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.

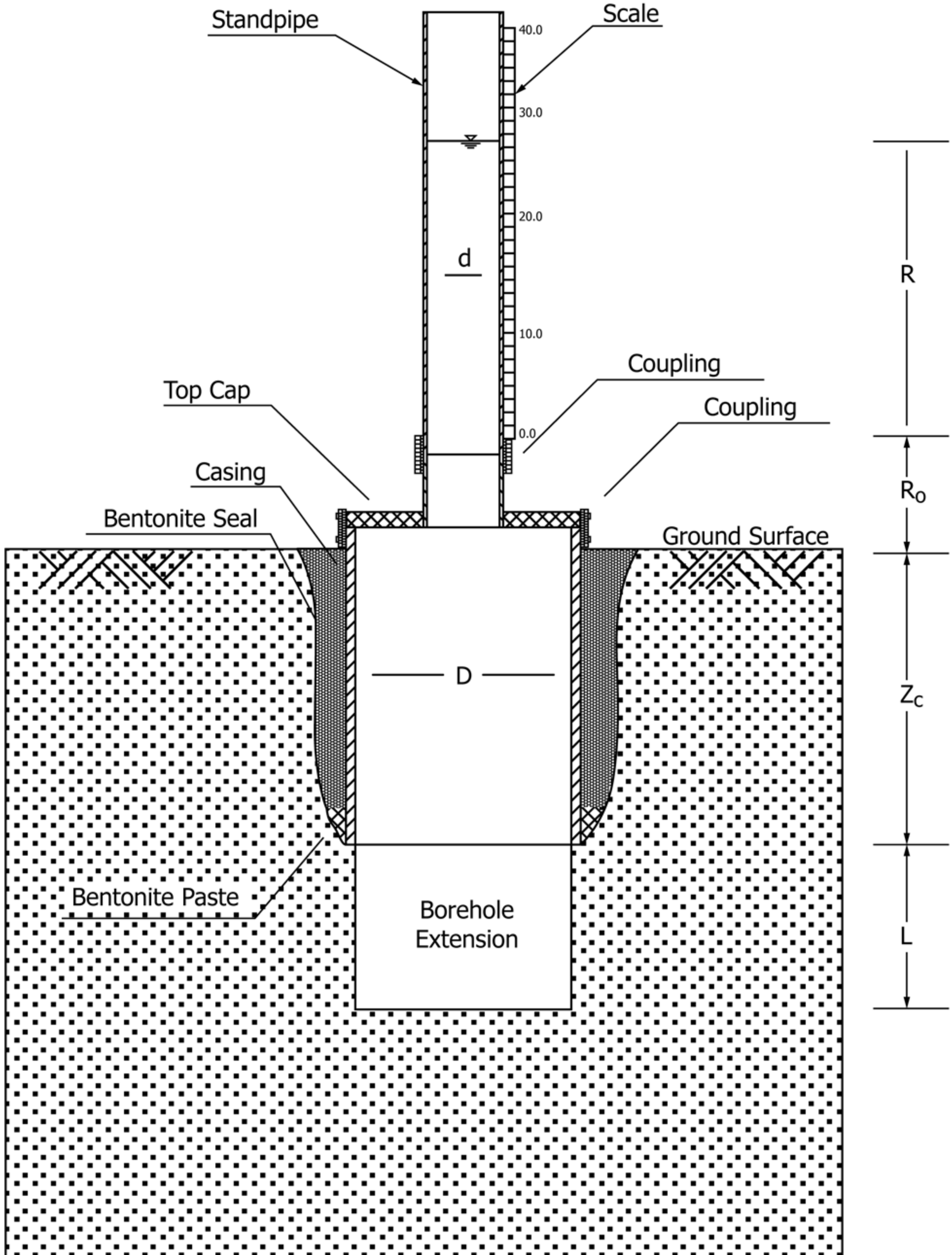


FIG. 1 Schematic of Borehole Test Showing Borehole Flush with Base (Methods B and C, Stage 1 of Method A) and with Extension for Stage 2 of Method A

