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Standard Guide for
Comparison of Field Methods for Determining Hydraulic Conductivity in Vadose Zone[1]

This standard is issued under the fixed designation D5126/D5126M; 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.

ε^1 NOTE—The units statement in 1.6 and the designation were revised editorially in August 2010.

1. Scope

1.1 This guide covers a review of the test methods for determining hydraulic conductivity in unsaturated soils and sediments. Test methods for determining both field-saturated and unsaturated hydraulic conductivity are described.

1.2 Measurement of hydraulic conductivity in the field is used for estimating the rate of water movement through clay liners to determine if they are a barrier to water flux, for characterizing water movement below waste disposal sites to predict contaminant movement, and to measure infiltration and drainage in soils and sediment for a variety of applications. Test methods are needed for measuring hydraulic conductivity ranging from 1×10^{-2} to 1×10^{-8} cm/s, for both surface and subsurface layers, and for both field-saturated and unsaturated flow.

1.3 For these field test methods a distinction must be made between "saturated" (K_s) and "field-saturated" (K_{fs}) hydraulic conductivity. True saturated conditions seldom occur in the vadose zone except where impermeable layers result in the presence of perched water tables. During infiltration events or in the event of a leak from a lined pond, a "field-saturated" condition develops. True saturation does not occur due to entrapped air (**1**).[2] The entrapped air prevents water from moving in air-filled pores that, in turn, may reduce the hydraulic conductivity measured in the field by as much as a factor of two compared to conditions when trapped air is not present (**2**). Field test methods should simulate the "field-saturated" condition.

1.4 Field test methods commonly used to determine field-saturated hydraulic conductivity include various double-ring infiltrometer test methods, air-entry permeameter test methods, and borehole permeameter tests. Many empirical test methods are used for calculating hydraulic conductivity from data obtained with each test method. A general description of each test method and special characteristics affecting applicability is provided.

1.5 Field test methods used to determine unsaturated hydraulic conductivity in the field include direct measurement techniques and various estimation methods. Direct measurement techniques for determining unsaturated hydraulic conductivity include the instantaneous profile (IP) test method and the gypsum crust method. Estimation techniques have been developed using borehole permeameter data and using data obtained from desorption curves (a curve relating water content to matric potential).

1.6 The values stated in either SI units or inch-pound units [presented in brackets] are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.6.1 The gravitational system of inch-pound units is used when dealing with inch-pound units. In this system, the pound (lbf) represents a unit of force (weight), while the unit for mass is slugs. The rationalized slug unit is not given, unless dynamic (F = ma) calculations are involved.

1.7 *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.*

1.8 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this*

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

document means only that the document has been approved through the ASTM consensus process.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D2434 Test Method for Permeability of Granular Soils (Constant Head)

D3385 Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer

D4643 Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating

3. Terminology

3.1 *Definitions:*

3.1.1 Definitions shall be in accordance with Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 Descriptions of terms shall be in accordance with Ref (**2**).

4. Summary of Guide

4.1 *Test Methods for Measuring Saturated Hydraulic Conductivity Above the Water Table*—There are several test methods available for determining the field saturated hydraulic conductivity of unsaturated materials above the water table. Most of these methods involve measurement of the infiltration rate of water into the soil from an infiltrometer or permeameter device. Infiltrometers typically measure conductivity at the soil surface, whereas permeameters may be used to determine conductivity at different depths within the soil profile. A representative list of the most commonly used equipment includes the following: infiltrometers (single and double-ring infiltrometers), double-tube method, air-entry permeameter, and borehole permeameter methods (constant and multiple head methods).

4.1.1 *Infiltrometer Test Method:*

4.1.1.1 Infiltrometer test methods measure the rate of infiltration at the soil surface (see Test Method D2434) that is influenced both by saturated hydraulic conductivity as well as capillary effects of soil (**3**). Capillary effect refers to the ability of dry soil to pull or wick water away from a zone of saturation faster than would occur if soil were uniformly saturated. The magnitude of the capillary effect is determined by initial moisture content at the time of testing, the pore size, soil physical characteristics (texture, structure), and a number of other factors. By waiting until steady-state infiltration is reached, the capillary effects are minimized.

