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 1×10^{-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, 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

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[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, 1×10^{-7} m/s to 1×10^{-11} m/s.

5.2 This test method particularly is useful for measuring liquid flow through soil moisture 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 5×10^{-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.

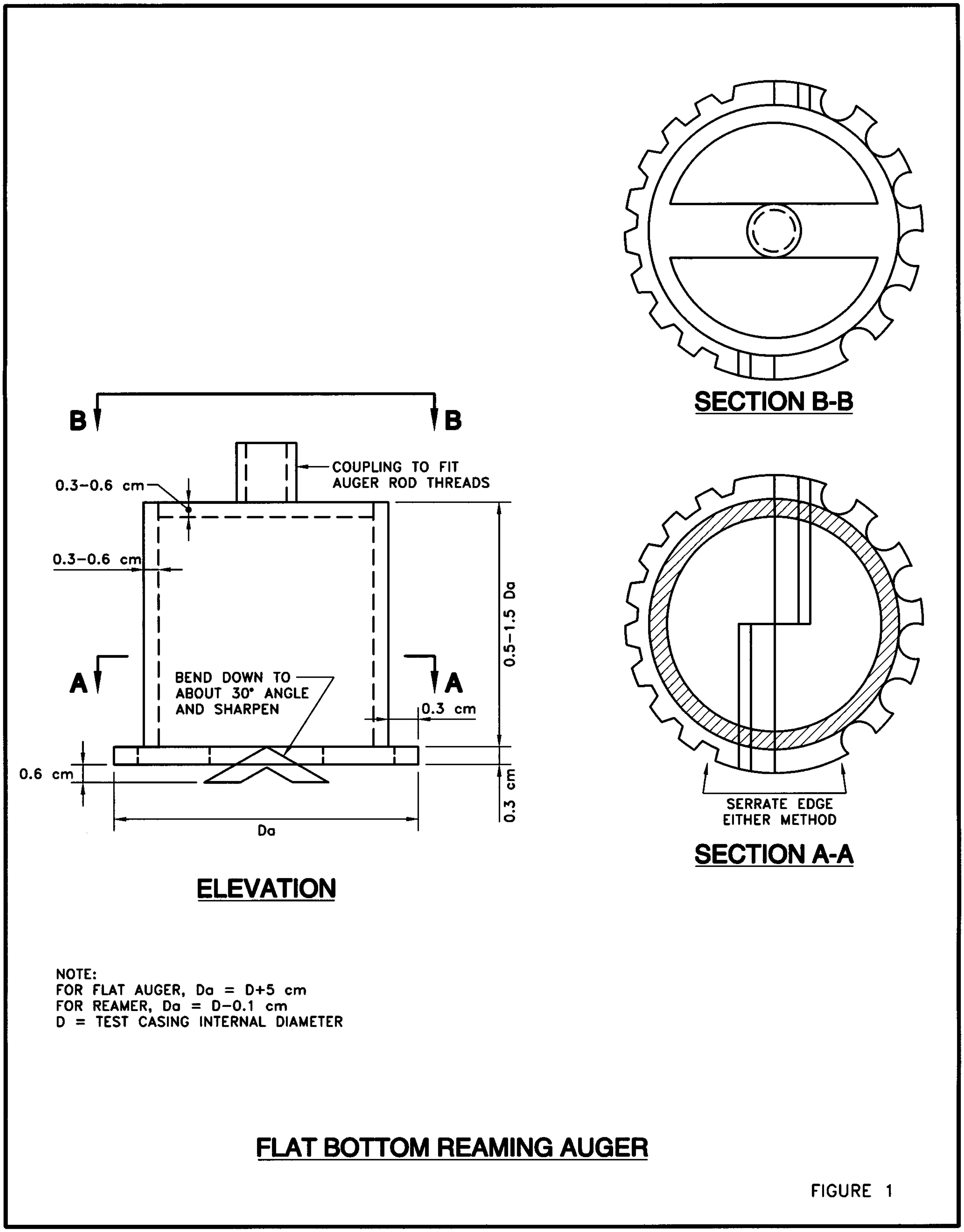
6.3 *Pressure/Flow System*:

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.