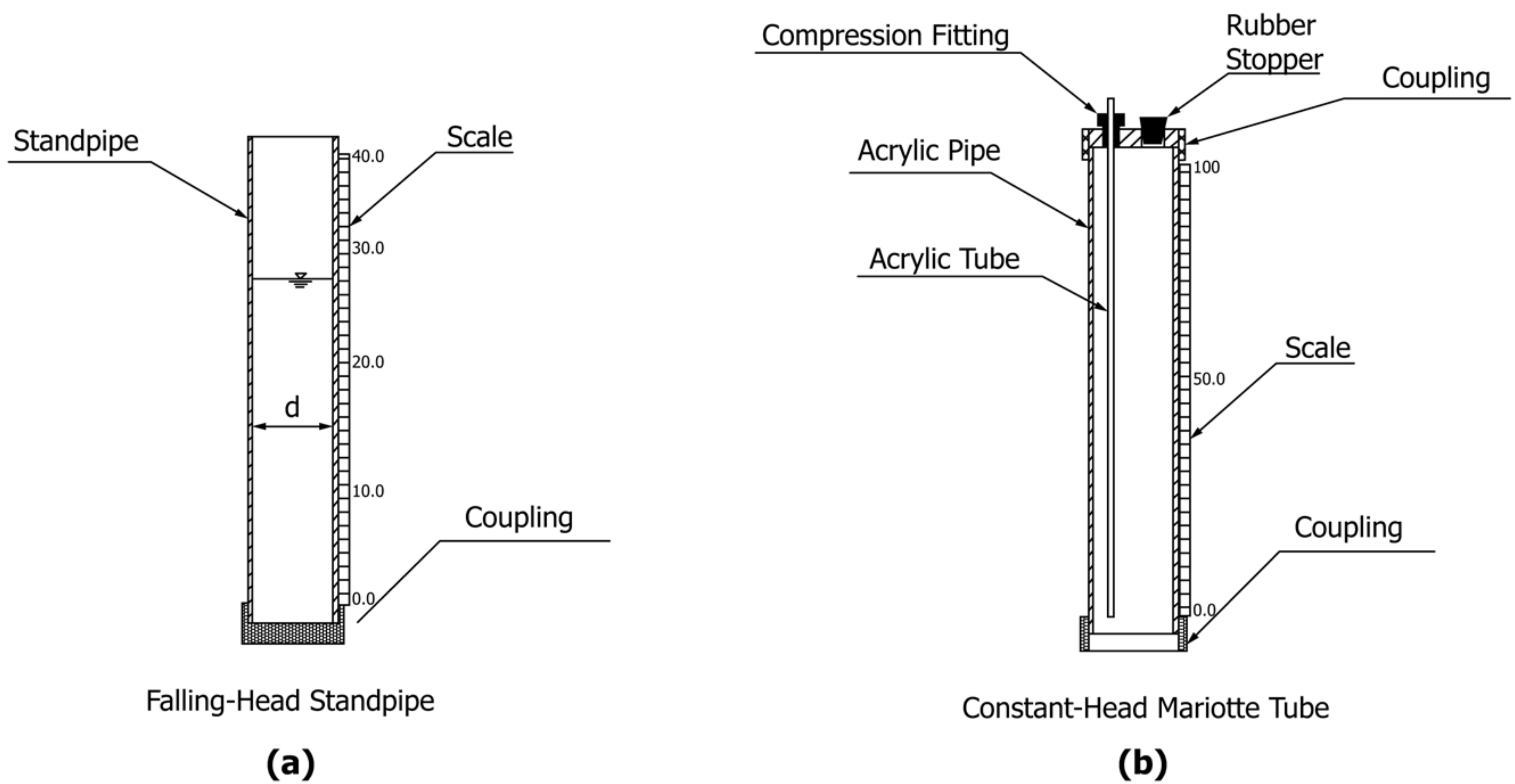


FIG. 2 Falling Head Standpipe (Methods A and B) (a) and Mariotte Tube (Method C) (b) Used for the Flow Assembly

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:*

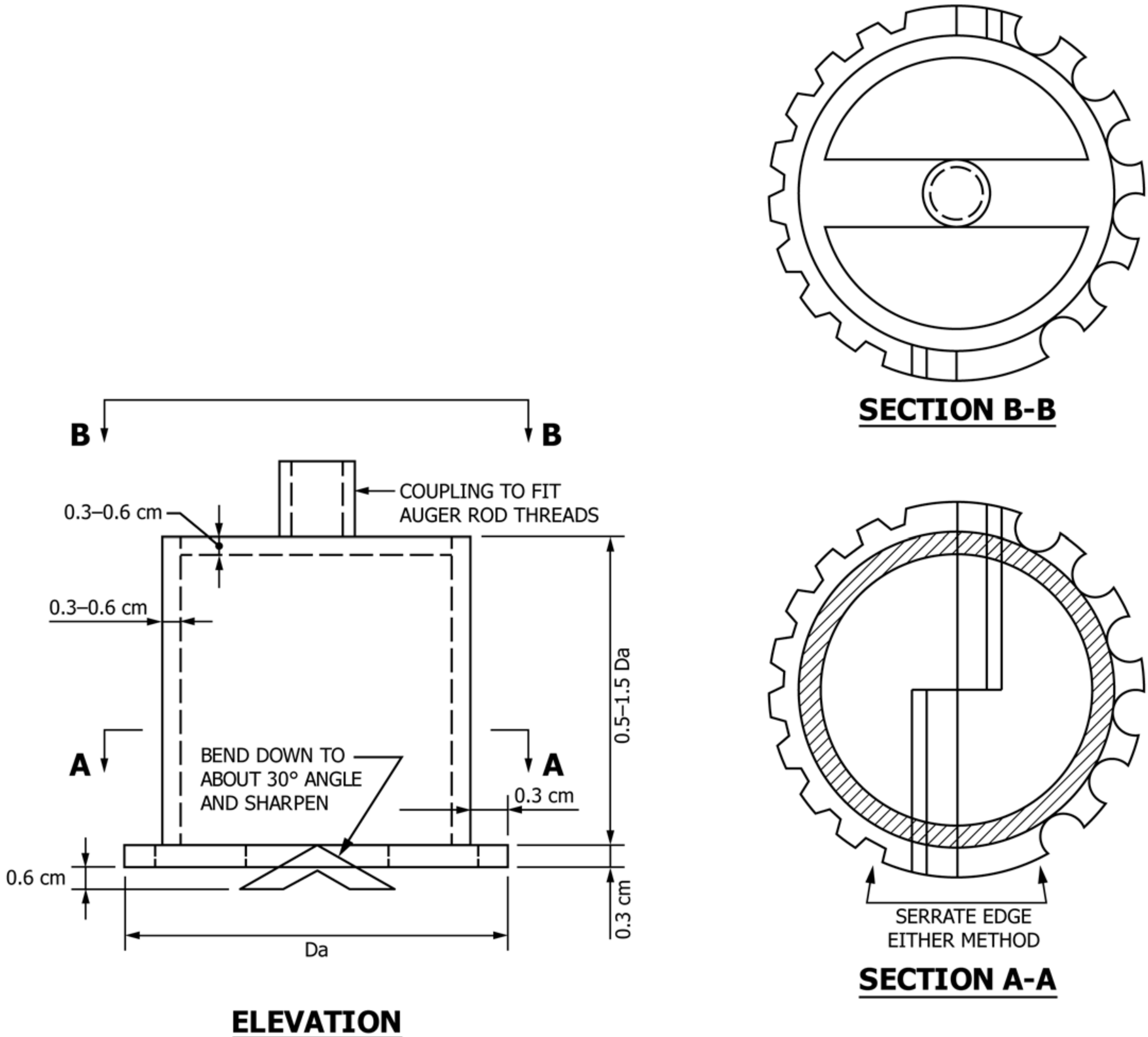
6.2.1 *Casing*—The casing shall be watertight but may be of any material or diameter. The minimum ID shall be 100 mm. The wall thickness shall be adequate to prevent collapse under the lateral pressure of the overburden and swelling bentonite. Schedule 40 PVC pipe is satisfactory. The bottom of the casing 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 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 *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.

