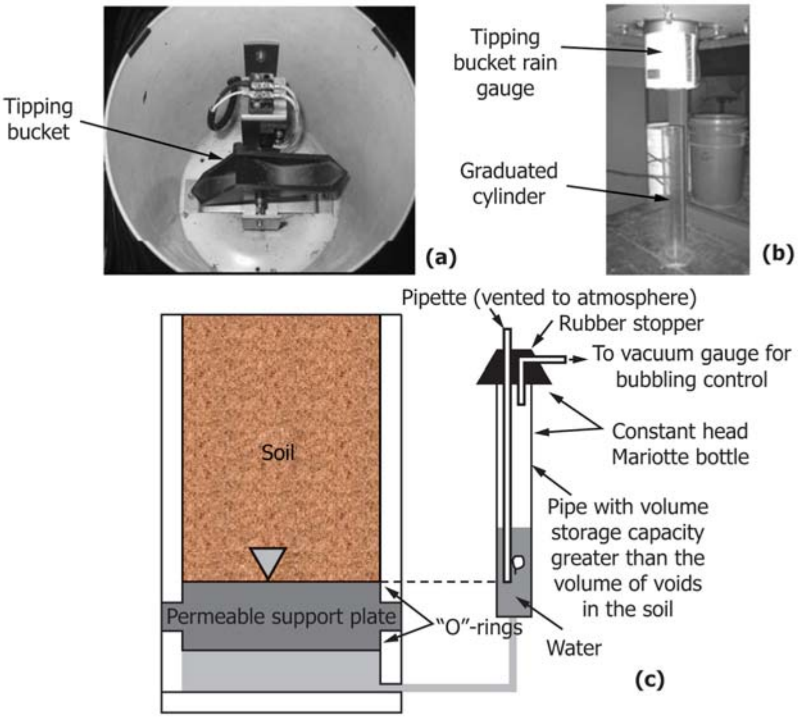

FIG. 6 Outflow Monitoring Systems: (*a*) Tipping Bucket (Inside); (*b*) Tipping Bucket (Outside) with Graduated Cylinder; (c) Manometer Outflow System

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).

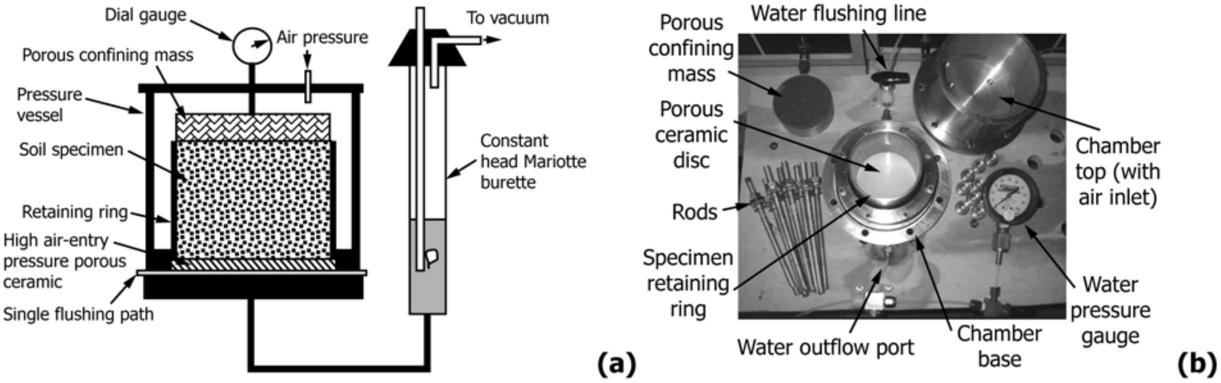

FIG. 7 Pressure Chamber Setup: (*a*) Schematic; (*b*) Picture of Disassembled Setup

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, non-collapsing 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.

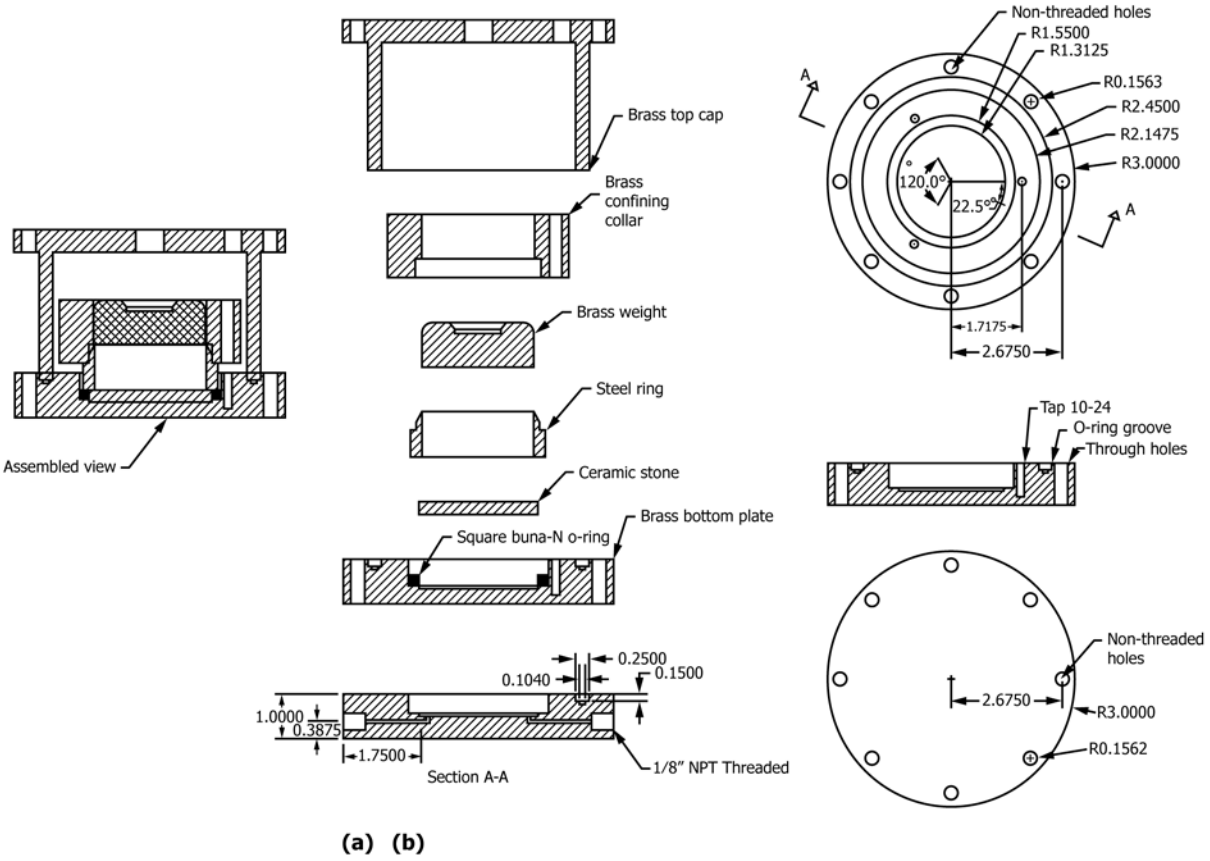

FIG. 8 Pressure Chamber Setup: (*a*) Expanded Cross-Section; (*b*) Base Detail

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.

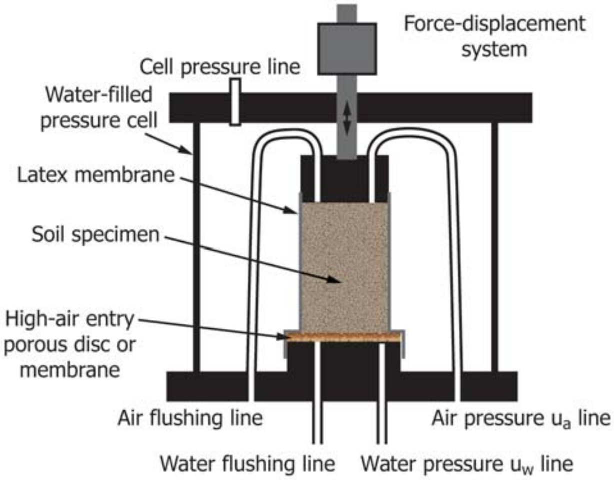

FIG. 9 Flexible Wall Permeameter for Unsaturated Soils Testing

6.3.1.4 The centrifuge shall have a means of supporting the permeameter system. A schematic view of the centrifuge permeameter orientation during centrifugation is shown in Fig. 10(*a*). The permeameter may be mounted horizontally, or can be supported using a swinging-basket system. A schematic of an example swinging-basket is shown in Fig. 10(*b*).

6.3.2 *Flow Pump (Category C):*

6.3.2.1 A flow pump capable of supplying flow rates from 0.1 to 1000 mL/h shall be used to supply fluid to the rotary union of the centrifuge.

6.3.3 *Centrifuge Permeameter Setup (Category C):*

6.3.3.1 The centrifuge permeameter is the system within the centrifuge that is used to hold the soil specimen, supply infiltration to the surface of the soil specimen, and collect water from the bottom of the soil specimen. Definitions of relevant geometry variables for centrifuge permeameters are shown in Fig. 10(*a*) and Fig. 10(*b*). The value r_0 is defined as radial distance from the central axis of the centrifuge to the bottom of the soil specimen having length *L*. Isometric and cross-section views of an example centrifuge permeameter are shown in Fig. 11(*a*) and Fig. 11(*b*), respectively.

6.3.3.2 The component of the centrifuge permeameter that holds the soil specimen shall be a rigid-wall cylinder (that is, the permeameter). The permeameter shall be constructed of acrylic or another material that is not electrically conductive.

