experience has shown that [illegible] piezometers provide adequate open area for float operation. Pipe diameters greater than 2 inches are difficult to install properly.

3–4. Single Well Drawdown Test for Hydraulic Conductivity.—Coarse sands and gravels usually make the auger-hole (pump-out) and piezometer tests difficult to run. An alternative pump-out test can be made to obtain a rough estimate of hydraulic conductivities in these materials. The test is a small-scale version of a regular pump test for large wells.

Equipment for the test is the same as that used for the auger-hole test except the recorder board and tripod are not used. A gasoline-driven pump with a valved discharge should be used. A calibrated bucket and a stopwatch are used to determine flow rate.

Hole preparation is much the same as for the auger-hole test; however, hand augering is usually too difficult. Once the hole is prepared and the static water level is measured, water is pumped from the hole at a constant rate. After some time, the water level in the hole will reach a steady state level. Steady state can be assumed to exist when the water level in the hole drops less than 0.1 foot in 2 hours. When steady state conditions exist, the flow rate and depth of water in the hole are recorded. These data, along with the distance from the static water level to the bottom of the hole, are used in one of the equations shown on figure 3–11. Use the equation that most nearly approaches the test conditions.

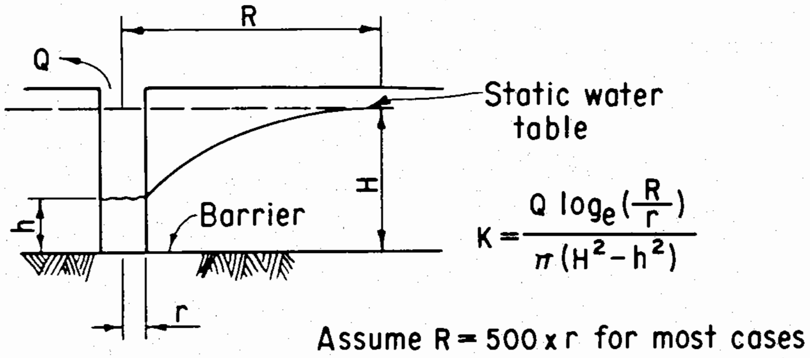
This method should be used only in highly permeable sands and gravels to obtain an estimate of hydraulic conductivity when the auger-hole or piezometer tests fail to give satisfactory results.

B. Inplace Hydraulic Conductivity Tests Above a Water Table

3–5. Objective.—The two methods that have been adapted for use in drainage investigations are the shallow well pump-in test and the ring permeameter test. These tests are used to determine the hydraulic conductivity rates of soils above a water table, and these rates are then used in predicting the subsurface drainage requirements. To reduce as much as possible any extraneous effects on hydraulic conductivity, the water used in the tests must be free of sediment and should be warmer than the soil.

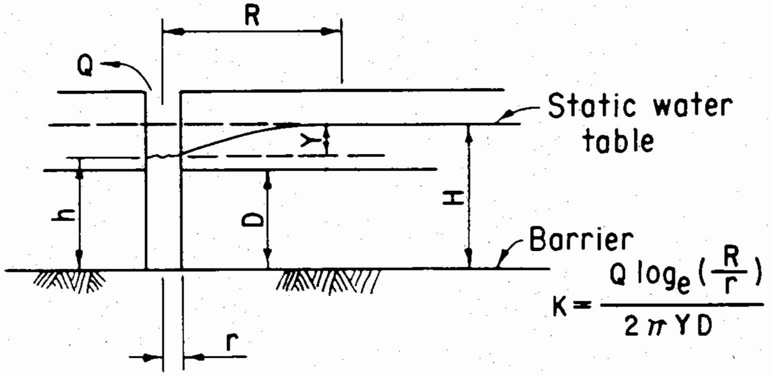
3–6. Shallow Well Pump-in Test for Hydraulic Conductivity.—(a) *Introduction.*—The shallow well pump-in test for hydraulic conductivity, also known as the well permeameter test, is used when the water table is below the zone to be tested. Essentially, this test consists of measuring the volume of water flowing laterally from a well in which a constant head of water is maintained. The lateral hydraulic conductivity determined by this test is a composite rate for the full depth of the hole being tested.