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

6.4 *Temperature System*—A 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 tape.

6.6 *Miscellaneous:*

6.6.1 *Plastic Sheeting*—Clear or white plastic sheeting, nominal thickness at least 0.1 mm. Provide one 3 by 3 m 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. 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 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.

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

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

6.6.5 *Aluminum Foil*—1 roll.

6.6.6 *Rubber Bands.*

6.6.7 *Flashlight.*

7. Test Site

7.1 Each individual test requires an area approximately 3 by 3 m. Tests shall not be located closer than 3-m center-to-center. A group of at least five tests is suggested for evaluation of a typical test pad for 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 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.

7.5 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 ±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 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*—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)*—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.

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 25 mm into the soil at the bottom of the borehole. Sufficient bentonite pellets to fill approximately 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 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 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 advance the borehole to the bottom of the casing. 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.

8.1.7 *Surface Protection*—After installing the casing, cover the ground surface with clear or white plastic sheet. Use sand, gravel, sandbags, or other weights to keep the plastic in place during high winds.

8.1.8 *Hydration*—Allow the bentonite (and grout, if any) to hydrate a minimum of 12 h before applying head to the test. Place a cap or other protective material over the top of the casing to prevent desiccation or entry of rainfall during the hydration period.

8.1.9 *Temperature Effect Gauge*—The temperature effect gauge (TEG) is installed in the same manner as described above.

8.2 *Assemble Flow Monitoring System and Standpipe*—Assemble the cap and, flow monitoring system. Ensure the assembly is watertight.

8.3 *Complete System Setup:*

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. Tying the retrieval wires to a small float (half the casing diameter or less) aids in their recovery.

8.3.3 *Fill Casing*—Fill the casing slowly with water, but no higher than 25 mm below the base of any internal threads. Introduce water in a manner that does not erode soil at the bottom of the casing. The water should be at similar temperature as the soil in the tested zone, or groundwater if present above bottom-of-casing, to prevent air bubbles from degassing.

8.3.4 *Add Flow Monitoring System*—Place the top assembly and seal it onto the casing. If a threaded casing is used, prevent rotation of the casing 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 (Ro) to the nearest mm. Measure and record inside diameter of standpipe (d) to nearest mm.

8.3.5 *Check System*—Fill the remainder of the casing and flow monitoring system with water, making sure that no air bubbles are trapped in the cap or flow control system. The maximum water level above ground surface shall not exceed the height equal to the depth of embedment of the casing. Check all joints carefully for water leaks by wiping the joints dry and watching for the formation of water drops. If leaks are observed, reassemble the apparatus until all leaks are eliminated.

8.4 *Begin Test*—Record the date and time (to 1 s) and the scale reading (R) corresponding to the bottom of the meniscus of the water in the standpipe. Take additional readings when the meniscus has moved at least 10 times the smallest division on the scale. 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. Typical forms for recording test data are given in Fig. 4, Fig. 5, and Fig. 6, and If Method C is being used, ensure that an air bubble(s) is emanating from the outlet of the Mariotte tube and is emitted regulary into the annulus of the Mariotte tube. If no bubbles are present, wait until a bubble emanates before initiating water level readings. If bubbles form slowly or erratically, use a Mariotte tube having smaller diameter.

8.4.1 *Refills*—One standpipe full of water may not be adequate to reach equilibrium. When the water level in the standpipe becomes low, or approaches the elevation of the outlet in the Mariotte tube in Method C, record the water level and refill the standpipe using the same method employed for the initial filling. Record the new water level and its associated time, TEG reading, and TEG temperature and note as "refill." Continue making readings as for the first filling. 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.

8.4.2 *Criteria for Termination*—Each stage may be terminated when a plot of logK1, logK2, or logK versus time exhibits no temporal trend and fluctuates about a stable value (no more than 20 % the mean) for at least the time spans listed in Table 2.

