Chapter 17

WATER TESTING FOR PERMEABILITY

General

Most rock and soil contains numerous open spaces where water may be stored and through which water can move. Permeability, or hydraulic conductivity, is a measure of the ease of movement of fluid and gas through the open spaces and fractures. The properties of soil and rock have significant impact on water movement through the interstitial spaces. Water movement through soil and rock significantly impacts the ability to control water during construction. The movement of water through slopes must be known to understand the stability of slopes. Permeability in this chapter is considered synonymous with the term hydraulic conductivity and is a measurement of the groundwater flow through a cross-sectional area. This chapter discusses how to measure permeability and how to best determine or estimate appropriate permeability values.

In addition to permeability, there are other hydrologic parameters that may impact the understanding of groundwater but are either more difficult to determine or are not a significant consideration in most engineering situations. These other hydraulic parameters of subsurface materials are transmissivity, porosity, and storage. For a more detailed explanation of these hydrologic parameters and the methods used to obtained the values, see chapters 5, 6, and 10 of the Reclamation *Groundwater Manual*.

Transmissivity

Transmissivity is the average permeability multiplied by the saturated thickness. Transmissivity is particularly important in areas with multiple aquifers. Determining the aquifer thickness may not be practical or necessary

if permeability and recharge are relatively low and the need for groundwater control is short term. Transmissivity values are often based on individual permeability values or averaged permeability values. It is important that any permeability value used with the saturated thickness of an aquifer be appropriate and representative. Since most aquifers are rarely homogeneous and isotropic, any field derived data must be qualified by indicating if averaging or selecting the highest or lowest permeability value for a particular site is appropriate.

Porosity

Porosity is the percentage of interstitial space within the soil or rock relative to the total volume of soil or rock. Porosity is not necessarily directly proportional to permeability. Porosity is a significant factor in understanding the stability of soil and rock, but only the effective porosity, the interconnected pores, contribute to permeability. Not all pores or interstitial spaces are connected. Porosities are typically high for sands and gravels (30-40 percent) with high permeabilities (10 to 10^{-2} cm/sec). Clays have higher porosities (45-55 percent) but have very low permeabilities (10^{-6} to 10^{-8} cm/sec). Effective porosity is important in high permeability materials, but the total porosity is rarely relevant except in contaminant transport modeling. In the field, porosity is typically estimated by borehole geophysics.

Storage

Storage is a dimensionless term defined as the volume of water released from or taken into interstitial spaces in the soil or rock. Storage is often interchanged with the terms specific yield, effective porosity, coefficient of storage, and storativity. The water stored within the effective porosity is controlled by the material's ability to

retain and to release water. Understanding storage is particularly important in high permeability materials or localized zones connected with a large source of water.

A glossary of abbreviations and definitions is shown in table 17-1 that are used in the various permeability calculations. Not all the parameters listed in the table are necessary for every calculation. These parameters are derived from the *Groundwater Manual*, chapter 10. Abbreviations used in the figures and text of this chapter are consistent throughout the chapter. Definitions apply to angled holes as well as vertical wells.

Geologic Conditions

Understanding and measuring the above parameters is important, but understanding the hydrogeologic conditions is essential. Obtaining representative and appropriate hydrologic values is critical in any site investigation. Identifying the water bearing zones and selecting the appropriate test method is very important. Improper test methods, poor well construction, and improper isolation can significantly impact any test design. It is essential that the various aquifers and boundaries in heterogeneous settings be identified and that the various water surfaces existing at the site be located. Obtaining values without a good understanding of subsurface conditions can be misleading and can result in surprises once the actual site conditions are exposed. Obtaining water level data and permeability values has little value without an understanding of the factors controlling the groundwater. Proper evaluation of permeability values requires that the values be correlated with geologic conditions.

Table 17-1.—A glossary of abbreviations and definitions used in permeability calculations

K	=	Coefficient of permeability in feet (meters) per year under a unit gradient.
Q	=	Steady flow into the well in ft^3/sec [m^3/sec].
H	=	The effective head of water in the well in feet (m). For packer tests, determining the effective head is defined in figure 17-5. The effective head may be natural or induced.
a	=	Exposed surface area of the test section in ft^2 (m^2). Note that this area in an uncased borehole or using a single packer for some tests would include the exposed area at the bottom of the borehole.
ℓ	=	Length of test (packer tests) or screened (perforated) section of well isolated from the adjacent material in feet (m).
r	=	The radius to the borehole sidewall.
r_e	=	The effective radius to borehole sidewall that is reduced because of an obstruction such as a slotted riser (perforated casing), caved material, gravel, or sand pack.
r_1	=	The outer radius of a riser or casing.
r_c	=	The inside radius of a riser or casing.
D	=	Distance from the ground surface to the bottom of the test section.
U	=	Thickness of unsaturated materials above the water surface, including the capillary zone.
T_u	=	U-D+H = The distance from the induced water surface in the well to the static natural water surface.
S	=	Thickness of saturated material overlying a relatively impermeable layer.
C_u	=	Conductivity coefficient for unsaturated materials with partially penetrating cylindrical test wells.
C_s	=	Conductivity coefficient for saturated materials with partially penetrating cylindrical test wells.

Selecting the Appropriate Test

There are numerous ways to determine or estimate permeabilities. The appropriate method for estimating permeabilities must be based on the subsurface conditions and how significantly the values obtained will impact the project. The required level of understanding of the subsurface water conditions should be weighed relative to the cost and the impact on stability and constructability of the feature and on the changes in quality and quantity of water important to the site. Soil classification and Standard Penetration Testing (SPT) blow counts provide crude estimates of soil permeabilities. There are numerous geophysical methods for estimating permeabilities by using flowmeters, acoustic velocities, and gamma borehole logging techniques. The Reclamation *Ground Water Manual*, chapters 8 and 10, provides detailed explanations of various test methods for determining permeabilities. Except for the aquifer tests, most methods described in this chapter determine the vertical or horizontal permeability.

The most accurate test method for determining permeability is conducting a relatively long-term aquifer test. This method is not covered in this chapter. A full-term aquifer test (pumping test as described in chapter 8 of the Reclamation *Ground Water Manual*) is rarely justified during initial site investigations because of the cost and time required to perform an aquifer test and possibly handle the discharged water. This chapter discusses the less costly methods used to determine permeability. These methods are less accurate, primarily because these tests are too short in duration and because the interval being tested is not necessarily "truly" undisturbed, open, dimensioned as assumed, and representative.

Stable Boreholes

Packer tests are commonly performed in boreholes because the tests are inexpensive and can be performed quickly, with minimal disruption to the primary task of most site investigations, which is determining the subsurface materials and geology. The Gravity Permeability Test Method 1 for consolidated material is used only within the vadose zone and is the preferred method if the packer test method cannot be used. The principal problem of any gravity permeability test method is that a uniform supply of water is necessary so that a constant head can be maintained above the static water surface. The falling head tests should be used in stable boreholes if the packer test and gravity tests (both above and below the static water surface) cannot be performed.

Unstable Boreholes

There are a number of permeability tests that can be used in unstable materials such as soils that are noncohesive, uncemented, or unindurated or fractured rock that collapses into the borehole. Slug tests are used primarily when water availability or usage is a problem. Piezometer tests are good where water surfaces are high and where water bearing units are relatively thin layered but significant. Unfortunately, the piezometer test is limited to relatively shallow depths (around 20 feet [6 m]) and is rarely successful in cohesionless or gravelly or coarser soils. Gravity permeability tests are used in unstable soils or in rock. Gravity permeability tests require costly construction techniques, delay or prevent further advancement of the borehole, and require a supply of water.

Borehole permeabilities are appropriate for the interval tested unless the test interval is greater than 10 feet

(3 m). For intervals greater than 10 feet (3 m), the test may not be an accurate reflection of the entire saturated column. The permeability values should be plotted on the drill log, along with the water take and test pressures. The test interval should be drawn on the log so that the water test data can be related to fracture data.

Permeability Testing in Rock

Permeability tests are routinely performed in rock, particularly by pressure or packer tests. The permeability calculation assumes laminar flow in an isotropic, homogeneous medium. In reality, the test water take is effectively controlled by fractures because the intact rock permeability is effectively zero in most cases. The water may be flowing into one or into many fractures in the test interval, but the permeability calculation assumes laminar flow in an isotropic, homogeneous medium. The length of the test interval is governed by the rock characteristics. Typically, the test interval may be 10 feet (3 m) long, but the water can be going into one ¼-inch (8-mm) fracture. Test intervals greater than 20 feet (6 m) are inadvisable because, typically, there are a few fractures or a relatively small zone that controls the groundwater flow in bedrock. The calculated permeability of the packer test interval may be a magnitude different from the actual rock mass permeability. Only in the case of a highly fractured rock mass is the calculated permeability relatively reliable and the result is still a relative or effective permeability.

Orientation.—The orientation of the drill hole relative to the fractures significantly affects the number of fractures intercepted by the hole and the perceived permeability. A vertical hole drilled in a material that has predominantly vertical fractures such as flat-bedded sediments will not intercept the predominant control on

the rock mass permeability. The drill holes should be oriented to cross as many fractures as possible not only for more meaningful permeability tests, but also to get meaningful rock mass design parameters. If hole orientation is not practical, the results may be corrected for the orientation bias.

Jacking.—The pressure used for the water test should consider geologic structure. Flat-lying, bedded sediments are very susceptible to jacking along bedding planes. The combination of weak bedding planes, typically low vertical confining pressures, or high horizontal in place stresses can result in jacking and apparently high permeabilities. Test pressures of half the typical pressure of 1 pound per square inch per foot (psi/ft) (0.2 kg/cm^2/m) of depth are often appropriate.

Hydrofracturing.—In place stresses in many areas are not lithostatic and horizontal stresses are significantly lower than vertical stresses. The theoretical overburden stress (roughly 1 pound per square inch per foot depth [0.2 kg/cm^2/m]) is typically used to determine the test pressure. If the horizontal stress is much lower than the vertical stress, hydrofracturing can occur, resulting in an induced high permeability value.

Stepped Pressure Tests.—Stepped pressure tests are an effective method of conducting water tests. Pressures are stepped up to the maximum pressure and then stepped down through the original pressures. Comparison of the calculated permeability values and the pressure versus flow curves for the steps can tell you whether the flow is laminar, if jacking or hydrofracturing is occurring, and if fractures are being washed out. If the pressures are increased to where jacking or hydrofracturing is occurring, the design grout pressures can be set as high as possible to get effective grout

injection, yet preclude fracturing or induce fracturing if desired. Chapter 16 discusses these tests in detail.

Test Equipment.—The test equipment can affect the test results. At moderate to high flows, the friction loss and restriction because of the piping (plumbing) and the packer is important. Significant pressure loss occurs between the gauge and the packer. At high flows, the plumbing system "permeability" can be the controlling factor rather than the permeability of the test interval. If meters and gauges are located in relation to each other as recommended, the arrangement of pipe, hose, etc., will not seriously influence the tests, although sharp bends in hose, 90-degree fittings on pipes, and unnecessary changes in pipe and hose diameters should be avoided. Laying the system out on the ground and pumping water through the plumbing to determine the capacity of the system is a good idea, especially if using small diameter piping or wireline packers.

In many investigations, information on the permeability of saturated or unsaturated materials is required. Permeability within the vadose zone, including the capillary fringe, is typically estimated by permeameter or gravity permeability tests. Permeability tests within saturated materials are typically performed as a falling head, packer, or aquifer test. Water within the unsaturated zone is suspended within the material but is primarily moving downward by gravity. In unsaturated conditions, the material permeabilities are obtained by one of several field permeameter tests. Since the material is not saturated, permeability tests require more equipment and a lot of water. These tests measure the volume of water flowing laterally while maintaining a constant head.

Laboratory permeability tests of subsurface materials usually are not satisfactory. Test specimens are seldom

undisturbed, and a specimen typically represents only a limited portion of the investigated material. Field tests have been devised that are relatively simple and less costly than aquifer pumping tests (although aquifer tests do provide relatively accurate permeability values). These tests are usually conducted in conjunction with exploratory drilling or monitoring existing wells.

Permeability testing of existing monitoring wells may help determine material characteristics when evaluation of existing data indicates gaps or when it is necessary to confirm previous assumptions. Properly conducted and controlled permeability tests will yield reasonably accurate and reliable data. Several locations may need to be tested to provide data on spatial variations of subsurface material characteristics.

The quality of water used in permeability tests is important. The presence of only a few parts per million of turbidity or air dissolved in water can plug soil and rock voids and cause serious errors in test results. Water should be clear and silt free. To avoid plugging the soil pores with air bubbles, use water that is a few degrees warmer than the temperature of the test section.

For some packer tests, pumps of up to 250 gallons per minute (gal/min) (950 liters per minute [L/min]) capacity against a total dynamic head of 160 feet (50 m) may be required.

The tests described below provide semiquantitative values of permeability. There have been numerous types of permeability tests devised with varying degrees of accuracy and usefulness. The tests described below are relatively simple and generally provide useful permeability data. If the tests are performed properly, the values obtained are sufficiently accurate for some engineering purposes. The tests assume laminar flow

and a homogeneous medium. These conditions are not often encountered, and fracture flow is what usually occurs in rock. The equations given for computing permeability are applicable to laminar flow. The velocity where turbulent flow occurs depends, in part, on the grain size of the materials tested. A maximum average velocity for laminar flow is about 0.1 foot per second (ft/sec) (25 millimeters per second [mm/sec]). If the quotient of the water intake in cubic units per second divided by the open area of the test section in square units times the estimated porosity of the tested material is greater than 0.10, the various given equations may not be accurate or applicable. The values obtained are not absolute and can vary from the true permeability by plus or minus an order of magnitude.