(b) *Equipment.*—Equipment requirements for the shallow well pump-in test include the following items previously described for the auger-hole test in section 3–2: 3- and 4-inch-diameter soil augers, hole scratcher, perforated



$$K = \frac{Q \log_e\left(\frac{R}{r}\right)}{\pi (H^2 - h^2)}$$

(a) Pumping from a uniform stratum, water table in stratum being pumped.



$$K = \frac{Q \log_e\left(\frac{R}{r}\right)}{2 \pi Y D}$$

(b) Pumping from a confined stratum, water table above stratum being pumped.

K = Hydraulic conductivity, $ft^3/ft^2/day$
Q = Flow rate at steady state conditions ft^3/day
Y = Drawdown from static water surface = H - h, ft
H = Height of static water table above bottom of hole, ft
h = Depth of water in hole at steady state pumping conditions, ft
D = Flow thickness of strata between bottom of the hole and overlying (confining) stratum, ft.
R = Distance from centerline of well to point of zero drawdown, ft
r = Effective radius of well, ft

Figure 3–11.—Determination of hydraulic conductivity by pumping from a uniform or confined stratum. 103–D–1630.

casing, burlap, and wristwatch with a second hand. Additional equipment items are:

(1) Water-supply tank truck of at least 350-gallon capacity with gasoline-powered water pump.

(2) Calibrated head tank, 50-gallon minimum. This tank should have fittings so that two or more tanks can be connected when required.

(3) Twenty-five feet of 1- to 2-inch heavy-walled hose for rapid filling of head tank from supply tank.

(4) Wooden platform to keep head tank off the ground and to prevent rusting.

(5) A 1-inch-diameter pipe 4 feet long to be driven into the ground and wired to head tank to keep tank in position.

(6) Constant-level float valve (carburetor) which must fit inside the casing.

(7) A rod threaded to fit the threads on top of the carburetor, used to regulate the depth that the float valve is lowered into the hole.

(8) Sufficient ⅜- or ½-inch i.d. flexible rubber tubing to connect tank to carburetor.

(9) Plexiglass cover, 12 by 12 inches by ⅛ inch thick, with hole in center for carburetor rod, and two other holes, one for rubber tubing and one for measuring water level and temperature of water in the hole.

(10) Filter tank and filter material.

(11) Steel fenceposts with post driver, four required per site. Approximately 85 feet of fencing wire (needed only when site must be fenced).

(12) Thermometer which can be lowered into hole, Celsius scale preferred.

(13) Ten-foot steel tape, clipboard, computation sheet, and a 16-inch tiling spade.

Figure 3–12 shows a schematic of the equipment set up for this test.

The constant-level float valve (carburetor) suggested for use in this test and in the ring permeameter test, described later, can be constructed out of various materials and can be made in different shapes. The only requirements are that it must fit inside a 4-inch-diameter hole, have adequate capacity, cause minimum aeration of water, and control of water level within plus or minus 0.05 foot. Material to construct a carburetor that has proven satisfactory consists of the following:

(1) Twenty inches of ¾- by ⅛-inch metal strap,

(2) One large tractor carburetor, needle valve, a needle valve seat at least ⅛ inch in diameter, a float made of styrofoam,

(3) Two ¾- by ¼-inch bushings, and

(4) One ¾-inch coupling.

A photograph of a typical carburetor is shown on figure 3–13.