4.1.1.2 Most infiltrometers generally employ the use of a metal cylinder placed at shallow depths into the soil, and include the single-ring infiltrometer, the double-ring infiltrometer, and the infiltration gradient method. Various adaptations to the design and implementation of these methods have been employed to determine the field-saturated hydraulic conductivity of material within the unsaturated zone (**4**). The principles of operation of these methods are similar in that the steady volumetric flux of water infiltrating into the soil enclosed within the infiltrometer ring is measured. Saturated hydraulic conductivity is derived directly from solution of Darcy's Equation for saturated flow. Primary assumptions are that the volume of soil being tested is field saturated and that the saturated hydraulic conductivity is a function of the flow rate and the applied hydraulic gradient across the soil volume.

4.1.1.3 Additional assumptions common to infiltrometer tests are as follows:

(a) The movement of water into the soil profile is one-dimensional downward.

(b) Equipment compliance effects are minimal and may be disregarded or easily accounted for.

(c) The pressure of soil gas does not offer any impedance to the downward movement of the wetting front.

(d) The wetting front is distinct and easily determined.

(e) Dispersion of clays in the surface layer of finer soils is insignificant.

(f) The soil is non-swelling, or the effects of swelling can easily be accounted for.

4.1.2 *Single-Ring Infiltrometer:*

4.1.2.1 The single-ring infiltrometer typically consists of a cylindrical ring 30 cm or larger in diameter that is driven several centimetres into the soil. Water is ponded within the ring above the soil surface. The upper surface of the ring is often covered to prevent evaporation. The volumetric rate of water added to the ring sufficient to maintain a constant head within the ring is measured. Alternatively, if the head of water within the ring is relatively large, a falling head type test may be used wherein the flow rate, as measured by the rate of decline of the water level within the ring, and the head for the later portion of the test are used in the calculations. Infiltration is terminated after the flow rate has approximately stabilized. The infiltrometer is removed immediately after termination of infiltration, and the depth to the wetting front is determined either visually, with a penetrometer-type probe, or by moisture content determination for soil samples (see Test Method D4643).

4.1.2.2 A special type of single-ring infiltrometer is the ponded infiltration basin. This type of test is conducted by ponding water within a generally rectangular basin that may be as large as several metres on a side. The flow rate required to maintain a constant head of water within the pond is measured. If the depth of ponding is negligible compared to the depth of the wetting front, the steady state flux of water across the soil surface within the basin is presumed to be equal to the saturated hydraulic conductivity of the soil.

4.1.2.3 Another variant of the single-ring infiltrometer is the air-entry permeameter (see Fig. 1). The air-entry permeameter is discussed in 4.1.4.

4.1.3 *Double-Ring Infiltrometer:*

4.1.3.1 The underlying principles and method of operation of the double-ring infiltrometer are similar to the single-ring infiltrometer, with the exception that an outer ring is included to ensure that one-dimensional downward flow exists within

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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.

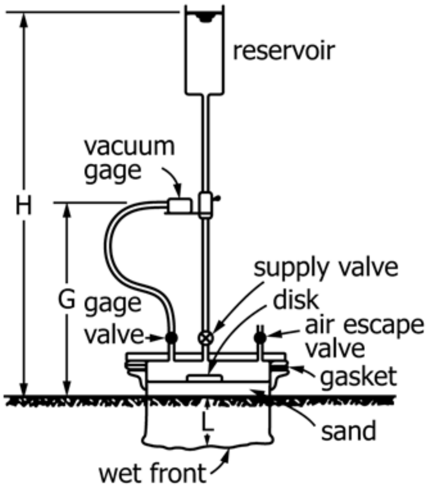

FIG. 1 Diagram of the Equipment for the Air-Entry Permeameter Technique (from Klute, 1986)

the tested horizon of the inner ring. Water that infiltrated through the outer ring acts as a barrier to lateral movement of water from the inner ring (see Fig. 2). Double-ring infiltrometers may be either open to the atmosphere, or most commonly, the inner ring may be covered to prevent evaporation. For open double-ring infiltrometers, the flow rate is measured directly from the rate of decline of the water level within the inner ring for falling head tests, or from the rate of water input necessary to maintain a stable head within the inner ring for the constant head case; for sealed double-ring infiltrometers, the flow rate is measured by weighing a sealed flexible bag that is used as the supple reservoir for the inner ring (**5**).