Length, volume, pressure, and time measurements should be made as accurately as available equipment will permit, and gauges should be checked periodically for accuracy. Keep the accuracy of the results in mind when determining the needed accuracy of the measurements. Results should be reported in feet per year or centimeters per second for most engineering uses.

In an open hole test, the total open area of the test section is computed by:

$$a = 2\pi r\ell + \pi r^2$$

where:

a = total open area of the hole face plus the hole bottom
r = radius of the hole
ℓ = length of the test section of the hole

When perforated casing is used and the open area is small, the effective radius, r_e, is used instead of the actual radius, r.

$$r_e = \frac{a_p}{a} r$$

a_p = total open area of perforations
a = area of each perforation

If fabricated well screens are used, estimates of the screen open area generally can be obtained from the screen manufacturer.

Permeability tests are divided into four types: pressure tests, constant head gravity tests, falling head gravity tests, and slug tests. In pressure tests and falling head gravity tests, one or two packers are used to isolate the test section in the hole. In pressure tests, water is forced into the test section through combined applied pressure and gravity head or the tests can be performed using gravity head only. In falling head tests, only gravity head is used. In constant head gravity tests, no packers are used, and a constant water level is maintained. Slug tests use only small changes in water level, generally over a short time.

Pressure Permeability Tests in Stable Rock

Pressure permeability tests are run using one or two packers to isolate various zones or lengths of drill hole. The tests may be run in vertical, angled, or horizontal holes. Compression packers, inflatable packers, leather cups, and other types of packers have been used for pressure testing. Inflatable packers are usually more economical and reliable because they reduce testing time and ensure a tighter seal, particularly in rough-walled, oversize, or out-of-round holes. The packer(s) are inflated through tubes extending to a tank of compressed air or nitrogen at the surface. If a pressure sensing instrument is included, pressure in the test section is

transmitted to the surface. Although this arrangement permits an accurate determination of test pressures, manual observations should still be made to permit an estimate of permeability if pressure sensors fail. When double packers are used, the hole can be drilled to total depth and then tested. When a single packer is used, the hole is advanced and tested in increments.

Methods of Testing

In stable rock the hole is drilled to the total depth without testing. Two inflatable packers 5 to 10 feet (1.5 to 3 m) apart are installed on the drill rod or pipe used for making the test. The section between the packers is perforated. The perforations should be at least ¼ inch (6 mm) in diameter, and the total area of all perforations should be more than two times the inside cross-sectional area of the pipe or rod. Tests are made beginning at the bottom of the hole. After each test, the packers are raised the length of the test section, and another test is made of the appropriate section of the hole.

In unstable rock, the hole is drilled to the bottom of each test interval. An inflatable packer is set at the top of the interval to be tested. After the test, the hole is then drilled to the bottom of the next test interval.

Cleaning Test Sections

Before testing, the test section should be surged with clear water and bailed or flushed out to clean cuttings and drilling fluid from the hole. If the test section is above the water table and will not hold water, water should be poured into the hole during the surging, then bailed out as rapidly as possible. When a completed hole is tested using two packers, the entire hole can be cleaned in one operation. Although cleaning the hole is frequently omitted, failing to clean the hole may result

in a permeable rock appearing to be impermeable because the hole wall is sealed by cuttings or drilling fluid.

Alternatives to surging and bailing a drill hole in indurated or consolidated material before pressure testing include rotating a stiff bristled brush while jetting with water. The jet velocity should be at least 150 ft/sec (45 m/sec). This velocity is approximately 1.4 gal/min per 1/16-inch- (5.3 L/min per 2-mm-) diameter hole in the rod. The drill hole should be blown or bailed out to the bottom after jetting.

Length of Test Section

The length of the test section is governed by the character of the rock, but generally a length of 10 feet (3 m) is acceptable. Occasionally, a good packer seal cannot be obtained at the planned depth because of bridging, raveling, fractures, or a rough hole. If a good seal cannot be obtained, the test section length should be increased or decreased or test sections overlapped to ensure that the test is made with well-seated packers. On some tests, a 10-foot (3-m) section will take more water than the pump can deliver, and no back pressure can be developed. If this occurs, the length of the test section should be shortened until back pressure can be developed, or the falling head test might be tried.

The test sections should have an $\ell/2r$ ratio greater than 5, where r is the radius of the hole and ℓ is the length of the test section. The packer should not be set inside the casing when making a test unless the casing has been grouted in the hole. Test sections greater than 20 feet (6 m) long may not allow sufficient resolution of permeable zones.

Size of Rod or Pipe to Use in Tests

Drill rods are commonly used to make pressure and permeability tests. NX and NW rods can be used if the take does not exceed 12 to 15 gallons per minute (45 to 60 liters per minute) and the depth to the top of the test section does not exceed 50 feet (15 m). For general use, 1¼-inch (32-mm) or larger pipe is better. Figures 17-1 through 17-4 show head losses at various flow rates per 10-foot (3-m) section for different sizes of drill rod and 1¼-inch (32-mm) pipe. These figures were compiled from experimental tests. Using 1¼-inch (32-mm) pipe, particularly where holes 50 feet (15 m) or deeper are to be tested, is obviously better than using smaller pipe. The couplings on 1¼-inch (32-mm) pipe must be turned down to 1.8 inch (45 mm) outside diameter for use in AX holes.

Pumping Equipment

Mud pumps should not be used for pumping the water for permeability tests. Mud pumps are generally of the multiple cylinder type and produce a uniform but large fluctuation in pressure. Many of these pumps have a maximum capacity of about 25 gal/min (100 L/min), and if not in good condition, capacities may be as small as 18 gal/min (70 L/min). Tests are often bad because pumps do not have sufficient capacity to develop back pressure in the length of hole being tested. When this happens, the tests are generally reported as “took capacity of pump, no pressure developed.” This result does not permit a permeability calculation and only indicates that the permeability is probably high. The fluctuating pressures of multiple cylinder pumps, even when an air chamber is used, are often difficult to read accurately because the high and low readings must be averaged to determine the approximate true effective

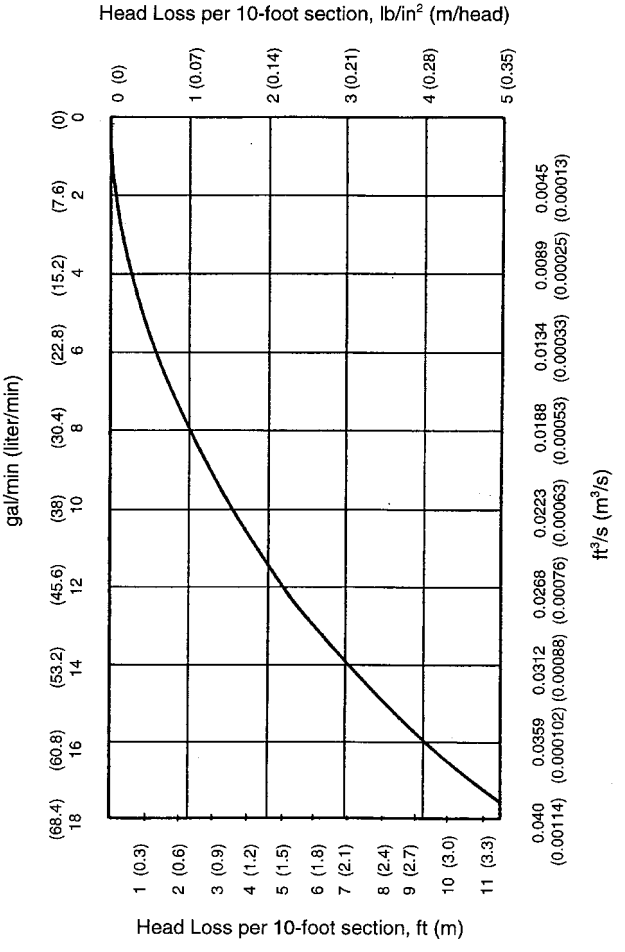


Figure 17-1.—Head loss in a 10-foot (3-m) section of AX (1.185-inch- [30.1-mm-] inside diameter [ID] drill rod.

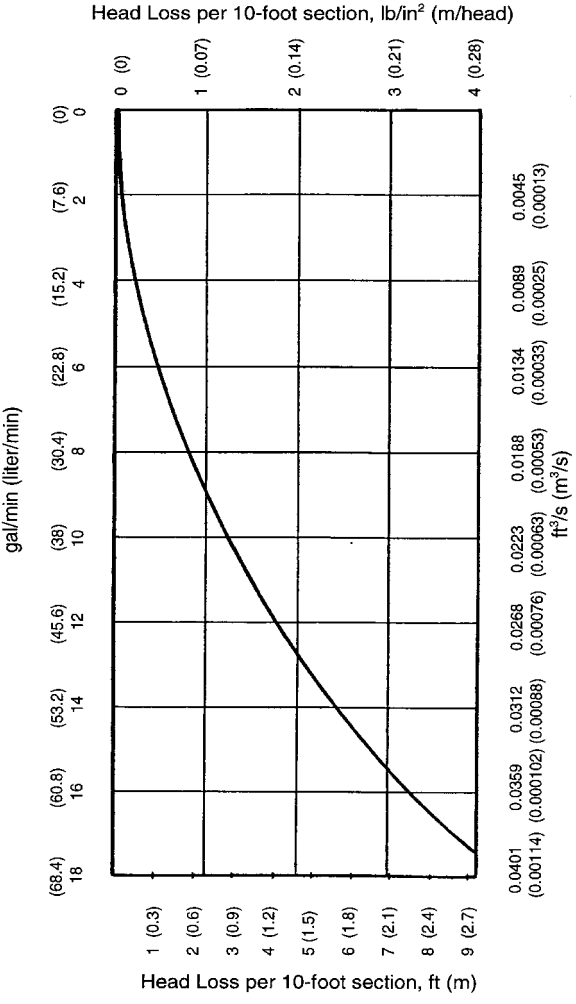


Figure 17-2.—Head loss in a 10-foot (3-m) section of BX (1.655-inch [42.0-mm] ID) drill rod.

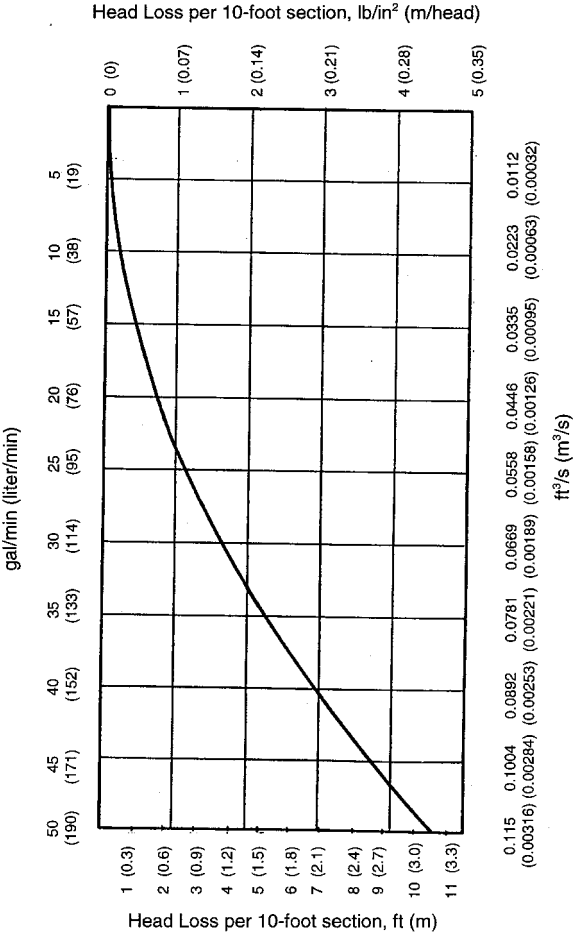


Figure 17-3.—Head loss in a 10-foot (3-m) section of NX (2.155-inch [54.7-mm] ID) drill rod.

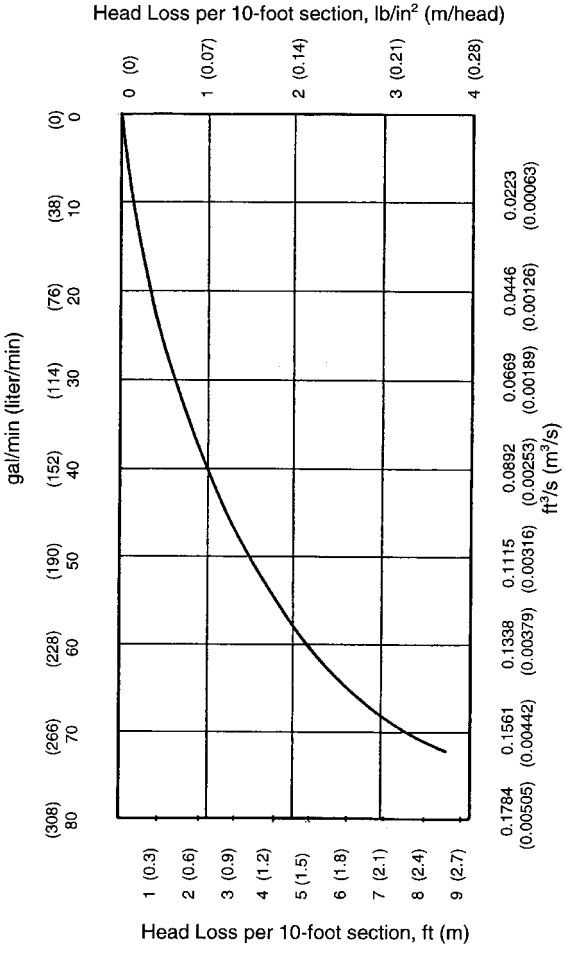


Figure 17-4.—Head loss in a 10-foot (3-m) section of 1¼-inch (32-mm) steel pipe.

pressure. In addition, mud pumps occasionally develop high peak pressures that may fracture the rock or blow out a packer.