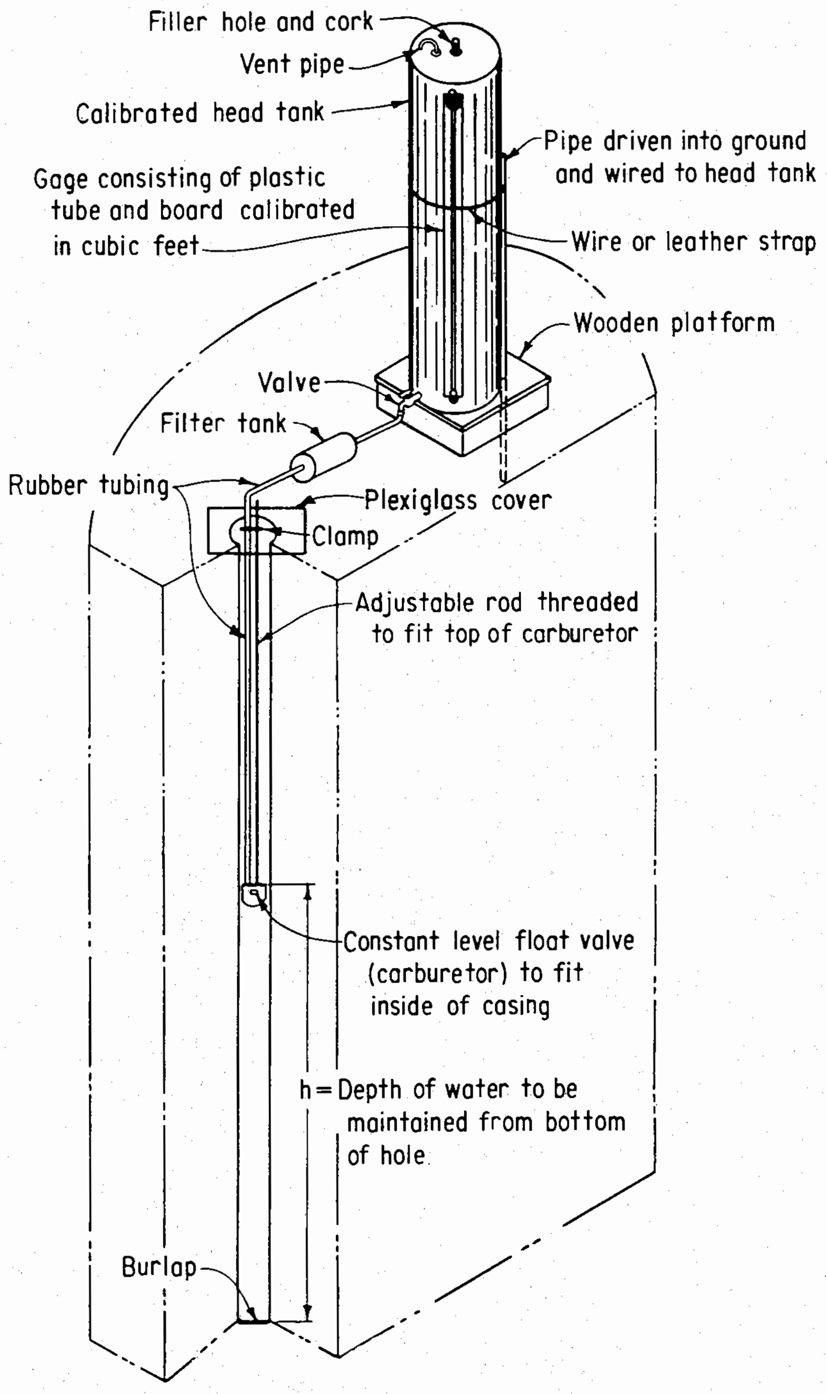


Figure 3–12.—Equipment setup for a shallow well pump-in test. 103–D–655.

