Designation: D5126/D5126M – 16

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.

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 is 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 SI units are to be regarded as standard. No other units of measurement are included in this standard.

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

1.7.1 The method used to specify how data are collected, calculated, or recorded in this standard is not directly related to the accuracy to which the data can be applied in design or other uses, or both. How one applies the results obtained using this standard is beyond its scope.

1.8 *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.*

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

[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Groundwater and Vadose Zone Investigations.

Current edition approved July 1, 2016. Published July 2016. Originally approved in 1990. Last previous edition approved in 2010 as D5126–90(2010)ε1. DOI: 10.1520/D5126-16.

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

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

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) (Withdrawn 2015)[4]

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

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

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

D6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions:*

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

3.2 Descriptions of other related terms can be found in Ref (**3**).

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 (**4**). 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 (**5**). 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 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:*

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

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

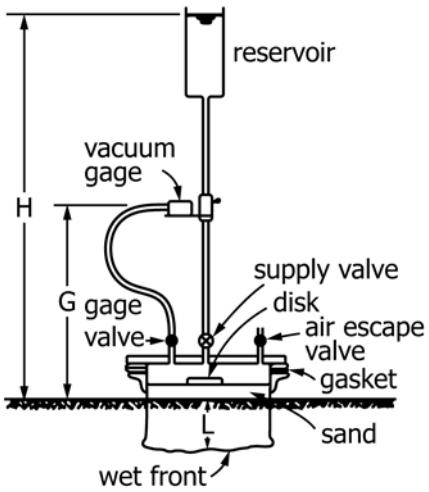


FIG. 1 Diagram of the Equipment for the Air-Entry Permeameter Technique (from Klute, 1986)

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 make sure that one-dimensional downward flow exists within 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 (**6**).

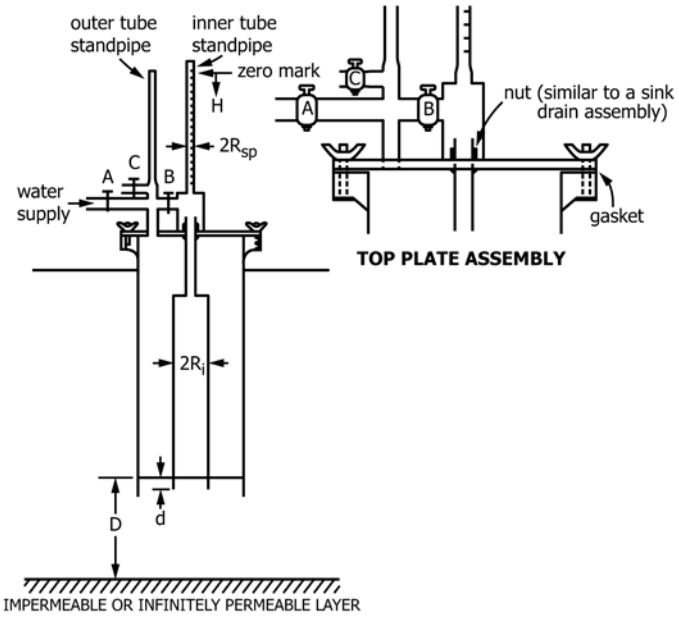


FIG. 2 Diagram of the Equipment Used for Double-Tube Test Method (from Klute, 1986)

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.

4.1.4 *Double-Tube Test Method:*

4.1.4.1 The double-tube test method proposed by Bouwer (**6**, **7**, **8**) has been described by Boersma (**9**) 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 (**6**, **7**, **8**) 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 in most cases at least every 5 cm, for a total minimum of 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, a minimum ten times as long as the time needed 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 (**10**).

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**, **10**). 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 needed 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 (**11**)). Shepard suggested that hydraulic conductivity could be predicted from the following:

$$K = cd^a \quad (1)$$

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(**11**).

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 (**12**), 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 (**13**, **14**).

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 (**15**) and Mualem

(16) 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. (4).

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 needed 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 will need to 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. (17), Reynolds et al. (18), and Philip (19)).

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 needed. 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 curves may 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.

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

6. Report: Test Data Sheets

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 as a minimum the following general information (data):

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 evaporation, pressure responses, accumulation of precipitation 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 (parameter used in solution),

6.1.8 Temperature of water used, and

6.1.9 Chemical composition of water used.

6.1.10 Record data in accordance with Practice D6026 and Test Method D2434, or Test Method D3385 as appropriate for the test and for significant digits and rounding.