Permeability tests made in drill holes should be performed using centrifugal or positive displacement pumps (Moyno type) having sufficient capacity to develop back pressure. A pump with a capacity of up to 250 gal/min (950 L/min) against a total head of 160 feet (48 m) is adequate for most testing. Head and discharge of these pumps are easily controlled by changing rotational speed or adjusting the discharge valve.

Swivels for Use in Tests

Swivels used for pressure testing should be selected for minimum head losses.

Location of Pressure Gauges

The ideal location for a pressure gauge is in the test section, but as close to the packer as possible.

Water Meters

Water deliveries in pressure tests may range from less than 1 gal/min (3.8 L/min) to as much as 400 gal/min (1,500 L/min). No one meter is sufficiently accurate at all ranges. Two meters are recommended: (1) a 4-inch (100-mm) propeller or impeller-type meter to measure flows between 50 and 350 gal/min (200 and 1,300 L/min), and (2) a 1-inch (25-mm) disk-type meter for flows between 1 and 50 gal/min (4 and 200 L/min). Each meter should be equipped with an instantaneous flow indicator and a totalizer. Water meters should be tested frequently.

Inlet pipes should be available to minimize turbulent flow into each meter. The inlet pipes should be at least 10 times the diameter of the meter inlet.

Length of Time for Tests

The minimum length of time to run a test depends on the nature of the material tested. Tests should be run until three or more readings of water take and pressure taken at 5-minute intervals are essentially equal. In tests above the water table, water should be pumped into the test section at the desired pressure for about 10 minutes in coarse materials or 20 minutes in fine-grained materials before making measurements.

Stability is obtained more rapidly in tests below the water table than in unsaturated material. When multiple pressure tests are made, each pressure theoretically should be maintained until stabilization occurs. This procedure is not practical in some cases, but good practice requires that each pressure be maintained for at least 20 minutes, and take and pressure readings should be made at 5-minute intervals as the pressure is increased and for 5 minutes as pressure is decreased.

Pressures Used in Testing

The pressure used in testing should be based on the rock being tested. Relatively flat-lying, bedded rock should be tested at 0.5 lbs/in^2 per foot (0.1 kg/cm^2/m) of depth to the test interval to prevent uplift or jacking of the rock. Relatively homogeneous but fractured rock can be tested at 1 lb/in^2 per foot (0.2 kg/cm^2/m) of test interval depth. Relatively unfractured rock can be tested at 1.5 lb/in^2 per foot (0.3kg/cm^2/m) of test interval depth.

Arrangement of Equipment

The recommended arrangement of test equipment starting at the source of water is: source of water; suction line; pump; waterline to settling and storage tank or basin, if required; suction line; centrifugal or positive displacement pump; line to water meter inlet pipe; water meter; short length of pipe; valve; waterline to swivel; sub for gauge; and pipe or rod to packer. All connections should be kept as short and straight as possible, and the number of changes in hose diameter, pipe, etc., should be kept as small as possible.

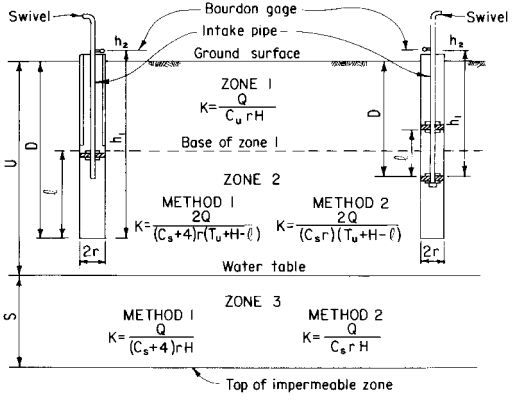
All joints, connections, and hose between the water meter and the packer or casing should be tight, and there should be no water leaks.

Pressure Permeability Tests

A schematic of the following two methods is shown in figure 17-5.

Method 1: The hole is drilled, cleaned, the tools are removed, a packer is seated the test interval distance above the bottom of the hole, water under pressure is pumped into the test section, and readings are recorded. The packer is then removed, the hole is drilled the test interval length deeper, cleaned, the packer is inserted using the length of the newly drilled hole as the test section, and the test performed.

Method 2: The hole is drilled to the final depth, cleaned, and blown out or bailed. Two packers spaced on pipe or drill stem to isolate the desired test section are used. Tests should be started at the bottom of the hole. After each test, the pipe is lifted a distance equal to l, shown on figure 17-5, and the test is repeated until the entire hole is tested.



K = coefficient of permeability, feet per second under a unit gradient
Q = steady flow into well, ft^3/s
$H = h_1 + h_2 - L$ = effective head, ft
h_1 (above water table) = distance between Bourdon gage and bottom of hole for method 1 or distance between gage and upper surface of lower packer for method 2, ft
h_1 (below water table) = distance between gage and water table, ft
h_2 = applied pressure at gage, 1 lb/in^2 = 2.307 ft of water
L = head loss in pipe due to friction, ft; ignore head loss for Q<4 gal/min in $1\frac{1}{4}$-inch pipe; use length of pipe between gage and top of test section for computations
$X = \frac{H}{T_u}(100)$ = percent of unsaturated stratum
ℓ = length of test section, ft
r = radius of test hole, ft
C_u = conductivity coefficient for unsaturated materials with partially penetrating cylindrical test wells
C_s = conductivity coefficient for semi-spherical flow in saturated materials through partially penetrating cylindrical test wells
U = thickness of unsaturated material, ft
S = thickness of saturated material, ft
$T_u = U - D + H$ = distance from water surface in well to water table, ft
D = distance from ground surface to bottom of test section, ft
a = surface area of test section, ft^2; area of wall plus area of bottom for method 1; area of wall for method 2
Limitations:
$Q/a \leq 0.10$, $S \geq 5\ell$, $\ell \geq 10r$, thickness of each packer must be $\geq 10r$ in method 2

Figure 17-5.—Permeability test for use in saturated or unsaturated consolidated rock and well indurated soils.

Data required for computing the permeability may not be available until the hole has encountered the water table or a relatively impermeable bed. The required data for each test include:

- Radius, r, of the hole, in feet (meters).
- Length of test section, ℓ, the distance between the packer and the bottom of the hole, Method 1, or between the packers, Method 2, in feet (meters).
- Depth, h_1, from pressure gauge to the bottom of the hole, Method 1, or from gauge to the upper surface of lower packer in Method 2. If a pressure transducer is used, substitute the pressure recorded in the test section before pumping for the h_1 value.
- Applied pressure, h_2, at the gauge, in feet (meters), or the pressure recorded during pumping in the test section if a transducer is used.
- Steady flow, Q, into well at 5-minute intervals, in cubic feet per second (ft^3/sec) (cubic meters per second [m^3/sec]).
- Nominal diameter in inches (mm) and length of intake pipe in feet (m) between the gauge and upper packer.
- Thickness, U, of unsaturated material above the water table, in feet (m).
- Thickness, S, of saturated material above a relatively impermeable bed, in feet (m).
- Distance, D, from the ground surface to the bottom of the test section, in feet (m).
- Time that the test is started and the time measurements are made.

- Effective head, the difference in feet (m) between the elevation of the free water surface in the pipe and the elevation of the gauge plus the applied pressure. If a pressure transducer is used, the effective head in the test section is the difference in pressure before water is pumped into the test section and the pressure readings made during the test.

The following examples show some typical calculations using Methods 1 and 2 in the different zones shown in figure 17-5. Figure 17-6 shows the location of the zone 1 lower boundary for use in unsaturated materials.

Pressure permeability tests examples using Methods 1 and 2:

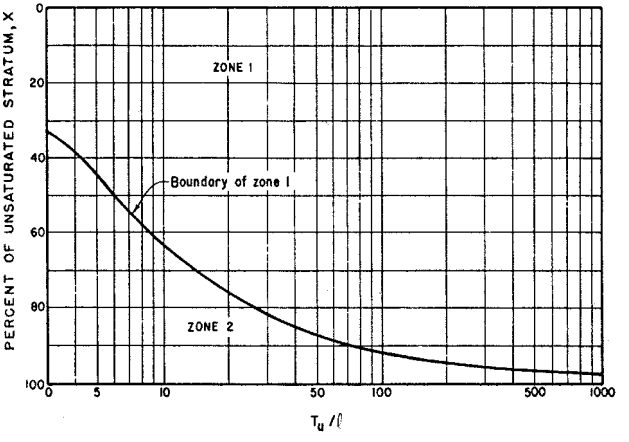


Figure 17-6.—Location of zone 1 lower boundary for use in unsaturated materials.

Zone 1, Method 1

Given: U = 75 feet, D = 25 feet, ℓ = 10 feet, r = 0.5 foot, h_1 = 32 feet, h_2 = 25 lb/in^2 = 57.8 feet, and Q = 20 gal/min = 0.045 ft^3/sec

From figure 17-4: head loss, L, for a 1¼-inch pipe at 20 gal/min is 0.76 foot per 10-foot section. If the distance from the gauge to the bottom of the pipe is 22 feet, the total head loss, L, is (2.2) (0.76) = 1.7 feet.

$H = h_1 + h_2 - L$ = 32 + 57.8 - 1.7 = 88.1 feet of effective head, $T_u = U - D + H$ = 75 - 25 + 88.1 = 138.1 feet

$$X = \frac{H}{T_u}(100) = \frac{88.1}{138.1}(100) = 63.8\%$$

$$\frac{C_u}{\ell} = \frac{138.1}{10} = 13.8$$

The values for X and T_u/ℓ lie in zone 1 (figure 17-6). To determine the unsaturated conductivity coefficient, C_u, from figure 17-7:

$$\frac{H}{r} = \frac{88.1}{0.5} = 176.2$$

$$\frac{\ell}{H} = \frac{10}{88.1} = 0.11 \quad \textit{also} \quad C_u = 62$$

then:

$$K = \frac{Q}{C_u r H} = \frac{0.045}{(62)\ (0.5)\ (88.1)} = 0.000016\ ft/s$$

$$K = 0.000016\ ft/s\ X\ 3.15X10^7 = 504\ ft/yr$$

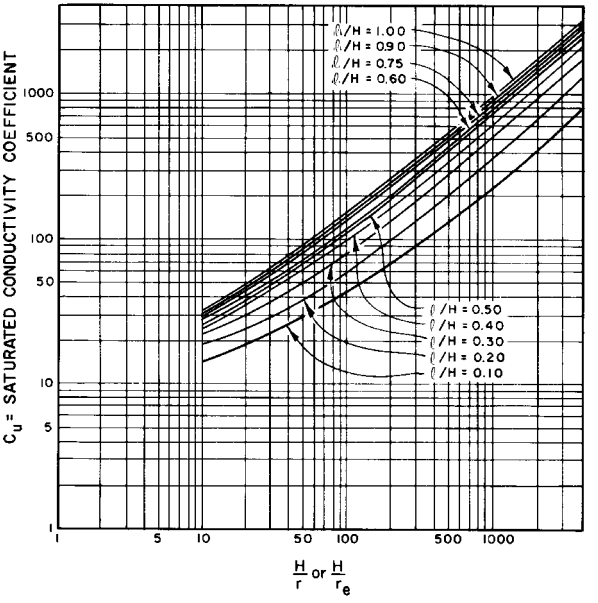


Figure 17-7.—Conductivity coefficients for permeability determination in unsaturated materials with partially penetrating cylindrical test wells.

Zone 2

Given: U, ℓ, r, h_2, Q, and L are as given in example 1, D = 65 feet, and h_1 = 72 feet

If the distance from the gauge to the bottom of the intake pipe is 62 feet, the total L is (6.2) (0.76) = 4.7 feet.

H = 72 + 57.8 - 4.7 = 125.1 feet

T_u = 75 - 65 + 125.1 = 135.1 feet

$$X = \frac{125.1}{135.1}(100) = 92.6\% \quad \textit{also} \quad \frac{T_u}{\ell} = \frac{135.1}{10} = 13.5$$

The test section is located in zone 2 (figure 17-6). To determine the saturated conductivity coefficient, C_s, from figure 17-8:

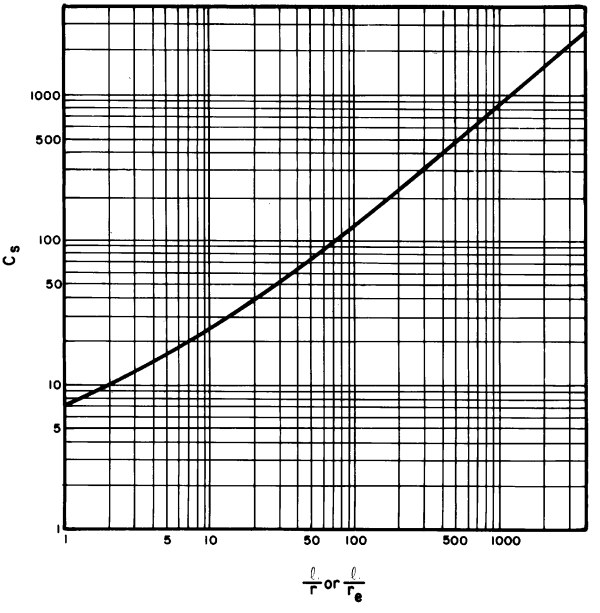


Figure 17-8.—Conductivity coefficients for semispherical flow in saturated materials through partially penetrating cylindrical test wells.

$$\frac{\ell}{r} = \frac{10}{0.5} = 20 \quad \textit{also} \quad C_s = 39.5$$

Method 1:

$$K = \frac{2Q}{(C_s + 4)r(T_u + H - \ell)}$$

$$K = \frac{(2)(0.045)}{(39.5 + 4)(0.5)(135.1 + 125.1 - 10)}$$

$$K = 0.000016 \; ft/s$$

$$K = 0.000016 ft/s \; X \; 3.15X10^7 = 504 \; ft/yr$$

Method 2:

$$K = \frac{2Q}{(C_s \, r)(T_u + H - \ell)}$$

$$K = \frac{(2)(0.045)}{(39.5)(0.5)(135.1 + 125.1 - 10)} = 0.000018 \; ft/s$$

$$K = 0.000018 \; ft/s \; X \; 3.15X10^7 = 567 \; ft/yr$$

Zone 3

Given:

U, ℓ, r, h_2, Q, and L are as given in example 1, D = 100 feet, h_1 = 82 feet, and S = 60 feet

If the distance from the gauge to the bottom of the intake pipe is 97 feet, the total L is (9.7) (0.76) = 7.4 feet.

