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Standard Test Method for ~~Field Measurement of Hydraulic Conductivity Limits of Porous Materials Using Two Stages of Infiltration from a Borehole~~Field Measurement of Hydraulic Conductivity Using Borehole Infiltration[1]

This standard is issued under the fixed designation D6391; 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

~~1.1This test method covers field measurement of limiting values for vertical and horizontal hydraulic conductivities (also referred to as *coefficients of permeability*) of porous materials using the two-stage, cased borehole technique. These limiting hydraulic conductivity values are the maximum possible for the vertical direction and minimum possible for the horizontal direction. Determination of actual hydraulic conductivity values requires further analysis by qualified personnel.~~

~~1.2This test method may be utilized for compacted fills or natural deposits, above or below the water table, that have a mean hydraulic conductivity less than or equal to 1×10~~

1.1 This test method covers field measurement of hydraulic conductivity (also referred to as *coefficient of permeability*) of porous materials using a cased borehole technique. When isotropic conditions can be assumed and a flush borehole is employed, the method yields the hydraulic conductivity of the porous material. When isotropic conditions cannot be assumed, the method yields limiting values of the hydraulic conductivity in the vertical direction (upper limit) if a single stage is conducted and the horizontal direction (lower limit) if a second stage is conducted. For anisotropic conditions, determination of the actual hydraulic conductivity requires further analysis by qualified personnel.

1.2 This test method may be used for compacted fills or natural deposits, above or below the water table, that have a mean hydraulic conductivity less than or equal to 1×10^{-5} m/s (1×10^{-3} cm/s).

1.3 Hydraulic conductivity greater than 1×10^{-5} m/s may be determined by ordinary borehole tests, for example, U.S. Bureau of Reclamation 7310 (**1**)[2]; however, the resulting value is an apparent conductivity.

1.4 For this test method, 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 (**2**). The entrapped air prevents water from moving in air-filled ~~pores that, in turn,~~pores, which may reduce the hydraulic conductivity measured in the field by as much as a factor of two compared with conditions when trapped air is not present (**3**). This test method ~~simulates~~develops the "field-saturated" condition.

1.5 Experience with this test method has been predominantly in materials having a degree of saturation of 70 % or more, and where the stratification or plane of compaction is relatively horizontal. Its use in other situations should be considered experimental.

1.6 As in the case of all tests for hydraulic conductivity, the results of this test pertain only to the volume of soil permeated. Extending the results to the surrounding area requires both multiple tests and the judgment of qualified personnel. The number of tests required depends on among other things: the size of the area, the uniformity of the material in that area, and the variation in data from multiple tests.

1.7 The values stated in SI units are to be regarded as the standard unless other units specifically are given. By tradition in U.S. practice, hydraulic conductivity is reported in cm/s although the common SI units for hydraulic conductivity are m/s.

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

1.8.1 The procedures in this standard 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

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

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

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 this standard.

1.9 *This standard does not purport to address 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.* This test method does not purport to address environmental protection problems, as well.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D653 Terminology Relating to Soil, Rock, and Contained Fluids
D1452 Practice for Soil Exploration and Sampling by Auger Borings D1587
D1587 Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes D2937
D2937 Test Method for Density of Soil in Place by the Drive-Cylinder Method
D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction D5084
D5084 Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter
D5092 Practice for Design and Installation of Ground Water Monitoring Wells
D6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, see Terminology :

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *horizontal conductivity, k_h, n*—the hydraulic conductivity in (approximately) the horizontal direction.

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

3.2.2.1 *Discussion*—The term *coefficient of permeability* often is used instead of *hydraulic conductivity*, but *hydraulic conductivity* is used exclusively in this test method. A more complete discussion of the terminology associated with Darcy's law is given in the literature **(4)**. It should be noted that both natural soils and recompacted soils usually are not isotropic with respect to hydraulic conductivity. Except for unusual materials, $k_h > k_v$.

3.2.3 *limiting horizontal conductivity, K2, n*—the hydraulic conductivity as determined in Stage 2 of this test method, assuming the tested medium to be isotropic. For ordinary soils, both compacted and natural, this is the minimum possible value for k_h.

3.2.4 *limiting vertical conductivity, K1, n*—the hydraulic conductivity as determined in Stage 1 of this test method, assuming the tested medium to be isotropic. For ordinary soils, both compacted and natural, this is the maximum possible value for k_v.

3.2.5 *test diameter, n*—the inside diameter (ID) of the casing.

3.2.6 *vertical conductivity, k_v, n*—the hydraulic conductivity in (approximately) the vertical direction.

4. Summary of Test Method

~~4.1The rate of flow of water into soil through the bottom of a sealed, cased borehole is measured in each of two stages, normally with a standpipe in the falling-head procedure. The standpipe can be refilled as necessary.~~

~~4.2In Stage 1, the bottom of the borehole is flush with the bottom of the casing for maximum effect of k_v. The test is continued until the flow rate becomes quasi-steady.~~

~~4.3For Stage 2, the borehole is extended below the bottom of the casing for maximum effect of k_h. This stage of the test also is continued until the flow rate becomes quasi-steady.~~

~~4.4The direct results of the test are the limiting hydraulic conductivities~~

4.1 The rate of flow of water into soil through the bottom of a sealed and cased borehole is measured in one or two stages, normally with a standpipe using a falling-head or constant-head procedure. The standpipe is refilled as necessary. A schematic of the test apparatus is shown in Fig. 1 with the dimensions to be recorded.

4.2 *Method A*—Method A is used when the soil being tested is treated as anisotropic. A falling-head test is conducted in two stages with the bottom of the borehole flush with the bottom of the casing in Stage 1 and extended below the bottom of the casing as a right circular cylinder in Stage 2 (Fig. 1). The borehole is extended for Stage 2 after Stage 1 is completed. A limiting hydraulic conductivity is computed from the falling head data in both stages. These limiting hydraulic conductivities are *K1* and *K2*~~. The actual hydraulic conductivities~~ *, respectively.*

[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.