6.3.3.3 The permeameter may have ports for instrumentation (see auxiliary equipment in section 6.4), and the outflow reservoir may be equipped with a pressure transducer suitable for measuring the pressure at the bottom of a water column during outflow. At least one of these ports shall be in the upper 30 % of the soil specimen height. The instrumentation may be embedded horizontally or vertically in the walls of the permeameter, as shown in the permeameter in Fig. 11(*a*) and Fig. 11(*b*), or it may be embedded within the soil specimen. Caution should be used when instrumentation is embedded within the soil specimen to avoid settlement of the soil under the increase weight of the instrument during centrifugation. Any settlement observed as a result of embedded instrumentation shall be reported.

6.3.3.4 The component of the centrifuge permeameter used to supply water to the top of the soil specimen (that is, the fluid distribution cap) shall be placed atop the soil specimen cylinder as shown in Fig. 11(*a*). The fluid distribution cap shall connected using rigid tubing to the rotary union of the centrifuge.

6.3.3.5 The component of the centrifuge permeameter used to collect water from the bottom of the specimen (that is, the outflow reservoir) shall be placed beneath the soil specimen cylinder. The outflow reservoir may rest atop the swinging basket of the centrifuge, or it can be integrated into the swinging basket of the centrifuge itself, as shown in Fig. 11(*a*). The centrifuge shall include a measurement device for recording outflow in the support chamber to the nearest 0.1 mL while the specimen is under centrifugation. One approach would be to use a pressure transducer to measure the hydrostatic pressure in the water at the bottom of the outflow reservoir.

6.3.3.6 The outflow reservoir shall have an air-release port to allow for air to escape when water flows from the bottom of the soil specimen during centrifugation.

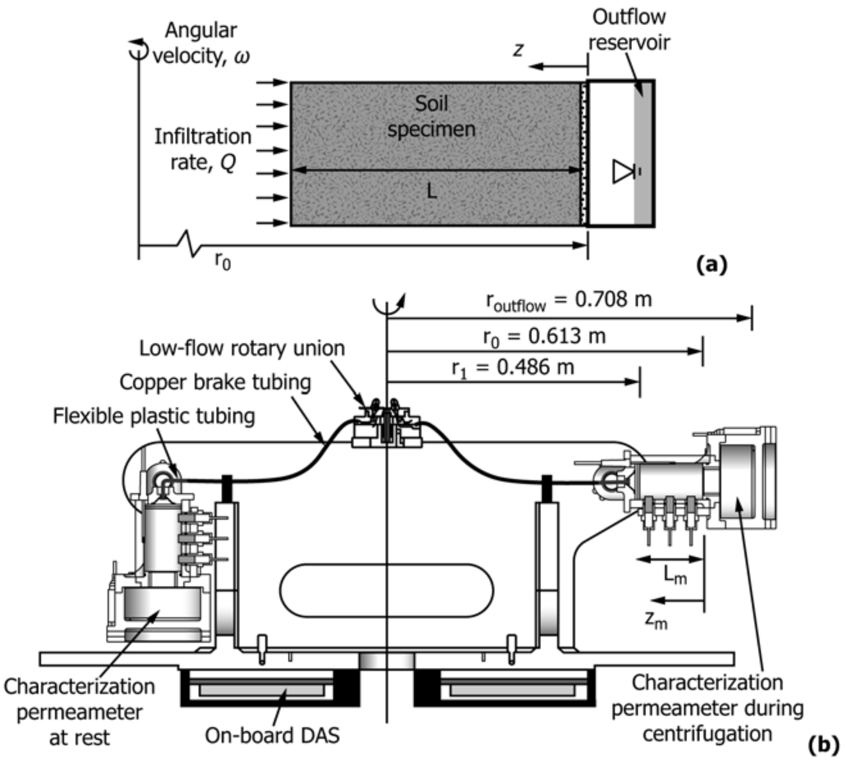

FIG. 10 Example Centrifuge Permeameter Setup (7): (*a*) Centrifuge Permeameter Orientation; (*b*) Example of Permeameter Support in a Geotechnical Centrifuge

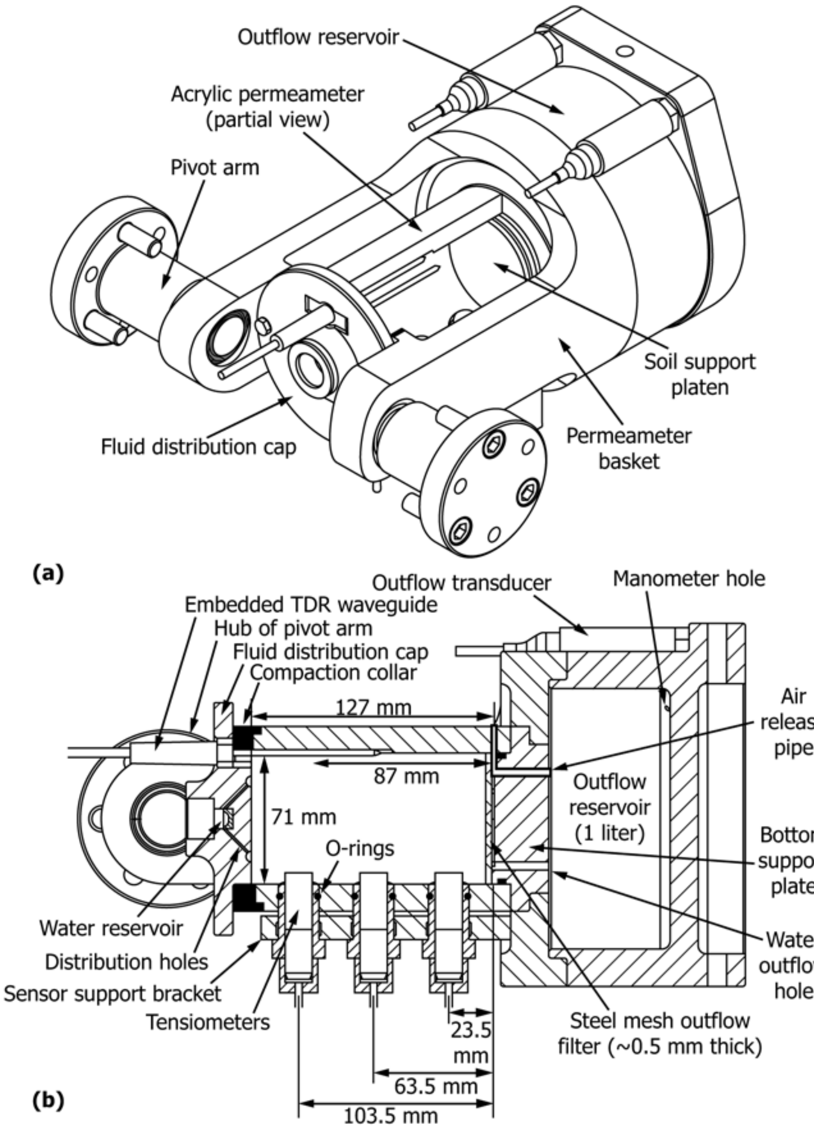

FIG. 11 Schematic of a Centrifuge Permeameter (7): (*a*) Isometric View with Detail of Swinging Bucket Support System; (*b*) Cross-Section View

6.4 *Auxiliary Instrumentation (Categories A and C):*

6.4.1 *Tensiometers (Categories A and C):*

6.4.1.1 Tensiometers are used to measure matric suction in unsaturated soils.

6.4.1.2 Tensiometers typically consist of a vacuum gauge connected via a water reservoir to a water-saturated, high air-entry porous disc embedded within a soil mass. Due to continuity of suction at the interface between the soil and the porous disc, water will flow across the interface until the water pressure within the reservoir is the same as the suction within the soil.

6.4.1.3 A tensiometer designed to be screwed into threaded holes in the side-wall of a column may be used [Fig. 12(*a*) and Fig. 12(*b*)]. Other tensiometer designs that incorporate a porous ceramic attached to a pipe (which serves as the water reservoir), permitting the suction measurement point to be further into the specimen from the column side-wall also may be used.

6.4.1.4 Tensiometers shall be thoroughly saturated through the use of a saturation chamber [Fig. 12(*c*)] that can apply both positive and negative water pressures to the tensiometer. A tensiometer can be considered saturated when similar measurements are obtained during cycles of water pressure from 300 kPa (43.5 psi) to –80 kPa (12 psi). A high-vacuum pump shall be used to apply the negative water pressures.

Note 4—Tensiometers can be used reliably to measure matric suction values up to 80 kPa (12 psi). Tensiometers with a smaller water reservoir (< 1 mL) have been used to measure matric suction values over 1000 kPa (145 psi) when great care is taken for saturation (**16**).

6.4.2 *Time Domain Reflectometer (Categories A and C):*

6.4.2.1 TDR is used to infer the volumetric water content in the test soils.

6.4.2.2 A TDR system includes a cable tester and a waveguide. The waveguide may be buried within the soil mass (Categories A or C) or embedded within the centrifuge permeameter sidewall (Category C).