4.1.3.2 Refer to Test Method D3385 for measuring infiltration rates in the range of 10^{-2} to 10^{-5} cm/s. A modified double-ring infiltrometer test method for infiltration rates from 10^{-5} to 10^{-8} cm/s is also being developed.

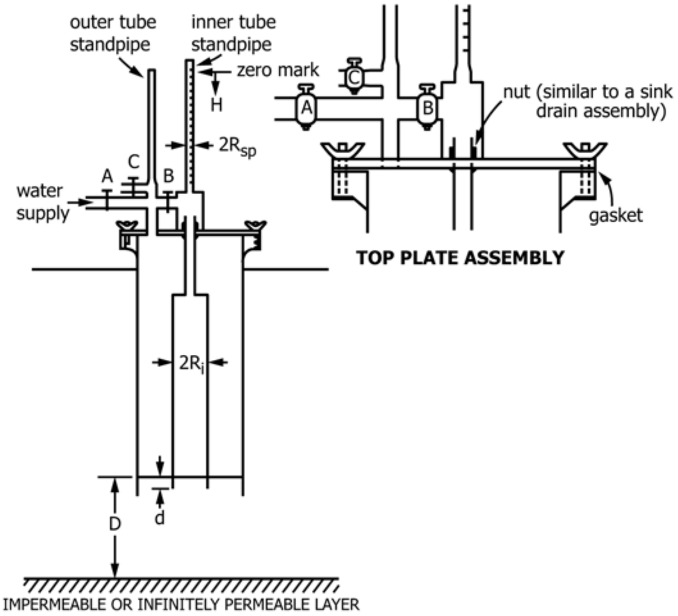

FIG. 2 Diagram of the Equipment Used for Double-Tube Test Method (from Klute, 1986)

4.1.4 *Double-Tube Test Method:*

4.1.4.1 The double-tube test method proposed by Bouwer (**5**, **6**, **7**) has been described by Boersma (**8**) as a means of measuring the horizontal, as well as the vertical, field-saturated hydraulic conductivity of material in the vadose zone.

4.1.4.2 This test method as proposed by Bouwer (**5**, **6**, **7**) utilizes two coaxial cylinders positioned in an auger hole. The difference between the rate of flow in the inner cylinder and the simultaneous rate of combined flow from in the inner and outer cylinders is used to calculate K_{fs}.

4.1.4.3 A borehole is augured to the desired depth and a hole conditioning device is used to square the bottom of the hole. The hole is then cleaned and a 1 to 2-cm layer of coarse protective sand is placed in the bottom of the hole. An outer tube is then placed in the hole and sunken about 5 cm into the soil. The outer tube is then filled with water and a smaller inner tube is placed at the center of the outer tube. It is then driven into the soil. A top plate assembly (see Fig. 2) consisting of water supply valves and standpipes for the inner and outer cylinders is installed. Water is then supplied to both cylinders. The standpipe for the outer cylinder is allowed to overflow and the standpipe gage for the inner cylinder is set at 0 by adjusting the appropriate water supply values. After an equilibrium period of approximately 1 h, the hole is saturated.

4.1.4.4 After saturation is achieved, the level of fall of water in the inner standpipe, *H*, is recorded at given time intervals, *t*. *H* is recorded at least every 5 cm, for a total of at least 30 cm (Test 2). During this test, water in the outer standpipe remains at a constant head.

4.1.4.5 After the data is recorded, the inner reservoir is again filled and the inner standpipe water level is set to 0. The system is allowed to re-equilibrate for a period of time at least ten times as long as the time required to collect the first data set.

4.1.4.6 After waiting, Test 2 is performed. The levels in the outer standpipe and inner standpipe are both brought to 0. Once again the drop in the inner standpipe in cm, *H*, is recorded as a function of time, *t*. During the second test, however, water levels in both tubes drop simultaneously. Both tests are then performed a second time or until the results of two consecutive runs are consistent.

