Designation: D 6391 – 99 (Reapproved 2004)

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

This standard is issued under the fixed designation D 6391; 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 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.

1.2 This 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 $1 \times 10^{-5}$ m/s ($1 \times 10^{-3}$ cm/s).

1.3 Hydraulic conductivity greater than $1 \times 10^{-5}$ 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, 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 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 *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]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids
D 1452 Practice for Soil Investigation and Sampling by Auger Borings
D 1587 Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes
D 2937 Test Method for Density of Soil in Place by the Drive-Cylinder Method
D 3740 Practice for Minimum Requirements for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
D 5084 Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter
D 5092 Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers

[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.

[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.

D 5126 Guide for Comparison of Field Methods for Determining Hydraulic Conductivity in the Vadose Zone

## 3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, see Terminology D 653.

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, 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.

4.2 In 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.

4.3 For 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.

4.4 The direct results of the test are the limiting hydraulic conductivities *K1* and *K2*. The actual hydraulic conductivities $k_v$ and $k_h$ can be calculated from these values **(5)**.

## 5. Significance and Use

5.1 This test method provides a means to measure both the maximum vertical and minimum horizontal hydraulic conductivities, especially in the low ranges associated with fine-grained clayey soils, $1\times10^{-7}$ m/s to $1\times10^{-11}$ m/s.

5.2 This test method particularly is useful for measuring liquid flow through soil moisture barriers, such as compacted clay liners or covers used at waste disposal 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. This requirement must be increased to eight test diameters if the barrier is not underlain by a drainage blanket or by a material far less permeable than the barrier being tested.

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 are not related to flow. This problem is most pronounced when a small diameter standpipe is used in soils having hydraulic conductivities of $5\times10^{-10}$ m/s or less.

5.7 The 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.

5.8 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 for studies of the influence of level of stress on the hydraulic properties of the soil.

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 D 3740 are generally considered capable of competent and objective testing. Users of this test method are cautioned that compliance with Practice D 3740 does not in itself assure reliable testing. Reliable testing depends on many factors; Practice D 3740 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.

6.1.2 *Flat Auger*—The flat auger (see Fig. 1) is used to prepare the borehole for casing installation. It shall 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.) larger than the outside diameter of the casing.

6.1.3 *Reamer*—The reamer (see Fig. 1) is used to complete the Stage 2 cavity. The base of the reamer shall be capable of reaming the bottom of the advanced borehole to a level plane, perpendicular to the borehole axis, and having the inside diameter of the casing. The bottom plate of the reamer shall have a diameter about 0.1 cm (0.04 in.) less than the inside diameter of the casing. The vertical side of the cutting plate shall be serrated.

6.1.4 *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.

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.

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.

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 not introduce any sealants into 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.

6.2.3.2 *Grouted Sealant*—The annular space may be grouted above the placed sealant. Any of the grouting methods specified in Practice D 5092 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.

6.3 *Pressure/Flow System*:

6.3.1 *Flow Control System*—The plumbing for the flow control system is 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.

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.

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.

6.3.4 *Watch*—Readable to 1 s.