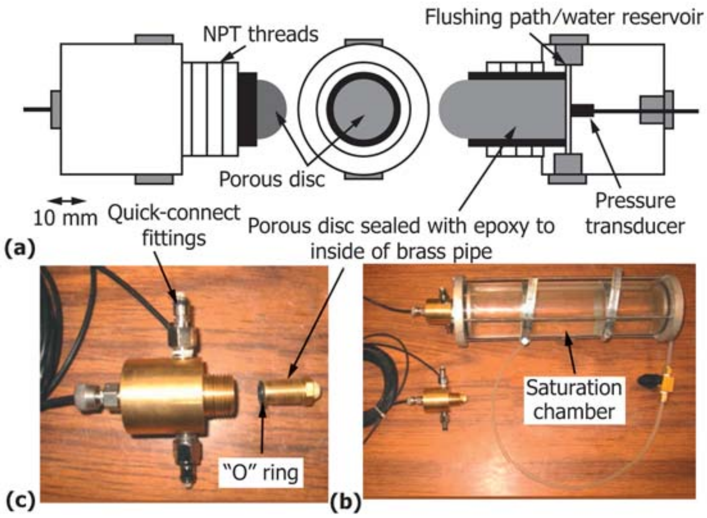

FIG. 12 Example of a Tensiometer for Column Testing (7): (*a*) Schematic Views; (*b*) Tensiometer with Saturation Chamber; (*c*) Switching of Ceramic Stone

6.4.2.3 The output of a TDR measurement is the travel time of an electromagnetic pulse (generated by the cable tester) through the waveguide. The travel time is related to the geometry of the waveguide, temperature, soil density, soil mineralogy, and the volumetric water content of the soil. TDR measurements shall be calibrated for the test soil by measuring the travel time and the volumetric water content using Test Methods D2216 for soil specimens prepared with different water contents having the same density. During calibration, the waveguides shall be in the same configuration as used in HCF measurement.

6.4.2.4 The TDR shall be capable of measuring volumetric water content values from 0 to 50 % with a resolution of at least 0.1 % (0.001 m^3/m^3). The calibrated TDR approach used in the column and centrifuge permeameter tests shall have an accuracy of at least 3.0 % (0.03 m^3/m^3) of the volumetric water content measured independently following Test Methods D2216.

6.4.3 *Capacitance Probes (Category A):*

6.4.3.1 Capacitance Probes shall be used to infer volumetric water content in the test soils.

6.4.3.2 A capacitance probe system consists of a data acquisition system and a probe.

6.4.3.3 The output of the capacitance probe is the charge time of a capacitor formed by two conductor plates separated by soil (that is, a capacitor). The charge time is related to the geometry of the waveguide, temperature, soil density, soil mineralogy, and the volumetric water content of the soil. For most proprietary capacitance probes, the raw charge time is not reported. Instead, a relative volumetric water content value is typically output from the probe. Capacitance probe measurements shall be calibrated for the test soil by measuring and comparing the probe output and the volumetric water content using Test Methods D2216 for soil specimens prepared with different water contents having the same density. During calibration, the probes shall be in the same configuration as used in HCF measurement.

6.4.3.4 The capacitance probes used in the column or centrifuge permeameter tests shall be capable of measuring values of volumetric water content from 0 to 50 % have a resolution of at least 0.1 % (0.001 m^3/m^3). The calibrated capacitance probes shall have an accuracy that is within 3.0 % (0.03 m^3/m^3) of the volumetric water content value measured independently following Test Methods D2216.

6.4.4 *Relative Humidity Sensor:*

6.4.4.1 This sensor shall be used to measure the relative humidity of air in evaporation tests. The sensor shall also have the capability of measuring the air temperature.

6.5 *Laboratory Environment*—The laboratory temperature shall be maintained within 3°C during the test. The apparatus shall be shielded from direct sunlight or other sources of heat that may cause variations in temperature. If very precise measurements are required, the apparatus may be isolated using thermal insulation.

7. Reagents and Materials

7.1 *Saturating Liquid:*

7.1.1 Unless otherwise specified by the requestor, the saturating liquid used in the test methods of this study shall be water. The saturating liquid shall be used to saturate the porous discs and membranes (Category B), the specimen, and the outflow measuring components of the selected apparatus. It shall also be used to supply water to the specimen for infiltration.

7.1.2 Tap water shall be used in the tests unless otherwise specified by the requestor. Distilled or deionized water shall not be used unless otherwise specified by the requestor.

7.1.3 A biocide may be added to the water to minimize microbial growth during a test. If a biocide is added, the type and concentration of the biocide shall be included in the report.

7.1.4 Deaired water shall be used in the tests. Water shall be deaired by agitation of water in a reservoir attached to the high vacuum pump. To prevent dissolution of air back into the water, deaired water shall not be exposed to the atmosphere for prolonged periods.

8. Preparation of Soil Specimens in the Apparatus

8.1 *Preliminary Characterization of Soils (All Categories):*

8.1.1 Measure the specific gravity of solids on a sub-sample of the soil to be tested following Test Methods D854.

8.2 *Specimens Prepared from Disturbed Cohesionless Samples (Categories A and C):*

8.2.1 For Methods A1 to A4, air dry and crush a representative sample that has a mass at least twice that required to fill the column.

8.2.2 For Methods A1 and A2 and Method C, the test will start from approximately dry conditions. Accordingly, a specimen of cohesionless soil shall be prepared using dry pluviation to reach the specified target dry density.

8.2.3 For Methods A3 and A4, the soil specimens will start from approximately water-saturated conditions. Accordingly, a specimen of cohesionless soil shall be prepared using dry pluviation as in Methods A1 and A2 then subsequently saturated as described in Section 9. Alternatively, specimens of cohesionless soil may be prepared using wet placement in submerged conditions following the approach described in Test Method D5101.

8.2.4 *Placement of Instrumentation (Category A):*

8.2.4.1 Tensiometers shall be inserted through the walls of the column at specified heights. The installed heights of the tensiometers shall be reported. Care shall be taken to ensure intimate contact between the soil and the porous ceramic tip of the tensiometer.

8.2.4.2 TDR waveguides or capacitance probes shall be installed within the middle of a specified lift during pluviation. The heights of the TDR waveguides or capacitance probes shall be reported. A rubber stopper, having a central hole for the cable or a similar sealing device, shall be used to provide a seal between the TDR or capacitance probe cable and the column.

8.3 *Specimens Prepared from Disturbed Cohesive Samples (Categories A, B, and C):*

8.3.1 Air dry and crush a representative sample of soil that has a mass at least twice that required to fill the column (Category A), retaining ring (Method B1), compaction mold (Method B2), or permeameter (Category C).

8.3.2 Moisten the loose sample of air-dry soil to a specified target gravimetric water content using tap water. Measure the actual gravimetric water content of the soil sample using Test Methods D2216.

8.3.3 Before placement of soil within the column (Category A), retaining ring (Method B1), compaction mold (Method B2), or centrifuge permeameter (Category C), a thin film of vacuum grease may be placed on the inside wall of the column. This is intended to help minimize side-wall leakage during infiltration and minimize friction during compaction.

8.3.4 Place a known mass of the moistened soil into the column (Category A), retaining ring (Method B1), compaction mold (Method B2), or centrifuge permeameter (Category C). Densify or compact the soil to the dry density specified by the requestor. For Method A, soil shall be compacted in lifts of specified height using static compaction, a piston compactor, or a drop weight. The method of compaction shall be documented, as shall the procedures of compaction for each lift.

8.3.5 Trim the upper surface of the specimen so that it is at the desired height within the column, or level with the top of the retaining ring, mold, or permeameter. Record the weight of the empty ring, mold, or permeameter to the nearest 0.1 g before soil placement, then weigh the ring, mold, or permeameter together with the compacted soil. The weight of the ring may be subtracted to obtain the total weight of soil.

8.3.6 *Placement of Instrumentation (Category A):*

8.3.6.1 Tensiometers shall be inserted through the walls of the column at specified heights. The installed heights of the tensiometers shall be reported. Care shall be taken to ensure intimate contact between the soil and the porous ceramic tip of the tensiometer.

8.3.6.2 TDR waveguides or capacitance probes shall be installed within the middle of a specified lift during compaction. The heights of the TDR waveguides or capacitance probes shall be reported. During compaction, the TDR waveguides or capacitance probe shall initially be placed in a loose lift of soil with a slight upward orientation so that they will be horizontal after compaction. A rubber stopper with a central hole or similar sealing device shall be used to provide a seal between the TDR or capacitance probe wiring and the column.

8.4 *Specimens Prepared from Undisturbed Samples (Categories B and C):*

8.4.1 Obtain an undisturbed specimen core using Practice D1587. For Categories B and C, place the undisturbed sample obtained from a Shelby tube on the bench and gently place the retaining ring or mold on the surface of soil.

8.4.2 Use trimming tools to gently remove soil that protrudes beyond the edge of the retaining ring or mold so that it can slide over the soil specimen with little effort. Continue trimming until the soil fills the retaining ring or mold. Trim the top of the specimen flush with the top of the retaining ring, mold, or permeameter.

8.4.3 Weigh the specimen in the retaining ring, mold, or permeameter and record the weight to the nearest 0.01 g. Measure the gravimetric water content of the remaining material using Test Methods D2216.

9. Preparation of Apparatus for Measurement of the HCF

9.1 *Infiltration or Imbibition Column Test Preparation (Methods A1 and A2):*

9.1.1 The soil specimens evaluated in these tests shall start from unsaturated conditions. After compaction or pluviation of soil within the column, the apparatus is ready for testing.

9.2 *Drainage or Infiltration Column Test Preparation (Methods A3 and A4):*

9.2.1 The soil specimens evaluated in these tests shall start from approximately water-saturated conditions. If cohesionless specimens are prepared using wet pluviation, they are ready for testing. Otherwise, a manometer tube (described in Section 6) connected to the bottom of the column shall be slowly raised until the water level in the column is at the soil surface.

9.2.2 Care shall be taken not to raise the water level too quickly, which may result in occlusion of air bubbles in the soil specimen. The water level shall be raised at a rate slow enough to prevent a critical gradient from forming in the soil specimen, which may lead to uplift and a change in soil density.