NOTE 3—If the test is solely to verify that the actual vertical hydraulic

Borehole Hydraulic Conductivity Test - ASTM D 6391 Method A

Stage 1 - Fixed Variables

d =	1.27	cm
D =	11.43	cm
Z_c =	61.0	cm
R_0 =	22.9	cm
b_1 =	61.0	cm
W =	121.9	cm

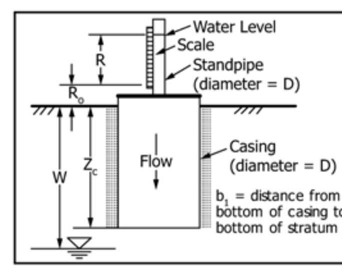
G_1 = 0.0403 cm

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

$H = R + (R_0 + W)$

$$G_1 = \frac{\pi d^2}{11D}$$

$$K_1 = \frac{R_T G_1}{(t_2 - t_1)} \ln\left(\frac{Z_1}{Z_2}\right)$$



Date	Time	Reading	Temp	Δt	H_1	H_2	TEG			H'_2	R_T	K_1	Cumul.	Cumul.	Remarks
		R	T	$(t_2 - t_1)$			R_i	R_f	$C=(R_f - R_i)$	$=(H_2 - C)$			Volume	Time	
		cm	°C	s	cm	cm	cm	cm	cm	cm		cm/s	mL	hr	
8/1	8:00	64.8	21.0			209.6		65.0					0.0	0.0	Start
8/1	8:30	47.8	21.0	1800	209.6	192.6	65.0	65.0	0	192.6	0.97	1.84E-06	21.6	0.5	
8/1	9:00	36.3	21.0	1800	192.6	181.1	65.0	65.0	0	181.1	0.97	1.34E-06	36.2	1.0	
8/1	10:00	19.7	22.0	3600	181.1	164.5	65.0	65.2	0.2	164.3	0.96	1.05E-06	57.3	2.0	End
8/1	10:01	66.7	22.0	0	164.5	211.5		65.0	65	146.5			57.3	2.0	Refill
8/1	12:00	47.0	23.0	7140	211.5	191.8	65.2	65.8	0.6	191.2	0.94	5.35E-07	82.3	4.0	
8/5	17:00	50.0	26.0	363600	191.8	194.8			0	194.8			82.3	105.0	Refill
8/6	8:00	38.1	19.0	54000	194.8	182.9	67.0	64.2	–2.8	185.7	0.94	3.36E-08	97.4	120.0	Stop

Stage 2 - Fixed Variables

d =	1.27	cm
D =	10.16	cm
Z_c =	61.0	cm
R_0 =	22.9	cm
b_2 =	53.3	cm
L =	15.2	cm
W =	121.9	cm

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

$Z = R + (R_0 + W)$

F = 0.94599

$G5_{num}$ = 44.9829

$G5_{den}$ = 39.002

G_5 = 1.15335

G_4 = 3.29556

G_3 = 2.38515

G_2 = 0.01672

$$K_2 = \frac{R_T G_2}{(t_2 - t_1)} \ln\left(\frac{Z_1}{Z_2}\right)$$

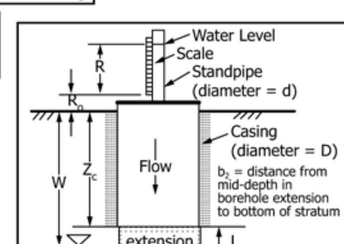
$$F = 1 - 0.5623 \exp\left(-1.566\frac{L}{D}\right)$$

$$G_2 = \left(\frac{d^2}{16FL}\right) G_3$$

$$G_4 = \frac{L}{D} + \left[1 + \left(\frac{L}{D}\right)^2\right]^{\frac{1}{2}}$$

$$G_3 = 2\ln(G_4) + a\ln(G_5)$$

$$G_5 = \frac{\left(4\frac{b_2}{D} + \frac{L}{D}\right) + \left[1 + \left(4\frac{b_2}{D} + \frac{L}{D}\right)^2\right]^{\frac{1}{2}}}{\left(4\frac{b_2}{D} - \frac{L}{D}\right) + \left[1 + \left(4\frac{b_2}{D} - \frac{L}{D}\right)^2\right]^{\frac{1}{2}}}$$



Date	Time	Reading	Temp	Δt	H_1	H_2	TEG			H'_2	R_T	K_2	Cumul.	Cumul.	Remarks
		R	T	$(t_2 - t_1)$			R_i	R_f	$C=(R_f - R_i)$	$=(H_2 - C)$			Volume	Time	
	H:M	cm	°C	s	cm	cm	cm	cm	cm	cm		cm/s	mL	hr	
8/6	9:30	65.4	20			210.2		64.3					0	0.0	
8/6	10:00	59.4	21	1800	210.2	204.2	64.3	64.3	0	204.2	0.99	2.50E-07	7.6	0.5	
8/6	10:30	54.3	22	1800	204.2	199.1	64.3	64.5	0.2	198.9	0.96	2.20E-07	14.1	1.0	
8/6	11:30	45.7	23	3600	199.1	190.5	64.5	64.8	0.3	190.2	0.94	1.87E-07	25.0	2.0	
8/6	13:30	33.3	24	7200	190.5	178.1	64.8	66.1	1.3	176.8	0.91	1.48E-07	40.8	4.0	
8/9	7:30	21.3	16		178.1	166.1	66.9	62.9	–4	170.1	1.01		0.0	0.0	
8/9	16:00	9.2	19	30600	166.1	154.0	62.9	64	1.1	152.9	1.07	4.55E-08	15.4	8.5	

FIG. 4 Example Data/Computation Form for Method A

Borehole Hydraulic Conductivity Test - ASTM D 6391 Method B

Test ID:	MC-4	**Installer:**	XW
Project:	Monticello	**Analyst:**	CHB
Trial No.	1	**TEG (y/n):**	NO

SOLUTION -TRIAL 1

K (m/s) = 7.99E-05

Total Time (d) = 0.008 0.200 hrs

$$K = R_T \frac{a \pi d^2}{11D}$$

Fixed Variables

d (cm) =	30.48
D (cm) =	30.48
R_o (cm) =	0
Final Time:	1/0/00 2:17

Fitted Variables

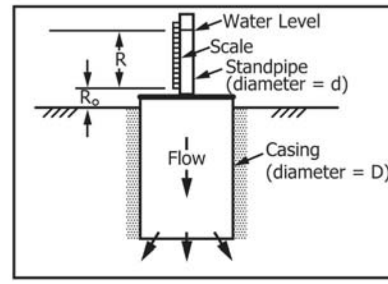
a (s^{-1}) =	0.0009182
Z* (m) =	0.31
Z_o (m) =	0.60
MSE (m^2) =	1.87E-05
Bias (m) =	−2.89E-08

Temporal Field Data

Time (m/d/yr h:m)	R (cm)
1/0/00 2:05	29
1/0/00 2:07	23
1/0/00 2:08	19
1/0/00 2:10	15
1/0/00 2:12	10
1/0/00 2:14	5
1/0/00 2:17	0