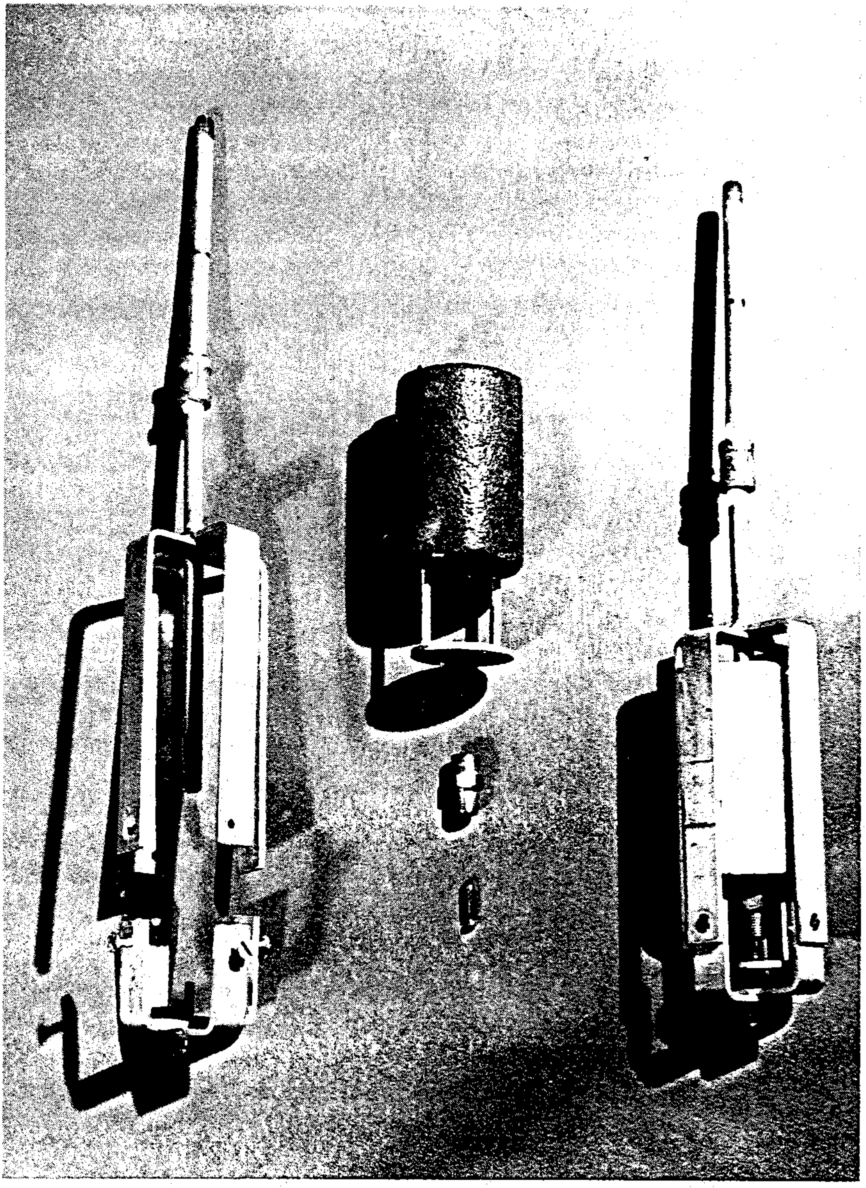


Figure 3-13.—Typical constant-level float valve used in hydraulic conductivity tests. Fully assembled float valve is shown on the right. P801-D-77013.

(c) Procedure.—A two-man team can efficiently install the equipment and conduct the shallow well pump-in test. The hole for the test should first be hand augered with a 3-inch-diameter auger and then reamed with the 4-inch-diameter auger. A complete log, including texture, structure, mottling, and color, should be obtained for use in interpreting and projecting results. Upon completion of the hole to the desired depth, it should be carefully scratched to break up any compaction caused by the 4-inch auger and to remove any loose material that might be on the sides. In unstable soils, a thin-walled perforated casing should be installed, with perforations extending from the bottom of the hole up to the predetermined controlled water level. A commercial well screen should be used, but when not available, a 4-inch-diameter thin-walled casing with about 60 uniformly spaced hand-cut perforations per foot, ⅛-inch wide by 1 inch long, will be satisfactory for most soils.

The constant-level float valve should be installed and approximately positioned. The float valve is then connected with tubing to the head tank, which is on an anchored platform beside the hole. The ⅜- or ½-inch tubing will allow sufficient water to flow into the carburetor when testing moderately permeable soils. The hole should then be filled with water to approximately the bottom of the carburetor. The valve on the head tank is then opened, and the height of the carburetor is carefully adjusted so that the water level will be maintained at the desired depth. The use of the plexiglass cover to keep small animals and debris out of the hole and to hold the carburetor float adjusting rod helps in the observation of the carburetor during the test. The time and the reading on the tank gage are recorded after everything is operating satisfactorily. The tank should be refilled when necessary. Each time the test site is visited, a record should be kept of the time, tank gage readings, and volume of water added. Reading times are determined by the type of material being tested and will range from 15 minutes to 2 hours. Although not a necessity, the use of automatic recorders is desirable so that a complete record may be kept of water movement into the hole. When water temperature fluctuations exceed 2°C, viscosity corrections should be applied.

If the test water contains suspended material, a filter tank should be installed between the head tank and the carburetor. Polyurethane foam is a satisfactory filter material. Figure 3-14 shows a typical filter tank and material.