9.2.3 After the water level is above the soil surface, continue upward water flow through the soil specimen under a constant hydraulic gradient until all air-bubbles from all portions of the apparatus have escaped and the specimen is approximately saturated with water.

9.3 *Pressure Chamber and Flexible Wall Permeameter Test Preparation (Category B):*

9.3.1 The hydraulic conductivity of the water-saturated porous disc or membrane shall be evaluated periodically (once a month of regular use) using Test Methods D5084. To measure the hydraulic conductivity of the porous disc, the setup shall be assembled without soil, and a hydraulic gradient shall be applied across the disc or membrane. The inflow and outflow shall be measured using the pressure panel, If the hydraulic conductivity of the water-saturated disc/membrane calculated using Darcy's law has decreased more than a factor of five relative to its hydraulic conductivity when new, cleanse or discard the disc/membrane. After cleansing, re-check its hydraulic conductivity using the same approach as above.

9.3.2 In Methods B1 or B2, the porous discs or membranes shall be placed in a dry condition within the setups. They may be dried within a 110°C oven, but should be cooled to room temperature before placement in the setup.

9.3.2.1 For Method B1, the soil specimen shall be placed atop the porous disc, after which a filter paper and the top platen shall be placed atop the specimen. The pressure chamber may then be assembled. For Method B2, the soil specimen shall be placed atop the porous disc or membrane, after which a piece of filter paper and the top platen shall be placed atop the specimen. A membrane expander shall be used to place the latex membrane around the specimen and platens. Care shall be taken to ensure a good contact between the latex membrane and the porous disc or cellulose membrane. There shall be no soil particles in the area of overlap between the latex membrane and porous disc or cellulose membrane. The latex membrane shall be held to the top and bottom platens with "O"-rings.

9.3.3 A vacuum of at least -80 kPa (-12 psi) shall be applied to the pore air on both sides of the specimen. After approximately 30 min, de-aired water shall be supplied to the bottom of the porous disc or membrane while vacuum is applied to the top. All connections and tubing on the bottom of the porous disc shall be flushed with water to remove air bubbles. The vacuum shall be maintained on the system to verify that all gas bubbles have escaped.

9.3.4 A back-pressure of at least 300 kPa (43.5 psi) shall be applied to the water on each side of the specimen. In Method B2, this back-pressure may be applied in stages to measure Skempton's B parameter ($B = \Delta u_w/\Delta\sigma$). After allowing a period of at least 24 h under back-pressure (or after measuring a B parameter greater than 0.9), the soil is assumed to be saturated.

9.3.5 The hydraulic conductivity of the water-saturated soil-disc system shall be evaluated by imposing a suitable hydraulic gradient across the specimen and measuring the water inflow and outflow using the pressure panel. The hydraulic conductivity of the water-saturated soil can be deduced using the known hydraulic conductivity of the porous disc (see 9.3.1) and the measured hydraulic conductivity of the soil-disc system, which is equal to the geometric average of the hydraulic conductivity values of the soil and disc.

9.4 *Centrifuge Permeameter Test Preparation (Category C):*

9.4.1 The centrifuge infiltration test shall start from as compacted or in-situ water content conditions.The soil will then be saturated in the centrifuge by spinning the specimen to a constant g-level while applying an infiltration rate v such that the calculated target hydraulic conductivity during steady-state flow through the soil layer is equal to the saturated hydraulic conductivity of the soil (see definition of the target hydraulic conductivity in 10.3.1). The saturated hydraulic conductivity of the soil may be estimated using the grain size distribution and porosity of the soil specimen (for example, Hazen's equation: $k_s = CD_{10}{}^2$, where C is a constant ranging from 0.4 to 1.2 and D_{10} is a characteristic grain size diameter).

9.4.2 Measurements from the instrumentation in the centrifuge permeameter (tensiometers, TDR) shall be used to verify the initial degree of saturation in the soil, which shall be reported.

10. Procedures

10.1 *Column Test Procedures (Category A):*

10.1.1 *Infiltration Column Test Procedures (Method A1):*

10.1.1.1 A constant infiltration rate shall be applied to an initially unsaturated soil specimen. The infiltration rate shall be a value less than the hydraulic conductivity of the soil when saturated, which may be estimated using an empirical approach (for example, Hazen's equation), or through soil-specific measurement using Test Methods D5084. If not requested, the infiltration rate shall be 1000 times smaller than the hydraulic conductivity when saturated.

10.1.1.2 Measure transient changes in volumetric water content and suction at different depths throughout the soil specimen using TDR, capacitance probes, or tensiometers, or through sampling to measure gravimetric water content using Test Methods D2216. If sampling is used, soil specimens with a mass of at least 50 g shall be obtained from ports in the column wall. These ports shall be sealed with a plug except during the process of sampling. In the case that only volumetric water content is measured but not suction (or vice versa), an independently-measured SWRC shall be used to estimate the other variable.

10.1.1.3 Measure inflow by observing the change in the water level in the water reservoir connected to the peristaltic pump. The measured inflow and the peristaltic pump velocity shall be reported. Measure the outflow from the soil specimen using the tipping bucket system. Infiltration shall be maintained until steady-state conditions are reached under the applied infiltration rate (that is, when outflow equals inflow).

10.1.1.4 If the HCF will be calculated using transient infiltration data (see 11.1.2), the test may be stopped after steady-state conditions are reached.

10.1.1.5 If the HCF will be calculated using steady-state infiltration data (see 11.1.3), at least two additional infiltration rates shall be applied to the soil specimen. These infiltration rates shall be applied by changing the peristaltic pump velocity. The pump velocity shall not be changed until steady-state conditions have been verified (that is, measured inflow equals measured outflow). Unless otherwise requested, these infiltration rates shall be values corresponding to 100 and 10 times the hydraulic conductivity of the soil when saturated.

10.1.1.6 If an evaluation of hysteresis in the HCF is requested **(18)**, the infiltration rate may be decreased (that is, leading to a drying of the soil) by lowering the peristaltic pump velocity. If transient analysis will be used for analysis, only one (smaller) infiltration rate shall be applied to dry the specimen. If steady-state analysis will be used for analysis, the infiltration rates applied during drying shall be the same as those applied during wetting.

10.1.2 *Imbibition Column Test Procedures (Method A2):*

10.1.2.1 Close the valve on the tube connecting the manometer to the bottom of the column. Configure the manometer so that a water pressure equal to zero will be applied to the bottom of the initially unsaturated soil specimen once the valve is opened. Configure the Mariotte bottle attachment on the manometer so that it is approximately filled with water, as water will flow from the Mariotte bottle into the soil in this test.

10.1.2.2 Open the valve on the drainage port at the base of the soil specimen, which will apply a constant hydraulic head to the soil.

10.1.2.3 Measure transient changes in volumetric water content and suction at different depths throughout the soil specimen as described in section 10.1.1.2.

10.1.2.4 Measure the amount of water that enters the soil specimen using the manometer tube. Maintain a constant water pressure at the base of the column using a Mariotte tube.

10.1.2.5 When water stops entering the base of the soil specimen due to capillary rise, the test may be stopped.

10.1.3 *Drainage Column Test Procedures (Method A3):*

10.1.3.1 Close the valve on the tube connecting the manometer to the bottom of the column. Configure the manometer so that a water pressure equal to zero will be applied to the top of the initially unsaturated soil specimen once the valve is opened. Configure the Mariotte bottle attachment on the manometer so that it is approximately empty, as water will flow from the soil into the Mariotte bottle in this test.

10.1.3.2 Open the drainage port at the bottom of the column and configure the constant-head manometer so that it is level with the base of the initially water-saturated soil specimen.

10.1.3.3 Measure transient changes in volumetric water content and suction at different depths throughout the soil specimen as described in section 10.1.1.2.

10.1.3.4 At the same time that the volumetric water content and suction are measured, measure the volume of water outflow from the base of the column using the manometer tube. A Mariotte tube shall be used to maintain a constant water pressure at the base of the soil specimen while still permitting measurement of outflow.

10.1.3.5 When the outflow from the soil specimen ceases (that is, less than 1 % change in 30 minutes), the test can be stopped.

10.1.4 *Evaporation Column Test Procedures (Method A4):*

10.1.4.1 Close the valve on the tube connecting the manometer to the bottom of the column. Configure the manometer so that a water pressure equal to zero will be applied to the top of the initially unsaturated soil specimen once the valve is opened.

10.1.4.2 Open the valve and ensure that no flow occurs into the soil (that is, it is water saturated and at hydraulic equilibrium). Close the valve for the remainder of the test.

10.1.4.3 Apply a constant relative humidity boundary condition to the soil surface using a fan and infrared lamp. Measure the relative humidity with time using a humidity gauge.

10.1.4.4 Measure transient changes in volumetric water content and suction at different depths throughout the soil specimen as described in section 10.1.1.2.

10.1.4.5 When the volumetric water content and suction cease to change with time (that is, within 1 % of the value measured 24 h earlier), the test may be stopped.

10.2 *Axis Translation Test Procedures (Category B):*

10.2.1 *Axis Translation Test Procedures in Pressure Chamber (Method B1):*

10.2.1.1 The soil specimen shall start from initially water-saturated conditions. Water shall be allowed to pond atop the soil specimen within the pressure chamber. The water level within the pressure chamber shall be equal to or greater than the surface of the soil specimen. A back-pressure of at least 300 kPa (43.5 psi) shall be applied to the water on both sides of the specimen using the pressure panel.