Z-t Computations

Z (m)	t (s)	Fit Z (m)	ε (m)	$ε^2$ (m)
0.29	0	0.290	−3.69E-04	1.36E-07
0.23	120	0.227	−3.10E-03	9.61E-06
0.19	180	0.198	8.03E-03	6.45E-05
0.15	300	0.145	−5.14E-03	2.64E-05
0.10	420	0.097	−2.77E-03	7.68E-06
0.05	540	0.055	4.57E-03	2.09E-05
0.00	720	−0.001	−1.22E-03	1.49E-06



Fitted Z-t Function

t (s)	Z (m)
0	0.290
36	0.270
72	0.251
108	0.233
144	0.215
180	0.198
216	0.181
252	0.165
288	0.150
324	0.135
360	0.120
396	0.106
432	0.093
468	0.080
504	0.067
540	0.055
576	0.043
612	0.031
648	0.020
684	0.009
720	−0.001

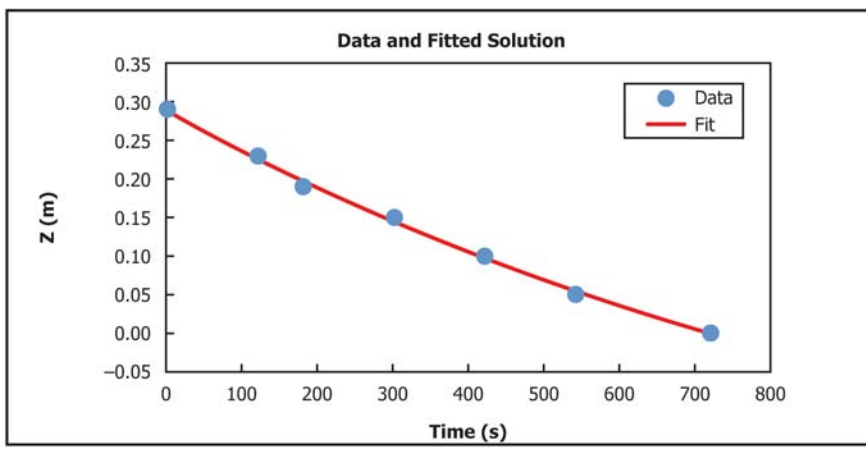


FIG. 5 Example Data/Computation Form for Method B

conductivity, k_v , is less than some specified value and the limiting vertical conductivity, *K1*, is less than that value, Stage 2 in Method A may be omitted. In such cases, Stage 1 may be terminated if K_1 remains below the specified value for a period at least as long as that given in Table 2 provided there is no upward trend in the hydraulic conductivity measurements.

8.5 *Conduct Stage 2 (Method A only):*

8.5.1 *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. or bail to the groundwater level of the stratum being tested. Remove the sock.

8.5.2 *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 test diameters and not more than 2 test diameters.

8.5.3 *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 6.1.5. Prepare the bottom as described in 8.1.3. Measure and record depth (L) and diameter (D) of borehole extension to the nearest mm.

8.5.4 *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 80 mm above the casing bottom with pea gravel.

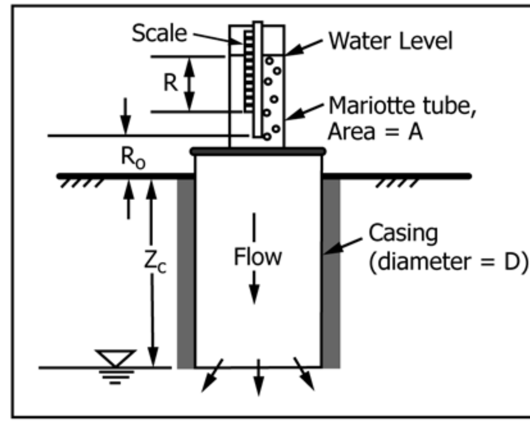
8.5.5 *Reassemble the System*—Refill the casing with water as described in 8.3.3, reattach and seal the top assembly with its equipment, and refill the standpipe. Concurrently, empty and refill the TEG with water having the same temperature (within 1 °C) as that used in the test.

8.5.6 *Perform Stage 2*—Conduct Stage 2 using the same procedure as described in 8.4. The termination criteria are the same. See Fig. 4 for a typical form for recording the data.

8.6 *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

Borehole Hydraulic Conductivity Test - ASTM D 6391 Method C

Project:	Helena
Date:	08/19/08
Test ID:	1
Installer:	XW
Analyst:	JS



Fixed Variables:

Casing Diameter, D	cm	30.48
Mariotte Area, A	cm^2	79.8
Bubble Pt Elevation, Ro	cm	10
Casing Embedment, Zc	cm	60.96
TEG (yes/no)	yes/no	NO

Temporal Field Data: / **Computations:**

Time (Date, H:M)	R (cm)	T (°c)	Comments	Q (mL/s)	Elapsed Time (d)	R_t (–)	K (cm/s)
8/19/08 15:00	51.5	20.1	Start				
8/19/08 16:27	46.7	20.6		7.34E-02	0.060	0.992	1.22E-05
8/19/08 17:02	45.0	20.5		6.46E-02	0.085	0.987	1.07E-05
8/20/08 7:50	0.7	19.8	Next Day	6.64E-02	0.701	0.997	1.11E-05
8/20/08 15:00	51.9	21.1	Refill		1.000		
8/21/08 8:05	35.0	20.1	Next Day	2.19E-02	1.712	0.986	3.63E-06
8/21/08 12:30	32.7	20.8		1.15E-02	1.896	0.989	1.92E-06
8/21/08 16:05	31.3	21.1		8.66E-03	2.045	0.977	1.42E-06
8/22/08 8:27	50.0	19.6	Refill, Next Day		2.727		
8/22/08 12:40	48.4	20.9		8.41E-03	2.903	0.994	1.41E-06
8/22/08 16:00	47.4	21.5		6.65E-03	3.042	0.972	1.09E-06
8/23/08 7:46	42.8	19.4	Next Day	6.46E-03	3.699	0.989	1.08E-06
8/23/08 11:57	40.9	20.6		1.01E-02	3.873	1.000	1.69E-06
8/23/08 15:42	39.5	21.3		8.29E-03	4.029	0.977	1.36E-06
8/24/08 7:55	41.0	19.3	Refill, Next Day		4.705		
8/24/08 12:11	38.6	20.7		1.25E-02	4.883	1.000	2.10E-06
8/24/08 15:37	37.3	21.3		8.39E-03	5.026	0.976	1.38E-06
8/25/08 8:22	31.0	19.0	Next Day	8.34E-03	5.724	0.997	1.40E-06