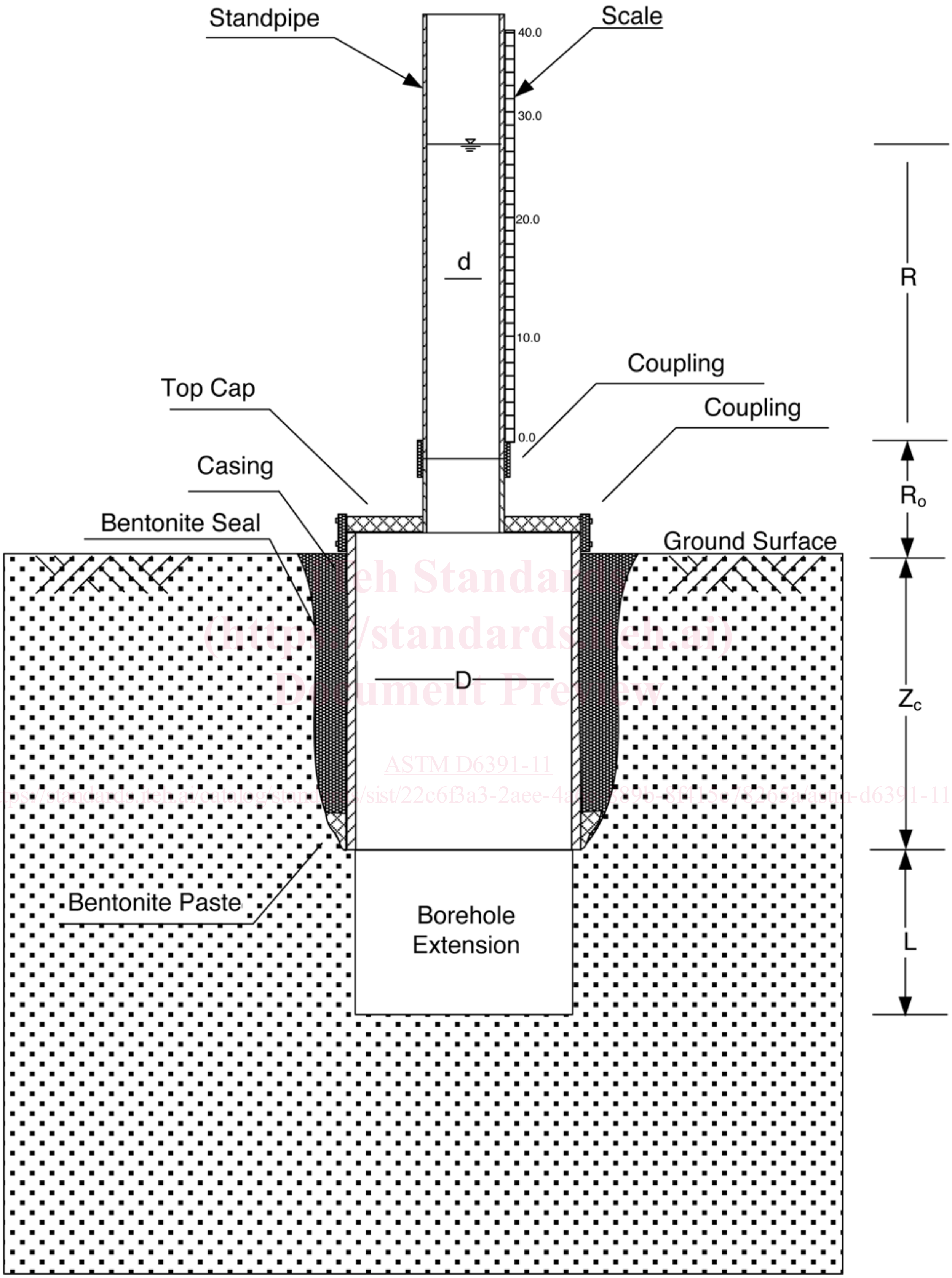


FIG. 1 Schematic of Borehole Test Showing Borehole Flush with Base (Methods B and C, Stage 1 of Method A) and with Extension for Stage 2 of Method A

Stages 1 and 2 are continued until the limiting conductivity for each stage is relatively constant.
Methods to calculate actual vertical and horizontal hydraulic conductivities (k_v and k_h~~can be calculated from these values~~) **from** *K1* **and** *K2* **are described in (5) and (6).**

4.3 *Method B*—Method B employs a falling head and is used when the soil being tested is treated as isotropic. A falling head test is conducted in a borehole flush with the bottom of the casing (Fig. 1). Hydraulic conductivity of the soil is computed from the falling head data. The test is continued until the hydraulic conductivity becomes essentially constant.

4.4 *Method C*—Method C employs a Mariotte tube to apply a constant head and is also used when the soil being tested is treated as isotropic. A constant head test is conducted in a borehole flush with the bottom of the casing. Hydraulic conductivity of the soil is computed from the steady flow rate measured during the test. The same apparatus and test set up is used for Methods B and C, except the falling-head standpipe used in Method B (Fig. 2a) is replaced by a constant-head Mariotte tube (Fig. 2b).

5. Significance and Use

5.1 This test method provides a means to measure ~~both~~ the hydraulic conductivity of isotropic materials and the maximum vertical and minimum horizontal hydraulic conductivities of anisotropic materials, especially in the low ranges associated with fine-grained clayey soils, 1×10^{-7} m/s to 1×10^{-11} m/s.

5.2 This test method ~~particularly~~ is useful for measuring liquid flow through soil ~~moisture~~hydraulic barriers, such as compacted clay ~~liners or covers~~ barriers used at waste ~~disposal~~containment facilities, for canal and reservoir liners, for seepage blankets, and for amended soil liners, such as those used for retention ponds or storage tanks. Due to the boundary condition assumptions used in deriving the equations for the limiting hydraulic conductivities, the thickness of the unit tested must be at least ~~six times the test diameter.~~ 600 mm. This requirement ~~must be~~ is increased to ~~eight test diameters~~ 800 mm if the ~~barrier is not~~ material being tested is underlain by a ~~drainage blanket or by a material~~ material that is far less ~~permeable than the barrier being tested.~~ permeable.