10.2.1.2 The hydraulic conductivity of the saturated soil-porous disc system shall be measured after a period of 24 h by applying a hydraulic gradient to the specimen and measuring the inflow and outflow volumes using the pressure panel.

10.2.1.3 While the air pressure is maintained constant in the pressure panel, drain the water out of the air flushing line on the top of the specimen and from the burette on the pressure panel connected to the top of the specimen. The air pressure shall be the same as the back-pressure applied in the previous step. Throughout the test, the air pressure shall be maintained at a value equal to or greater than the water pressure to prevent uplift of the porous disc.

10.2.1.4 While holding the air pressure on the top of the specimen constant, the water pressure applied to the bottom of the specimen shall be decreased using the pressure panel. When the water pressure is decreased, the suction will increase (the difference between air and water pressures). If the applied suction is greater than the air entry suction, outflow of water from the specimen will occur, which shall be measured using the graduated burette connected to the bottom of the specimen. The volume shall be measured at sufficient increments to capture the nonlinear shape of the outflow curve with time. A greater amount of outflow will occur from the specimen immediately after application of the suction increment.

10.2.1.5 When outflow ceases (that is, when the current measurement is within 1 % of the previous measurement over a duration of 1 h), the next requested suction increment shall be applied to the soil specimen. Specifically, the water pressure applied to the bottom of the specimen shall be decreased to apply the requested values of matric suction to the specimen. The volume of outflow shall be measured with time using the graduated burette until outflow ceases for that increment before moving to the next increment.

10.2.1.6 If hysteresis (re-wetting) measurements are requested, at the end of the highest suction value requested, the suction shall be decreased in increments until the specimen returns to a suction of zero. During each increment, the volume of inflow back into the specimen shall be measured using the pressure panel.

10.2.2 *Axis Translation Test Procedures in Flexible Wall Permeameter (Method B2):*

10.2.2.1 The soil specimen shall start from water-saturated conditions. Apply a back-pressure to saturate the specimen according to procedures described in Test Methods D5084 for determination of the hydraulic conductivity of saturated soils.

10.2.2.2 Measure the hydraulic conductivity of the soil-porous disc system using the procedures described in Test Methods D5084.

10.2.2.3 While the air pressure is maintained constant in the pressure panel, drain the water out of the air flushing line on the top of the specimen and from the burette on the pressure panel connected to the top of the specimen. The air pressure shall be the same as the back-pressure applied in the previous step. Throughout the test, the air pressure shall be maintained at a value equal to or greater than the water pressure to prevent uplift of the porous disc.

10.2.2.4 While holding the air pressure on the top of the specimen constant, the water pressure applied to the bottom of the specimen shall be decreased using the pressure panel. When the water pressure is decreased, the suction will increase (the difference between air and water pressures). If the applied suction is greater than the air entry suction, outflow of water from the specimen will occur, which shall be measured using the graduated burette connected to the bottom of the specimen. The volume shall be measured at sufficient increments to capture the nonlinear shape of the outflow curve with time. A greater amount of outflow will occur from the specimen immediately after application of the suction increment.

10.2.2.5 When outflow ceases (that is, when the current measurement is within 1 % of the previous measurement over a duration of 1 h), the next requested suction increment shall be applied to the soil specimen. Specifically, the water pressure applied to the bottom of the specimen shall be decreased to apply the requested values of matric suction to the specimen. The volume of outflow shall be measured with time using the graduated burette until outflow ceases for that increment before moving to the next increment.

10.2.2.6 If hysteresis (re-wetting) measurements are requested, at the end of the highest suction value requested, the suction shall be decreased in increments until the specimen returns to a suction of zero. During each increment, the volume of inflow back into the specimen shall be measured using the pressure panel.

10.3 *Centrifuge Permeameter Test Procedures (Category C):*

10.3.1 This test shall start with the soil in as-compacted or as-received (in the case of undisturbed soil specimens) conditions. After the soil specimen and instrumentation are assembled within the centrifuge permeameter, spin the centrifuge at a requested, constant angular velocity ω. Concurrently, apply a constant infiltration rate v to the upper surface of the soil specimen confined within the centrifuge permeameter using the flow pump (located outside of the centrifuge). It is recommended to start with a "target" hydraulic conductivity value that is close to the saturated hydraulic conductivity of the soil.

NOTE 5—During infiltration into a centrifuge permeameter, the hydraulic conductivity may not be constant over the length of the specimen because the water content and suction may not be uniform with height during the applied flow process. As the water content changes, the hydraulic conductivity will also change. The value of *k* obtained from Category C will be representative of the upper zone of the soil specimen. This thickness of this upper zone will depend on the applied flow process and centrifuge speed, but its main characteristic is that there will be negligible effects of the outflow boundary conditions on the volumetric water content distribution in the specimen, and water flow will occur under a negligible suction gradient. The hydraulic conductivity can be estimated using Darcy's law, as follows:

$$k(\theta,\psi) = \frac{-v}{\frac{\omega^2}{g}(r_0 - z) - \frac{1}{\rho_w g}\frac{d\psi}{dz}} \tag{2}$$

where:

g = the acceleration due to gravity,

r_0 = the radius of the base of the soil specimen in the centrifuge permeameter, and

z = a coordinate starting from the base of the soil specimen, in the opposite direction of the radius [see Fig. 10(*a*)].

However, because the suction gradient is included in this equation ($d\psi/dz$), it cannot be used to define the hydraulic conductivity until the suction gradient is measured (after or during the test). In order to plan out the testing program, a target value of hydraulic conductivity may be defined by assuming that the suction gradient is negligible through the specimen (**9**), as follows:

$$k_{target} = \frac{-v}{\frac{\omega^2}{g}(r_0 - z)} \tag{3}$$

As k_{target} varies with radius in the soil specimen, the value of k_{target} in the upper 30 % of the specimen shall be used as a representative value of the hydraulic conductivity of the specimen during steady-state infiltration (**7**).

10.3.2 Measure the volumetric water content using the TDR and the suction using the tensiometers at least every 1 min after starting the test. Measurements from each instrument shall be made at the same time. Measure the volume outflow from the soil specimen in the outflow reservoir using the pressure transducer.

10.3.3 Evaluate the measurements from the TDR, tensiometers, and pressure transducer in the outflow reservoir to check if steady-state conditions have been attained. Specifically, if the volumetric water content or suction measurements are approximately constant with time, and if the outflow is approximately equal to the inflow, then steady-state conditions are attained.

10.3.4 After steady-state conditions have been attained, decrease the angular velocity of the centrifuge while concurrently decreasing the infiltration rate using the flow pump. This will impose a lower value of k_{target} on the soil specimen. Similar to 10.3.2, measure changes in volumetric water content, suction, and outflow.

10.3.5 If requested, repeat application of the previous increments of k_{target} in reverse order, to re-wet the specimen and measure the changes in volumetric water content and matric suction using the TDR and tensiometers, respectively, to evaluate hysteresis in the HCF.

11. Interpretation of Results

11.1 *Column Test Result Interpretation (Category A):*

11.1.1 *Infiltration Column Test (Method A1):*

11.1.1.1 *Plotting of Instrumentation Data for Visual Inspection:*

(1) Plot the volumetric water content and suction measured by the sensors at different depths as a function of time. An example of time series of volumetric water content inferred from six TDR waveguides are shown in Fig. 13 in a soil specimen with a thickness of 0.75 m. A constant infiltration rate of 8×10^{-8} m/s was applied to the soil surface in the example test. In this example, the volumetric water content at all depths in the column is initially equal to 15 %. As the wetting front passes through the soil specimen, the volumetric water content inferred by each TDR increases gradually to approximately 24 %. After the wetting front reaches the base at a time of 520 h, water begins to accumulate in the lower portion of the soil specimen due to the capillary break effect. The volumetric water content begins to progressively increase with height in the column up to a height of 500 mm (19.6 in.). By the time outflow is collected from the base of the column, the volumetric water content at a height of 50 mm (1.96 in.) from the base is 40 % (degree of saturation of 0.8). Despite the accumulation of water at the base of the soil specimen, the upper portion of the soil specimen was unaffected by the capillary break effect. In this portion of the soil specimen, flow is occurring under a unit hydraulic gradient (constant volumetric water content and suction with height). At a time of 1600 h, the infiltration rate was increased to 1.5×10^{-7} m/s, which led to an increase in volumetric water content to 25 % at the top of the soil specimen.

(2) Plot the volumetric water content and suction as a function of height in the soil specimen for different times throughout the test (that is, isochrones). For example, the data shown in Fig. 13 reinterpreted as isochrones is shown in Fig. 14. The isochrones in Fig. 14 show how the volumetric water content gradually progresses vertically downward through the soil specimen. The accumulation of water at the base of the soil specimen after 550 h is indicated by a bulge in the volumetric water content distribution near the base of the soil specimen. The steady-state volumetric water content at the top of the soil specimen is 24 % during application of an infiltration rate of 8×10^{-8} m/s, while it is 25 % during an application of an infiltration rate of 1.5×10^{-7} m/s. During application of both of these infiltration rates, the isochrones in Fig. 11 indicate that a unit hydraulic gradient is present in the upper portion of the soil specimen (that is, the volumetric water content and suction do not change with height). In these cases, the values of k corresponding to the measured volumetric water content values are equal to the applied infiltration rates.

11.1.1.2 *Transient Analysis (Method A1):*

(1) The instantaneous profile method is the approach that shall be used to calculate points on the hydraulic conductivity function using the transient measurements of volumetric water content and matric suction.