4.1.5 *Air-Entry Permeameter:*

4.1.5.1 The air-entry permeameter is similar to a single-ring infiltrometer in design and operation in that the volumetric flux of water into the soil within a single permeameter ring is used to calculate field-saturated hydraulic conductivity. The primary differences between the two test methods are that the air-entry permeameter typically penetrates deeper into the soil profile and measures the air-entry pressure of the soil. Air-entry pressure is used as an approximation of the wetting front pressure head for determination of the hydraulic gradient, and consequently field-saturated hydraulic conductivity.

4.1.5.2 The air-entry permeameter consists of a single ring, typically 30 cm in diameter, sealed at the top, that is driven into the soil approximately 15 to 25 cm. Water is introduced into the permeameter through a standpipe, to the top of which is attached a water supply reservoir. Water is allowed to infiltrate into the soil within the permeameter ring, and the flow rate is measured by observing the decline of the water level within the reservoir. After a predetermined amount of water has infiltrated (based upon the estimated available storage of the soil interval contained within the ring), and the flow rate is relatively stable, infiltration is terminated and the wetted profile is allowed to drain. The air-entry value is the minimum pressure measured over the standing water inside of the permeameter ring attained during drainage. Once the minimum pressure is achieved, the permeameter is removed, and the depth to the wetting front is determined (**9**).

4.1.6 *Borehole Permeameter:*

4.1.6.1 Borehole permeameter test methods encompass a wide range of test designs, methods of operation, and methods of solution. The common feature among the different types of borehole tests is that the rate of water infiltration into a cylindrical borehole is used to determine field-saturated hydraulic conductivity. One of the most popular borehole infiltration tests is the constant-head borehole infiltration test, wherein the flow rate necessary to maintain a constant water level within a borehole is measured. The steady state flow rate, borehole geometry, borehole radius (r), and depth of ponding within the borehole (h), along with certain capillary parameters, are typically used in the solution. Hence, by accounting for capillary effects, borehole test methods attempt to measure field-saturated hydraulic conductivity rather than infiltration rate. Another variation of this test consists of conducting multiple constant head borehole infiltration tests within the same borehole. Different water levels are established within the borehole for each individual test. Results from one or more tests at different ponded heights are solved simultaneously to independently find hydraulic conductivity and capillarity.

4.1.6.2 Borehole infiltration tests are the only currently available tests that can measure field-saturated hydraulic conductivity at depth within the unsaturated zone. Borehole tests may be conducted at great depth within the unsaturated zone, and are frequently used to measure the variability of conductivity with depth by conducting tests at selected horizons within an advancing borehole.

4.1.6.3 During constant head borehole tests, water is introduced into a cylindrical borehole and maintained at a predetermined level. This may be accomplished by use of a float valve connected to an external water supply reservoir, or with a Mariotte-siphon device (**2**, **9**). The flow rate into the borehole necessary to maintain the water at the prescribed level is measured at various times. The flow rate at steady state is used in the solution of field-saturated hydraulic conductivity. The dimensions and geometry of the borehole and the depth to the water table are also required for the solution.

4.1.7 *Empirical Methods—Saturated Hydraulic Conductivity:*

4.1.7.1 A number of empirical methods have been developed for estimation of hydraulic conductivity from grain size data (Shepard (**10**)). Shepard suggested that hydraulic conductivity could be predicted from the following:

$$K = cd^a \tag{1}$$

where:

c = a dimensionless constant found through regression analysis,

d = the mean pore throat or particle diameter, and

a = an exponent generally ranging from 1.65 to 1.85.

4.1.7.2 Values for c and a were found to vary substantially depending on the degree of sorting of particles and the amount of induration. Both c and a decreased as the degree of sorting became poorer and as the induration increased. The amount of secondary porosity ("structure" in soils, or "fractures" in rock and sediment) is also expected to affect the values for c and a. Estimates of K for a particular value of d varied by nearly three orders of magnitude depending on the choice of values for c and a (**10**).

4.2 *Test Methods for Measuring Unsaturated Hydraulic Conductivity:*

4.2.1 *Instantaneous Profile Test Method (IP):*

4.2.1.1 Several references, including Watson (**11**), describe the IP test method. The relationship between water potential and hydraulic conductivity can be determined by measuring the rate of drainage and water potential and then solving a form of the Richards equation. The Richards equation solves for the change in water content through time for non-steady, uniform, unsaturated flow by relating water potential and unsaturated hydraulic conductivity.