6.1.11 Names of personnel performing test and developing report.

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 (4)).

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

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 (**12**)) as follows:

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

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, (**11**)):

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

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 (**20**), U.S. Bureau of Reclamation (**21**)) have proposed borehole test methods that are entirely dependent on "free surface" solutions that ignore capillarity. More recently, Stephens et al. (**17**), Philip (**19**), and Reynolds and Elrick (**18**) have shown that unsaturated flow can greatly affect the infiltration rate from a borehole—especially in fine-textured soils, and needs to 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.

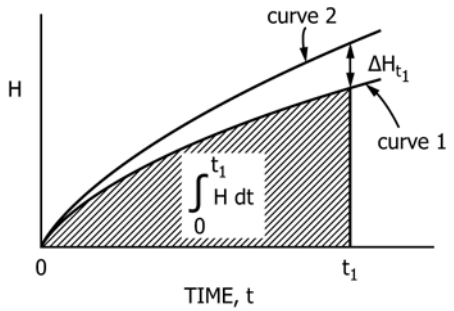


FIG. 3 Graph of *H* versus *t* for Double-Tube Procedure (from Klute, 1986)

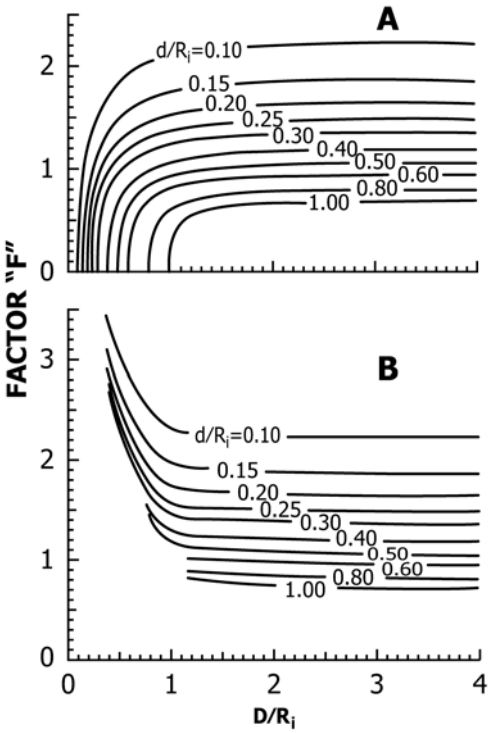


FIG. 4 Values of *F* for the Double-Tube Test Method, (*A*) An Impermeable Layer Below the Hole; and (*B*) An Infinitely Permeable Layer Below the Hole (from Klute, 1986)

6.5.2 The solution methods of Stephens et al. (**17**) and Philip (**19**) 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. (**17**) 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 (**16**)), or by a fit to moisture retention curves using a model developed by Van Genuchten (**16**).

6.5.4 The Philip (**19**) 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 should be either known *a priori* or estimated from a catalog of soil hydraulic properties based on soil texture.

6.5.5 Reynolds and Elrick (**18**) 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 (**18**) 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 (**22**). Graphical plots of tensiometric data and soil water content data through time are used to estimate instantaneous water flux at known levels of water content and water potential. An alternative analytical solution was described by Hillel (**23**). Unsaturated hydraulic conductivity data are subject to hysteresis. The IP test method provides data from the desorption loop.

6.7 *Gypsum Crust Test Method:*

6.7.1 The gypsum crust test method yields a single measurement of unsaturated hydraulic conductivity as a function of measured water potential for each crust constructed. The unsaturated hydraulic conductivity values are associated with the absorption loop rather than the desorption loop obtained with drainage methods.

6.7.2 In the crust test method, a steady unsaturated flux of water is attained with a unit hydraulic gradient (influenced only by gravity). Under these conditions, the measured water flux is equal to the hydraulic conductivity:

$$K(h) = Q/A \tag{5}$$

where:

$K(h)$ = unsaturated hydraulic conductivity at head = h,
Q = outflow of water (cm^3/s), and
A = area of soil cylinder (cm^2).