H = 82 + 57.8 - 7.4 = 132.4 feet

$$\frac{\ell}{r} = \frac{10}{0.5} = 20 \quad \textit{also} \quad C_s = 39.5 \textit{ from figure } 17\text{-}8$$

Method 1:

$$K = \frac{Q}{(C_s + 4)rH} = \frac{0.045}{(39.5 + 4)(0.5)(132.4)} = 0.000016\, ft/s$$

$$K = 0.000016\, ft/s \times 3.15 \times 10^7 = 504\, ft/yr$$

Method 2:

$$K = \frac{Q}{C_s\, rH} = \frac{0.045}{(39.5)(0.5)(132.4)} = 0.000017\, ft/s$$

$$K = 0.000017\, ft/s \times 3.15 \times 10^7 = 536\, ft/yr$$

Multiple Pressure Tests

Multiple pressure tests are pressure permeability tests that apply the pressure in three or more approximately equal steps. For example, if the allowable maximum differential pressure is 90 lb/in^2 (620 kilopascal [kPa]), the test would be run at pressures of about 30, 60, and 90 lb/in^2 (210 kPa, 415 kPa, and 620 kPa).

Each pressure is maintained for 20 minutes, and water take readings are made at 5-minute intervals. The

pressure is then raised to the next step. After the highest step, the process is reversed and the pressure maintained for 5 minutes at the same middle and low pressures. A plot of take against pressure for the five steps is then used to evaluate hydraulic conditions. These tests are also discussed in chapter 16.

Hypothetical test results of multiple pressure tests are plotted in figure 17-9. The curves are typical of those often encountered. The test results should be analyzed using confined flow hydraulic principles combined with data obtained from the core or hole logs.

Probable conditions represented by plots in figure 17-9 are:

1. Very narrow, clean fractures. Flow is laminar, permeability is low, and discharge is directly proportional to head.

2. Practically impermeable material with tight fractures. Little or no intake regardless of pressure.

3. Highly permeable, relatively large, open fractures indicated by high rates of water intake and no back pressure. Pressure shown on gauge caused entirely by pipe resistance.

4. Permeability high with fractures that are relatively open and permeable but contain filling material which tends to expand on wetting or dislodges and tends to collect in traps that retard flow. Flow is turbulent.

5. Permeability high, with fracture filling material which washes out, increasing permeability with time. Fractures probably are relatively large. Flow is turbulent.

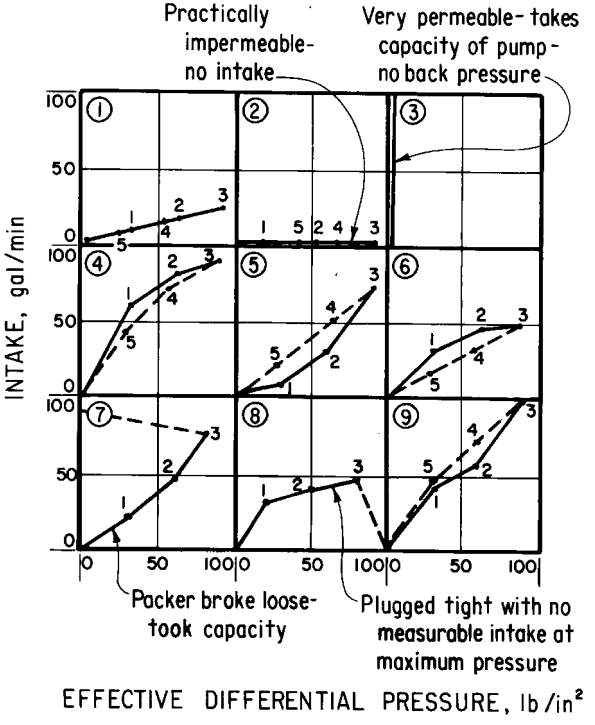


Figure 17-9.—Plots of simulated, multiple pressure permeability tests.

6. Similar to 4, but fractures are tighter and flow is laminar.

7. Packer failed or fractures are large, and flow is turbulent. Fractures have been washed clean; highly permeable. Test takes capacity of pump with little or no back pressure.

8. Fractures are fairly wide but filled with clay gouge material that tends to pack and seal when under pressure. Takes full pressure with no water intake near end of test.

9. Open fractures with filling that tends to first block and then break under increased pressure. Probably permeable. Flow is turbulent.

Gravity Permeability Tests

Gravity permeability tests are used primarily in unconsolidated or unstable materials. Gravity tests are performed in unconsolidated materials but are typically performed at greater depths. Gravity tests can be run only in vertical or near-vertical holes. A normal test section length is 5 feet (1.5 m). If the material is stable, stands without caving or sloughing, and is relatively uniform, sections up to 10 feet (3 m) long may be tested. Shorter test sections may be used if the length of the water column in the test section is at least five times the diameter of the hole. This length to diameter ratio is used in attempting to eliminate the effect of the bottom of the borehole. The diameter of the borehole sidewalls is the outside of any screen and annular packing of sand and or gravel. After each test, the casing for open hole tests is driven to the bottom of the hole, and a new test section is opened below the casing. If perforated casing is used, the pipe can be driven to the required depth and cleaned out, or the hole can be drilled to the required depth and the casing driven to the bottom of the hole and the hole cleaned out.

Cleaning and Developing Test Sections

Each newly opened test section should be developed by surging and bailing. Development should be done slowly and gently so that a large volume of loosely packed material is not drawn into the hole and only the compaction caused by drilling is broken down and the fines will be removed from the formation.

Measurement of Water Levels Through Protective Pipe

Measuring water depths inside a ¾- to 1½-inch- (20- to 40-mm-) small-diameter perforated pipe in the hole dampens wave or ripple action on the water surface caused by the inflow of water resulting in more accurate water level measurements. Water may also be introduced through the pipe and water level measurements made in the annular space between the pipe and the casing.

In an uncased test section in friable materials liable to wash, the end of the pipe should rest on a 4- to 6-inch (100- to 150-mm) cushion of coarse gravel at the bottom of the hole. In more stable material, the pipe may be suspended above the bottom of the hole, but the bottom of the pipe should be located at least 2 feet (0.6 m) below the top of the water surface maintained in the hole.

Pumping Equipment and Controls

Pressure is not required in the test, but pump capacity should be adequate to maintain a constant head during the test.

Accurate control of the flow of water into the casing is a problem on many gravity tests. The intake of the test section necessary to maintain a constant head is sometimes so small that inflow cannot be sufficiently controlled using a conventional arrangement. A precise method of controlling low flows, such as using needle valves, is important. Many meters are inaccurate at very low flows.

Water Meters

Water deliveries in gravity tests may range from less than 1 gal/min (3.8 L/min) to several hundred gallons per minute. No one meter is sufficiently accurate at all ranges. Two meters are recommended: (1) a 4-inch (100-mm) propeller- or impeller-type meter to measure flows between 50 and 350 gal/min (200 and 1,300 L/min) and (2) a 1-inch (25-mm) disk-type meter for flows between 1 and 50 gal/min (4 and 200 L/min). Each meter should be equipped with an instantaneous flow indicator and a totalizer. Water meters should be tested frequently.

Length of Time for Tests

As in pressure tests, stabilized conditions are very important if good results are to be obtained from gravity tests. Depending on the type of test performed, one of two methods is used. In one method, the inflow of water is controlled until a uniform inflow results in a stabilized water level at a predetermined depth. In the other method, a uniform flow of water is introduced into the hole until the water level stabilizes.

Arrangement of Equipment

A recommended arrangement of test equipment, starting at the source of water, is: suction line; pump; waterline to settling and storage tank or basin, if required; suction line; centrifugal or positive displacement pump; line to water meter inlet pipe; water meter; short length of pipe; valve; and the waterline to the casing. All connections should be kept as short and straight as possible, and the changes in diameter of hose, pipe, etc., should be kept to a minimum. If a constant head tank is used, the tank should be placed so that water flows directly into the casing.

Gravity Permeability Test - Method 1

For tests in unsaturated and unstable material using only one drill hole, Method 1 is the most accurate available. Because of mechanical difficulties, this test cannot be economically carried out at depths greater than about 40 feet (12 m) when gravel fill must be used in the hole. When performing the test, after the observation and intake pipes are set, add gravel in small increments as the casing is pulled back; otherwise, the pipes may become sandlocked in the casing. For tests in unsaturated and unstable material at depths greater than about 12 meters (40 feet), Method 2 should be used (described later).

The procedures for testing soil conditions are:

Unconsolidated Materials – A 6-inch (150-mm) or larger hole is drilled or augered to the test depth and then carefully developed. A cushion of coarse gravel is placed at the bottom of the hole, and the feed pipe

(I) and the observation pipe (O) are set in position (figure 17-10). After the pipes are in position, the hole is filled with medium gravel to a depth at least five times the diameter of the hole. If the drill hole wall material will not stand without support, the hole must be cased to the bottom. After casing, the gravel cushion and pipes are put in, and the casing is pulled back slowly as medium gravel is fed into the hole. The casing should be pulled back only enough to ensure that the water surface to be maintained in the hole will be below the bottom of the casing. About 4 inches (100 mm) of the gravel fill should extend up into the casing.

A metered supply of water is poured into the feed pipe until three or more successive measurements of the water level taken at 5-minute intervals through the observation pipe are within 0.2 foot (5 mm). The water supply should be controlled so that the stabilized water level is not within the casing and is located more than five times the hole diameter above the bottom of the hole. The water flow generally has to be adjusted to obtain the required stabilized level.

Consolidated Materials – The gravel fill and casing may be omitted in consolidated material or unconsolidated material that will stand without support even when saturated. A coarse gravel cushion is appropriate. The test is carried out as in unconsolidated, unstable materials.

Tests should be made at successive depths selected so that the water level in each test is located at or above the bottom of the hole in the preceding test. The permeability coefficients within the limits ordinarily

employed in the field can be obtained from figures 17-7 and 17-8. The test zone and applicable equations are shown in figures 17-6 and 17-10.

Data required for computing the permeability may not be available until the hole has penetrated the water table. The required data are:

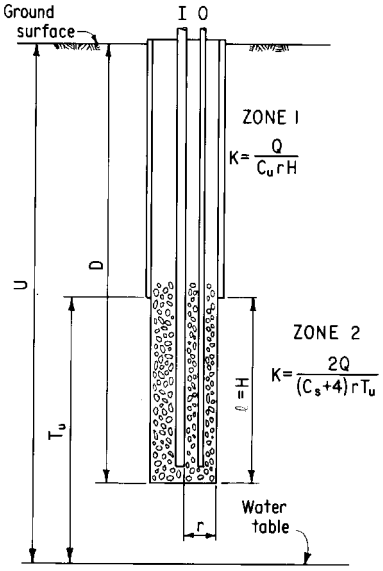
- Radius of hole, r, in feet (meters)
- Depth of hole, D, in feet (meters)
- Depth to bottom of casing, in feet (meters)
- Depth of water in hole, H, in feet (meters)
- Depth to top of gravel in hole, in feet (meters)
- Length of test section, ℓ, in feet (meters)
- Depth-to-water table, T_u, in feet (meters)
- Steady flow, Q, introduced into the hole to maintain a uniform water level, in ft^3/sec (m^3/sec)
- Time test is started and time each measurement is made

Some examples using Method 1 are:

Zone 1, Method 1

Given:

$H = \ell = 5$ feet, $r = 0.5$ foot, $D = 15$ feet, $U = 50$ feet, and $Q = 0.10$ ft^3/sec



K = coefficient of permeability, feet per second under a unit gradient
Q = uniform flow into well, ft^3/s
r = radius of test section, ft
H = height of column of water in well, ft
ℓ = length of test section, ft (for this method, $\ell = H$)
C_u and C_s = conductivity coefficients
$X = \frac{H}{T_u}(100)$ = percent of unsaturated stratum
$T_u = U - D + H$ = distance from water surface in well to water table, ft
U = thickness of unsaturated permeable bed, ft
D = distance from ground surface to bottom of test section, ft
I = feed pipe for pouring water into well (a 2-inch standard pipe is usually satisfactory)
O = observation pipe ($1\frac{1}{4}$-inch o.d. pipe is satisfactory)
a = surface area of test section (area of wall plus area of bottom), ft^2
Limitations:
$\ell \geq 10r$ and $\frac{Q}{a} \leq 0.10$

Figure 17-10.—Gravity permeability test (Method 1).