4.2.1.2 To conduct an IP test, a small basin is constructed in which water is ponded. Neutron access tubing and a nest of tensiometers at varying depths are installed in the center of the basin. Water is ponded in the basin until the wetting front passes the bottom of the horizon being investigated. Movement of the wetting front is detected with a neutron probe. The soil basin is then covered to reduce evaporation and water content and water potential are measured periodically as water drains downward under the influence of gravity.

4.2.2 *Gypsum Crust Test Method:*

4.2.2.1 The gypsum crust test method is similar to infiltrometer methods in that the rate of water flux across an infiltrative surface is measured. A crust composed of varying mixtures of gypsum and coarse sand is poured over the surface of an exposed excavated cylinder of soil. After the crust cures, water is ponded on the crust. The presence of the crust causes unsaturated conditions to form in the soil beneath the crust.

4.2.2.2 The cylinder of soil is instrumented with a nest of tensiometers to measure water potential below the gypsum crust. The rate of flux of water necessary to maintain a constant head over the gypsum crust and the diameter of the cylinder is also recorded (**12**, **13**).

4.2.3 *Empirical Test Methods—Unsaturated Hydraulic Conductivity:*

4.2.3.1 A number of empirical test methods have been developed to estimate unsaturated hydraulic conductivity from other hydraulic parameters. Van Genuchten (**14**) and Mualem (**15**) developed methods for predicting unsaturated hydraulic conductivity from the desorption curve (that relates water content to water potential) and from K_s measurements. Reynolds and Elrick (**2**) developed a borehole permeameter method for measuring a fitting parameter used for estimating unsaturated hydraulic conductivity according to a model proposed by

Gardner. The fitting parameter is found by solving simultaneous equations developed from borehole water flux data for two ponded heights. The two ponded height test method is discussed further in 6.4. Infiltration data can be used to estimate hydraulic conductivities by solving the Green-Ampt or Philips Eq. (**3**).

5. Significance and Use

5.1 Saturated hydraulic conductivity measurements are made for a variety of purposes varying from design of landfills and construction of clay liners to assessment of irrigation systems. Infiltrometers are commonly used where infiltration or percolation rates through a surface or subsurface layer are desired. Evaluation of the rate of water movement through a pond liner is one example of this kind of measurement. Penetration of the liner by a borehole would invalidate the measurement of liner permeability. It has been noted that small-ring infiltrometers are subject to error due to lateral divergence of flow. Therefore, techniques using very large (1 to 2-m diameter) infiltration basins have been recommended for measuring the very slow percolation rates typically required for clay liners. The air-entry permeameter can be used instead of infiltrometer tests to avoid lateral divergence of flow. However, because a cylinder must be driven into the media tested, the actual soil column tested may be disrupted by introduction of the cylinder, especially in structured soils.

5.2 Borehole tests for determining saturated hydraulic conductivity are applicable for evaluating the rate of water movement through subsurface layers. For slowly permeable layers, an accurate method of measuring the rate of water movement into the borehole must be developed. Use of a flexible bag as a reservoir that can be periodically weighed is advisable for these conditions. A number of mathematical solutions for borehole outflow data are available (Stephens et al. (**16**), Reynolds et al. (**17**), and Philip (**18**)).

5.3 Information on unsaturated flow rates is needed to design hazardous waste landfills and impoundments where prevention of flow of contaminants into groundwater is required. Of the test methods available, the primary differences are cost and resultant bias and precision. The instantaneous profile test method appears to provide very reliable data because it uses a large volume of soil (several cubic metres) and is performed on undisturbed soils in the field. However, a single test can cost several thousand dollars. The gypsum crust test method, although more rapid than the instantaneous profile test method, sacrifices precision of results due to the smaller spatial extent of the tested area. Methods for estimating unsaturated hydraulic conductivity from fundamental soil hydraulic functions like the desorption curve may readily deviate from true values by an order of magnitude, but may be of use where relative differences in permeability between materials or across water content ranges is of interest.