5.3 The soil layer being tested must have sufficient cohesion to stand open during excavation of the borehole.

5.4 This test method provides a means to measure infiltration rate into a moderately large volume of soil. Tests on large volumes of soil can be more representative than tests on small volumes of soil. Multiple installations properly spaced provide a greater volume and an indication of spatial variability.

5.5 The data obtained from this test method are most useful when the soil layer being tested has a uniform distribution of hydraulic conductivity and of pore space and when the upper and lower boundary conditions of the soil layer are well defined.

5.6 Changes in water temperature can introduce ~~significant~~ errors in the flow measurements. Temperature changes cause fluctuations in the ~~standpipe levels, which~~water levels that are not related to flow. This problem is most pronounced when a small diameter standpipe or Marriotte bottle is used in soils having hydraulic conductivities of 5×10^{-10} m/s or less.

~~5.7The effects of temperature changes are taken into account by the use of a dummy installation, the temperature effect gage (TEG). The base of the TEG must be sealed to prevent flow. The fluctuations of the TEG are due solely to ambient changes and are used to correct the readings at the flowing tests.~~

~~5.8If the soil being tested will later be subjected to increased overburden stress, then the hydraulic conductivities can be expected to decrease as the overburden stress increases. Laboratory hydraulic conductivity tests or these tests under varying surface loads are recommended for studies of the influence of level of stress on the hydraulic properties of the soil.~~

5.7 The effects of temperature changes and other environmental perturbations are taken into account using a temperature effect gauge (TEG), which is an identical installation with a watertight seal at the bottom of the casing.

5.8 If the soil being tested will later be subjected to increased overburden stress, then the hydraulic conductivities can be expected to decrease as the overburden stress increases. Laboratory hydraulic conductivity tests or these tests under varying surface loads are recommended to study the influence of level of stress on the hydraulic properties of the soil **(8)**.

NOTE~~1—Notwithstanding the statements on precision and bias contained in this standard: the precision of this test method is dependent on the competence of the personnel performing it and the suitability of the equipment and the facilities used. Agencies that meet the criteria of Practice~~ 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 ~~test method~~standard are cautioned that compliance with Practice D3740 does not in itself assure reliable ~~testing.~~results. Reliable ~~testing depends~~results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

6. Apparatus

6.1 *Boring/Reaming Tools*:

6.1.1 *Drilling Equipment*~~—Equipment must be available to advance the borehole to the desired test level. This borehole diameter must be at least 5 cm (2 in.) larger than the outside diameter of the casing. The auger or bit used to advance the borehole below the casing for Stage 2 shall have a diameter about 1 cm (½ in.) less than the inside diameter of the casing. For tests in compacted materials above the water table, and wherever else possible, the borehole shall be advanced by dry augering. Either hand or mechanical augers are acceptable.~~ —Equipment must be available to advance the borehole to the desired test level. This borehole diameter must be at least 50 mm larger than the outside diameter of the casing. For tests in compacted materials above the water table, and wherever else possible, the borehole shall be advanced by dry methods. Either hand or mechanical methods are acceptable.

6.1.2 *Flat Auger*~~—The~~—A flat auger (see Fig. ~~1~~3) ~~is~~ may be used to prepare the ~~borehole for casing installation. It shall~~