$T_u = U\text{-}D + H = 50 - 15 + 5 = 40$ feet, also $T_u / \ell = 40/5 = 8$

$$X = \frac{H}{T_u}(100) = \frac{5}{40}(100) = 12.5\%$$

The values for X and T_u / ℓ lie in zone 1 (figure 17-6). To determine the unsaturated conductivity coefficient, C_u, from figure 17-7:

$$\frac{H}{r} = \frac{5}{0.5} = 10, \quad \frac{\ell}{H} = \frac{5}{5} = 1, \quad \text{also } C_u = 32$$

$$K = \frac{Q}{C_u r H} = \frac{0.10}{(32)(0.5)(5)} = 0.00125 \text{ ft/s}$$

$$K = 0.00125 \text{ ft/sec } X\ 3.15X10^7 = 39{,}400 \text{ ft/yr}$$

Zone 2, Method 1

Given:

H, ℓ, r, U, and Q are as given in example 1, $D = 45$ feet

$$T_u = 50 - 45 + 5 = 10 \text{ ft} \quad \text{also} \quad \frac{T_u}{\ell} = \frac{10}{5} = 2$$

$$X = \frac{5}{10}(100) = 50\%$$

Points T_u / ℓ and X lie in zone 2 on figure 17-6.

To determine the saturated conductivity coefficient, C_s, from figure 17-8:

$$\frac{\ell}{r} = \frac{5}{0.5} = 10 \quad \textit{also} \quad C_s = 25.5$$

From figure 17-10:

$$K = \frac{2Q}{(C_s + 4)rT_u} = \frac{(2)(0.10)}{(25.5 + 4)(0.5)(10)} = 0.00136 \text{ ft/sec}$$

Gravity Permeability Test - Method 2

This method may give erroneous results when used in unconsolidated material because of several uncontrollable factors. However, it is the best of the available pump-in tests for the conditions. The results obtained are adequate in most instances if the test is performed carefully. When permeabilities in streambeds or lakebeds must be determined below water, Method 2 is the only practical gravity test available.

A 5-foot (1.5-m) length of 3- to 6-inch- (75- to 150-mm-) diameter casing uniformly perforated with the maximum number of perforations possible without seriously affecting the strength of the casing is best. The bottom of the perforated section of casing should be beveled on the inside and case hardened for a cutting edge.

The casing is sunk by drilling or jetting and driving, whichever method will give the tightest fit of the casing in the hole. In poorly consolidated material and soils with a nonuniform grain size, development by filling the casing with water to about 3 feet (1 m) above the perforations and gently surging and bailing is advisable

before making the test. A 6-inch (150-mm) coarse gravel cushion is poured into the casing, and the observation pipe is set on the cushion.

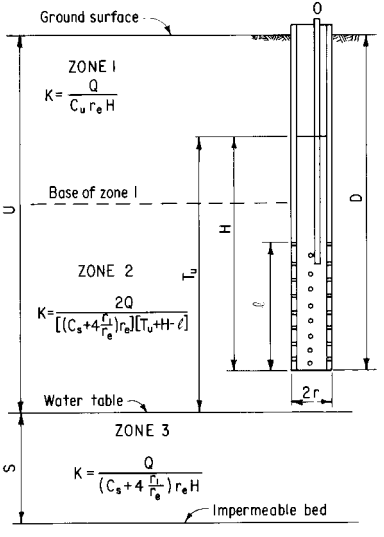
A uniform flow of water sufficient to maintain the water level in the casing above the top of the perforations is poured into the well. The water should be poured through a pipe and measurements made between the pipe and casing or reversed if necessary. Depth of water measurements are made at 5-minute intervals until three or more measurements are within ±0.2 foot (60 mm) of each other.

When a test is completed, the casing is sunk an additional 5 feet (1.5 m), and the test is repeated.

The test may be run in stable consolidated material using an open hole for the test section. Because the bottom of the casing is seldom tight in the hole and significant error may result from seepage upward along the annular space between the casing and the wall of the hole, this is not recommended. Measurements should be made to the nearest 0.01 foot (3 mm). The values of C_u and C_s within the limits ordinarily employed in the field can be obtained from figures 17-7 and 17-8. The zone in which the test is made and applicable equations can be found in figures 17-6 and 17-11, respectively.

Some data required for computing permeability are not available until the hole has encountered the water table.

The recorded data are supplemented by this information as the data are acquired. The data recorded in each test are:



K = coefficient of permeability, feet per second under a unit gradient
Q = steady flow into well, ft^3/s
H = height of water in well, ft
ℓ = length of perforated section, ft
r_1 = outside radius of casing (radius of hole in consolidated material), ft
r_e = effective radius of well = r_1 (area of perforations)/(outside area of perforated section of casing); $r_1 = r_e$ in consolidated material that will stand open and is not cased
C_u and C_s = conductivity coefficients
T_u = distance from water level in casing to water table, ft
a = surface area of test section (area of perforations plus area of bottom), ft^2; where clay seal is used at bottom, a = area of perforations
S = thickness of saturated permeable material above an underlying relatively impermeable stratum, ft
$X = \frac{H}{T_u}(100)$ = percent of unsaturated stratum
U = thickness of unsaturated material above water table, ft
D = distance from ground surface to bottom of test section, ft
O = observation pipe (1 to $1\frac{1}{4}$-inch pipe)
Limitations:
$S \geq 5\ell$, $\ell \geq 10r$, and $\frac{Q}{a} \leq 0.10$
Notes:
In zone 3, H is the difference in elevation between the normal water table and the water level in the well. In zones 2 and 3, if a clay seal is placed at the bottom of the casing, the factor $4\frac{r_1}{r_e}$ is omitted from the equations. Where the test is run with "ℓ" as an open hole, $\frac{r_1}{r_e} = 1$ and $(C_s + 4\frac{r_1}{r_e}) = (C_s + 4)$.

Figure 17-11.—Gravity permeability test (Method 2).

- Outside radius of casing, r_1
- Length of perforated section of casing, ℓ
- Number and diameter of perforations in length ℓ
- Depth to bottom of hole, D
- Depth-to-water surface in hole
- Depth of water in hole, H
- Depth-to-water table, U
- Thickness of saturated permeable material above underlying relatively impermeable bed, S
- Steady flow into well to maintain a constant water level in hole, Q
- Time test is started, and measurement is made

Some examples using Method 2 are:

Zone 1, Method 2

Given:

H = 10 feet, ℓ = 5 feet, r_1 = 0.25 foot, D = 20 feet, U = 50 feet, Q = 0.10 ft^3/sec, 128 0.5-inch-diameter perforations, bottom of the hole is sealed

Area of perforations = $128\pi\, r_1^{\,2} = 128\pi\,(0.25)^2 =$ 25.13 in^2 = 0.174 ft^2

Area of perforated section = $2\pi r_\ell = 2\pi\,(0.25)\,(5) =$ 7.854 ft^2

$$r_e = \frac{0.174}{7.854}(0.25) = 0.00554\ ft$$

$$T_u = U - D' + H = 50 - 20 + 10 = 40\ ft$$

$$also\ \frac{T_u}{\ell} = \frac{40}{5} = 8$$

$$X = \frac{H}{T_u}(100) = \frac{10}{40}(100) = 25\%$$

Points T_u / ℓ and X lie in zone 1 on figure 17-6.

Find C_u from figure 17-7:

$$\frac{H}{r_e} = \frac{10}{0.00554} = 1{,}805\ also\ \frac{\ell}{H} = \frac{5}{10} = 0.5$$

then, $C_u = 1{,}200$

From figure 17-11:

$$K = \frac{Q}{C_u r_e H} = \frac{0.10}{(1{,}200)(0.00554)(10)} = 0.0015\ ft/s$$

$$K = 0.0015\ ft/s\ X\ 3.15X10^7 = 47{,}300\ ft/yr$$

Zone 2, Method 2

Given:

Q, H, ℓ, r_p, r_e, U, ℓ/H, and H/r_e same as Zone 1, Method 2, D = 40 feet

$$T_u = 50 - 40 + 10 = 20\,ft \quad also \quad \frac{T_u}{\ell} = \frac{20}{5} = 4$$

$$X = \frac{10}{20}(100) = 50\%$$

Points T_u / ℓ and X lie in zone 2 on figure 17-6.

Find C_s from figure 17-8:

$$\frac{\ell}{r_e} = \frac{5}{0.00554} = 902 \quad also \quad C_s = 800$$

From figure 17-11:

$$K = \frac{2Q}{\left[\left(C_s + 4\frac{r_1}{r_e}\right) r_e\right](T_u + H - \ell)} =$$

$$\frac{0.20}{(5.43)(20 + 10 - 5)} = 0.0015\,ft/s$$

$$K = 0.0015\,ft/s \; X \; 3.15X10^7 = 47{,}300\,ft/yr$$

Zone 3, Method 2

Given:

Q, H, ℓ, r_1, r_e, ℓ/H, H/r_e, U, C_s, and ℓ/r_e are as given in Zone 2, Method 2, S = 60 feet

From figure 17-11:

$$K = \frac{Q}{\left(C_s + 4\frac{r_1}{r_e}\right) r_e H} = \frac{0.10}{(980.5)(0.00554)(10)} = 0.0018\ ft/s$$

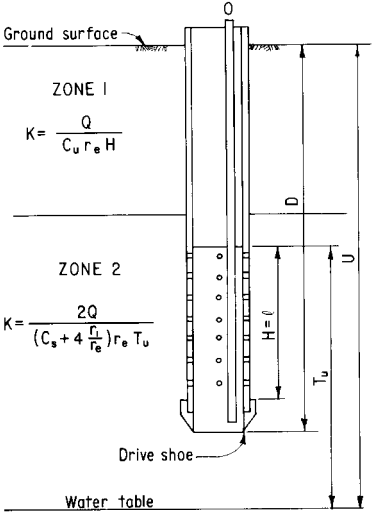
$$K = 0.0018\ ft/s\ X\ 3.15X10^7 = 56{,}700\ ft/yr$$

Gravity Permeability Test - Method 3

This method is a combination of gravity permeability test Methods 1 and 2. The method is the least accurate, but is the only one available for gravelly or coarse soils (figure 17-12).

In some materials, a casing that is beveled and case hardened at the bottom will not stand up to the driving. This is particularly true in gravelly materials where the particle size is greater than about 1 inch (25 mm). Under these conditions, Method 3 would probably not be satisfactory because a drive shoe must be used. Using a drive shoe causes excessive compaction of the materials and forms an annular space around the casing.

On completion of each test, a 3- to 6-inch-diameter (90- to 150-millimeter) perforated casing is advanced 5 feet (1.5 m) by drilling and driving. After each new test section is developed by surging and bailing, a 6-inch (150-mm) gravel cushion is placed on the bottom to support the observation pipe. A uniform flow of water sufficient to maintain the water level in the casing just at the top of the perforations is then poured into the well. The water is poured directly into the casing, and measurements are made through a 1¼-inch (32-mm) observation pipe. The test should be run until three or



K = coefficient of permeability, feet per second under a unit gradient
Q = steady flow into well, ft^3/s
r_i = outside radius of casing
r_e = effective radius of casing = r_i(area of perforations)/(outside area of ℓ)
ℓ = length of perforated section, ft
C_u and C_s = conductivity coefficients
H = height of column of water in perforated section, ft
T_u = distance from water level in casing to water table, ft
$X = \frac{U}{T_u}(100)$ = percent of unsaturated stratum
O = observation pipe ($1\frac{1}{4}$-inch o.d. pipe is satisfactory)
U = tickness of unsaturated material above water table, ft
D = distance from ground surface to bottom of test section, ft
a = surface area of test section (area of perforations plus area of bottom), ft^2; where clay seal is used at bottom, a = area of perforations

Limitations:
$\frac{Q}{a} \leq 0.10$, $\ell \geq 10r$

Note:
In zone 2, if clay seal is placed at bottom of casing, the factor $4\frac{r_i}{r_e}$ is omitted from equation.

Figure 17-12.—Gravity permeability test (Method 3).

more measurements taken at 5-minute intervals are within ±0.2 foot (60 mm) of the top of the perforations.

The values of C_u and C_s, within the limits ordinarily employed in the field, can be obtained from figures 17-7 and 17-8. The zone in which the test is made and applicable equations can be found on figures 17-6 and 17-12, respectively.

The data recorded in each test are:

- Outside radius of casing, r_1, in feet (meters)

- Length of perforated section of casing, ℓ, in feet (meters)

- Number and diameter of perforations in length ℓ

- Depth to bottom of hole, D, in feet (meters)

- Depth-to-water surface in hole, in feet (meters)

- Depth of water in hole, in feet (meters)

- Depth-to-water table, in feet (meters)

- Steady flow into well to maintain a constant water level in hole, Q, in ft^3/sec (m^3/sec)

- Time test is started and time each measurement is made

Zone 1, Method 3

Given: Q = 10.1 gal/min = 0.023 ft^3/sec, $H = \ell = 5$ feet, D = 17 feet, U = 71 feet, T_u = 54.5 feet, r_e = 0.008 foot, and r_1 = 1.75 inches = 0.146 foot (nominal 3-inch casing)

$$\frac{T_u}{\ell} = \frac{54.4}{5} = 10.9$$

$$Also\ X = \frac{H}{T_u}(100) = \frac{5}{54.5}(100) = 9.2\%$$

These points lie in zone 1 (figure 17-6).