FIG. 6 Example Data/Computation Form for Method C

TABLE 2 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

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 *Method A*—Calculate K_1 and K_2 using Eq 1-11. Alternate equations are given in Ref. **(6)**.

9.1.1 *Stage 1*—Compute K_1 using Eq 1 and 2 for each sequential pair of water levels during Stage 1 and graph K_1 vs. time as shown in Fig. 7 using data recorded in a data sheet simlar to example shown in Fig. 4.

$$K_1 = R_T \; G_1 \frac{ln\left(\frac{Z_1}{Z_2}\right)}{(t_2 - t_1)} \tag{1}$$

where:

$$G_1 = \left(\frac{\pi d^2}{11 D_1}\right)\left[1 + a\left(\frac{D_1}{4 b_1}\right)\right] \tag{2}$$

R_T = $2.2902(0.9842^T)/T^{0.1702}$ and T is temperature in °C,
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).
Z_1 = $Z_c + R_o + R$ at time t_1,
Z_2 = $Z_c + R_o + R - c$ at time t_2,
c = change in TEG scale reading between times t_1 and t_2 . 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*—Compute K_2 using Eq 3-8 for each sequential pair of water levels during Stage 2 and graph K_2 vs. time as shown in Fig. 7 using data recorded in a data sheet simlar to example shown in Fig. 4.

$$K_2 = R_T \; G_2 \frac{ln\left(\frac{Z_1}{Z_2}\right)}{(t_2 - t_1)} \tag{3}$$

$$G_2 = \left(\frac{d^2}{16FL}\right) G_3 \tag{4}$$

$$G_3 = 2 lnG_4 + a lnG_5 \tag{5}$$

$$G_4 = \frac{L}{D} + \sqrt{1 + \left(\frac{L}{D}\right)^2} \tag{6}$$

$$G_5 = \frac{\left[\frac{4b_2}{D} + \frac{L}{D}\right] + \sqrt{1 + \left(\frac{4b_2}{D} + \frac{L}{D}\right)^2}}{\left[\frac{4b_2}{D} - \frac{L}{D}\right] + \sqrt{1 + \left(\frac{4b_2}{D} - \frac{L}{D}\right)^2}} \tag{7}$$

$$F = 1 - 0.5623 \, e^{-1.566\frac{L}{D}} \tag{8}$$

where:
L = length of Stage 2 extension below bottom of casing (cm),
D = ID of Stage 2 extension (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 the time-weighted average $<K_1>$' from the K_1 data in Stage 1 during the period when K_1 appears temporally invariant (no apparent temporal trend up or down):

$$<K_1> = \frac{\sum_{i=1}^{n} K_{1,i}(t_2 - t_1)_i}{\sum_{i=1}^{n} (t_2 - t_1)_i} \tag{9}$$

where:
i = designates the i[th] of n time time increments in the temporally invariant range.

9.3 Calculate the time-weighted average $<K_2>$' from the K_2 data in Stage 2 during the period when K_2 appears temporally invariant (no apparent temporal trend up or down):

$$<K2> = \frac{\sum_{i=1}^{n} K_{2,i}(t_2 - t_1)_i}{\sum_{i=1}^{n} (t_2 - t_1)_i} \tag{10}$$

9.4 Method B

9.4.1 *Calculation Procedure 1*—Use Eq 1 and 2 to compute K_1* using data recorded in a data sheet simlar to example shown in Fig. 5. In this case, K_1* equals the isotropic hydraulic conductivity, K.

9.4.2 *Calculation Procedure 2*

9.4.2.1 Graph the water level, Z, as a function of time, as shown in Fig. 8 for a given fill of the standpipe.

9.4.2.2 Fit Eq 11 to the Z-t data in the graph like that shown in Fig. 8.

$$Z_t = Z^* + Z_o exp(-at) \tag{11}$$

by adjusting Z*, Z_o, and *a* until the differences between the measured data (Z_i, t_i) and the fit of Eq 11 are minimized, i.e.