6. Report

6.1 The reporting requirements for each test vary substantially. However, the variability of hydraulic conductivity in soils, and the sensitivity of some test methods to factors such as textural stratifications, anisotropic conditions, changes in temperature or barometric pressure, initial and final water contents, and depth to groundwater, suggest that a detailed description of each test site be recorded. Record the following:

6.1.1 Soil series (for comparison to existing data),

6.1.2 Soil horizon characteristics above and below layer tested (to help interpret deviations from theoretical response),

6.1.3 Initial and final water content (measure or describe subjectively depending upon method and to identify which numerical solution is most applicable),

6.1.4 General climatic conditions (for example, barometric pressure, temperature, precipitation, cloud cover to estimate possible evaporation, pressure responses, accumulation of prescription that might bias results),

6.1.5 Diameter of borehole or infiltration ring (parameter used in solution),

6.1.6 Rate of outflow, infiltration, or drainage (parameter used in solution),

6.1.7 Water potential (tensiometer) readings as required (parameter used in solution),

6.1.8 Temperature of water used, and

6.1.9 Chemical composition of water used.

6.2 *Infiltrometer Tests:*

6.2.1 Infiltrometer tests are useful for measuring the rate of infiltration but do not provide a direct measure of field-saturated hydraulic conductivity. Since entrapped air exists within the wetting front, true saturated conditions do not form during infiltration tests. Experience indicates that field saturated K_{fs} is approximately 50 to 75 % less than K_s (**1**, **2**).

6.2.2 Infiltration data can be fitted to empirical models such as those developed by Green and Ampt and Philip (described by Bouwer (**3**)).

$$I = S_i t^{1/2} + At \qquad (2)$$

where:

I = cumulative infiltration (cm of H_2O),
S_i = sorbtivity of soil (determined from plot of cumulative infiltration against $t^{1/2}$),
t = time increment in seconds, and
A = approximates ½ K_{fs}.

6.3 *Air-Entry Permeameter:*

6.3.1 As soon as minimum pressure is reached, air begins to bubble up through the wetting front. Field-saturated K_{fs} can be calculated from the critical “air-entry value” or minimum pressure. Field-saturated K_{fs} is approximately equal to ½ of K_s in most soils or ¼ of K_s in fine-textured (clayey) soils.

6.3.2 Field saturated K_{fs} is calculated (from Amoozegar and Warrick (**11**)) as follows:

$$K_{fs} = L(dH/dt)(R/Rc)^2/(H+L-(P/2\ pg)) \qquad (3)$$

where:

K_{fs} = field-saturated hydraulic conductivity (cm/s),
L = depth of wetting front (cm),
H = ponded height of water above the soil (cm),
dH/dt = rate of fall just before water supply was shut off (cm/s),
R/Rc = Radius of the reservoir divided by the cylinder radius, and

$P/2\,pg$ = air entry value (minimum pressure divided by the unit weight of liquid (cm)).

6.4 *Double-Tube Test Method:*

6.4.1 Data from both tests are plotted on a graph of *H* versus *t* (*H* is on the *y* axis). Due to the decrease in head in the inner tube and the greater head in the outer tube, in Test 1, *H* decreases more rapidly through time than in Test 2. A curve of *H* verses *t* data for Test 2 will lie above the curve for Test 1 because in Test 2 the head is the same in both the inner and outer tubes.

6.4.2 Saturated hydraulic conductivity (*K*) is calculated using the *H* versus *t* graphs (see Fig. 3 and Fig. 4) and the following equation (Amoozegar and Warrick, (**10**)):

$$K = R^2_{sp}\, dHt_1 / \left(FR_i \int_{t0}^{t1} Hdt \right) \tag{4}$$

where:

R_{sp} = radius inner tube standpipe,
R_i = radius inner tube,
dHt_1 = vertical distance between the two curves at t = t_1,
$\int_{t0}^{t1} Hdt$ = areas under the lower curve between t = 0 and t = t_1, and
F = a dimensionless quantity dependent on the geometry of the flow system.