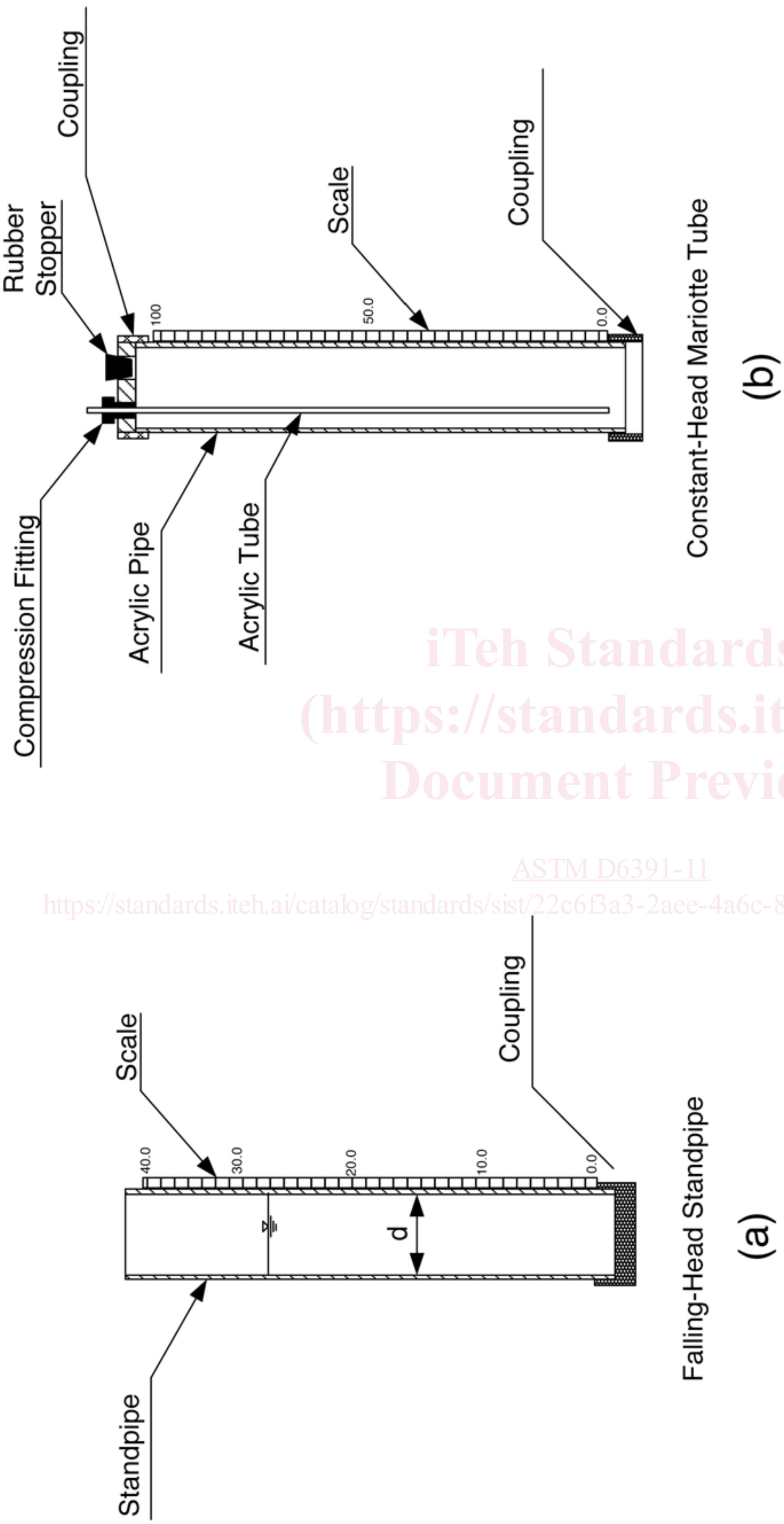
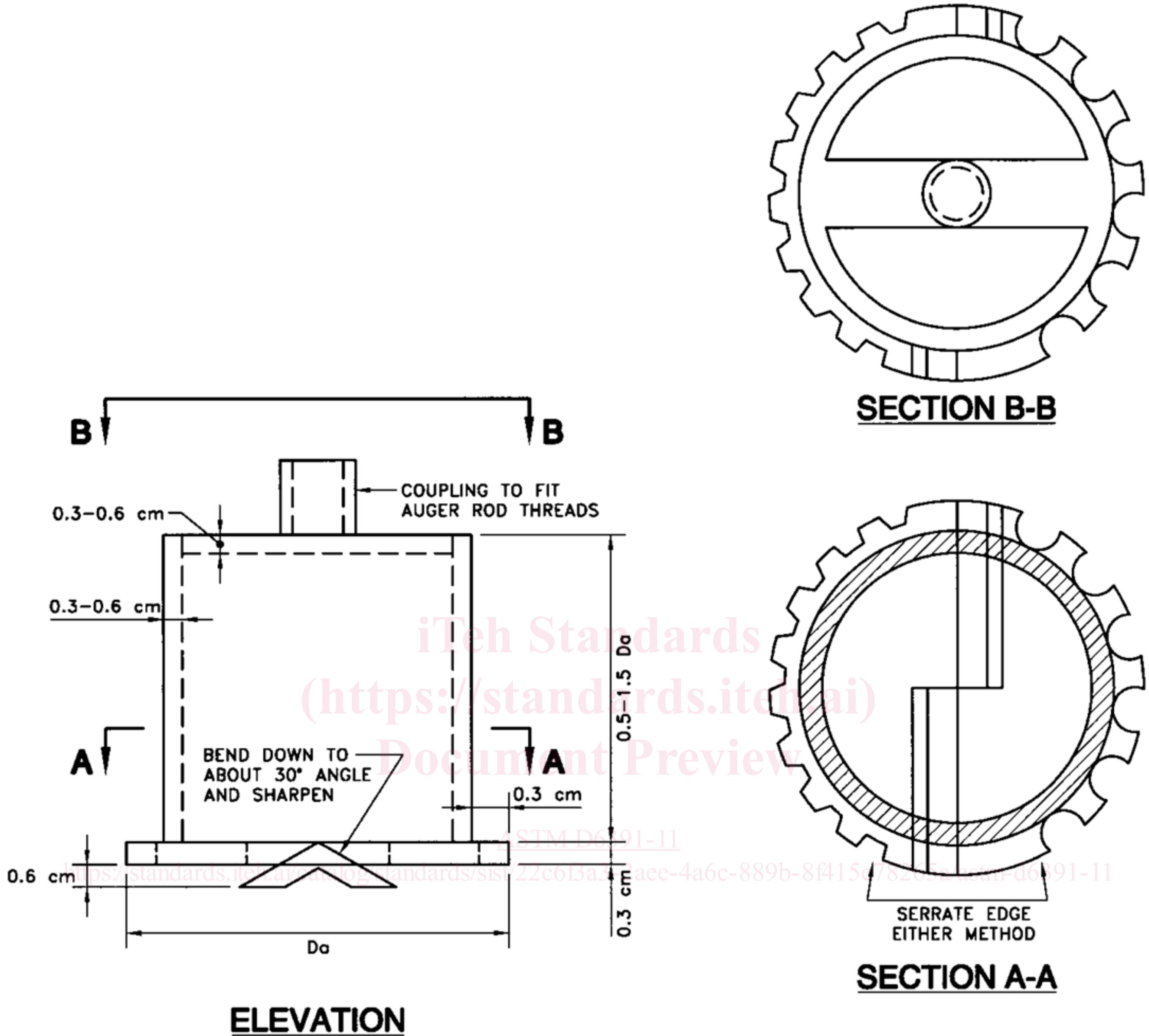


FIG. 2 Falling Head Standpipe (Methods A and B) (a) and Mariotte Tube (Method C) (b) Used for the Flow Assembly



NOTE—~~FIG. 3 D~~or the Flat Auger, D_o= D + 50 mm where D is the inside dia~~-S~~meter of the borehole casing. For the reamer, D_o= D – 1 mm.

FIG. 3 Schematic of Apparatus Used as Flat Auger (Borehole Excavation) and Reamer (Borehole Extension in Stage 2 of Method A)

borehole. The auger should be capable of reaming the bottom of the borehole to a level plane perpendicular to the borehole axis. The flat auger shall have a diameter about ~~5 cm (2 in.)~~50 mm larger than the outside diameter of the casing.

6.1.3 *Clay Spade*—A clay spade may be used to prepare the borehole for casing installation. The spade can also be used to create a level based in the bottom of the borehole.

