Designation: D6391 – 11

Standard Test Method for 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

1.1 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, 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 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 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.

[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.

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 Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes

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 Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter

D5092 Practice for Design and Installation of Groundwater Monitoring Wells

D6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions:*

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

4.1 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*, respectively.

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) 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 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 is useful for measuring liquid flow through soil hydraulic barriers, such as compacted clay barriers used at waste 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 600 mm. This requirement is

[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.

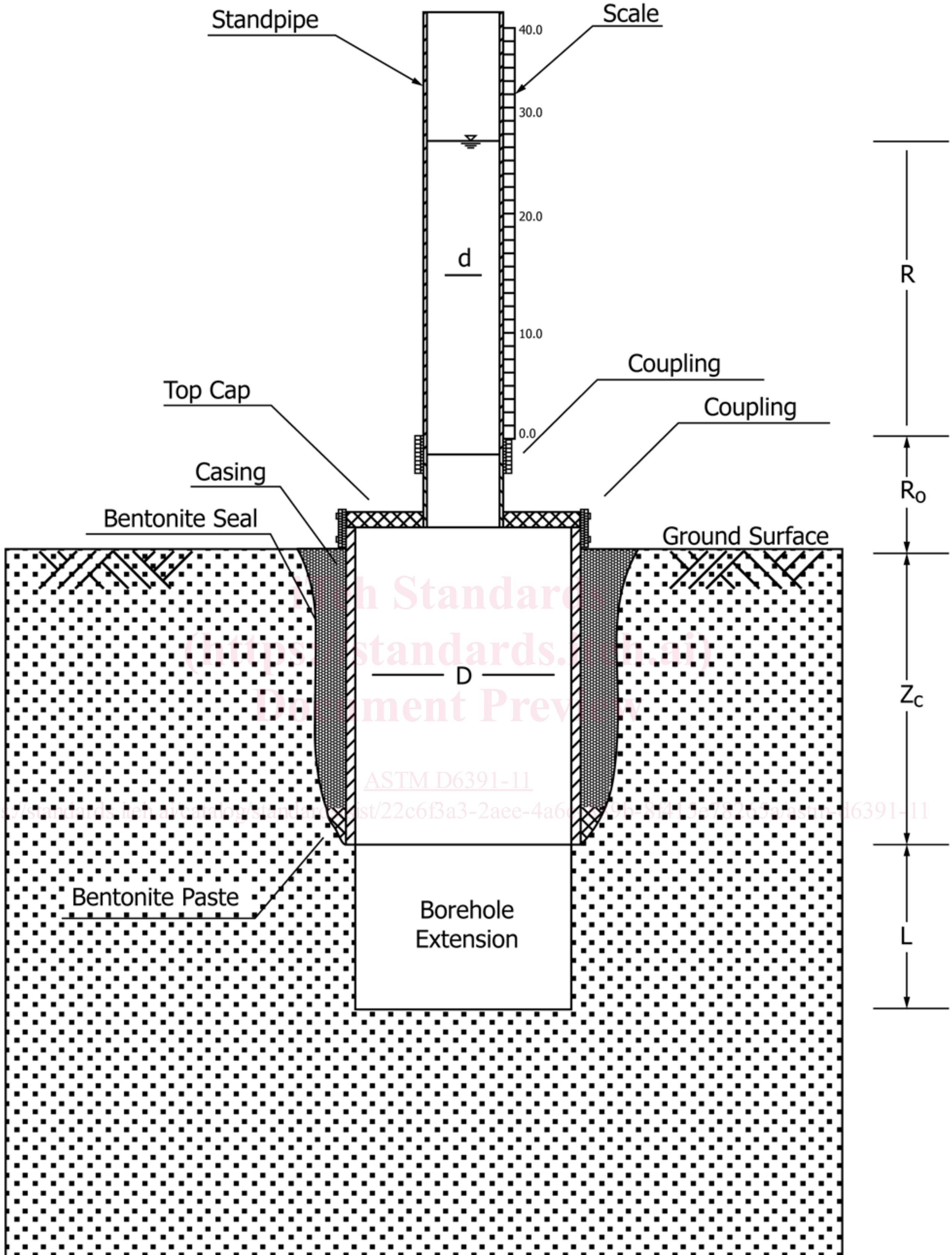


FIG. 1 Schematic of Borehole Test Showing Borehole Flush with Base (Methods B and C, Stage 1 of Method A) and with Extension for Stage 2 of Method A