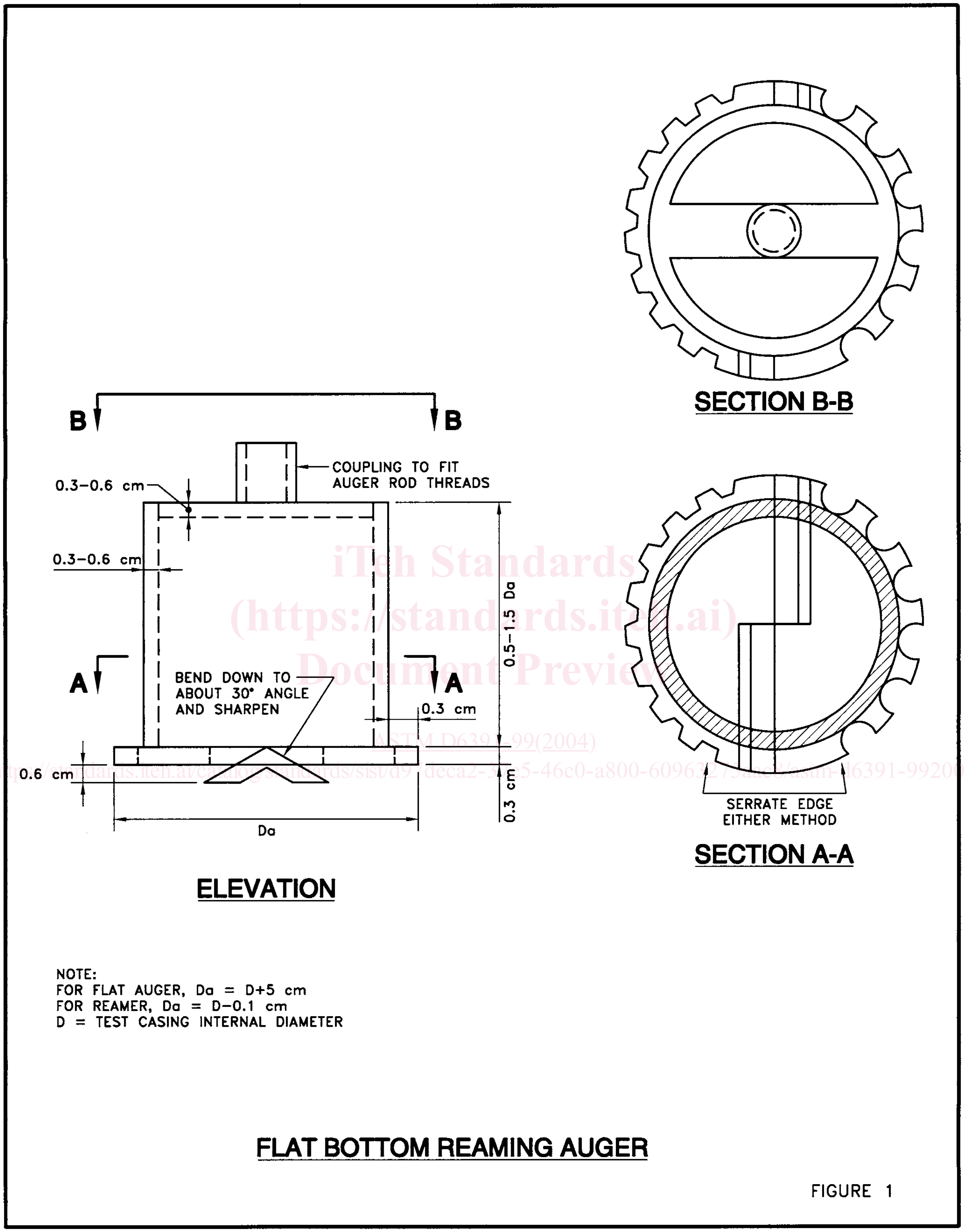


**FIG. 1 Flat Bottom Reaming Auger**

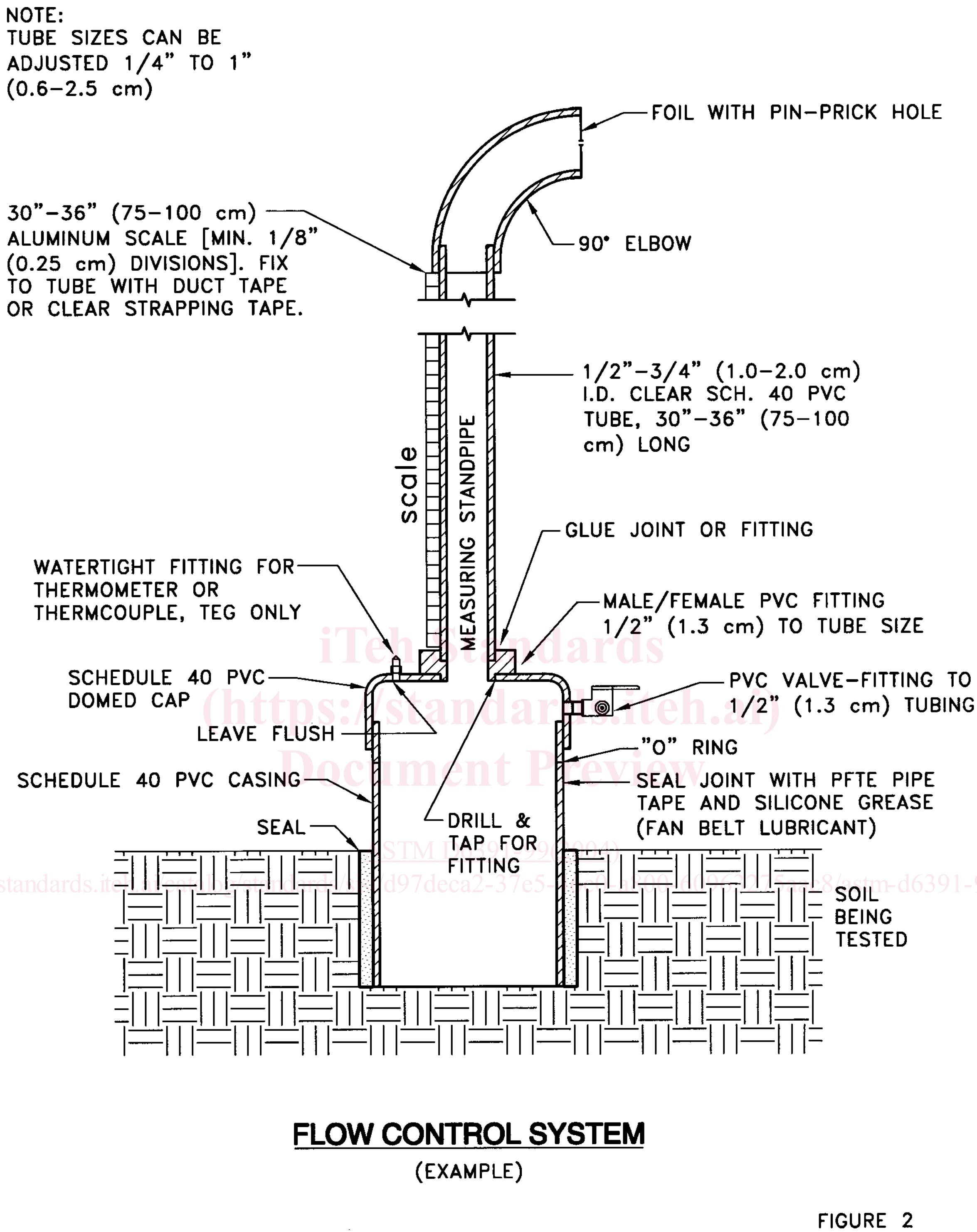


**FIG. 2 Flow Control System (Example)**

6.3.5 *Miscellaneous Hand Tools*—Adjustable and pipe wrenches, knife, strap wrenches (two) to fit casing, silicone grease, such as automotive fan belt lubricant, PTFE (polytetrafluoroethylene) 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 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). 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 (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.

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

6.6.5 *Aluminum Foil*—1 roll.

6.6.6 *Rubber Bands.*

6.6.7 *Flashlight.*

## 7. Test Site

7.1 On a compacted fill, each individual test requires an area approximately 4 by 4 m (13 by 13 ft). Tests shall not be located closer than 40 test diameters 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. 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 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.

7.5 Compacted 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 D 1452 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.

7.6 In 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.

7.7 The 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 a vertical permeability at least ten times that of the layer being tested, and "relatively impervious" means having a permeability less than 1⁄10 that of the layer being tested.

7.7.1 Where 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.

7.7.2 Where 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.

## 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.

8.1.1 *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

**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 |