6.1.4 *Reamer*~~—The~~—A reamer (see Fig. ~~1~~3) ~~is~~ may be used to complete the ~~Stage 2 cavity.~~ borehole extension for tests conducted with a second stage. The base of the reamer shall have a diameter slightly less than the inside diameter of the casing and shall be capable of reaming the bottom of the advanced borehole to a level plane that is perpendicular to the primary axis of the borehole. The bottom plate of the reamer shall have a diameter about ~~0.1 cm (0.04 in.)~~ 1 mm less than the inside diameter of the casing. The vertical side of the cutting plate ~~shall~~should be serrated.

~~6.1.4~~6.1.5 *Scarifier*~~—A bent fork, wire brush, or similar roughener small enough to fit easily within the casing and having a handle long enough to reach the bottom of Stage 2, is used to roughen the walls of the Stage 2 cavity.~~ —A bent fork, wire brush, or similar device for roughening the surface of the sidewall, which is small enough to fit within the casing and having a handle long enough to reach the bottom of Stage 2, is used to scarify the walls and base of the borehole extension for Stage 2.

6.2 *Borehole Casing*:

6.2.1 *Casing*~~—The casing shall be watertight but may be of any material or diameter. Its minimum ID shall be 10 cm (4 in.) unless the clearance provisions specified in 7.7 cannot be met. In such cases only, the ID may be reduced to 7.5 cm (3 in.). The wall thickness shall be adequate to prevent collapse under the lateral pressure of the overburden and swelling bentonite. Standard 10-cm (4-in.) ID Schedule 40 PVC threaded pipe is satisfactory. The bottom of the casing shall be cut off smooth and square. The casing shall have flush threads; external couplers interfere with sealing the annulus and internal couplers with advancing the borehole for Stage 2. Neither shall be used. The top of the casing shall be provided with a means of attaching the top assembly. Typical modifications include threading the top or attaching a flange. When threads are used, they must be flush. When a flange is used, the diameter shall be minimal so as not to interfere with sealing the annulus. Any casing joints and joint between top assembly and casing shall be provided with an O-Ring or other device to ensure watertightness.~~ —The casing shall be watertight but may be of any material or diameter. The minimum ID shall be 100 mm. The wall thickness shall be adequate to prevent collapse under the lateral pressure of the overburden and swelling bentonite. Schedule 40 PVC pipe is satisfactory. The bottom of the casing shall be smooth and square. The casing shall have flush connections for joints between the ground surface and the bottom of the casing; external connections interfere with sealing the annulus and internal connections affect advancing the borehole for Stage 2. The top of the casing shall be provided with a means of attaching the top assembly. When threads are used, they must be flush. When a flange is used, the diameter shall be minimal so as not to interfere with sealing the annulus. Any casing joints and joints between the top assembly and casing shall be provided with a means to ensure the joint is watertight.

6.2.2 ~~*Top Assembly*—This consists of a cap attached (normally by gluing) to a short piece of threaded casing, as illustrated in Fig. 2. The cap shall be domed or slanted upwards to minimize air entrapment. It shall be fabricated so as to receive the flow control system with a watertight joint. Provisions for bleeding any entrapped air shall be made. For the TEG (only), the top assembly also may be provided with a watertight fitting for the thermometer or thermocouple leads.~~ Top Cap—The top assembly consists of a cap that connects the casing to the standpipe as illustrated in Fig. 1. The cap may be domed or slanted upwards to minimize air entrapment and shall include a means to connect to the standpipe and casing with a watertight seal. Rubber couplings with hose clamps have been found satisfactory. Provisions for bleeding any entrapped air shall be made. For the TEG (only), the top assembly also may be provided with a watertight fitting for a device to measure temperature.

6.2.3 *Annular Sealant*—Bentonite is normally used to seal the annulus between the wall of the borehole and the wall of the casing. All sealants should be compatible with ambient geologic and geohydrologic conditions. ~~Do~~ Sealants shall not ~~introduce any sealants into~~be introduced to the interior of the casing.

6.2.3.1 *Directly Placed Sealant*~~—The annular sealant is best placed in the borehole dry and tamped for shallow installations. Bentonite should be granular or pelletized, sodium montmorillonite furnished in sacks or buckets from a commercial source and free of impurities, which adversely impact the sealing process. Pellets consist of roughly spherical or disk-shaped units of compressed bentonite powder. Granules consist of coarse particles of unaltered bentonite, typically smaller than 5 mm (0.2 in.). In order to reduce the potential for bridging, the diameter of pellets or granules selected should be less than one fifth the width of the annular space into which they are placed. The directly placed sealant shall extend to the ground surface or to a minimum of 1 m (3 ft) above the bottom of the casing, whichever is lesser. Either the placed sealant or the grouted sealant shall extend to the ground surface.~~ —The annulus shall be sealed with powdered or granular, sodium bentonite furnished in sacks or buckets from a commercial source. The bentonite shall be free of impurities that may adversely impact the sealing process. To reduce the potential for bridging, the diameter of granules should be less than one fifth the width of the annular space. The sealant shall extend to the ground surface or to a minimum of 1 m above the bottom of the casing, whichever is less.

6.2.3.2 *Grouted Sealant*—The annular space may be grouted above the ~~placed~~ sealant. Any of the grouting methods specified in Practice D5092 may be used.

6.2.3.3 *Sock*~~—The sock protects the soil at the bottom of the casing from disturbance when water is introduced and prevents collapse of the Stage 2 cavity. It is a cylinder composed of a semi-rigid, porous sidewall and bottom (such as a geogrid), lined with a geotextile, and filled with pea gravel or other highly pervious material. The hydraulic conductivity of all sock materials shall be at least ten times the anticipated hydraulic conductivity of the tested stratum in the horizontal direction. The outer diameter is 0.6 cm (¼ in.) less than the inner diameter of the casing. The length is approximately 8 cm (3 in.) longer than will be the borehole extension for Stage 2. Wires or other suitable means for retrieving the sock should be provided.~~ —The sock protects the soil at the bottom of the casing from disturbance when water is introduced and prevents collapse of the borehole extension for Stage 2. A non-woven geotextile, filled with pea gravel or other highly pervious material has been found satisfactory. The hydraulic conductivity of all sock materials shall be at least ten times the anticipated hydraulic conductivity of the tested stratum. Wires or other suitable means for retrieving the sock should be provided.