NOTE:
FOR FLAT AUGER, Da = D+5 cm
FOR REAMER, Da = D–0.1 cm
D = TEST CASING INTERNAL DIAMETER

FIG. 1 Flat Bottom Reaming Auger

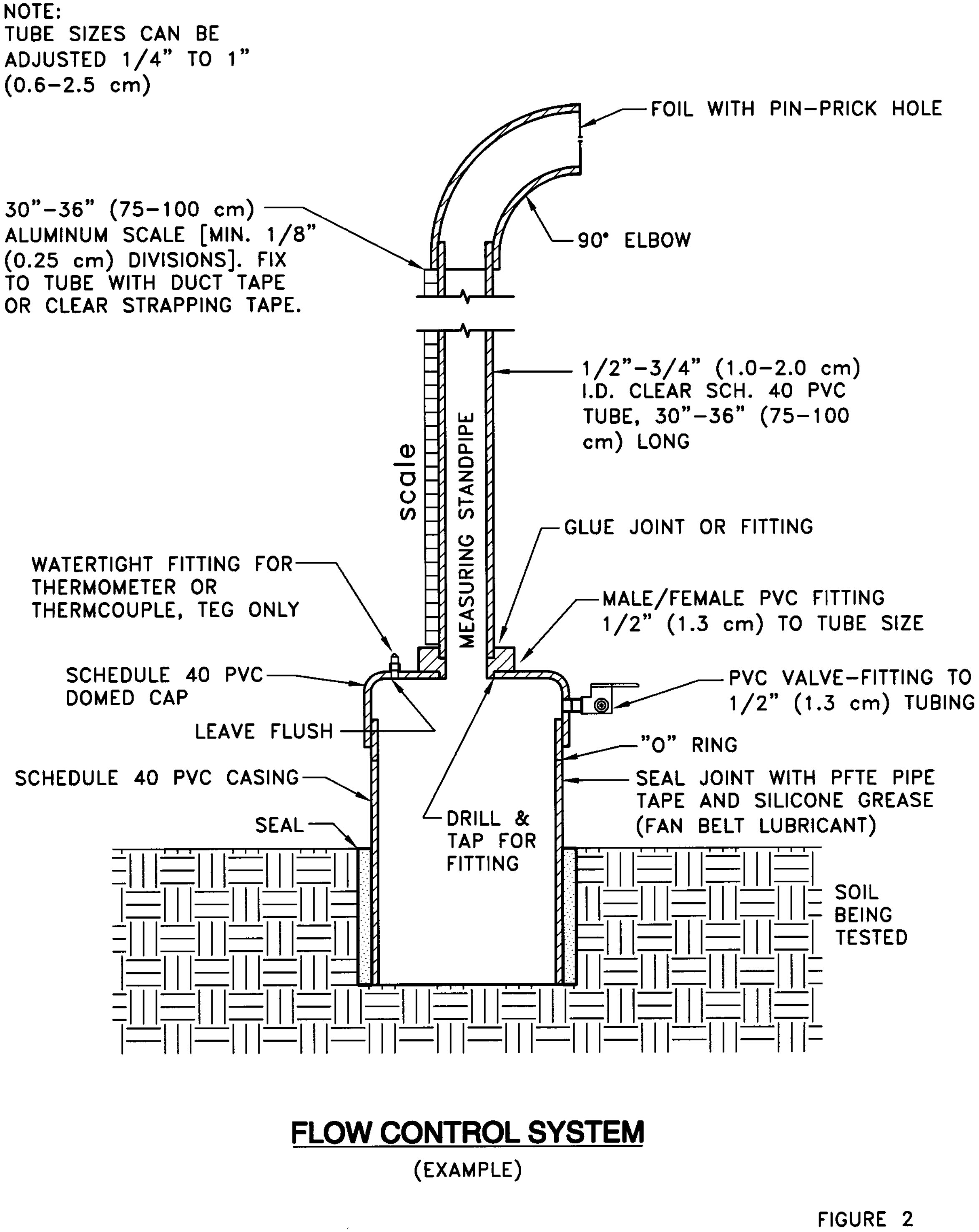


FIG. 2 Flow Control System (Example)

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.

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

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 $\frac{1}{10}$ 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 bottom-of-casing level. Dry augering without the use of drilling fluids is preferred; see Note 2.

NOTE 2—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.

8.1.4 *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 D 5092. 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 *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.) into the soil at the bottom of the borehole. Sufficient bentonite pellets to fill approximately 8 cm (3 in.) 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 D 5092. 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.