(2) Calculate the hydraulic gradient between each of the depths in the soil specimen where suction and volumetric water content measurements are made, as follows:

$$\left(\frac{dh}{dz}\right)_m = -1 - \frac{1}{\gamma_w}\left(\frac{\psi_m - \psi_{m-1}}{z_{m-1} - z_m}\right) \tag{4}$$

where:

h = the total hydraulic head,
γ_w = the unit weight of water, and
m = an integer assigned to each of the tensiometers at the upper soil surface.

(a) The upper tensiometer shall be assigned a value of $m = 1$ with increasing values assigned to each tensiometer with

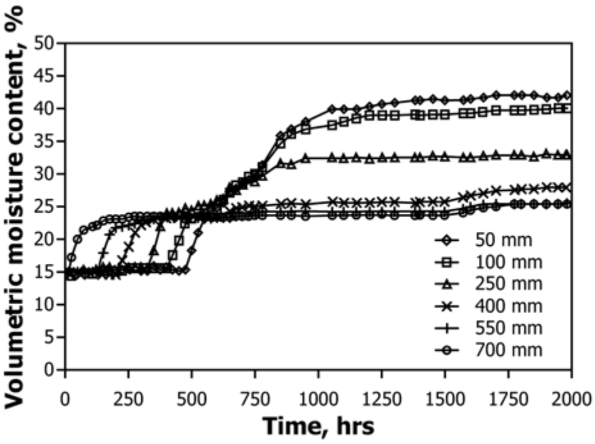

FIG. 13 Volumetric Water Content Time Series for Infiltration into a Soil Specimen (19)

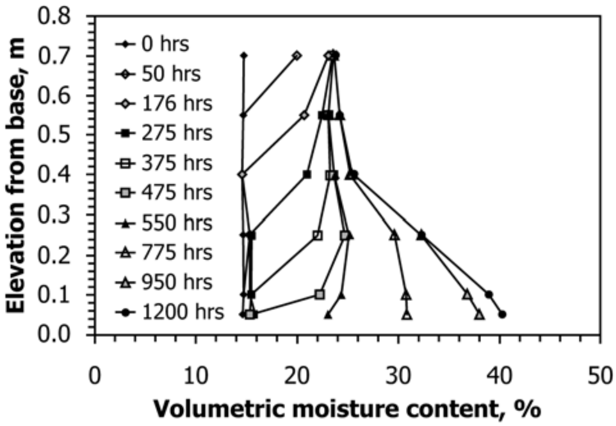

FIG. 14 Volumetric Water Content Profiles at Different Times During Infiltration

depth in the soil specimen. This equation is based on the assumption that the air pressure in the unsaturated soil is equal to zero so that the matric suction can be used in place of the pore water pressure ($\psi = -u_w$).

(b) In the case that tensiometers are not used in the column test, the hydraulic gradient may be inferred from volumetric water content data measured using TDR by calculating the suction values using the SWRC.

(3) Calculate the volume of water downstream from a given point *m* in the soil specimen by integrating the volumetric water content profile in the soil specimen during a given time interval Δt and depth interval z_i, as follows:

$$\Delta V^{j}_{w,m} = A \sum_{m=1}^{n} \left(\theta^{j} - \theta^{j-1}\right)\left(z_{m+1} - z_{m}\right) \tag{5}$$

where:

j = the current time step, and
n = the total number of measurement points ($n = 6$ for the data in Fig. 13).

(4) Calculate the hydraulic conductivity using the following equation:

$$k_j = \frac{\Delta V_i}{A\Delta t}\left(\frac{-1}{\left(\frac{dh}{dz}\right)_m}\right) \tag{6}$$

where:

z = the height from the specimen base,
$\Delta V_{w,I}$ = the volume of water that has passed a position *m* in the soil specimen during an time interval Δt,
A = the cross-sectional area of the specimen, and
h = the hydraulic head.

(5) Define points on the HCF by correlating the volumetric water content and suction at each time interval with the value of hydraulic conductivity calculated for the same interval using Eq 6.

11.1.1.3 *Steady-State Analysis (Method A1):*

(1) The assumption of a unit-gradient flow process shall be used to calculate points on the HCF using the applied infiltration rate and the measured volumetric water content and matric suction values.

(2) Check whether or not a unit hydraulic gradient is observed in the profiles of volumetric water content or suction. For example, in Fig. 14, the volumetric water content is relatively constant for elevations greater than 0.4 m.

(3) If unit-gradient conditions are observed, calculate the hydraulic conductivity by setting it equal to the negative of the applied infiltration rate.

(4) Define points on the HCF by correlating the calculated hydraulic conductivity with the measured, constant volumetric water content and suction values in the upper zone of the soil specimen (that is, 24 % in Fig. 14). The points on the HCF defined using this approach are also shown in Fig. 15.

NOTE 6—For steady-state conditions vertical infiltration with a deep water table, a unit hydraulic gradient is typically observed in the soil specimen [Fig. 15(*a*)], which means that the suction does not change with depth [Fig. 15(*b*) and Fig. 15(*c*)] and water flow is driven only by gravity in this zone. In the upper zone of the soil specimen, the hydraulic conductivity is equal to the imposed infiltration rate [Fig. 15(*d*)]. Accordingly, the volumetric water content and suction measured using the TDR and tensiometers, respectively, are correlated with the imposed infiltration rate. Points on the HCF can be defined by changing the imposed flow rate, and correlating these values with the measured volumetric water content and suction values. The parameters as well as the equations used to define the suction distributions in Fig. 16 are defined in (**7**).

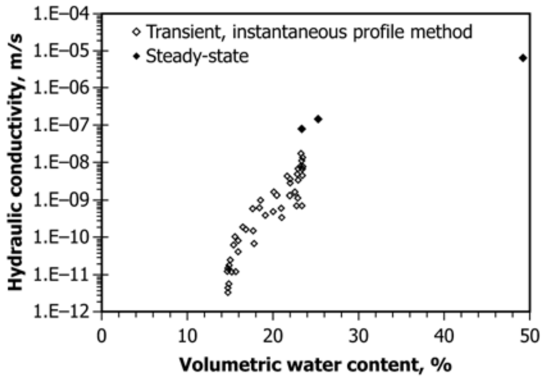

FIG. 15 Typical HCF Data Points for a Silt Defined Using a Column Infiltration Test (7)

11.1.2 *Imbibition Column Test Result Interpretation (Method A2):*

11.1.2.1 Plot the instrumentation measurements as described in section 11.1.1.1 and use the transient analysis explained in section 11.1.1.2 to define the HCF.

11.1.3 *Drainage Column Test Result Interpretation (Method A3):*

11.1.3.1 Plot the instrumentation measurements as described in section 11.1.1.1 and use the transient analysis explained in section 11.1.1.2 to define the HCF.

11.1.4 *Evaporation Column Test Result Interpretation (Method A4):*

11.1.4.1 Plot the instrumentation measurements as described in section 11.1.1.1 and use the transient analysis explained in section 11.1.1.2 to define the HCF.

11.2 *Axis Translation Test Result Interpretation (Category B):*

11.2.1 An approach developed by (**20**) shall be used to estimate the hydraulic conductivity from the outflow measurements from the axis translation test. The results from both Methods B1 and B2 may be interpreted using the same approach.

NOTE 7—In the approach of (**9**), the hydraulic conductivity of an unsaturated soil specimen evaluated in the axis translation technique should follow Fick's second law of diffusion, given by:

$$\frac{\partial \psi}{\partial t} = D\frac{\partial^2 \psi}{\partial z^2} \tag{7}$$

where D is equal to:

$$D = k\frac{d\psi}{d\theta} \tag{8}$$

An analytical solution to Eq 7 was proposed by (**20**), and may be used to determine the value of D in Eq 8 from the outflow data from axis translation tests, as follows:

$$\ln\left(\frac{V_\infty - V}{V_\infty}\right) = \ln\left(\frac{8}{\pi^2}\right) - \frac{D\pi^2 t}{4L^2} \tag{9}$$

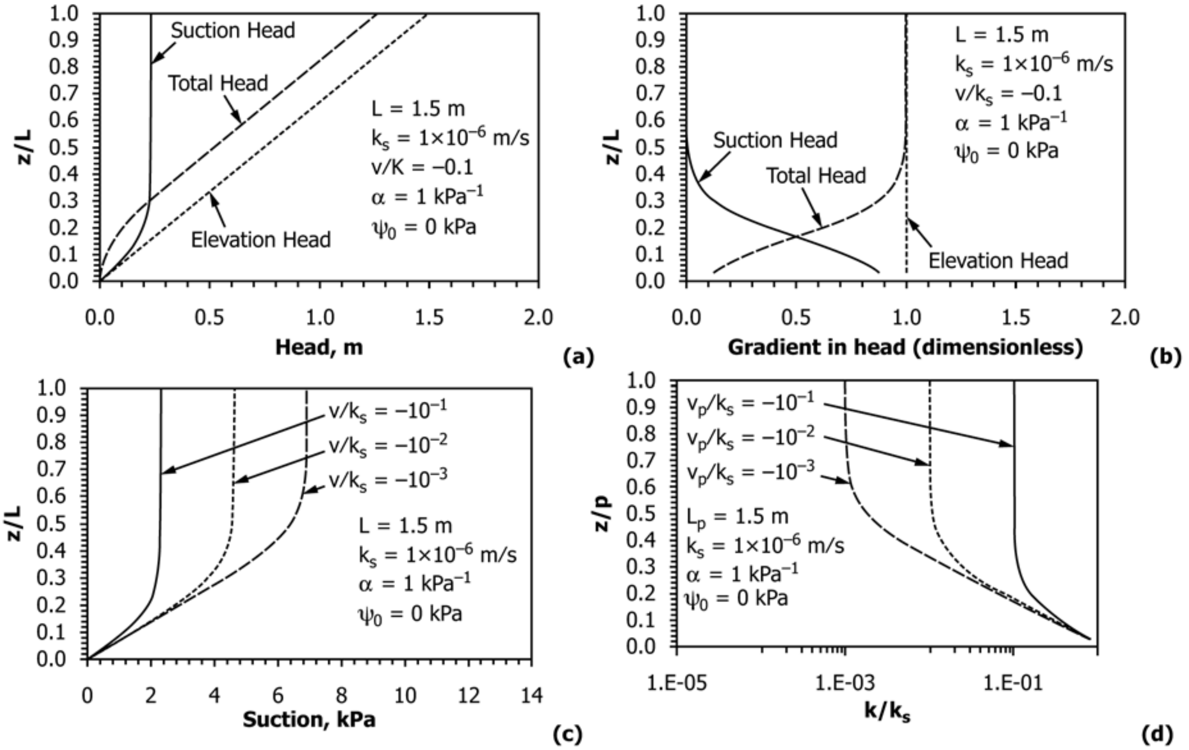

FIG. 16 Theoretical Steady-State Flow Results: (*a*) Components of Hydraulic Head; (*b*) Gradients of the Components of Hydraulic Head; (*c*) Suction Profiles; (*d*) Profiles of Hydraulic Conductivity in the Unsaturated Soil Specimen (7)

where:

V = the outflow with time during an applied suction increment [Fig. 16(*a*)],
V_∞ = the final (equilibrium) cumulative outflow value,
L = the length of the specimen, and
t = time.

11.2.2 Before starting the HCF calculation process, define the SWRC from the axis translation tests using the approach described by Test Methods D6836.

11.2.3 Plot the measured outflow volume V as a function of time for each of the suction increments applied in the test. An example of this plot is shown in Fig. 17(*a*).

11.2.4 Calculate and plot the left-hand-side of Eq 9 versus time for an applied suction increment. An example of this plot for the same data in Fig. 17(*a*) is shown in Fig. 17(*b*).

11.2.5 Fit a linear relationship to the transformed outflow data and calculate the slope and intercept.

11.2.6 Set the calculated slope equal to $D\pi^2/4L^2$ and calculated intercept equal to $\ln(8/\pi^2)$.

11.2.7 Using the value of *D* and the slope of the SWRC from the same test, calculate hydraulic conductivity corresponding to the applied increment in suction using Eq 8.

11.2.8 Define a point on the HCF by correlating measured hydraulic conductivity with the average suction and volumetric water content during the applied suction increment. Points on the HCF defined using Eq 8 are shown in Fig. 17(*c*).

NOTE 8—This approach is prone to errors at low volumetric water contents, where the diffusivity *D* is known to be variable. This analytical procedure relies on several simplifying assumptions, which include: (*i*) constant *k* over the applied suction increment, (*ii*) negligible flow of water due to gravity, (*iii*) homogeneous and rigid soil, and (*iv*) negligible impedance to outflow from the specimen due to the porous disc.

11.3 *Centrifuge Permeameter Test (Category C):*

11.3.1 Plot the inflow and outflow as a function of time on the same plot. Plot the volumetric water content and matric suction as a function time. Examples of these time series from a typical centrifuge permeameter testing stage in which a constant infiltration rate v and angular velocity (or g-level) are imposed on the soil specimen in the centrifuge permeameter are shown in Fig. 18. Specifically, the target hydraulic conductivity, g-level and infiltration rate from this typical centrifuge testing stage are shown in Fig. 18(*a*). The outflow results in Fig. 18(*b*) for times greater than 1 h have same slope as the inflow with time, so steady-state conditions have been attained in the specimen after this time. Similarly, the volumetric water content and suction equilibrate in the specimen around this same time, as shown in Fig. 18(*c*).

11.3.2 Define a point on the SWRC by correlating the volumetric water content and suction at steady-state conditions. If multiple stages are performed in the test, the SWRC will include all of such points obtained at steady-state conditions.

11.3.3 Use the suction measurements from the uppermost two tensiometers to calculate the suction head gradient as a function of time. Use the suction head gradient to calculate the total head gradient as a function of time:

$$\left(\frac{dh}{dz} = \frac{\omega^2}{g}(r_0 - z) - \frac{1}{\rho_w g}\frac{d\psi}{dz}\right)$$

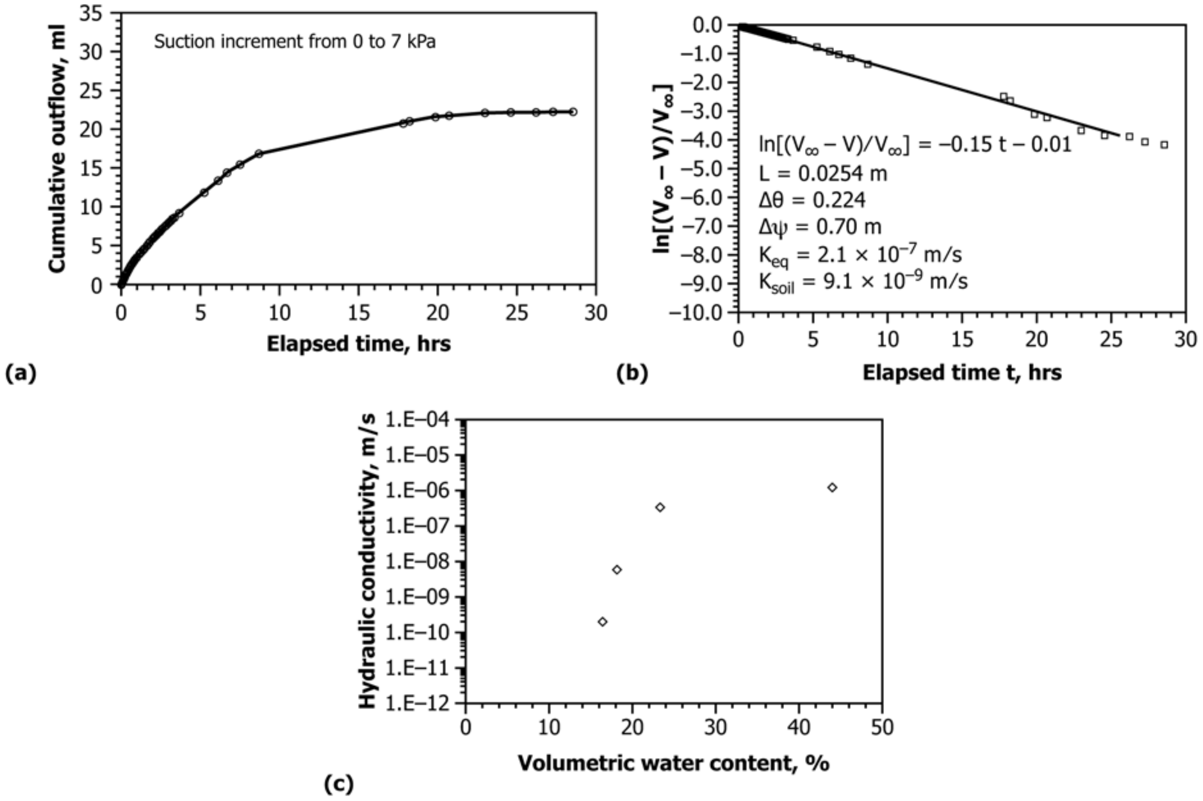

FIG. 17 Typical Pressure Chamber Results from a Single Suction Increment (7): (*a*) Outflow Results; (*b*) Outflow Results Interpreted Using Gardner's Method; (*c*) Points on the HCF Defined Using Eq 8

Use the total head gradient to calculate the hydraulic conductivity as a function of time using Darcy's law. Plot these three terms together on the same plot as shown in Fig. 18(*d*).

11.3.4 Define a point on the HCF by correlating the hydraulic conductivity calculated at steady-state conditions with the volumetric water content and suction measured during the same time period. Typical data points on the HCF defined using this method for a clay of low plasticity are shown in Fig. 18(*e*).

11.3.5 In the case that suction measurements at different heights in the specimen are not available (that is, when using a centrifuge permeameter in a medical centrifuge, as described in Test Methods D6836), the suction gradient can be assumed to be negligible in the upper zone of the soil specimen for g-levels greater than 100 (**20**). In this case, the hydraulic conductivity is assumed to equal the target hydraulic conductivity calculated using Eq 3.

NOTE 9—Similar to the column infiltration test, the matric suction in the upper portion of the specimen will be constant and water flow will be driven by the centrifuge elevation head [Fig. 19(*a*)]. This corresponds to a unit hydraulic gradient in the upper zone of the specimen [Fig. 19(*b*)]. The hydraulic conductivity will change in the upper zone of the specimen with either a change in infiltration rate or centrifuge angular velocity [Fig. 19(*c*) and Fig. 19(*d*), respectively].

12. Report

12.1 The report shall include the following information:

12.1.1 Sample identifying information.

12.1.2 A description of the soil, any special characteristics of the specimen, and the selection or processing procedure, or both (for example, removal of stones). For compacted materials, provide descriptive information on the method of compaction, the compaction water content, and the compacted dry unit weight.

12.1.3 A drawing of the apparatus used, including the dimensions of test specimens, and spatial locations of sensors for measurement of volumetric water content or suction, if any.

12.1.4 The type of water used to saturate and test the soil specimens.

12.1.5 The method of saturation.

12.1.6 The method used to define the HCF (for example, Method A1, A2, A3, B1, B2 or C). For Methods B1 and B2, state whether a porous plate or porous membrane was used and the air entry pressure of the porous plate or membrane. For Method C, state the manufacturer and model number for the centrifuge and specimen support chamber.