6.7.3 If a unit hydraulic gradient does not form due to presence of texturally variable layers or due to compacted zones, two tensiometers can be installed at the top and bottom of the zone of study. The unsaturated hydraulic conductivity can then be calculated from the following:

$$K(h) = Q/(dH/dz)A \tag{6}$$

where:

dH/dz = the measured hydraulic gradient (unitless).

7. Precision and Bias

7.1 *Precision*—Test data on precision is not presented due to the nature of the tests in this guide. It is either not feasible or too costly at this time to have ten or more agencies participate in an in situ testing program at a given site.

7.1.1 The Subcommittee D18.21 is seeking any data from the users of this guide that might be used to make a limited statement on precision.

7.2 *Bias*—There is no accepted reference value for the methods described in this guide, therefore bias cannot be determined.

7.3 *General Discussion on the Precision and Bias of Saturated Hydraulic Conductivity Test Methods:*

7.3.1 Each of the test methods described make certain assumptions to enable the hydraulic conductivity to be calculated (see Table 1). In general, the simpler test methods, especially infiltration test methods, rely on many more assumptions that are frequently violated. Care should be taken to understand potential source of analytical error and bias, and to avoid errors while conducting field tests. Most test methods assume soils to be homogeneous (usually the same in all directions) or at least isotropic (no changes vertically); that is seldom the case in field soils. Errors caused by non-homogeneous or anisotropic conditions vary from test to test. Appropriate test methods for a particular situation should be chosen based on the cost of testing, the bias and precision needed, the depth at which a layer is to be tested, the characteristics of the soil profile (uniform or layered), and the approximate hydraulic conductivity range expected.

7.3.1.1 The accuracy of hydraulic conductivity tests is highly dependent on the spatial variability of soils or sediments to be tested. Studies indicate that hydraulic properties of field soils are highly variable (Neilsen et al. (**24**)) and that numerous readings (at closely spaced locations) would typically be needed to characterize a "site" or field-sized area. Field-saturated hydraulic conductivity values tend to be log-normally distributed rather than normally distributed meaning that a majority of the net flux of water may occur in a few permeable spots (**24**).

7.3.1.2 Infiltrometer test methods should be used cautiously if the saturated hydraulic conductivity is to be determined. Infiltration is affected by both hydraulic conductivity as well as by capillary effects. Infiltration measurements are sensitive to disruption of the infiltration surface (for example, compaction, sealing by rain splash), presence of textural stratification, chemistry of the water used, and water temperature. Water that is low in salts or high in sodium is dispersive and may result in lower calculated values of K_{fs}.

7.3.2 *Single-Ring Infiltrometer:*

7.3.2.1 The single-ring infiltrometer is subject to divergent flow due to the effects of unsaturated flow heterogeneities and anisotropy, because with most applications, the wetting front is allowed to propagate below the bottom of the ring. These effects may lead to inaccuracies in the determination of saturated hydraulic conductivity.

7.3.3 *Double-Ring Infiltrometers:*

7.3.3.1 As with single-ring infiltrometers, the wetting front is allowed to advance below the bottom of the ring, but it's assumed that infiltration through the outer ring functions as an effective barrier to lateral flow beneath the ring. However, the accuracy of this assumption may be limited (see Fig. 5).

7.3.3.2 Bouwer (**4**) discussed the ratio of the inner ring to the outer ring necessary to maintain vertical flow in the inner ring. He suggested that an error of several hundred percent can occur unless cylinders of very large diameter are used because of edge effects. For large diameter (1 m or more) cylinders the

TABLE 1 Review and Comparison of Test Methods for Measuring Hydraulic Conductivity in the Vadose Zone