8.1.7 *Hydration*—Allow the bentonite (and grout, if any) to hydrate a minimum of 12 h before applying head to the test.

8.1.8 *Temperature Effect Gage*—This unit is to be set in the same manner as described above, except that the borehole is slightly deeper to accommodate the bottom cap, it is not necessary to ream the hole bottom flat, and crushing bentonite for the bottom 1 cm (0.5 in.) of the seal can be omitted.

8.2 *Assemble Flow Control System and Standpipe*—The cap, flow control system, and standpipe should be assembled as illustrated on Fig. 2. PTFE tape and silicone grease should be used to waterproof all joints. Check the assembly for leaks by attaching it to a spare TEG casing and filling with water. No leakage can be tolerated.

8.3 *Conduct Stage 1*:

8.3.1 *Check Embedment*—Recheck the casing to ensure the correct embedment has been maintained. Also, note and record the presence or absence of water inside the casing; if present, record the depth.

8.3.2 *Insert Sock*—Place the sock to the bottom of the casing, unless done previously. Tying the retrieval wires to a small (half the casing diameter or less) float aids in their recovery.

8.3.3 *Fill Casing*—Fill the casing slowly with water, but no higher than 2 cm (1 in.) below the base of any internal threads. Introduce the water in such a manner that it does not erode the exposed soil at the bottom of the casing. The water should be warmer than the soil in the tested zone, or groundwater if present above bottom-of-casing, to prevent air bubbles from coming out of solution.

8.3.4 *Add Flow Control System and Standpipe*—Screw the top assembly with these items onto the casing, sealing the joint with the O-Ring, PTFE tape, and silicone grease. Prevent casing rotation with a strap wrench while tightening the top assembly. Attach the scale to the standpipe with clear wrapping tape or equivalent means, with the zero down. Measure and record the distance from the bottom of the casing to the zero point on the scale.

8.3.5 *Fill and Check Test System*—Open the valve (Fig. 2) and fill the remainder of the casing, flow control system, and standpipe with water, making sure that no air bubbles are trapped in the cap or flow control system. The maximum water level should not exceed that which produces the theoretical hydraulic fracturing pressure at the bottom of the casing. All filling should be via the refill hose, not down the standpipe, so as to avoid having water droplets above the water level in the standpipe. Close the filling valve. Check the casing/cap joint and all other joints carefully for water leaks by wiping the joints dry and watching for the formation of water drops at the joints. No leakage can be tolerated.

8.3.6 *Begin Stage 1 of the Test*—Record the date and time (to 1 s), plus the scale reading corresponding to the bottom of the meniscus of the water in the standpipe. Take additional such readings at least according to the schedule in Table 2, using whichever method produces the greater number of readings. Thereafter, the frequency of readings will depend on the behavior of the test. In soils of low hydraulic conductivity, daily or twice-daily readings may be adequate after two to three days. At each reading of the test, record the scale reading and bottom water temperature of the TEG. A typical form for recording test data is given in Fig. 3.

8.3.7 *Refills*—One standpipe full of water may not be adequate for a full Stage. When the water level in the standpipe becomes low, record the water level and refill in the same manner as the initial filling of the standpipe. Record the new water level and its associated time, TEG reading, and TEG temperature and note as "refill". When the person conducting the test will be away for some length of time, such as overnight, check the drop rate against the expected time to determine whether or not refilling is necessary.

8.3.8 *Criteria for Termination*—Each stage may be terminated when a plot of log (limiting conductivity) versus log (time) fluctuates about a stable value of apparent conductivity. This is achieved when arithmetic time-weighted averages (see Eq 10 and Eq 11) neither fluctuate by more than 20 % nor show an upward or downward trend with time. These averages must maintain the above behavior for at least the time spans listed in Table 3.

8.4 *Conduct Stage 2*:

NOTE 3—If the test is solely to verify that the actual vertical hydraulic conductivity, k_v , is less than some specified value and the limiting vertical conductivity, *K1*, is less than that value, Stage 2 may be omitted.

8.4.1 *Empty the Casing*—Remove the top assembly with its attached equipment. Siphon, vacuum, or bail, or a combination thereof, all water from within the casing for tests where the casing is set in a dry hole. Otherwise, siphon/vacuum/bail to the groundwater level of the stratum being tested. Remove the sock.