6.5 *Borehole Permeameter Test Methods:*

6.5.1 Unlike the previous described infiltrometer and permeameter test methods, borehole permeameters account for three-dimensional flow as a result of lateral, as well as downward, flow components. The actual configuration of the flow field around the borehole is highly dependent on the geometry of the borehole, the hydraulic properties of the soil and the capillary suction of the soil. Many of the earlier solutions for falling-head and constant-head type borehole tests ignore the effects of unsaturated flow away from the borehole. Several authors (Glover (**19**), U.S. Bureau of Reclamation (**20**)) have proposed borehole test methods that are entirely dependent on "free surface" solutions that ignore capillarity. More recently, Stephens et al. (**16**), Philip (**18**), and Reynolds and Elrick (**17**) have shown that unsaturated flow can greatly affect the infiltration rate from a borehole—especially in fine-textured soils, and must be considered in the solution for hydraulic conductivity. Each of these workers has proposed testing methods and/or solutions which account for unsaturated flow away from a wetted bulb around the borehole.

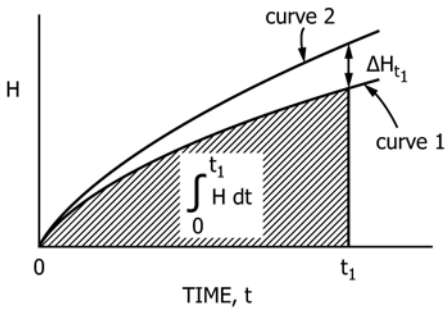

FIG. 3 Graph of *H* versus *t* for Double-Tube Procedure (from Klute, 1986)

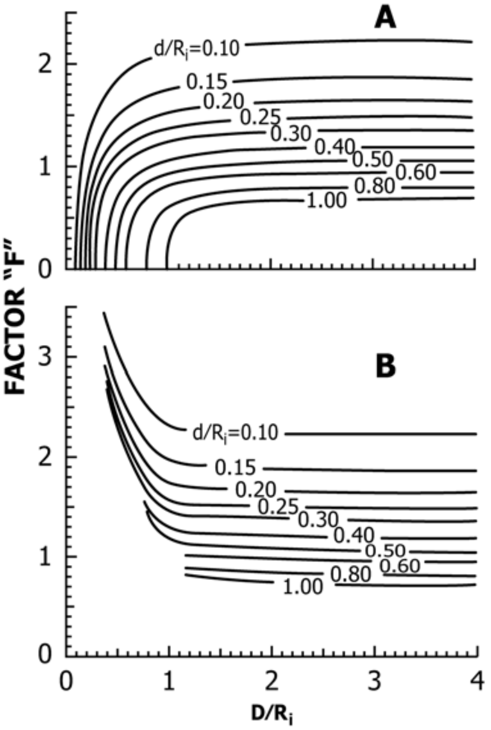

FIG. 4 Values of *F* for the Double-Tube Test Method, (*A*) An Impermeable Layer Below the Hole; and (*B*) An Infinitely Permeable Layer Below the Hole (from Klute, 1986)

6.5.2 The solution methods of Stephens et al. (**16**) and Philip (**18**) require that certain capillary parameters be either determined separately or be estimated based on soil texture.

6.5.3 The methods of solution proposed by Stephens et al. (**16**) account for capillary effects and are based on multivariate regression equations developed from numerical simulations. Capillary parameters are determined from a catalog of soil hydraulic properties based on soil texture (for example, Mualem (**15**)), or by a fit to moisture retention curves using a model developed by Van Genuchten (**15**).

6.5.4 The Philip (**18**) method is an approximate quasi-analytical solution that accounts for unsaturated flow from a borehole. The solution is based on an approximation of the borehole geometry as an elongate half-spheroid. The capillary parameter must be either known *a priori* or estimated from a catalog of soil hydraulic properties based on soil texture.

6.5.5 Reynolds and Elrick (**17**) described an analytical solution for borehole permeameter data that involves a simultaneous solution for data collected at two different ponded heights. This approach was found to be sensitive to slight field measurement error and to texturally stratified systems with the result that negative values for K_{fs} are frequently obtained. Reynolds and Elrick (**17**) suggested an alternative analytical solution where capillary effects are estimated based on soil texture and structure.

6.6 *Instantaneous Profile (IP) Test Method:*

6.6.1 A detailed description of calculating unsaturated hydraulic conductivity (or diffusivity) for different depth increments is provided in Green and others (**21**). Graphical plots of tensiometric data and soil water content data through time are