6.3 *Pressure/Flow System*:

6.3.1 ~~*Flow Control System*—The plumbing for the flow control system is illustrated in~~ Flow Monitoring System—The flow monitoring system illustrated in Fig. 2 ~~. It can be composed of metal or plastic components. All flow system components shall have a diameter of at least 75 % that of the standpipe. Nominal 13-mm (0.5-in.) components have been satisfactory for 10-cm (4-in.) diameter tests.~~ consists of a standpipe or Mariotte tube and scale composed of metal or plastic components. All connections shall have a diameter of at least 75 % that of the standpipe. Nominal 13-mm components have been satisfactory for tests with a 100-mm diameter casing.

6.3.2 *Standpipe*~~—The standpipe, also shown on Fig. 2, should be only as tall as needed to apply a maximum head (measured~~

~~at the bottom of the casing) equal to or less than the head allowable by hydraulic fracturing considerations; the hydraulic head at the bottom of the casing should not exceed 1.5 times the total overburden pressure at that level. The standpipe must be transparent and strong enough to withstand wind forces. Clear Schedule 40 PVC has been found satisfactory. Inside diameters of 1 to 2 cm (0.5 to 0.75 in.) have been satisfactory for 10-cm (4-in.) diameter tests. Provisions shall be made to prevent precipitation from entering the standpipe and to minimize evaporation from it, while allowing equalization of air pressure. One satisfactory method is to set a 90° elbow on the top of the standpipe, cover the elbow's outlet with aluminum or similar foil, and prick a small (1 mm ±) hole in the foil for air pressure equalization.~~ —The standpipe shown on Fig. 1 should be only as tall as needed to apply a maximum head (measured at the bottom of the casing) equal to or less than the head allowable by hydraulic fracturing considerations; the hydraulic head at the bottom of the casing should not exceed 1.5 times the total overburden pressure at that level. The standpipe must be transparent and strong enough to withstand wind forces. Clear Schedule 40 PVC has been found satisfactory. Inside diameters of 10 to 20 mm have been satisfactory for tests conducted with a 100-mm diameter casing. For 300-mm-diameter casing, standpipes with an inside diameter between 50 and 100 mm have been satisfactory. The diameter may need to be larger or smaller depending on the rate of infiltration in a particular test. The diameter may be changed to provide acceptable reading accuracy depending on the rate of infiltration into the borehole. Provisions shall be made to prevent entry of precipitation or loss by evaporation from the standpipe while ensuring the air pressure in the standpipe is in equilibrium with the atmosphere. One satisfactory method is to set a 90° elbow on the top of the standpipe, cover the outlet of the elbow with aluminum foil, plastic sheet, or parafilm, and puncture the covering with a small (approx. 1 mm) hole for air pressure equalization.

6.3.3 *~~Scale~~*~~—The standpipe should be graduated or a scale affixed; either must have a resolution of 1 mm (1⁄16 in.). If a scale is used, its base should be on a known reference point of the flow control system, which can be readily reestablished.~~ Mariotte Tube—A Mariotte tube is used for constant head tests (Fig. 2b). The tube shall be large enough to permit unimpeded flow of air during permeation. Clear acrylic tubes having an inside diameter of 10 mm have been satisfactory for tests conducted with a100-mm diameter casing. For 300-mm-diameter casing, standpipes with an inside diameter between 50 and 100 mm have been satisfactory. The diameter may be changed to provide acceptable reading accuracy depending on the rate of infiltration into the borehole.

6.3.4 *Scale*—The standpipe or Mariotte tube shall be graduated or a scale shall be affixed; either must have a resolution of 1 mm. If a scale is used, the base shall be set at a known reference point of the flow monitoring system that can be readily reestablished.

6.3.5 *Watch*—Readable to 1 s.

~~6.3.5~~

6.3.6 *Miscellaneous Hand Tools*—Adjustable and pipe wrenches, flathead screwdriver, knife, strap wrenches (two) to fit casing, silicone ~~grease, such as~~ grease (e.g., automotive fan belt ~~lubricant, PTFE (polytetrafluoroethylene)~~lubricant), polytetrafluoroethylene (PTFE) tape, refill hose, funnel to fit refill hose, 100-mL plastic cylinder flask.

6.4 *Temperature System*—A ~~thermometer or thermocouple, readable to 0.5°C~~device for measuring temperature ±0.5 °C with a range sufficient to cover the anticipated air and water temperatures during the test and long enough to extend to the bottom of the TEG.

6.5 *Survey Equipment*—Surveyor's level and rod, and a 15 to 30-m ~~(50 to 100-ft)~~ tape.

6.6 *Miscellaneous*:

6.6.1 *Plastic Sheeting*—Clear or white plastic sheeting, nominal thickness at least 0.1 ~~mm (5 mils).~~ mm. Provide one 3 by 3 m ~~(10 by 10 ft)~~ sheet per test, including the TEG.

6.6.2 *Water Supply*—Preferably water of the same quality as that involved in the problem being examined but having a turbidity of 5 ~~Nephelometric Turbidity Units~~nephelometric turbidity units (NTU) or less. Only potable water should be used if there is a possibility that the introduced water could enter the groundwater regime. All water to be introduced into the test apparatus shall be allowed to stand open at least 12 h prior to use for deairing. See 8.3.3 for temperature requirements.