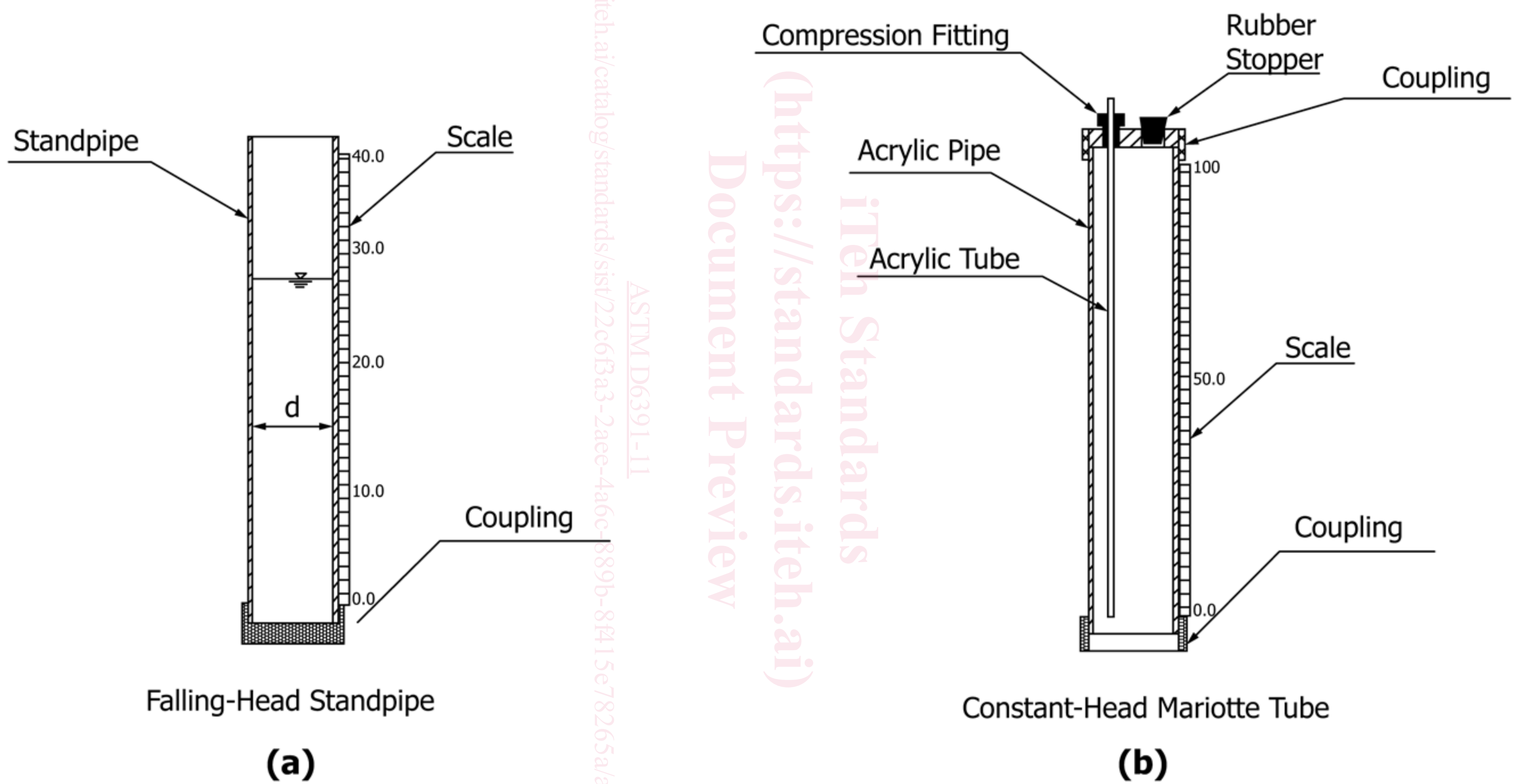


FIG. 2 Falling Head Standpipe (Methods A and B) (a) and Mariotte Tube (Method C) (b) Used for the Flow Assembly

increased to 800 mm if the material being tested is underlain by a material that is far less 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 errors in the flow measurements. Temperature changes cause fluctuations in the 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.

5.7 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 (**7**).

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 that compliance with Practice D3740 does not in itself assure reliable results. Reliable 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 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*—A flat auger (see Fig. 3) may be used to prepare the 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 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*—A reamer (see Fig. 3) may be used to complete the 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 1 mm less than the inside diameter of the casing. The vertical side of the cutting plate should be serrated.