TABLE 2 Reading Intervals

Elapsed Time, h	Total Change in Scale Reading (cm)	(in)
0.5	2	1
1.0	5	2
2.0	10	4
4.0	20	8
8.0	40	16

8.4.2 *Advance the Borehole*—Extend an open borehole having the same diameter as the inside of the casing to a depth below bottom-of-casing not less than 1.0 test diameters nor more than 2.5 test diameters. The soil being tested shall continue for at least the clearances listed in 7.7. It is desirable to secure an undisturbed sample of the tested zone with a thinwall sampler (see Practice D 1587 or Test Method D 2937), but this is not recommended for soils containing gravel-sized particles (retained on the No. 4 Sieve). The thinwall sampler or auger/bit shall have a diameter 1 cm (0.5 in.) or more smaller than the casing ID, and sampling or drilling shall be terminated with the deepest point being at least 2 cm (1 in.) above the proposed bottom of the borehole.

8.4.3 *Ream the Borehole*—Ream the borehole to the desired depth and diameter using the reamer to minimize sidewall smear. Roughen the inside walls using the scarifier discussed in 6.1.4. The bottom should be prepared as outlined in 8.1.2.

8.4.4 *Replace the Sock*—Place the sock to the bottom of the borehole. Alternatively, but only where an inclusion of high-conductivity material in the tested stratum is of no consequence, the hole may be filled to 8 cm (3 in.) above the casing bottom with pea gravel.

8.4.5 *Reassemble the System*—Refill the casing with water as described in 8.3.3, reattach and seal the top assembly with its equipment, and refill the standpipe through the refill hose. Concurrently, empty and refill the TEG with water having the same temperature (within 1°C) as that used in the test.

8.4.6 *Perform Stage 2*—Conduct this portion of test as outlined previously for Stage 1. The termination criteria are the same. See Fig. 3 for a typical form for recording the data.

8.5 *Demobilization*—Remove and store the top assembly with its attached systems. For tests in compacted fills, empty the casing, remove sock and casing, then backfill the resulting hole with layers of tamped and wetted bentonite pellets or as directed. Casings for tests in natural deposits can be left as piezometers or plugged and abandoned like monitoring wells, as directed.

9. Calculation

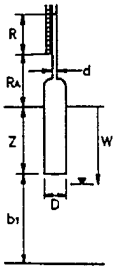
9.1 *Equations*—The data from the tests shall be calculated using the following equations **(5)**. Alternate equations are given in Ref. **(6)**, but have not been verified by application.

9.1.1 *Stage 1*:

$$K1 = R_t \; G1 \; Ln(H1/H2')/(t_2 - t_1)(cm/s) \quad (1)$$

where:

$$G1 = (\pi d^2/11D_1)[1+a(D_1/4b_1)] \quad (2)$$



STAGE 1 CALCULATIONS

d = 1.27 cm

D = 11.43 cm

Z = 61.0 cm

R_A = 22.9 cm

b_1 = 61.0 cm

$\Delta V = 0.785d^2(\Delta R) = 1.27\,\Delta R$

$H = R + (R_A + W)$; $[W \leq Z + b_1 \leq 20D_1]$

H = R+ 144.8

$K_1 = R_T G_1 \frac{\ln(H_1/H'_2)}{t_2 - t_1}$

$= 0.0384\, R_T \frac{\ln(H_1/H'_2)}{t_2 - t_1}$

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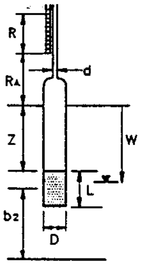
Date	Time	Δt= (t_2-t_1) (sec.)	TEST UNIT			TEG			$H'_2 = H_2 - C$ (cm)	Temp. (°C)	Rt Factor	K1 (cm/sec)	Cum. Vol. (cc)	Cum. Hrs.	Remarks
			R (cm)	H1 (cm)	H2 (cm)	Ro (cm)	Rf (cm)	C=Rf−Ro (cm)							
8/01	0800	–	64.8	-	209.6	–	65.0	0.0	–	21	–	–	0.0	0.0	START
	0830	1800	47.8	209.6	192.6	65.0	65.0	0.0	192.6	21	0.97	1.76×10^{-6}	21.5	0.5	
	0900	1800	36.3	192.6	181.1	65.0	65.0	0.0	181.1	21	0.97	1.27×10^{-6}	36.0	1.0	
	1000	3600	19.7	181.1	164.5	65.0	65.2	0.2	164.3	22	0.96	9.99×10^{-7}	57.1	2.0	END RUN
	1001	–	66.7	–	211.5	–	65.2	–	–	22	–	–	–	2.0	REFILL
	1200	7140	47.0	211.5	191.8	65.2	65.8	0.6	191.2	23	0.94	5.09×10^{-7}	82.0	4.0	
							etc.								
8/05	1700	-	50.0	-	194.8	-	67.0	–	-	26	–	–	-	105.0	REFILL
8/06	0800	54000	38.1	194.8	182.9	67.0	64.2	-2.8	185.7	19	0.94	3.20×10^{-8}	205.5	120.0	STOP



STAGE 2 CALCULATIONS

d = 1.27 cm

D = 10.16 cm

Z = 61.0 cm

R_A = 22.9 cm

b_2 = 53.3 cm

L = 15.2 cm

$\Delta V = 0.785d^2(\Delta R) = 1.27\,\Delta R$

$H = R + (R_A + W)$; $[W \leq Z + b_1 \leq 20D_1]$

H = R+ 144.8

$K_2 = R_T G_2 \frac{\ln(H_1/H'_2)}{t_2 - t_1}$

$= 0.0157\, R_T \frac{\ln(H_1/H'_2)}{t_2 - t_1}$

Project: Twin Pines

File No.: C9404-27

Test No.: FP-1

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Date	Time	Δt= (t_2-t_1) (sec.)	TEST UNIT			TEG			$H'_2 = H_2 - C$ (cm)	Temp. (°C)	Rt Factor	K2 (cm/sec)	Cum. Vol. (cc)	Cum. Hrs.	Remarks
			R (cm)	H1 (cm)	H2 (cm)	Ro (cm)	Rf (cm)	C=Rf−Ro (cm)							
8/06	0930	–	65.4	-	210.2	–	64.3	–	–	20	–	–	0.0	0.0	START
	1000	1800	59.4	210.2	204.2	64.3	64.3	0.0	204.2	21	0.99	2.49×10^{-7}	7.6	0.5	
	1030	1800	54.3	204.2	199.1	64.3	64.5	0.2	188.9	22	0.96	2.19×10^{-7}	14.1	1.0	
	1130	3600	45.7	199.1	190.5	64.5	64.8	0.3	190.2	23	0.94	1.87×10^{-7}	24.9	2.0	
	1330	7200	33.3	190.5	178.1	64.8	66.1	1.3	176.8	24	0.91	1.48×10^{-7}	40.6	4.0	
						e	tc								
8/09	0730	52200	21.3	197.0	166.1	66.9	62.9	-4.0	170.1	16	1.01	4.49×10^{-8}	252.6	70.0	
	1600	30600	9.2	166.1	154.0	62.9	64.0	1.1	152.9	19	1.07	4.56×10^{-8}	267.9	78.5	STOP

FIGURE 3

FIG. 3 Data Sheet

TABLE 3 Minimum Stable Time Spans

Limiting Conductivity *K1* or *K2* (m/sec)	Stable Time Span, h
$>10^{-8}$	12
10^{-8}– 10^{-9}	24
10^{-9}– 10^{-10}	48
10^{-10}– 10^{-11}	72

R_t = ratio of kinematic viscosity of permeant at temperature of test permeant during time increment t_1 to t_2 to that of reference fluid and temperature. For most tests, this means water at 20°C (68°F) (see Table 1 of Test Methods D 5084 for water as the permeant),

d = ID of standpipe (cm),

D_1 = effective diameter of Stage 1 (cm), equals ID of casing under dry hole conditions when no inward seepage was noted when setting casing, otherwise equals outside diameter of casing:

a = +1 for impermeable base at b_1,
= 0 for infinite (+20D_1) depth of tested material,
= –1 for permeable base at b_1, and

b_1 = thickness of tested layer between bottom of casing and top of underlying stratum (cm).