6.6.3 *Antifreeze*—Where air temperatures below freezing are anticipated, an antifreeze solution may be used as the permeating fluid in lieu of water. The temperature-kinematic viscosity relation of the solution must be determined and used in the appropriate equations of Section 9. Ethanol (ethyl alcohol) in potable form has been used in Table 1~~. Ethanol at concentrations of 1:1 or stronger can cause structural changes in the soil and should not be used. However, it is the responsibility of the user to obtain any necessary regulatory approval for the solution used, since groundwater pollution may result from antifreeze compounds. The user is advised that soil freezing/thawing will change its hydraulic conductivity.~~ . Ethanol at concentrations of 1:1 or stronger can cause structural changes in the soil and should not be used. Groundwater pollution may result from the use of antifreeze compounds. The user is responsible for obtaining any necessary regulatory approval for the solution used. The user is advised that soil freezing and

TABLE 1 Ethanol Proportions

Minimum Temperature, (°C)	Proportion Water/Ethanol
–5	5:1
–10	3:1
–15	2.3:1
–20	1.8:1
–25	1.5:1

thawing can alter the hydraulic conductivity. Tests shall not be conducted on soil that is frozen or is undergoing freezing and thawing during the test.

6.6.4 *Vacuum Cleaner (Optional)*—An industrial-type vacuum cleaner can be used to clear cuttings, etc., from the ~~bottoms~~bottom of ~~Stages 1 and 2.~~ the borehole.

6.6.5 *Aluminum Foil*—1 roll.

6.6.6 *Rubber Bands.*

6.6.7 *Flashlight.*

7. Test Site

~~7.1On a compacted fill, each~~ 7.1 Each individual test requires an area approximately ~~4~~3 by ~~4 m (13 by 13 ft).~~ 3 m. Tests shall not be located closer than ~~40 test diameters~~ 3-m center-to-center. A group of at least five tests is suggested for evaluation of a typical test pad ~~(up to 20 by 25 m)~~ for ~~waste-retention structures.~~ waste containment facilities. Larger areas may require more tests and the program should be designed on a sound statistical basis.

7.2 The layer being tested must maintain its full thickness at least ~~30 test diameters~~3 m horizontally in all directions from the center of the test.

7.3 Stratification or the plane of compaction should be essentially horizontal.

7.4 If a compacted fill is being tested, the test area shall be covered with clear or white plastic immediately after the final lift is placed.

~~7.5Compacted fills typically are underlain by either a permeable layer, such as a drainage blanket or an impermeable layer, such as a geomembrane. Such conditions shall be recorded, together with the phreatic surface, if any, within the fill. See Practice~~

7.5 Compacted fills shall be underlain by a soil layer no less permeable than intended for the fill or a permeable layer such as a geotextile, geocomposite drain, or sand layer. Such conditions shall be recorded, together with the phreatic surface, if any, within the fill. See Practice D1452 ~~for determining the phreatic surface. Where no such bottom condition exists, the nature of the underlying soil and depth to the groundwater phreatic surface shall be furnished. The thickness of the tested material near each test location shall be determined to the nearest 2 cm (1 in.) by before-and-after survey or post-test borings.~~

~~7.6In natural deposits, the stratigraphic sequence to at least ten test diameters below the proposed bottom level for Stage 2 shall be determined by borings, or test pits, or both, and the position of the phreatic surface in the tested stratum also determined. Borings or test pits shall not be made within 3.6 m (12 ft) of the test location before the test; any borings within 10 m (30 ft) of the test location shall be grouted prior to testing. Any test pits within this distance shall be backfilled prior to testing. Test pits shall not be made closer to the test location than half the test pit depth.~~

~~7.7The minimum allowable thickness for the layer being tested depends on the boundary conditions. Minimum allowable test geometries are given below for typical cases. Here, "relatively pervious" means having an estimated vertical hydraulic conductivity at least ten times that of the layer being tested, and "relatively impervious" means having an estimated hydraulic conductivity less than 1⁄10 that of the layer being tested.~~

~~7.7.1Where the layer being tested extends to the ground surface and is underlain by either a relatively pervious or relatively impervious layer, the thickness of the layer being tested shall not be less than six times the test diameter. The casing shall extend at least 2.5 test diameters below the top of the ground surface and the bottom of Stage 2 shall be at least 2.0 test diameters above the bottom of the stratum being tested, leaving room for a Stage 2 extension of 1.5 test diameters. If the underlying material does not meet the criteria specified in 7.7, the bottom of Stage 2 shall be at least 4.0 test diameters above the bottom of the stratum being tested. The casing embedment remains the same, so that the required thickness of the layer being tested becomes 8.0 test diameters.~~

~~7.7.2Where the layer being tested does not extend to the ground surface but is overlain by a relatively pervious material, the clearances specified in 7.7.1 shall apply except that the casing shall extend at least 2.5 test diameters below the top of the stratum being tested. If the overlying stratum is relatively impervious, the casing shall extend at least 5.0 diameters below the top of the stratum being tested, for a minimum test layer thickness of 8.5 to 10.5 test diameters.~~ for determining the phreatic surface. Where no such bottom condition exists, the nature of the underlying soil and depth to the groundwater phreatic surface shall be furnished. The thickness of the tested material near each test location shall be determined to ±10 mm before-and-after survey or post-test borings.

7.6 In natural deposits, the stratigraphic sequence shall be determined by borings, or test pits, or both to at least 1 m below the proposed bottom level for Stage 2 and the position of the phreatic surface in the tested stratum shall be determined. Borings or test pits shall not be made within 3 m of the test location before the test; any borings within 10 m of the test location shall be grouted prior to testing. Any test pits within this distance shall be backfilled prior to testing. Test pits shall not be made closer to the test location than half the test pit depth.

8. Procedure

8.1 *Set and Seal Casing*~~—This is the single most important step in the entire procedure and must be done with care.~~ —This important step must be done with care.

8.1.1 *Minimum Clearances*—When the layer being tested extends to the ground surface and is underlain by a layer having substantially different hydraulic conductivity, the casing shall extend at least 200 mm below the ground surface and be no closer than 200 mm from the bottom of the stratum being tested, including the borehole extension for Stage 2. If the layer being tested does not extend to the ground surface, but is overlain by a relatively pervious material, the casing shall extend at least 200 mm below the top of the stratum being tested. If the overlying stratum is relatively impervious, the casing shall extend at least 500 mm below the top of the stratum being tested.