Find C_u from figure 17-7:

$$\frac{H}{r_e} = \frac{5}{0.008} = 625\ also\ \frac{\ell}{H} = 1$$

then, C_u = 640

From figure 17-12:

$$K = \frac{Q}{C_u r_e H} = \frac{0.023}{(640)(0.008)(5)} = 0.0009\ ft/s$$

$$K = 0.0009\ ft/s\ X\ 3.15X10^7 = 28{,}400\ ft/yr$$

Zone 2, Method 3

Given: Q, H, ℓ, U, r_e, and r_1 are as given in Zone1, Method 3, D = 66 feet and T_u = 10 feet

$$\frac{T_u}{\ell} = \frac{10}{5} = 2 \quad \textit{also} \quad X = \frac{5}{10}(100) = 50\%$$

These points lie in zone 2 (figure 17-6).

Find C_s from figure 17-8:

$$\frac{\ell}{r_e} = \frac{5}{0.008} = 625 \quad \textit{also} \quad C_s = 595$$

From figure 17-12:

$$K = \frac{2Q}{\left(C_s + 4\frac{r_1}{r_e}\right) r_e T_u} = \frac{(2)(0.023)}{(668)(0.008)(10)} = 0.00086 \; ft/s$$

$$K = 0.00086 \; ft/s \; X \; 3.15X10^7 = 27{,}100 \; ft/yr$$

Gravity Permeability Test - Method 4

This method can be used to determine the overall average permeability of unsaturated materials above a widespread impermeable layer. The method does not detect permeability variations with depth. The method is actually an application of steady-state pumping test theory.

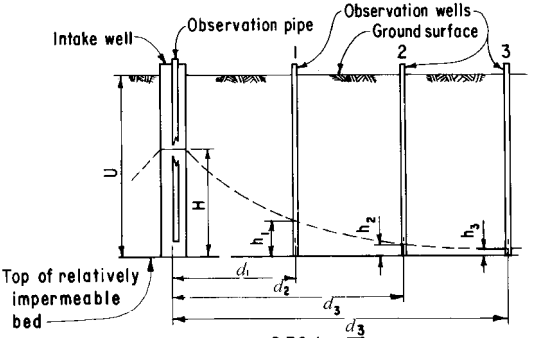
A well, preferably 6 inches (150 mm) or larger in diameter, is drilled to a relatively impermeable layer of wide areal extent or to the water table. If the saturated thickness is small compared to the height of the water column that can be maintained in the hole, a water table will act as an impermeable layer for this test. The well is uncased in consolidated material, but a perforated casing

casing or screen should be set from the bottom to about 5 feet (1.5 m) below the ground surface in unconsolidated material. The well should be developed by pouring water into the hole while surging and bailing before testing.

Before observation wells are drilled, a test run of the intake well should be made to determine the maximum height, *H*, of the column of water that can be maintained (figure 17-13) above the top of the impermeable layer. A 1- to 1¼-inch (25- to 32-mm) observation pipe should be inserted to near the bottom of the intake well to for water-level measurements. The spacing of the observation wells can be determined from this test run.

A minimum of three observation wells should be installed to the top of the impermeable layer or water table. Suitable pipe, perforated for the bottom 10 to 15 feet (3 to 4.5 m), should be set to the bottom of these wells. The observation wells should be offset from the intake well by distances equal to multiples of one-half the height, *H*, of the water column that will be maintained in the intake well.

The elevations of the top of the impermeable layer or water table in each well are determined, and the test is started. After water has been poured into the intake at a constant rate for an hour, measurements are made of water levels in the observation wells. Measurements are then made at 15-minute intervals, and each set of measurements is plotted on semi-log paper. The square



$$K = \frac{2.3Q \log \frac{d_3}{d_2}}{\pi (h_2^2 - h_3^2)}$$

K = coefficient of permeability, feet per second under a unit gradient

Q = uniform flow into intake well, ft^3/s

d_1, d_2, and d_3 = distance from intake well to observation holes, ft

h_1, h_2, and h_3 = height of water in observation holes d_1, d_2, and d_3 respectively, above elevation of top of impermeable layer, ft

H = height of column of water in intake pipe above top of impermeable stratum, ft

U = distance from ground surface to impermeable bed, ft

Figure 17-13.—Gravity permeability test (Method 4).

of the height of the water level above the top of the impermeable bed, h^2, is plotted against the distance from the intake well to the observation holes, d, for each hole (figure 17-14). When the plot of a set of measurements is a straight line drawn through the points within the limits of plotting, conditions are stable and the permeability may be computed.

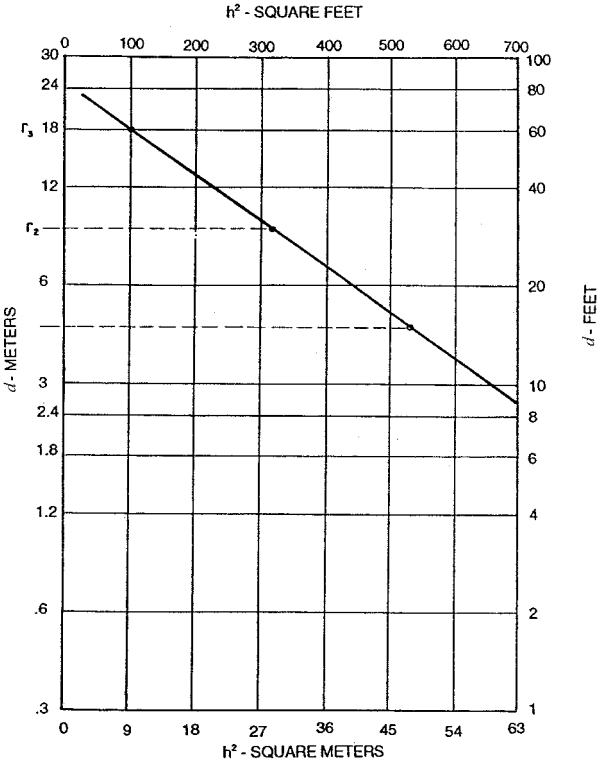


Figure 17-14.—Plot of h^2 versus d for gravity permeability test (Method 4).

The data recorded in each test are:

- Ground elevations at the intake well and the observation wells
- Elevations of reference points at the intake well and the observation wells, in feet (meters)

- Distances from center of the observation wells to center of the intake well, d_1, d_2, and d_3, in feet (meters)
- Elevation of top of impermeable bed at the intake well and the observation wells, in feet (meters)
- Depths of water below reference point in the intake well and the observation wells at 15-minute intervals, in feet (meters)
- Uniform flow of water, Q, introduced into well, in ft^3/sec (m^3/sec)
- Time pumping is started and time each measurement is made

Method 4

Given: U = 50 feet, Q = 1 ft^3/sec, H = 30 feet, d_1 = 15 feet, d_2 = 30 feet, d_3 = 60 feet, h_1 = 23.24 feet, h_2 = 17.89 feet, h_3 = 10.0 feet, h_1^2 = 540 ft^2, h_2^2 = 320 ft^2, and h_3^2 = 100 ft^2

A plot of d against h^2, as shown on figure 17-14, shows that a straight line can be drawn through the plotted points, meaning that stable conditions exist and the permeability may be computed.

From figure 17-13:

$$\log \frac{d_3}{d_2} = 0.3010, \ \log \frac{d_3}{d_1} = 0.6021, \ \textit{also} \ \log \frac{d_2}{d_1} = 0.3010$$

$$K = \frac{2.3\ Q \log \frac{d_3}{d_2}}{\pi(h_2^2 - h_3^2)} = \frac{2.3\ Q \log \frac{d_3}{d_1}}{\pi(h_1^2 - h_3^2)} = \frac{2.3\ Q \log \frac{d_2}{d_1}}{\pi(h_1^2 - h_2^2)}$$

$$K = \frac{(2.3)(1)(0.3010)}{\pi(220)} =$$

$$\frac{(2.3)(1)(0.6020)}{\pi(440)} = \frac{(2.3)(1)(0.3010)}{\pi(220)} = 0.001\ ft/s$$

$$K = 0.001\ ft/s\ X\ 3.15X10^7 = 315{,}000\ ft/yr$$

Falling Head Tests

Falling head tests are used primarily in open holes in consolidated rock. Falling head tests use inflatable packers identical to those used for pressure testing and can be used as an alternate method if the pressure transducer or other instrumentation fails. The method of cleaning the hole is the same as that described under pressure testing.

Tests Below the Static Water Level

Tests below the static water level should be done as follows:

- Use inflatable straddle packers at 10-foot (3-m) spacing on a 1¼-inch (32-mm) drop pipe (inside diameter = 1.38 inches [35 mm]). Set packers initially at the bottom of the hole and inflate to 300 lb/in^2 (2,000 kPa) of differential pressure.

- After packers are inflated, measure the water level in the drop pipe three or more times at 5-minute intervals until the water level stabilizes. The stabilized level will be the static water level in the test section.

- Pour 2 gallons (8 liters [L]) or more of water as rapidly as possible into the drop pipe after the water level stabilizes. One gallon (4 l) of water will raise the water level in a 1¼-inch (32-mm) pipe 13 feet (4 m) if the section is tight.

- Measure the water level as soon as possible after the water is poured in. Measure the initial depth to water, record the time as soon as possible, and repeat twice at 5-minute intervals. If the rate of decline exceeds 15 feet (4.5 m) in 13 minutes, the transmissivity of a 10-foot (3-m) test section is greater than 200 ft^2 (18 m^2) per year, and the average permeability is greater than 20 feet (6 m) per year.

The transmissivity value determined is only an approximation, but the value is sufficiently accurate for many engineering purposes.

The equation for analysis is:

$$T = \frac{V}{2\pi s \Delta t}$$

where:

T = transmissivity of test section, in ft^2/sec (m^2/sec)

V = volume of water entering test section in period Δt, in ft^3 (m^3). (A 1-foot [30-cm] decline in 1¼-inch [32-mm] pipe = 0.01 ft^3 [0.000283 m^3])

s = decline in water level in period Δt, in feet (meters)

Δt = period of time, in seconds, between successive water level measurements (i.e., $t_1 - t_o$, $t_2 - t_1$, etc.)

- If the log indicates the test section is uniform and without obvious points of concentrated leakage, the average permeability of the test section, in feet per second (m/sec), can be estimated from $K = T / \ell$, where ℓ is the length of the test section, in feet (m). If the log indicates a predominantly impervious test section, but includes a zone or zones of concentrated flow, the average K of the zones can be estimated from $K = T / \ell'$, where ℓ' is the thickness of the permeable zone or zones, in feet (m).

- After each test, deflate the packers, raise the test string 10 feet (3 m), and repeat the test until the entire hole below the static water level has been tested.

Tests Above the Water Table

Tests above the water table require different procedures and analyses than tests in the saturated zone. Tests made in sections straddling the water table or slightly above the water table will give high computed values if the equations for tests below the static water level are used and low computed values if the following equations are used. For tests above the water table, the following procedure is used:

- Install a 10-foot- (3-m-) spaced straddle packer at the bottom of the hole, if the hole is dry, or with the top of the bottom packer at the water table if the hole contains water. Inflate the packer.

- Fill the drop pipe with water to the surface, if possible, otherwise, to the level permitted by pump capacity.

- Measure the water level in the drop pipe and record with time of measurement. Make two or more similar measurements while the water-table declines.

- Upon completion of a test, raise the packer 10 feet (3 m) and repeat this procedure until all of the open or screened hole is tested.

The equation for analysis is:

$$K = \frac{r_1^2}{2\ell\Delta t}\left[\frac{\sinh^{-1}\frac{\ell}{r_e}}{2}\ln\left(\frac{2H_1 - \ell}{2H_2 - \ell}\right) - \ln\left(\frac{2H_1H_2 - \ell H_2}{2H_1H_2 - \ell H_1}\right)\right]$$

where:

r_1 = inside radius of drop pipe, in feet (mm) (0.0575 foot [17.25 mm] for 1¼-inch [32-mm] pipe)

r_e = effective radius of test section, in feet (mm) 0.125 foot [37.5 mm] for a 3-inch [75-mm] hole)

Δt = time intervals (t_1-t_0, t_2-t_1), in seconds

$sinh^{-1}$ = inverse hyperbolic sine

ln = natural logarithm

H = length of water column from bottom of test interval to water surface in standpipe, in feet (m) (H_0, H_1, H_2 lengths at time of measurements t_0, t_1, t_2, etc.)

- For the particular equipment specified and a 10-foot (3-m) test section, the equation may be simplified to:

$$K = \frac{1.653 \times 10^{-4}}{\Delta t}\left[2.5\ln\left(\frac{H_1 - 5}{H_2 - 5}\right) - \ln\left(\frac{H_1H_2 - 5H_2}{H_1H_2 - 5H_1}\right)\right]$$

Slug Tests

Slug tests are performed by "rapidly" changing water levels in a borehole. The rapid change is induced by adding or removing small quantities of water, air, or an object that displaces the groundwater. The time required to restore the water level to its original level is used to calculate the permeability. Slug tests are typically performed in areas where access or budget is limited or the extraction or addition of water has a potential impact to the surrounding area. Slug tests are appropriate where the aquifer will not yield enough water to conduct an aquifer test or the introduction of water could change or impact the water quality. A major factor in conducting slug tests is ensuring that the water level during the test reflects the aquifer characteristics and is not unduly affected by the well construction. Where the water surface is shallow and clean water is readily available, water injection or bailing is often the easiest method. The displacement or air injection method may be desirable at locations where the water level is deep and rapid injection or removal of water is difficult.

A number of slug test methods exist. The choice depends on the hydrologic and geologic conditions and the well size and construction.