Characteristics	Single-Ring Infiltrometer (4)	Double-Ring Infiltrometer (4)	Double-Tube Test Method (8)	Air-Entry Permeameter (10)	Borehole Permeameter Methods						
					Free Surface (20)	Capillarity Fixed (2)	Capillarity Predicted (16)	2-Head Simultaneous Solution (2)	Instantaneous Profile (21)	Gypsum Crust (21)	Empirical (14, 15)
Relative accuracy	Low	Fair	Fair	Good	Poor	Good	Good	Variable	Good	Good	Low
Relative cost	Low	Low-Moderate	Moderate	Moderate	Low to Moderate				High	High	Low
Time required (at $K_{fs} = 10^{-5}$ cm/s)	<4 h	<4 h	4 h to 1 day	<4 h	<4 h				1 day	4 h to 1 day	4 h
Depth of testing practical	Surface	Surface	0 to 0.3 m	0 to 0.3 m	Any				0 to 1.5 m	0 to 0.3 m	Any
Range of K_{fs} (cm/s) for which test is suited	10^{-2} to 10^{-6}	10^{-2} to 10^{-6} 10^{-6} to 10^{-8} (with flexible bag for inner reservoir)	$<10^{-6}$	$<10^{-8}$	$<10^{-6}$ $<10^{-8}$ (with precautions for temperature effects on reservoir volume)				—	—	—
Advantages	Simple apparatus, rapid, can estimate K_{is} from infiltration data, can increase diameter to reduce scale effects and edge effect	Similar to single-ring		Measures vertical K_{fs} only, accounts for capillary effects	Simple numerical solution, good approximation for sands	Accounts for capillarity effects	—	Simple solution, accounts for capillarity	Excellent method for deriving K (unset) curve	Good for values of Y near zero	Simple, rapid
Drawbacks	Lateral flow affects accuracy, measures infiltration not K_{fs}, surface crust reduces infiltration, measured on surface of soil only	Similar to single-ring	Cumbersome apparatus, time-consuming numerical solution	Sometimes difficult to drive tube, difficult to identify wetting front in wet soil	Does not account for capillary effects, high error for medium to fine unstructured soil	Must assume ratio of capillary to flux effects, difficult to predict	Requires description data	Occasionally gives negative values	Time-consuming, affected by barometric changes	Time-economical, only one value of K (unset) and water potential per test	Low accuracy

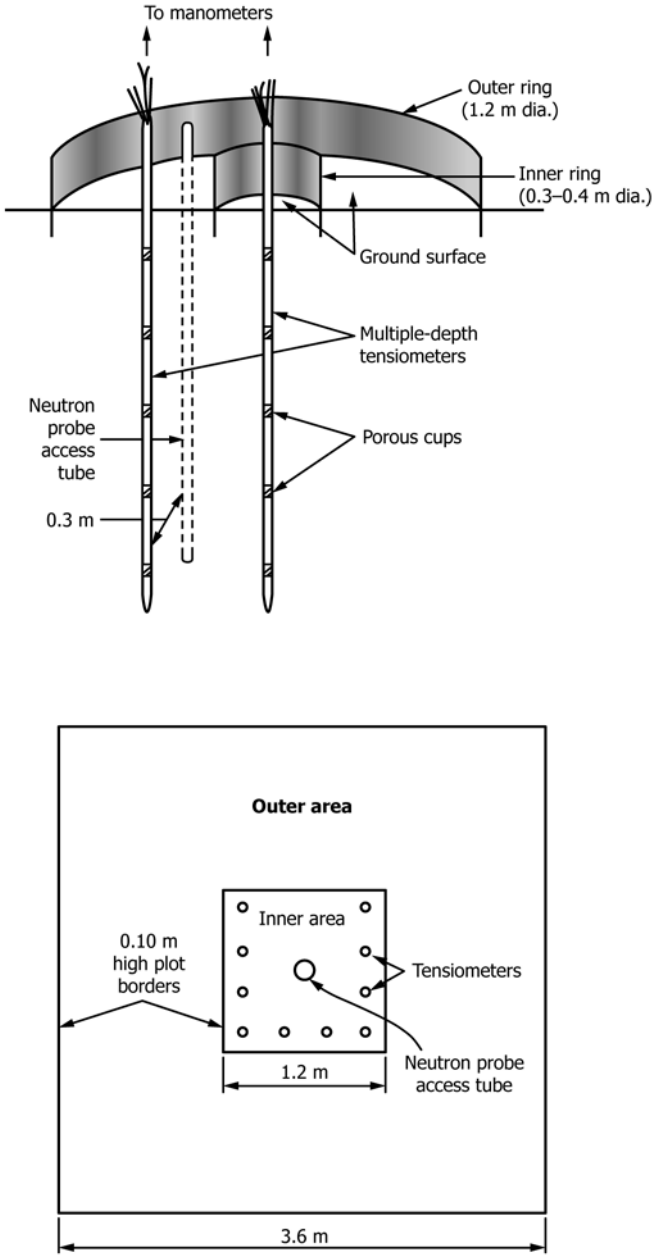


FIG. 5 Sectional and Plan View of Double-Ring Infiltrometer With Instruments Installed for Unsteady Drainage-Flux Method (from Klute, 1986)

"edge" effects become small enough that a "double-ring" system is not necessary. Edge effects are not corrected through use of a double-ring infiltrometer though they are somewhat reduced. Bouwer (**4**) mentioned that true vertical infiltration below a ring infiltrometer only occurs after a surface soil crust forms that limits the rate of water intake. Hence, the rate of infiltration thus measured does not represent fully saturated flow.