The nomographs shown on figures 3-15 and 3-16 are used for estimating the minimum and maximum volume of water to be discharged during a pump-in hydraulic conductivity test. These nomographs provide an excellent guide on the amount of water that should be discharged into the hole before the readings become unreliable. The nomographs are especially useful in sands because the minimum amount of water will be discharged into the hole in a very short time. Readings should be taken as soon as this occurs. To use the nomographs, the specific yield must be estimated from the hydraulic conductivity, texture, and structure of the soil. Knowing the depth of water maintained from the bottom of the hole, *h*, and the radius of the hole, *r*, the minimum and maximum amounts of water to meet the conditions set up in the mathematical model can be

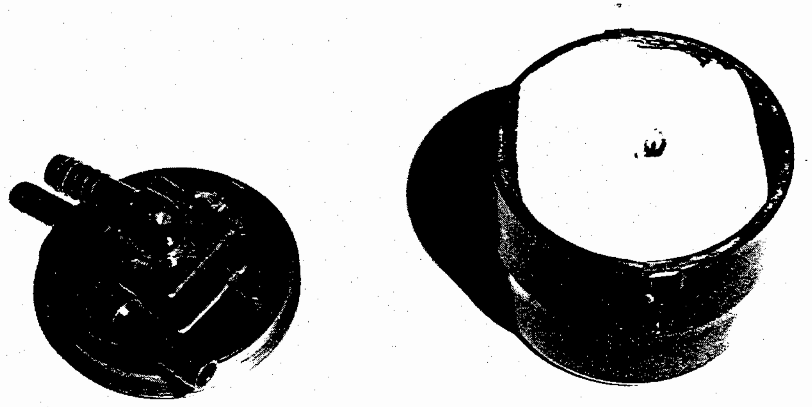


Figure 3–14.—Typical filter tank and filter material. P801–D–77014.

determined. When the minimum amount has been discharged into the soil, the hydraulic conductivity should be computed following each reading. The test can be terminated when a relatively constant hydraulic conductivity value has been reached, and the total volume discharged into the soil is not greater than the maximum value taken from the nomograph.

(d) Calculations.—A sample computation sheet for the shallow well pump-in test is shown on figure 3–17. Figures 3–18 through 3–21 show equations and nomographs used in the computations. The use of these figures depends upon the depth of water maintained from the bottom of the hole, h, and the depth of the water table or depth to an impervious strata from the surface of water maintained, T_u. The h value can be determined accurately, but the depth to an impervious or restrictive zone, T_u, requires a deep pilot hole near the test site. Any zone which appears, from visual inspection, to have a much lower hydraulic conductivity than the zone above should be considered as a restrictive zone for determining T_u. A water table should also be considered a barrier when estimating T_u. If an inplace hydraulic conductivity test in this zone indicates the zone is not restrictive, the hydraulic conductivity can be recomputed using a larger T_u value and the appropriate equation or nomograph.

(e) Limitations.—One of the principal limitations of this test for hydraulic conductivity is that it is very time consuming to set up and complete, and considerable equipment is required. Also, a relatively large amount of water is required, especially if the material has a hydraulic conductivity over 2 or 3 inches per hour. In soils high in sodium, the water used should contain 1,500 to 2,000 parts per million of salts, preferably calcium. Another limitation is that the hole cannot be augered to accurate dimensions in rocky material or coarse gravels. Also, comparisons of electric analog test results with values from the auger-hole test show that the h/r ratio must be equal to or greater than 10.

With water moving outward from the hole, the fines near the surface sometimes form a seal before a constant hydraulic conductivity rate has been reached. If a constant rate cannot be obtained by the time the estimated maximum flow has occurred, the fines can be flushed back into the hole by removing the equipment and bailing all water out of the hole or by gently surging the hole with a solid surge block and then pumping the water out. This procedure is not always successful, but should be tried before abandoning the test site. This problem is generally avoided by use of a filter on the supply line.

3–7. Ring Permeameter Test.—(a) *Introduction.*—In drainage studies, the lateral hydraulic conductivity of the soil is required for drain spacing determinations. Usually the vertical hydraulic conductivity is assumed to be sufficient to permit deep percolation from irrigation and rainfall to reach the saturated zone in which it moves horizontally. However, slowly permeable layers interfere with percolation and cause temporary perched water tables in the root zone. Thus, a means of determining the vertical hydraulic conductivity of such a tight layer is desirable.