Selecting the Slug Test

The method of inducing a rise or fall in the water surface depends on the purpose of the test and conditions at the site. Where the water level is shallow and clean water is readily available, water injection or bailing is often the easiest method. One limitation of the test accuracy is the initial water flowing down the inside wall of the well. Causing a rapid rise by displacing water in the well by

dropping a pipe or weight or injecting air may be preferable at remote sites where water may not be readily available. The displacement or air injection method may also be desirable at locations where the water level is deep and rapid injection or removal of water may require collection and treatment or at well sites that are being used for water chemistry studies.

Conducting the Slug Test

Before introducing the slug, the well's sidewall, screen, or filter pack needs to be clear of any obstructions that will impede the movement of water from the riser to the surrounding materials. The riser diameter and length need to be measured as accurately as possible, and the water level must be stabilized and recorded as accurately as possible. The water level measurements must begin immediately following the introduction of the slug. Where the water level changes slowly, measurements may be made by using a water level indicator. For most tests, water levels should be recorded by a pressure transducer and automatic data logger.

Hvorslev Slug Test

The Hvorslev slug test is the simplest method of analysis. This analysis assumes a homogeneous, isotropic, infinite medium in which both the soil and water are incompressible. It neglects well bore storage and is not accurate where a gravel pack or thick sand pack is present. Figure 17-15 is a sketch of the geometry of this test and the method of analysis. This method is used where the slug test is conducted below an existing water surface.

The test analysis requires graphing the change in head versus time. Head changes are given by $(H\text{-}h) / H\text{-}H_0$ and

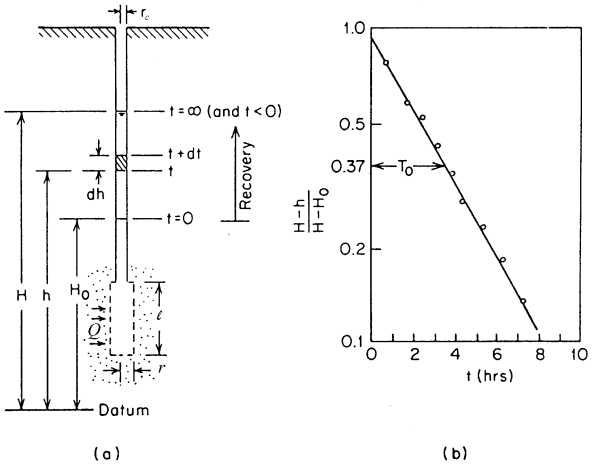


Figure 17-15.—Hvorslev piezometer test.

should be plotted semi-log against time. The graph should approximate a straight line; and at the point 0.37, the T_0 value is defined as the basic time lag. Using the graphical solution for T_0, the dimension of the cavity, and the appropriate shape factor, F, a solution for permeability can be found by:

$$K = \frac{\pi r_c^2}{F T_0}$$

Figure 17-16 provides shape equations for various well geometries.

Bouwer Slug Test

The Bouwer slug test assumes no aquifer storage and finite well bore storage. The well can be partially penetrating and partially screened. The method was

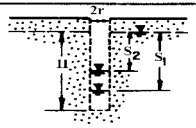
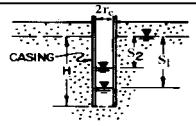
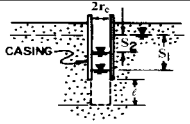
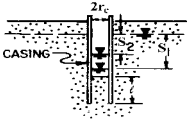
	CONDITION	DIAGRAM	SHAPE FACTOR, F	PERMEABILITY, K BY VARIABLE HEAD TEST	APPLICABILITY
OBSERVATION WELL OR PIEZOMETER IN SATURATED ISOTROPIC STRATUM OF INFINITE DEPTH	(A) UNCASED HOLE		$F = 16\pi H F_s r$	(FOR OBSERVATION WELL OF CONSTANT CROSS SECTION) $K = \frac{r}{16HF_s} \times \frac{(S_2-S_1)}{(t_2-t_1)}$ FOR $\frac{H}{r} < 50$	SIMPLEST METHOD FOR PERMEABILITY DETERMINATION. NOT APPLICABLE IN STRATIFIED SOILS. FOR VALUES OF F_s, SEE FIGURE 17-16b.
	(B) CASED HOLE, SOIL FLUSH WITH BOTTOM.		$F = \frac{\pi r_c}{2}$	$K = \frac{2\pi r_c}{H(t_2-t_1)} \ln\left(\frac{S_1}{S_2}\right)$ FOR $6'' \leq H \leq 60''$	USED FOR PERMEABILITY DETERMINATION AT SHALLOW DEPTHS BELOW THE WATER TABLE. MAY YIELD UNRELIABLE RESULTS IN FALLING HEAD TEST WITH SILTING OF BOTTOM OF HOLE.
	(C) CASED HOLE, UNCASED OR PERFORATED EXTENSION OF LENGTH "ℓ"		$F = \frac{2\pi \ell}{\ln\left(\frac{\ell}{r_c}\right)}$	$K = \frac{r_c^2}{2L(t_2-t_1)} \ln\left(\frac{\ell}{r_c}\right) \ln\left(\frac{S_1}{S_2}\right)$ FOR $\frac{\ell}{r_c} > 8$	USED FOR PERMEABILITY DETERMINATIONS AT GREATER DEPTHS BELOW WATER TABLE.
	(D) CASED HOLE, COLUMN OF SOIL INSIDE CASING TO HEIGHT "ℓ"		$F = \frac{\pi r_c^2}{2\pi r_c + 4\ell}$	$K = \frac{2\pi r_c + 4\ell}{H(t_2-t_1)} \ln\left(\frac{S_1}{S_2}\right)$	PRINCIPAL USE IS FOR PERMEABILITY IN VERTICAL DIRECTION IN ANISOTROPIC SOILS.

Figure 17-16a.—Shape factors for computing permeability from variable head tests.

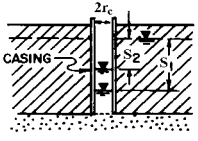
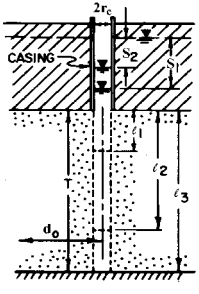
	CONDITION	DIAGRAM	SHAPE FACTOR, F	PERMEABILITY, K BY VARIABLE HEAD TEST	APPLICABILITY
OBSERVATION WELL OR PIEZOMETER IN AQUIFER WITH IMPERVIOUS UPPER LAYER	(E) CASED HOLE, OPENING FLUSH WITH UPPER BOUNDARY OF AQUIFER OF INFINITE DEPTH		$F = 4r_c$	(FOR OBSERVATION WELL OF CONSTANT CROSS SECTION) $K = \frac{\pi r_c}{4(t_2-t_1)} \ln\left(\frac{S_1}{S_2}\right)$	USED FOR PERMEABILITY DETERMINATION WHEN SURFACE IMPERVIOUS LAYER IS RELATIVELY THIN. MAY YIELD UNRELIABLE RESULTS IN FALLING HEAD TEST WITH SILTING OF BOTTOM OF HOLE.
	(F) CASED HOLE, UNCASED OR PERFORATED EXTENSION INTO AQUIFER OF FINITE THICKNESS: (1) $\frac{\ell_1}{T} \leq 0.2$ (2) $0.2 < \frac{\ell_2}{T} < 0.85$ (3) $\frac{\ell_3}{T} = 1.00$ NOTE: d_o EQUALS EFFECTIVE RADIUS TO SOURCE AT CONSTANT HEAD.		(1) $F = C_s r_c$	$K = \frac{\pi r_c}{C_s(t_2-t_1)} \ln\left(\frac{S_1}{S_2}\right)$	USED FOR PERMEABILITY DETERMINATIONS AT DEPTHS GREATER THAN ABOUT 5FT. FOR VALUES OF C_s, SEE FIGURE *17-16b*.
			(2) $F = \frac{2\pi \ell_2}{\ln(\ell_2/r_c)}$	$K = \frac{r_c^2 \ln\left(\frac{\ell_2}{r_c}\right)}{2\ell_2(t_2-t_1)} \ln\left(\frac{S_1}{S_2}\right)$ FOR $\frac{\ell}{r_c} => 8$	USED FOR PERMEABILITY DETERMINATIONS AT GREATER DEPTHS AND FOR FINE GRAINED SOILS USING POROUS INTAKE POINT OF PIEZOMETER.
			(3) $F = \frac{2\pi \ell_3}{\ln\left(\frac{d_o}{r_c}\right)}$	$K = \frac{R^2 \ln\left(\frac{d_o}{r_c}\right)}{2\ell_3(t_2-t_1)} \ln\left(\frac{S_1}{S_2}\right)$	ASSUME VALUE OF $\frac{d_o}{r_c}$ = 200 FOR ESTIMATES UNLESS OBSERVATION WELLS ARE MADE TO DETERMINE ACTUAL VALUE OF d_o.

Figure 17-16a (cont.).—Shape factors for computing permeability from variable head

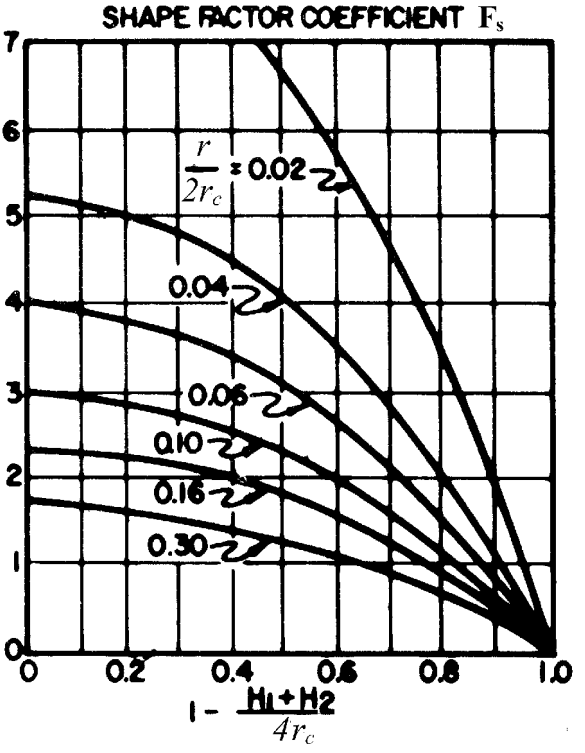


Figure 17-16b.—Shape factor coefficient F_s.

originally developed for unconfined aquifers but can also be used for confined or stratified aquifers if the top of the screen or perforated section is located some distance below the upper confining layer. The analysis is based on the Thies equation and determines permeability, K, of the aquifer around the well from the equation:

$$K = \frac{r_c^2 \ln\left(\frac{d_e}{r}\right)}{2\ell} \frac{1}{t} \ln\left(\frac{s_0}{s_t}\right)$$

where:

ℓ = length of the perforated section of the casing or riser

s_0 = the vertical difference between the water surface inside the well and the static water level at time zero

s_t = s at time t

t = time of reading

r_c = inside radius of the riser or casing

r = the effective radius of the well, including the perforated casing, sand or gravel pack, and any remaining annular space to the sidewall of the borehole

d_e = effective radial distance; the distance between the well and the observation well; the distance over which the water level, s, returns to the static level

H = the height of water within the well

S = aquifer thickness

See figure 17-17 for the configuration definition.

The values of d_e were determined using an electrical resistance analog network. The effective radial distance is influenced by the well diameter, well screen length, well depth, and the aquifer thickness. Various values for r_c, ℓ, H, and S were used in the analog network for analysis of their impacts on d_e.

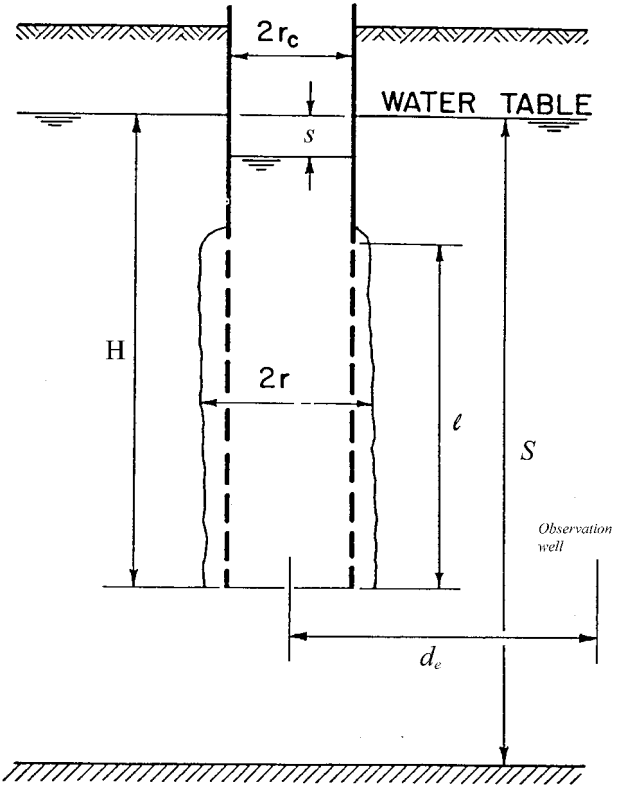


Figure 17-17.—Slug test on partially penetrating, screened well in unconfined aquifer with gravel pack and developed zone around screen.