7.3.4 *Air-Entry Permeameter:*

7.3.4.1 The same restrictions and assumptions apply for the air-entry permeameter as for the infiltrometer test methods. However, since the wetting front is not allowed to advance below the bottom of the permeameter ring, make sure one-dimensional vertically downward flow occurs. In addition, since the hydraulic gradient is measured during the test, the infiltration rate need not necessarily reach steady state during the first portion of the test. One potential problem with the air-entry permeameter test method is determining the depth of the wetting front after completion of the test. Visual determination is especially difficult in soils with higher initial moisture content.

7.3.5 *Double-Tube Test Method:*

7.3.5.1 Depending on the permeability of the soil, the double-tube method requires over 200 L of water and 2 to 6 h for completion.

7.3.5.2 The test method is not suitable for rocky soils because of the difficulty in driving tubes into the ground. Due to soil disturbance around the inner tube, the diameter of the outer tube should be a minimum of two times that of the inner tube (Bouwer and Riel, 1967). An inner tube with a diameter <10 cm is not recommended. The K value obtained utilizing this method is affected by both the horizontal and vertical conductivities of soil.

7.3.6 *Borehole Permeameter Test Methods:*

7.3.6.1 Permeameter test methods rely on an accurate measure of steady-state flow. The length of time needed to establish steady flow can range from minutes, for small-diameter borehole tests in coarse-textured soils, to months, for large-diameter borehole tests in clays. The analytical solution used will also affect the accuracy of the results. Stephens and others (**25**) compared large- and small-diameter borehole test methods to the air-entry permeameter method for several geologic materials. Various analytical solutions were used to find K_{fs} from the borehole data. It was found that accuracy of permeameter test methods is sensitive to the spatial variability of soils both vertically and laterally. Test results are sensitive to the condition of the sidewall of the test borehole. Care should be taken to avoid smearing of the borehole that creates a hydraulic barrier.

7.4 *Precision and Bias of Unsaturated Hydraulic Conductivity Measurements:*

7.4.1 Test methods for unsaturated hydraulic conductivity are subject to the same limitations as methods for saturated hydraulic conductivity. Little comparative information is available concerning precision and bias of hydraulic conductivity tests, hence one method cannot be clearly judged to be superior to another.

7.4.2 *Instantaneous Profile Test Method (IP):*

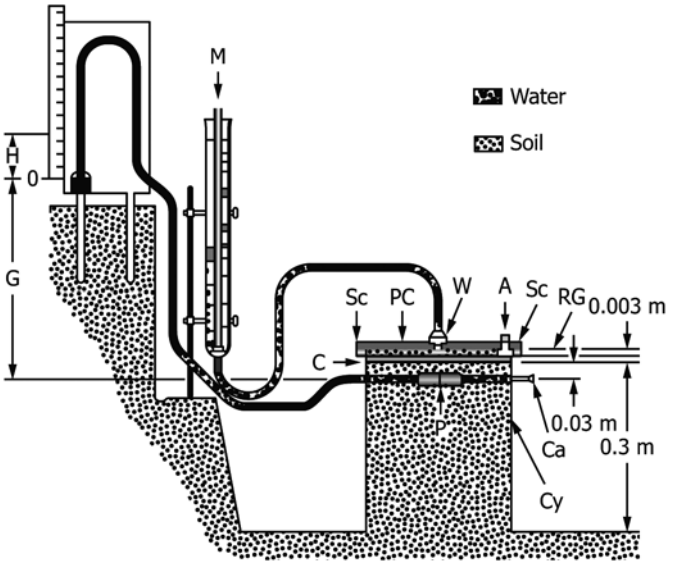
7.4.2.1 The IP test method is thought to be an accurate test of unsaturated hydraulic conductivity. However, it is costly and time consuming to perform. Errors in measurement of water content or water potential will affect the accuracy of calculated unsaturated hydraulic conductivity. Digital manometer-type tensiometers are suggested for measuring water potential. Rapid changes in barometric pressure may affect soil water potential readings. Stratification within the soil profile being measured will also affect accuracy. Presence of a water table within about three to four feet of the base of the zone of measurement should be avoided (**12**).