6.1.5 *Scarifier*—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:*

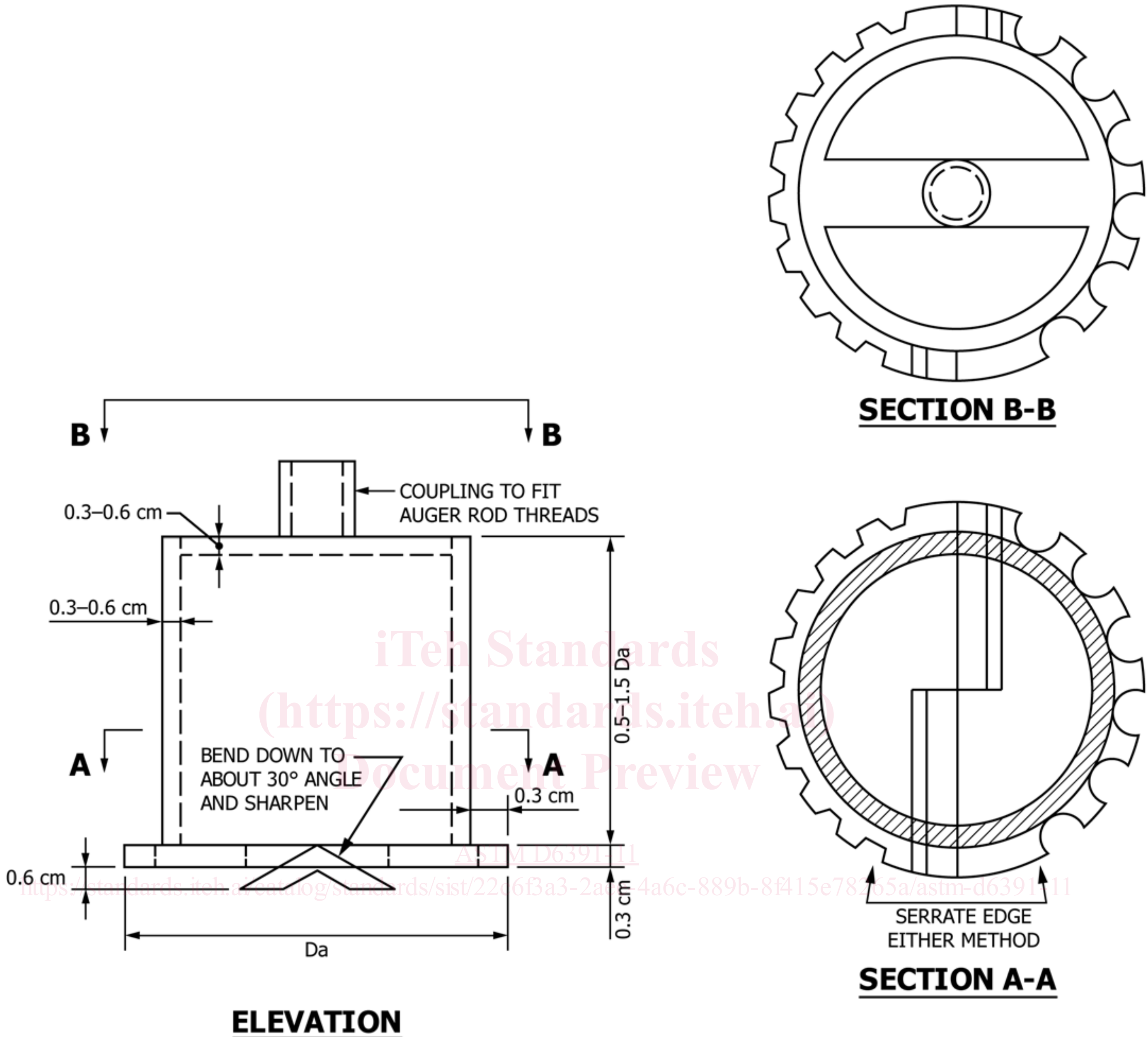
6.2.1 *Casing*—The casing shall be watertight but may be of any material or diameter. The minimum ID shall be 100 mm. The wall thickness shall be adequate to prevent collapse under the lateral pressure of the overburden and swelling bentonite. Schedule 40 PVC pipe is satisfactory. The bottom of the casing 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 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. Sealants shall not be introduced to the interior of the casing.

6.2.3.1 *Directly Placed Sealant*—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 sealant. Any of the grouting methods specified in Practice D5092 may be used.



NOTE 1—For the Flat Auger, D_o = D + 50 mm where D is the inside diameter 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)

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 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 Monitoring System*—The flow monitoring system illustrated in Fig. 2 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 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