The term, $ln\ (d_e/r)$, is related to the geometry of the test zone and the amount of aquifer penetration of the well. Two separate solutions are required to address partially penetrating wells and fully penetrating wells. For

partially penetrating wells, an empirical equation relating $ln\ (d_e/r)$ to the geometry of the test zone is:

$$\ln\frac{d_e}{r} = \left[\frac{1.1}{\ln\left(\frac{H}{r}\right)} + \frac{A + B\ln\left(\frac{S-H}{r}\right)}{\frac{\ell}{r}}\right]^{-1}$$

In this equation, A and B are dimensionless coefficients that can be read on figure 17-18. An effective upper limit of $ln[(S\text{-}H)/r]$ is 6. If the computed value of $ln[(S\text{-}H)/r]$ is greater than 6, then 6 should be used in the equation for $ln(d_e/r)$. When $S = H$, the well is fully penetrating, and the value of C should be used from figure 17-18 in the equation.

$$\ln\frac{d_e}{r_e} = \left[\frac{1.1}{\ln\left(\frac{H}{r_e}\right)} + \frac{C}{\frac{\ell}{r_e}}\right]^{-1}$$

Values of the field test data should be plotted as recovery, s, versus time for each data point reading. The value s should be plotted on a y-axis log scale, and values for corresponding time should be plotted on the x-axis. The points should approximate a straight line, which indicates good test data. Areas of the data that plot as curves (usually at the beginning of the test or near the end of the test) should not be used in the computation.

Piezometer Test

The piezometer test measures the horizontal permeability of individual soil layers below a water surface. This test

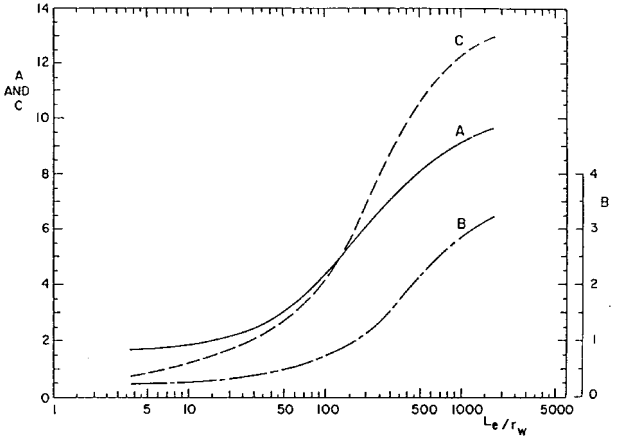


Figure 17-18.—Dimensionless parameters *A, B,* and *C* as a function of ℓ/r_e (F for calculation of $ln(d_e/r_e)$).

surface. This test may apply to large diameter direct push technology, as well as to any depth that an open hole can be maintained. This test is preferred over the auger-hole test described in section 10-6 of the *Ground Water Manual*, especially when the soils tested are less than 1.5 feet (0.5 m) thick and are below the water table. This method is particularly good for determining which layer below the capillary zone is an effective barrier.

Equipment

The following items are suggested equipment for the piezometer test.

- Riser between 1- to 2-inch (24- to 50-mm) inside diameter for a depth of around 15 feet (4.5 m) and black iron pipe with smooth inside wall for depths greater than 15 feet (4.5 m)

- Equipment capable of installing the riser and cavity below the riser

- Pump with hose and controller or bailer that will fit inside the casing

- Bottle brush for cleaning soil film from the inside of the test riser if the riser is driven without a protective point that can prevent soils from filling the inside of the tube

- Water level detector, stop watch, and transducer and data logger

Procedure

The test layer should be at least 1 foot (30 cm) thick so that a 4-inch (10-cm) length of cased hole or cavity can be located in the middle of the layer. This placement is especially important if a marked difference in the layers exists above and below the test layer. The differences may be changes in the percentages of fines (>15 percent), overall changes in the soil gradations, soil structure, or degree of cementation or induration within the soil horizon. After selecting an appropriate interval based on the soil investigation, an adjacent hole within 2 feet (0.6 m) of the test hole is advanced to around 2.0 feet (0.6 m) above the bottom of the 4-inch (10-cm) test interval, if using direct push technology, or to the top of the 4-inch (10-cm) interval. Then use a smaller diameter auger to ream the final 4-inch (10-cm) interval for the riser pipe. The final 2.0 feet (0.6 m) are driven to ensure that a reasonably good seal is obtained and also to minimize the disturbance. The lower 4 inches (10 cm) of the borehole are exposed, and the cavity must remain open. After some recovery has occurred, the riser should be cleaned with a brush to remove any soil film unless

should be screened within the lower cavity and then cleaned out by gently pumping or bailing water and sediment from the piezometer.

After the water surface has stabilized, the transducer is installed. The riser is bailed or pumped, depending on the diameter of riser and the depth to water. It is not necessary to remove all the water in the screened interval, but the water level should be lowered enough that at least three readings during the first half of the water rise will give consistent results.

Calculations

After completing the piezometer test, the permeability is calculated from:

$$K = \frac{3600\pi r^2 \ln\left(\frac{s_1}{s_2}\right)}{C_a(t_2 - t_1)}$$

where:

s_1 and s_2	=	distance from static water level at times t_1 and t_2, in inches (cm)
$t_2 - t_1$	=	time for water level change from s_1 to s_2, in seconds
C_a	=	a constant for a given flow geometry, in inches (cm)
ℓ	=	length of open cavity, in inches (cm)
d	=	H-ℓ, distance from the static water level to the top of the cavity, in inches (cm)
b	=	distance below the bottom of the cavity to the top of next layer, in inches (cm)

A sample calculation using this equation is shown in figure 17-19. The constant, C_a, may be taken from curves

A sample calculation using this equation is shown in figure 17-19. The constant, C_a, may be taken from curves shown in figures 17-19 or 17-20. The curve on figure 17-19 is valid when d and b are both large compared to ℓ. When $b = 0$ and d is much greater than ℓ, the curve will give a C_a factor for $\ell = 4$ and d = 1 that will be about 25 percent too large.

The chart on figure 17-20 is used for determining C_a when upward pressure exists in the test zone. When pressures are present, additional piezometers must be installed. The tip of the second piezometer should be placed just below the contact between layers in layered soil (figure 17-21). In deep, uniform soils, the second piezometer tip should be placed an arbitrary distance below the test cavity.

After installing the second piezometer, the following measurements should be made:

- Distance, Δd, in feet (m), between the ends of the riser pipes

- Difference, ΔH, in feet (m), between water surfaces in the two piezometers at static conditions

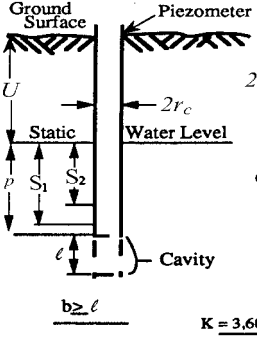
- Distance, d', in feet (m), between the center of the lower piezometer cavity and the contact between soil layers in the layered soils

The C_a value from figure 17-20 is used in the equation to determine the permeability.

Limitations

Installation and sealing difficulties encountered in coarse sand and gravel are the principal limitations of the

Location: Hole C-2 -- Sample Farm
Observer: A.P.B. Date: October 9, 1974



U = 218.44 centimeters (86.00 inches)
Ground Surface to static water level

$2r_c$ = 2.54 centimeters (1.00 inch)
Inside diameter of piezometer and cavity

p = 237.74 centimeters (93.60 inches)
Static water level to bottom of piezometer

ℓ = 10.16 centimeters (4 inches)
Length of cavity

C_a = 33.27 centimeters (13.1 inches)
Constant for a given flow geometry taken from curve.

K = Hydraulic conductivity, centimeters per hour (inches per hour)

b = depth to texture change

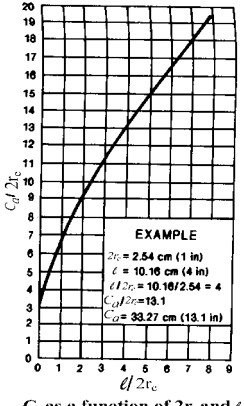
S_1, S_2 = Distance from static water level at time t_1 and t_2 in centimeters (inches).

$(t_2 - t_1)$ = Time for water to change from S_1 to S_2 (seconds)

$$K = \frac{3{,}600\,\pi\,(r_c)^2 \log_e (S_1/S_2)}{C_a (t_2 - t_1)}, \text{ centimeters per hour (inches per hour)}$$

Time (seconds) Y, centimeters (inches)				C_a, cent. (inches)	$t_2 - t_1$	S_1/S_2	$\log_e S_1/S_2$	$3{,}600\,\pi\,(r_c)^2$ cm²sec/hr (in²sec/hr)	K cm/hr (in./hr)
Initial (t_1)	Final (t_2)	Initial (S_1)	Final (S_2)						
0	30	218.44 (86.00)	197.87 (77.90)	33.27 (13.1)	30	1.104	0.099	18241.47 (2827.44)	1.80 (0.71)
30	60	197.87 (77.90)	178.44 (70.25)	33.27 (13.1)	30	1.109	0.103	18247.47 (2827.44)	1.88 (0.74)
60	90	178.44 (70.25)	160.02 (63.00)	33.27 (13.1)	30	1.115	0.109	18241.47 (2827.44)	1.99 (0.78)
90	120	160.02 (63.00)	145.47 (57.27)	33.27 (13.1)	30	1.100	0.095	18241.47 (2827.44)	1.74 (0.68)
120	150	145.47 (57.27)	131.17 (51.64)	33.27 (13.1)	30	1.109	0.103	18241.47 (2827.44)	1.88 (0.74)

Average for 5 readings = 1.86 (0.73)



C_a as a function of $2r_c$ and ℓ

Redrawn from LUTHIN & KIRKHAM (1949).
Revised by USBR (Mantel, 1972)

Figure 17-19.—Data and computation sheet for piezometer permeability test.

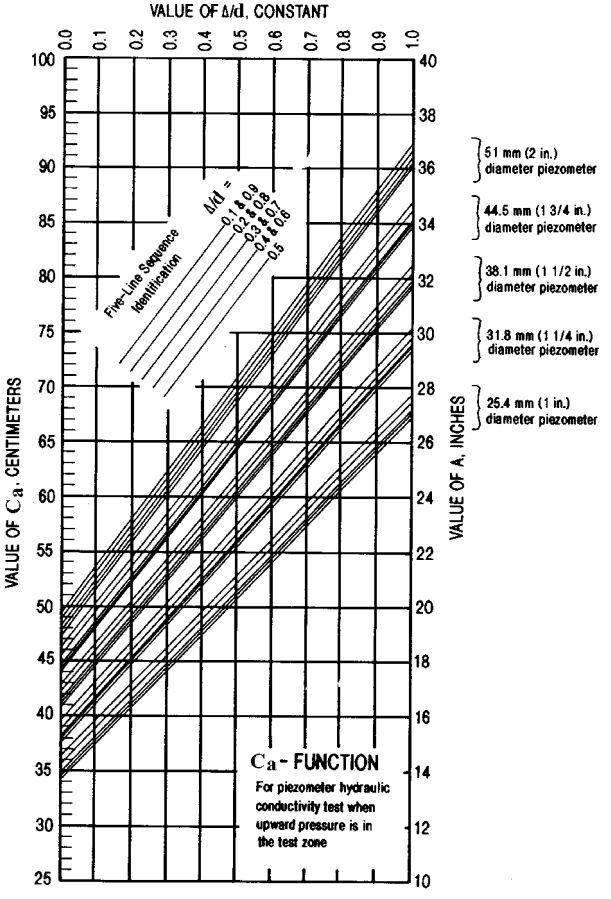


Figure 17-20.—Chart for determining C_a if upward pressure exists in the test zone.

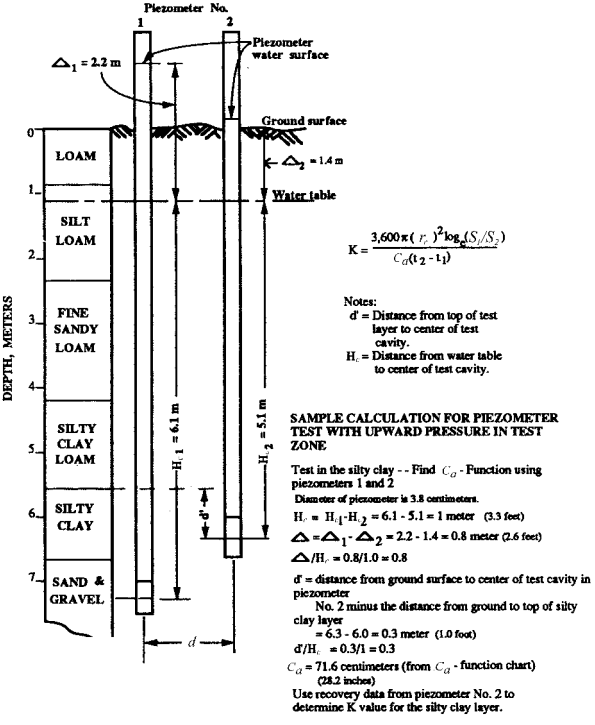


Figure 17-21.— Sample calculation for the piezometer test with upward pressure in the test zone.

piezometer test for permeability. Also, when the riser bottoms in gravel, a satisfactory cavity cannot be obtained. The practical limit of hole depth is about 20 feet (6 meters). Deeper holes require larger diameters (greater than 2 inches [5cm]), and driving the riser deeper is difficult.

Details on the equipment requirements and procedures are provided in chapter 3 of the *Drainage Manual*. Permeameter tests are typically restricted to shallow boreholes or excavations and require time to set up the equipment and perform the test. Where the permeability is relatively high (>1,000 feet per year [10^{-3} cm per second]), these tests require large amounts of water. With material having permeability values greater than 10^{6} feet per year (10 cm/sec), laboratory permeability testing is more cost effective. The samples are collected and tested in the laboratory in accordance with Reclamation Procedure 5605.

Bibliography

Bureau of Reclamation, U.S. Department of the Interior, *Drainage Manual*, 1993.

Bureau of Reclamation, U.S. Department of the Interior, *Ground Water Manual*, 1995.