$H1$ = effective head at beginning of time increment (cm), equal to distance from top of water in standpipe to top of underlying stratum or groundwater, whichever is shallower. For calculation purposes, *H1* shall not exceed the height of the water column above the bottom of the casing plus 20 test diameters,

$H2'$ = corrected effective head (cm) at end of time increment, calculated in the same manner as *H1*, = $H2– c$,

c = change in TEG scale reading between times t_1 and t_2 (cm). An increase in the height of water in the TEG standpipe is positive,

t_1 = time at beginning of increment(s), and

t_2 = time at end of increment(s).

9.1.2 *Stage 2*:

$$K2 = R_t\ G2\ Ln(H1/H2')/(t_2–t_1)(cm/s) \tag{3}$$

$$G2 = (d^2/16FL)G3 \tag{4}$$

$$G3 = 2Ln(G4)+\text{a}\ Ln(G5) \tag{5}$$

$$G4 = L/D + [1+(L/D)^2]^{1/2} \tag{6}$$

$$G5 = \frac{[4b_2/D+L/D]+[1+(4b_2/D+L/D)^2]^{1/2}}{[4b_2/D–L/D]+[1+(4b_2/D–L/D)^2]^{1/2}} \tag{7}$$

$$F = 1 – 0.5623\ \text{Exp}\ (–1.566\ L/D) \tag{8}$$

where:

L = length of Stage 2 extension below bottom of casing (cm),

D = ID of Stage 2 extension (cm). It shall be equal to the casing ID, and

b_2 = distance from center of Stage 2 extension to top of underlying stratum or groundwater (cm).

The other terms are as previously defined.

9.2 Calculate *K1* for each time increment of Stage 1 using Eq 1.

9.3 Calculate cumulative infiltration volume (*V1*) through the end of each Stage 1 time increment using Eq 9.

$$V = (\pi d^2/4)\ \Sigma\ (H1–H2')\ (cm/^2) \tag{9}$$

9.4 Calculate the time-weighted average *K1′* of the *K1* values of Stage 1 for its quasi-steady period only using Eq 10.

$$K1' = \Sigma K1_i\ (t_2–t_1)_i/\Sigma(t_2–t_1)_i\ (cm/s) \tag{10}$$

where:

i = a specific time increment.

9.5 Calculate *K2* for each time increment of Stage 2 using Eq 3.

9.6 Calculate cumulative infiltration volume (*V2*) through the end of each Stage 2 time increment using Eq 9.

9.7 Calculate the time-weighted average *K2′* of the *K2* values of Stage 2 for its quasi-steady period only using Eq 11.

$$K2' = \frac{\Sigma K2_i(t_2–t_1)_i}{\Sigma(t_2–t_1)_i}\ (cm/s) \tag{11}$$

10. Report

10.1 Report the following information:

10.1.1 A data sheet such as the one shown in Fig. 3 for each Stage (including project identification and test location),

10.1.2 A log-log plot of limiting hydraulic conductivity versus time, such as that shown in Fig. 4,

10.1.3 The time-weighted average values, *K1′* and *K2′*,

10.1.4 Thickness of layer tested, and

10.1.5 A description of material beneath the layer tested.

10.2 Additional optional information that can be presented in the report includes the following:

10.2.1 Total and dry density of the layer tested.

10.2.2 Initial water content of the layer tested.

10.2.3 Initial degree of saturation.

10.2.4 Water contents of samples taken after termination of test, with locations and depths referenced to the test.

10.2.5 Classification data on the layer tested.

10.2.6 Laboratory tests for hydraulic conductivity on the layer tested.

11. Precision and Bias

11.1 *Precision*—Due to the nature of the soil or rock materials tested by this test method, it is either not feasible or too costly at this time to produce multiple specimens, which have uniform physical properties. Any variation observed in the data is just as likely to be due to specimen variation as to operator or other testing variations. Subcommittee D18.04 welcomes proposals that would allow for development of a valid precision statement.

11.2 *Bias*—There is no accepted reference value for this test method; therefore, bias cannot be determined.