$$min\left\{\frac{1}{n}\sum_{i=1}^{n}(Z_i - Z_{ti})^2\right\} \tag{12}$$

subject to the unbiased constraint

$$\sum_{i=1}^{n}(Z_i - Z_{ti}) = 0 \tag{13}$$

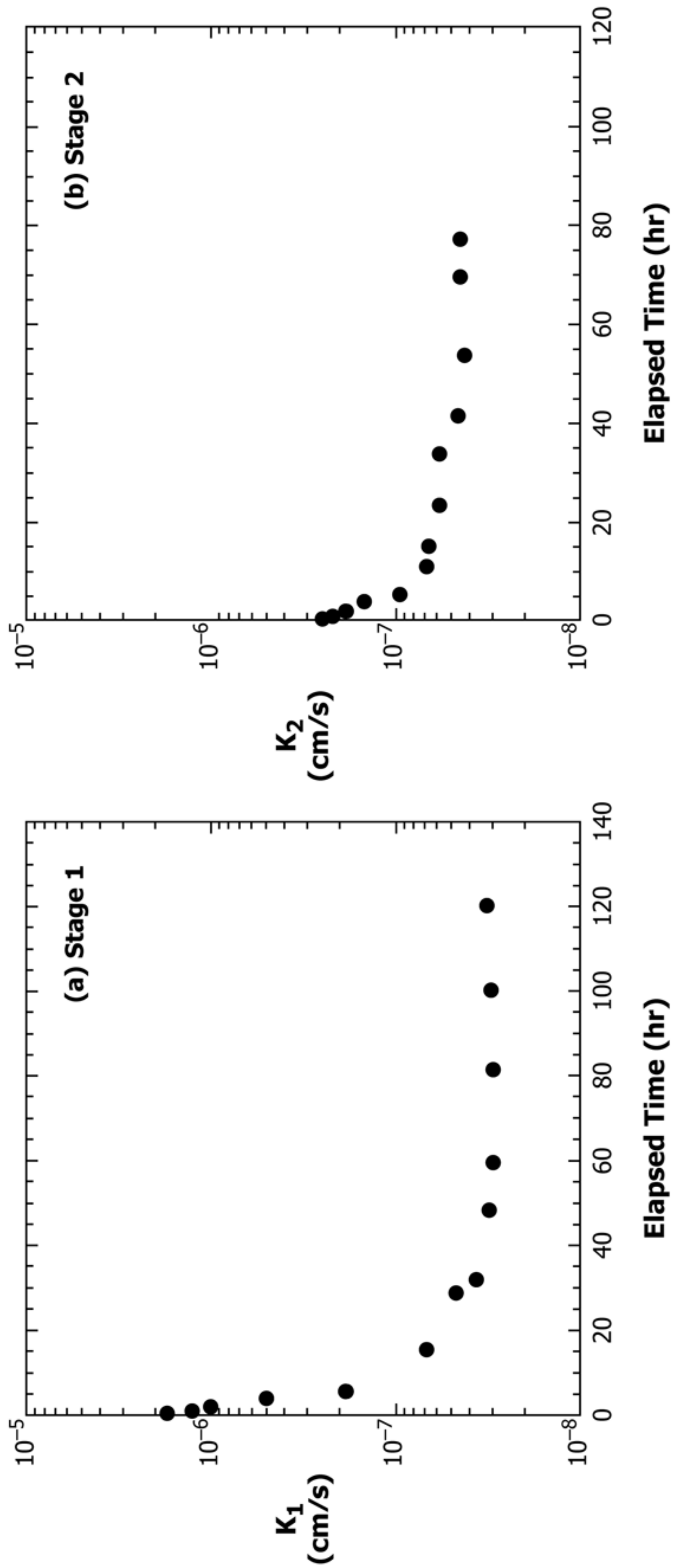


FIG. 7 Example of K_1 (a) and K_2 (b) vs. Elapsed Time for Stages 1 and 2 from Method A

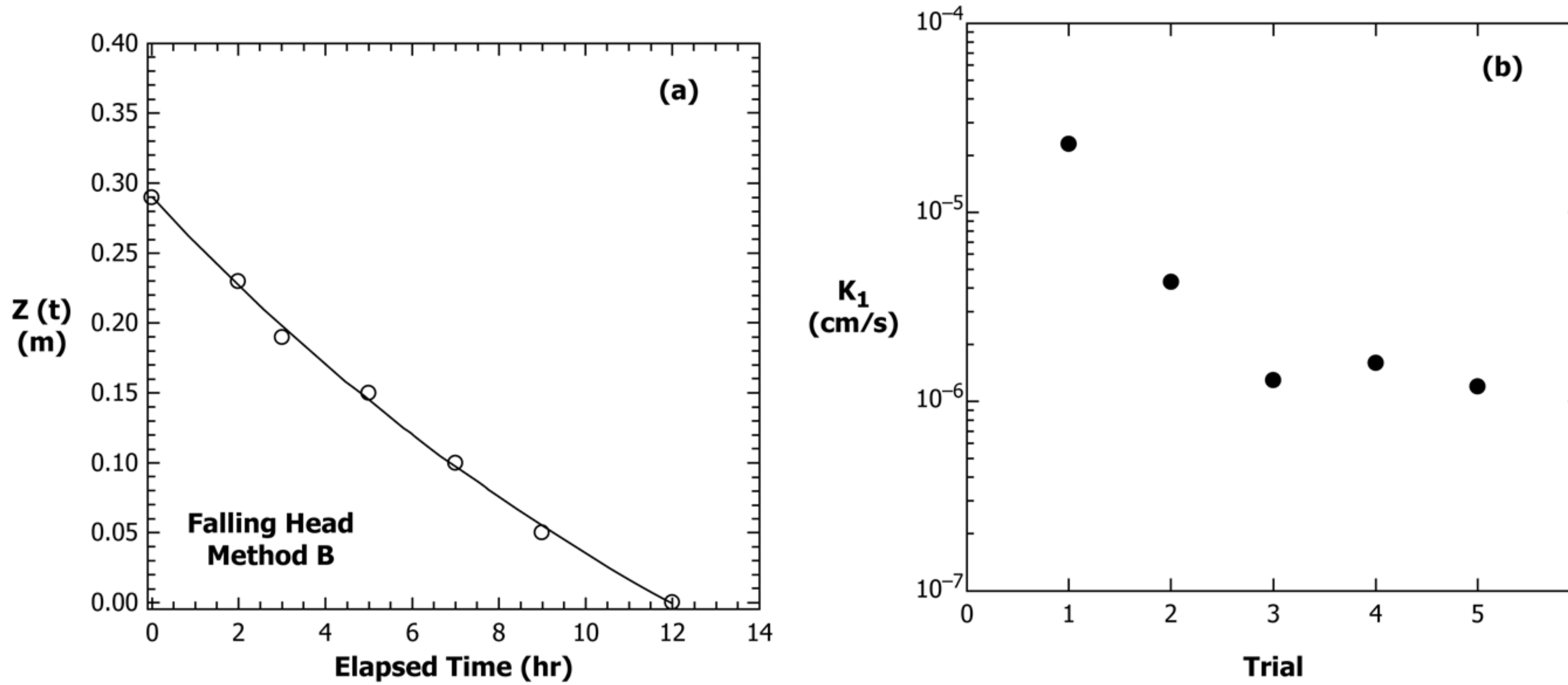


FIG. 8 Example of Z vs. Time (a) and K vs. Trial Number (b) for Falling-Head Procedure in Method B

where:

Z_i = R_o + R at the i^{th} reading at time t_i,
Z_{ti} = Z_t in Eq 11 at time t_i,
Z^* = constant related to the total head,
Z_o = constant related to the initial total head, and
a = constant related to the hydraulic conductivity.

NOTE 4—Fitting of Eq 11 generally is accomplished using an optimization tool in spreadsheet software.

9.4.2.3 Compute the hydraulic conductivity for a given fill of the standpipe as **(8)** .

$$K = R_T a \frac{\pi d^2}{11D} \tag{14}$$

where the variables R_T, d, and D were defined previously.

9.4.2.4 Repeat the computations in 9.4.2.1 and 9.4.2.2 for each fill of the standpipe.

9.4.2.5 Graph K vs. number of trials as shown in Fig. 8.

9.4.2.6 Compute the arithmetic mean of the final three hydraulic conductivities in Fig. 8 provided that these hydraulic conductivities exhibit no temporal trend and differ by no more than 25 %.

9.5 *Method C*—Compute the hydraulic conductivity using the following equation **(7)** using data recorded in a data sheet similar to example shown in Fig. 6.

9.5.1 Calculate K for each time increment using Eq 15.

$$K = R_T \frac{\pi\left(d_s^2 - d_m^2\right)\left(Z_1 - Z_2\right)}{2.75D\, H_b\left(t_2 - t_1\right)} \tag{15}$$

where:

d_s = the inside diameter of the standpipe,
d_m = the outside diameter of the Mariotte tube,
H_b = Z_c + R_o,
Z_1 = R at time t_1, and
Z_2 = R at time t_2.

9.5.2 Graph hydraulic conductivity vs. time as illustrated in Fig. 9.

9.5.3 Compute the time-weighted hydraulic conductivity, <K>, using Eq 16 from the final four data points in the temporally invariant period shown in Fig. 9:

$$<K> = \sum_{i=1}^{4} \frac{K_i\left(t_2 - t_1\right)_i}{\sum_{i=1}^{4}\left(t_2 - t_1\right)_i} \tag{16}$$

10. Report

10.1 Report the following information:

10.1.1 A data sheet indicating the method (A, B, or C) that was used and the data that were collected,

10.1.2 A graph of K_1 and K_2 (Method A) or <K> (Methods B and C) versus time,

10.1.3 Average values <K_1> and <K_2> (Method A) or <K> (Methods B and C),

10.1.4 Thickness of layer tested,

10.1.5 Description of material beneath the layer tested.

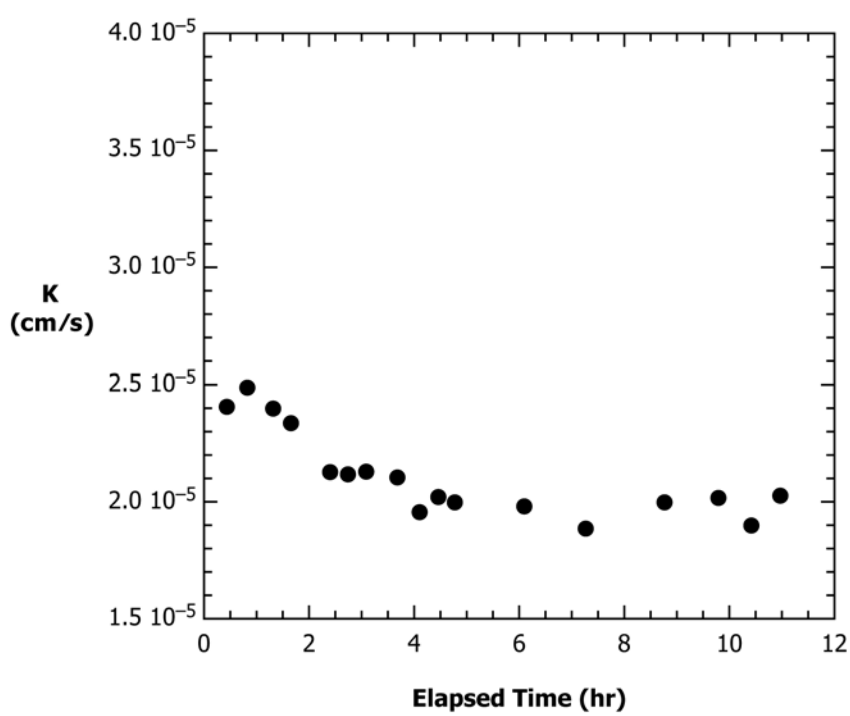


FIG. 9 Example of K vs. Time for Constant-Head Procedure in Method C

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

10.2.1 Total and dry unit weight 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 location.

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

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(8) Chaisson, P., "Methods of Interpretation of Borehole Falling-Head Tests Performed in Compacted Clay Liners," *Canadian Geotechnical Journal*, Vol. 42, 2005, pp. 79-90.

(9) Hvorslev, M. (1951), Time Lag and Soil Permeability In Ground-Water Observations, US Army Corps of Engineers, Vicksburg.