7.4.3 *Crust Test Method:*

7.4.3.1 The crust test method provides a single measurement of unsaturated hydraulic conductivity at a specific water potential, which is read off of a tensiometer installed below the crust (see Fig. 6). The water potentials that evolve below the crust are a function of the crust material used (for example, specific gypsum/sand mixture). A steady-state flow rate must be measured (see Fig. 7). This may take hours. Tensiometer readings are to be made accurately. The geometry of the excavated block of soil is critical to the solution, hence soil cylinders with a consistent diameter and accurately excavated. This is difficult in highly-structured or rocky soils (**13**).

8. Keywords

8.1 air-entry permeameter; air-entry value; borehole permeameter; hydraulic conductivity; infiltrometer; vadose zone monitoring



NOTE 1—*M* = constant-head device; *Sc* = wing nut; *PC* = plastic cover; *W* = water inlet; *A* = air outlet; *RG* = rubber gasket; *C* = gypsum-sand crust; *Ca* = tensiometer cap; *Cy* = metal cylinder with sharpened edge; *H* = height of mercury column above mercury pool; and *H* = height of mercury pool above tensiometer porous cup, *P*.

NOTE 2—In the past, the use of mercury manometers and other mercury containing devices was common. With the recognition of the hazards of mercury, mercury manometers have been replace with devices containing other nonhazardous liquids, or with digital devices. Digital device offer other benefits, such as data logging, greater field durability, varying ranges, and greater accuracy. Mercury should not be used.

NOTE 3—*WARNING*—Mercury has been designated by many regulatory agencies as a hazardous material that can cause serious medical issues. Mercury, or its vapor, has been demonstrated to be hazardous to health and corrosive to materials. Caution should be taken when handling mercury and mercury containing products. See the applicable product Safety Data Sheet (SDS) for additional information. Users should be aware that selling mercury and/or mercury containing products into your state or country may be prohibited by law.

FIG. 6 Schematic Diagram of a Field Installation of the Measurement Apparatus for Crust-Imposed Steady Flux Method

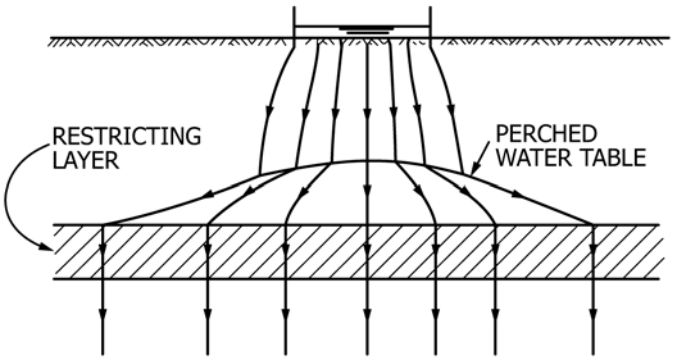


FIG. 7 Lateral Divergence of Flow Below an Infiltrometer

REFERENCES

(1) Bouwer, H., "Rapid Field Measurement of Air Entry Value and Hydraulic Conductivity of Soil as Significant Parameters in Flow System Analysis," Water Resources Research, Vol 2, No. 4, 1966, pp. 729–738.

(2) Reynolds, D. and Elrick, D. E., "A Method for Simultaneous *In-Situ* Measurement in the Vadose Zone of Field-Sa Hydraulic Conductivity, Sorptivity and the Conductivity-Pressure Head Relationship," Groundwater Monitoring Review, Vol 6, No. 4, 1986, pp. 84.

(3) *Glossary of Science Terms*, Soil Science Society of America, Madison, WI, 2008

(4) Bouwer, H., "Intake Rate: Cylinder Infiltrometer," Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, Agronomy Monograph No. 9, American Society of Agronomy, Madison, WI, 1986, pp. 825–844.

(5) Philip, J. R., "The Theory of Infiltration: The Infiltration Equation and its Solution," Soil Science, 1957, 83:345–357.

(6) Bouwer, H., "A Double Tube Method for Measuring Hydraulic Conductivity of Soil in Sites Above a Water Table," Soil Science Society of America Proceedings, 25:334–342, 1961.