12. Keywords

12.1 horizontal hydraulic conductivity; in-place hydraulic activity; vertical hydraulic conductivity

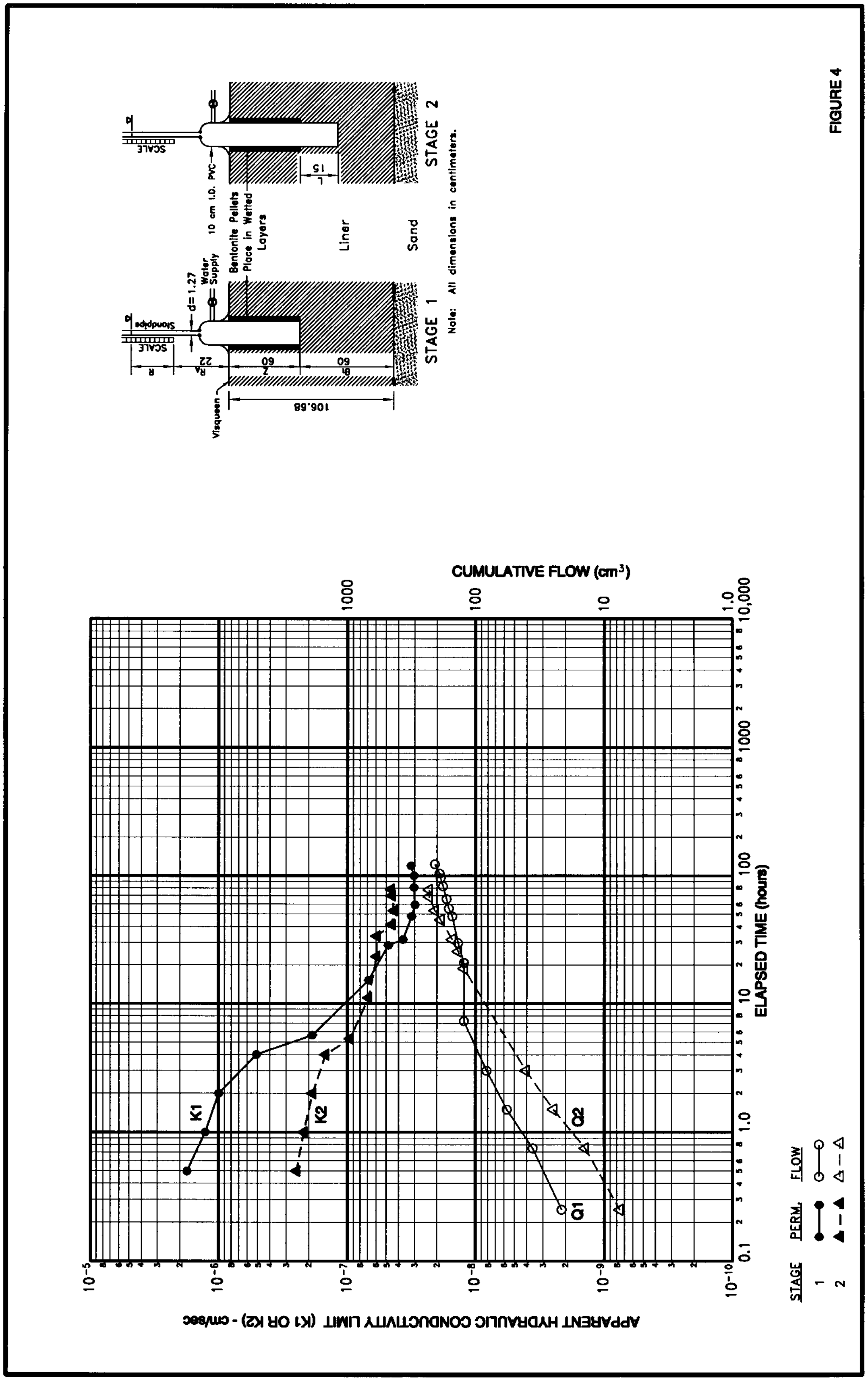

FIG. 4 Log Plot

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(**1**) U.S Department of the Interior, Bureau of Reclamation, Earth Manual, Part 2, Third Edition, 1990.

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(**5**) Trautwein, S. and Boutwell, G., "In-Situ Hydraulic Conductivity Tests for Compacted Soil Liners and Caps," *Hydraulic Conductivity and Waste Contaminant Transport in Soils, ASTM STP 1142*, ASTM International, 1994, p. 184–223.

(**6**) Cahpvis, R., "Shape Factors for Permeability Tests in Borehole and Piezometers,"*Groundwater*, Vol. 27, No. 5, 1989

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