8.1.2 *Drill Borehole*—Drill the borehole in a direction perpendicular to the stratification or plane of compaction, which may or may not be perpendicular to the ground surface. The angle of inclination, if any, shall be measured and reported. The hole must be at least 5 cm (2 in.) larger in diameter than the outside diameter of the casing. Stop the borehole when its maximum depth (usually the point of the auger or bit) is at least 2.5 cm (1 in.) above the desired bottom-of-casing level. Dry augering without the use of drilling fluids is preferred; see Note 2.

NOTE2—Sealing in wet holes cannot be controlled as well as in dry holes and the results may be somewhat less representative.

8.1.2*Ream Borehole*—Using the flat auger, ream the borehole to depth and to a diameter about 5 cm (2 in.) larger than the outside diameter of the casing. The bottom shall be smooth, flat, and free from cuttings, or particles, or both, exceeding ¼ the test diameter. An industrial-type vacuum cleaner can be used for this cleaning.

8.1.3*Insert Casing*—Set the casing within and parallel to the axis of the borehole, centered as much as possible, with a minimum 2.5 cm (1.0 in.) annular space between the wall of the borehole and the outside of the casing. The top of the casing should be as close to ground surface as possible, but not less than 2 cm (1 in.) for internally threaded casing or 2 cm (1 in.) plus the length of the threaded section for an externally threaded casing. Seat the casing firmly by hand. Measure the depth from top-of-casing to bottom-of-hole to ensure proper depth and seating. —Excavate the borehole in a direction perpendicular to the stratification or plane of compaction, which may or may not be perpendicular to the ground surface. The angle of inclination, if any, shall be measured and reported. The hole must be at least 50 mm larger in diameter than the outside diameter of the casing. Stop mechanical excavation at least 25 mm above the desired bottom-of-casing level. Dry excavation is preferred to the use of drilling fluids.

8.1.3 *Finish Borehole*—Finish the excavation with a hand tool to create a smooth and flat bottom. A reamer can be used for this purpose. Ensure the borehole is free from cuttings and particles larger than 10 mm. An industrial-type vacuum cleaner can be used to clean the borehole.

8.1.4 *Insert Casing*—Set the casing within and parallel to the axis of the borehole, centered as much as possible, with a minimum 25 mm annular space between the wall of the borehole and the outside of the casing. For threaded casings, the top of the casing should be as close to ground surface as possible, but not less than 20 mm for internally threaded casing or 20 mm plus the length of the threaded section for externally threaded casing. Seat the casing firmly by hand. Measure the depth from top-of-casing to bottom-of-hole (Zc) to the nearest mm.

8.1.5 *Seal Casing (Dry Holes)*—For dry holes, first crush bentonite to form a well-graded mixture ranging from powder to about 0.2 cm (1⁄16 in.) in a sufficient quantity to fill to a depth of about 1 cm (0.5 in.) of the annulus. Pour this mixture into the annulus with a uniform distribution, then, add sufficient dry crushed or pelletized bentonite to fill the annulus another 1 cm (0.5 in.). Tamp this layer lightly with a wooden dowel, or equivalent, smaller than the minimum annulus. Introduce water until it is just visible at the top of the bentonite. Note and record whether or not water has entered the interior of the casing. Add 2.5 cm (1 in.) of dry crushed or pelletized bentonite, tamp as before, and add water as before. Continue in these 2.5-cm (1-in.) increments to the ground surface, or a minimum of 1 m (3 ft) above the bottom of the casing for deep installations. Sealing above that level shall extend to the ground surface, and may be with the same procedure or by grouting in accordance with Practice —In a dry hole, the annulus is sealed with sodium bentonite placed in at least two layers. The lowermost layer shall consist of hydrated bentonite paste prepared with water and the bentonite used to seal the remainder of the annulus. The paste layer shall be tamped in place. Thickness of the paste layer shall be at least 20 mm but no more than 50 mm. The remainder of the annulus shall be sealed with dry powdered or granular sodium bentonite placed in layers no more than 50 mm thick. Each layer shall be moistened with water after placement and then tamped with a wooden dowel, or equivalent, smaller than the minimum annulus.

NOTE 2—For deep installations, the bentonite seal shall extend a minimum of 1 m above the bottom of the casing. Sealing above 1 m to the ground surface may be with the same procedure or by grouting in accordance with Practice D5092. Upon completion of sealing, note and record whether water has entered the interior of the casing, and remeasure the depth from top-of-casing to bottom-of-hole to ensure that the casing has not moved.

8.1.5.

8.1.6 *Seal Casing (Wet Holes)*—The following procedure shall be used where there is seepage of groundwater into the borehole at or above test level. The casing shall be pushed (not driven) approximately 2 cm (1 in.) 25 mm into the soil at the bottom of the borehole. Sufficient bentonite pellets to fill approximately 8 cm (3 in.) 75 mm of the annular space shall be placed and tamped. Additional bentonite layers shall be placed in the same manner until the seal reaches at least 1 m (3 ft) above the bottom-of-casing level. Hydration water shall be added if the top of the seal rises above the water level in the annulus. Sealing above the 1 m (3 ft) level may be by the same procedure or by grouting in accordance with Practice D5092. After the seal has hydrated a minimum of 12 h, empty the casing, and use the reamer to advance the borehole to exactly the bottom-of-casing level. If the tested stratum is pervious, empty the casing only to groundwater level to avoid disturbance of the tested stratum from water flow into the casing. Set the sock, then introduce and remove water as necessary to remove suspended solids.

8.1.6*Surface Protection*—For tests in compacted fills, replace the clear or white plastic square around the casing. Use sand, gravel, sandbags, or other weights to keep the plastic in place during high winds. Place a cap over the casing top to prevent desiccation or rainfall entry during the hydration period. . After the seal has hydrated a minimum of 12 h, empty the casing, and