(7) Bouwer, H., "Field Determination of Hydraulic Conductivity Above a Water Table with a Double-Tube Method," Soil Science Society of America Proceedings, 26:330–335, 1962.

(8) Bouwer, H., "Measuring Horizontal and Vertical Hydraulic Conductivity of Soil with the Double-Tube Method," Soil Science Society of America Proceedings, 28: 19–23, 1964.

(9) Boersma, L., "Field Measurement of Hydraulic Conductivity Below a Water Table," Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, Agronomy Monograph No. 9, American Society of Agronomy, Madison, WI, 1965.

(10) Amoozegar, A. and Warrick A. W., "Hydraulic Conductivity of Saturated Soils—Field Methods," Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, Agronomy Monograph 9, American Society of Agronomy, Madison, WI, 1986.

(11) Shepard, R. G., "Correlations of Permeability and Grain Size," Ground Water, 27(5):633–638, 1989.

(12) Watson, K. K., "An Instantaneous Profile Method for Determining the Hydraulic Conductivity of Unsaturated Porous Materials," Water Resources Research, 2:709–715, 1966.

(13) Bouma, J., Hillel, D. I., Hole, F. D., and Amerman, C. R., "Field Measurement of Hydraulic Conductivity by Infiltration through Artificial Crusts," Soil Science Society of America Proceedings, 33:362–344, 1971.

(14) Bouma, J. and Denning, J. C., "Field Measurement of Unsaturated Hydraulic Conductivity by Infiltration through Gypsum Crusts," Soil Science Society of America Proceedings, 36:846–847, 1972.

(15) Van Genuchten, M. T., "A Closed Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soil," Soil Science Society of America Journal, 44:892–898, 1980.

(16) Mualem, Y., "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media," Water Resources Research, 12:513–522, 1976.

(17) Stephens, D. B., Lambet, K., and Watson, D., "Regression Models for Hydraulic Conductivity and Field Test of the Borehole Permeameter," Water Resources Research, 23:2207–2214, 1987.

(18) Reynolds, W. D. and Elrick, D. E., "A Laboratory and Numerical Assessment of the Guelph Permeameter Method," Soil Science, 144:282–299, 1987.

(19) Philip, J. R., "Approximate Analysis of the Borehole Permeameter in Unsaturated Soil," Water Resources Research, 21(7):1025–1033, March 1986.

(20) Glover, R. E., "Flow from a Test-Hole Located Above Groundwater Level," U.S. Bureau of Reclamation, Eng. Meng., 8:69–71, 1953.

(21) Bureau of Reclamation, Drainage Manual, U.S. Government Printing Office, Washington DC, 1993, pp. 90–126.

(22) Green, R. E., Ahuja, L. R., and Chong, S. K., "Hydraulic Conductivity, Diffusivity, and Sorptivity of Unsaturated Soils: Field Methods," Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, Agronomy Monograph No. 9, 2nd Edition, American Society of Agronomy, Madison, WI, 1986, pp. 771–798.

(23) Hillel, D., Fundamentals of Soil Physics, Academic Press, New York, 1980.

(24) Neilsen, D. R., Biggar, J. W., and Erh, K. T., "Spatial Variability of Field-Measured Soil Water Properties," Hilgardia, 42:215–260, 1973.

(25) Stephens, D. B., Unruh, M., Havlena, J., Knowlton, R. G., Mattson, E., and Cox, W., "Vadose Zone Characterization of Low-Permeability Sediments Using Field Permeameters," Ground Water Monitoring Research, Vol 8, No. 2, 1988, pp. 59–66.

(26) *Glossary of Science Terms*, Soil Science Society of America, Madison, WI, 1987.

SUMMARY OF CHANGES

In accordance with Committee D18 policy, this section identifies the location of changes to this standard since the last edition (D5126–90(2010)$^{\varepsilon 1}$) that may impact the use of this standard. (July 1, 2016)

(1) Added D18 caveats for D3740, D6026.
(2) Editorial changes throughout for jargon, correction of typos, terminology section and clarity.
(3) Added summary of changes section.
(4) Removed the use of mercury in several places and added the mercury hazard caveat.
(5) Updated references to current editions.
(6) Changed from English units to SI in Table 1 and revised the 1.6 to reflect this as an SI standard.