12.1.7 For Method A1 and Method C, the time required to reach steady-state flow.

12.1.8 For Methods A2, A3, A4, the time elapsed until water flow stops.

12.1.9 For Method B1 and B2, the time for water flow to stop for each suction increment applied to the soil specimen.

12.1.10 If requested for Methods B1 and B2, the magnitudes of any volume change that occurs during each increment of suction.

12.1.11 For Method C, the magnitude of any settlement that occurs during centrifugation.

12.1.12 Approximate temperature of the soil during the test (typically the air temperature of the laboratory) to the nearest 1°C.

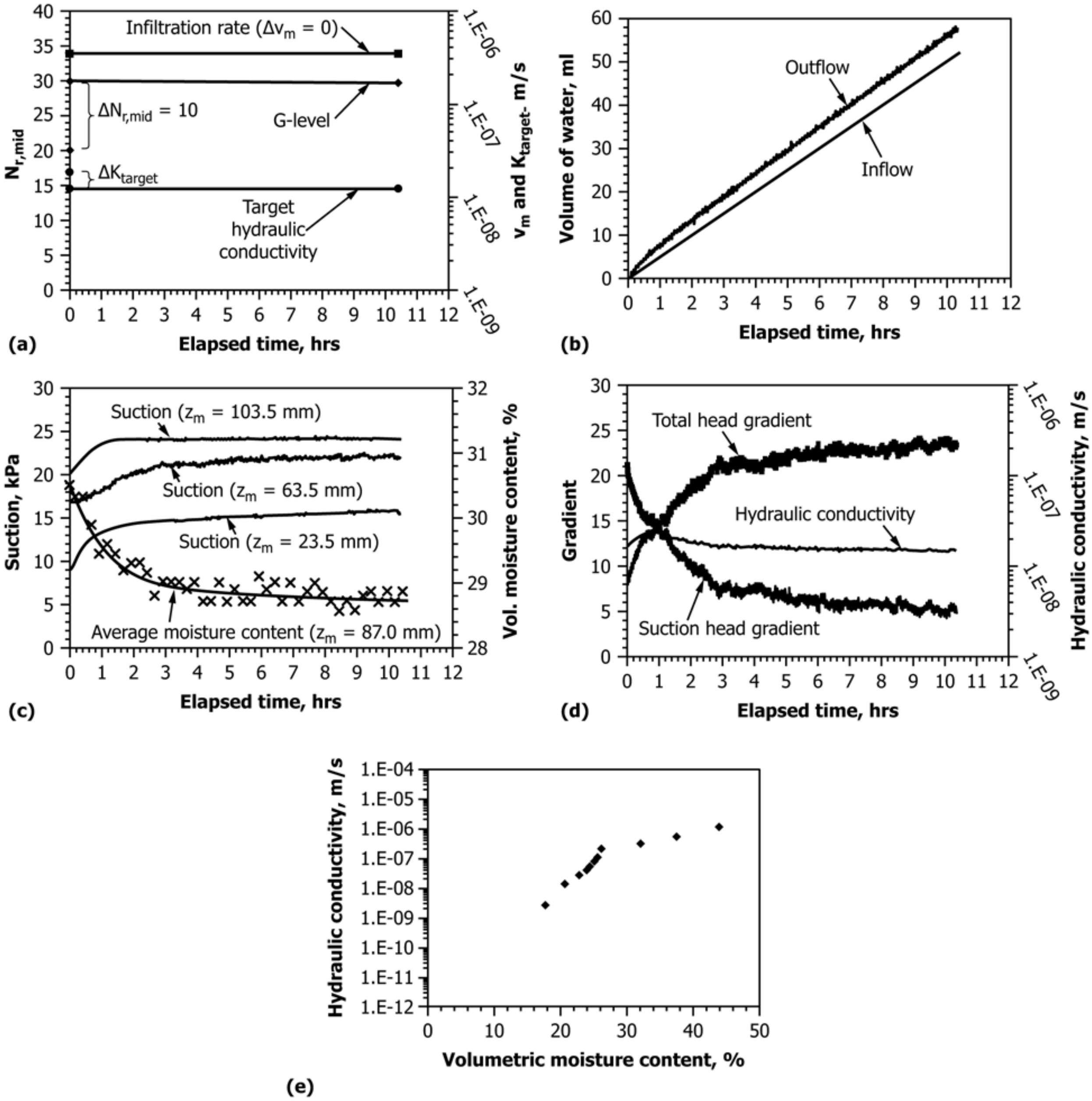

FIG. 18 Typical Centrifuge Permeameter Results for a Testing Stage: (*a*) Target Hydraulic Conductivity for a Stage; (*b*) Outflow and Inflow to the Soil Specimen; (*c*) Suction at Different Depths and Average Volumetric Water Content; (*d*) Gradient Values and Calculated Hydraulic Conductivity Values; (*e*) Points on the HCF Defined Using this Approach (21)

12.1.13 The gravimetric water content of the specimen after the last increment of suction was applied, as measured using Test Methods D2216. Also report the corresponding volumetric water content.

12.1.14 For Methods A1, A2, and A3, plots of volumetric water content and suction as a function of time for each of the different depths of the instrumentation, and plots of representative isochrones of volumetric water content and suction for different times during the test.

12.1.15 For the methods in Categories B and C (and for those in Category A when both volumetric water content and suction are measured), the SWRC. That is, a graph showing volumetric water content, gravimetric water content, or degree of saturation as a function of suction, and a table showing the gravimetric and volumetric water content corresponding to each suction value.

12.1.16 A graph showing the data points on the HCF; that is, a graph showing hydraulic conductivity as a function of either suction or volumetric water content and a table showing the volumetric water content, suction, and hydraulic conductivity values. The graph and table shall show the porosity of the soil.

13. Precision and Bias

13.1 *Precision*—Test data on precision are not presented due to the nature of the geological materials tested by this test method. Subcommittee D18.04 on Hydrologic Properties and

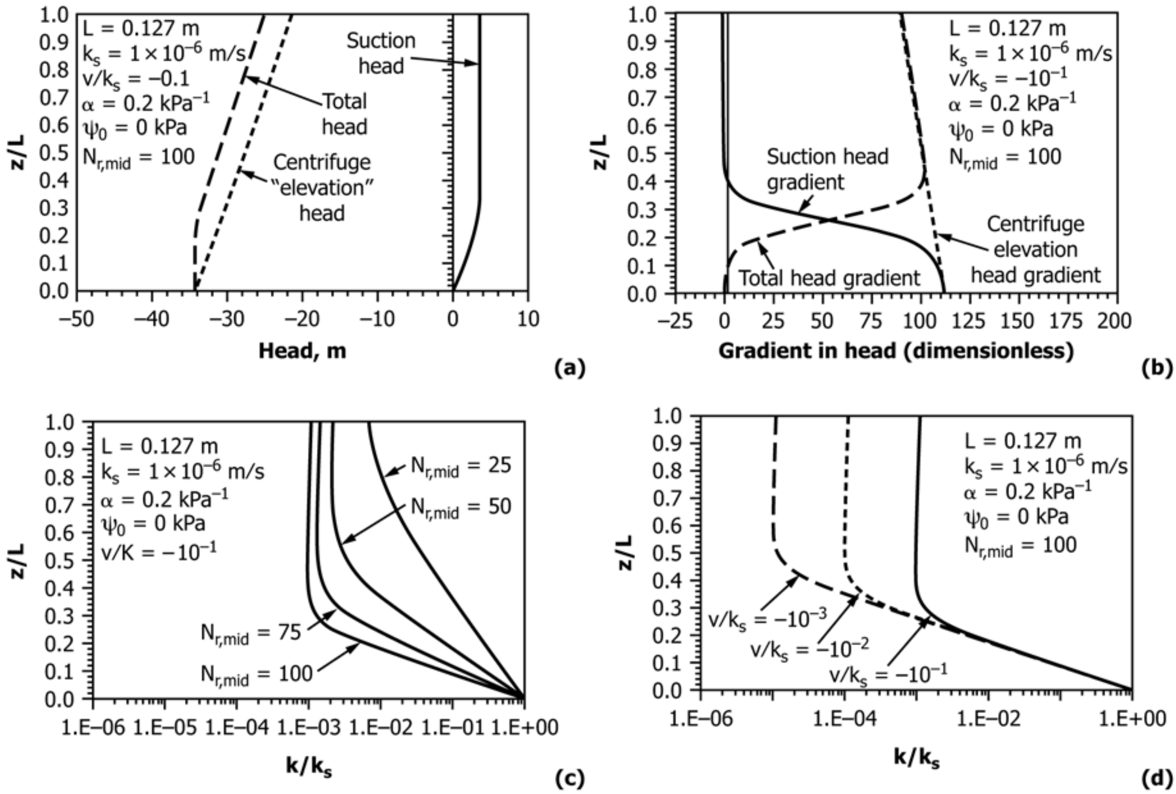

FIG. 19 Theoretical Steady-State Flow Results: (*a*) Components of Hydraulic Head; (*b*) Gradients of the Components of Hydraulic Head; (*c*) Suction Distributions; (*d*) Hydraulic Conductivity in the Unsaturated Soil Specimen (21)

Hydraulic Barriers is seeking data from the users of this test method that might be used to make a limited statement on precision.

13.2 *Bias*—The variability of soil and resultant inability to determine a true reference value prevents development of a meaningful statement of bias.

14. Keywords

14.1 column test; hydraulic conductivity function; permeameter; soil water retention curve; unsaturated soils

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