The ring permeameter test is a specialized inplace method of obtaining vertical hydraulic conductivity of a critical zone. The test is based on Darcy's law for movement of liquids through saturated material. The test is time consuming when compared with the auger-hole test, but the results are uniformly dependable. Tensiometers and piezometers are used to confirm existence of saturated conditions, absence of a perched water table, and fulfillment of the requirements of Darcy's law.

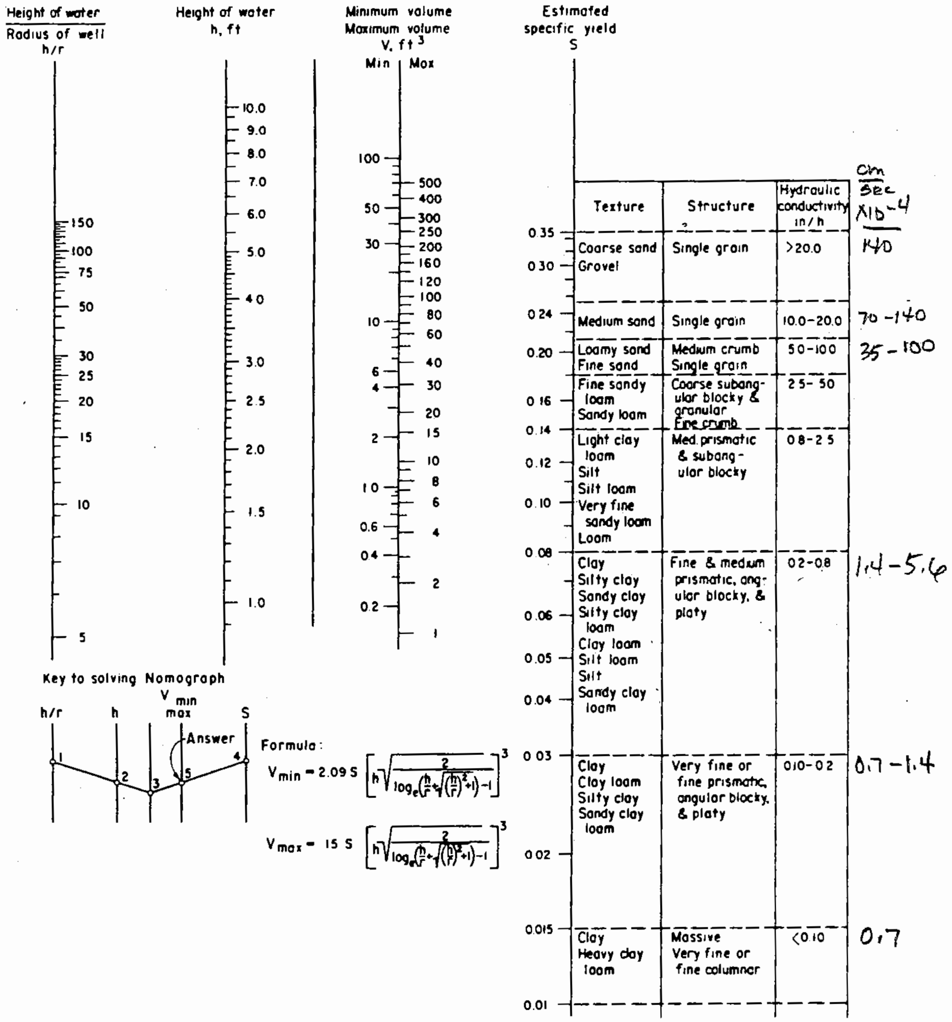
(b) Equipment.—Equipment required for the ring permeameter method is as follows:

(1) A 14-gage steel, welded-seam cylinder, 18-inch i.d. by 20 inches high, with a reinforcing band on top and sharpened bottom edge (seam weld must be ground flush).

(2) A 20-inch-diameter by ½-inch-thick driving disk with a 17¾-inch-diameter by ½-inch-thick center ring. This disk fits inside the 18-inch cylinder and has a 2-foot length of 1-inch pipe welded in the center for a hammer guide.

(3) A 50- to 75-pound driving hammer (heavy steel cylinder with hole in the center and pipe welded to center which fits over the 1-inch pipe on driving disk).

(4) A water-supply tank truck of at least 350-gallon capacity and a gasoline-powered water pump to fill the tank truck. Also, about 25 feet of 1- or 1½-inch heavy-walled hose are needed for filling the tank from the water truck.



Formula:

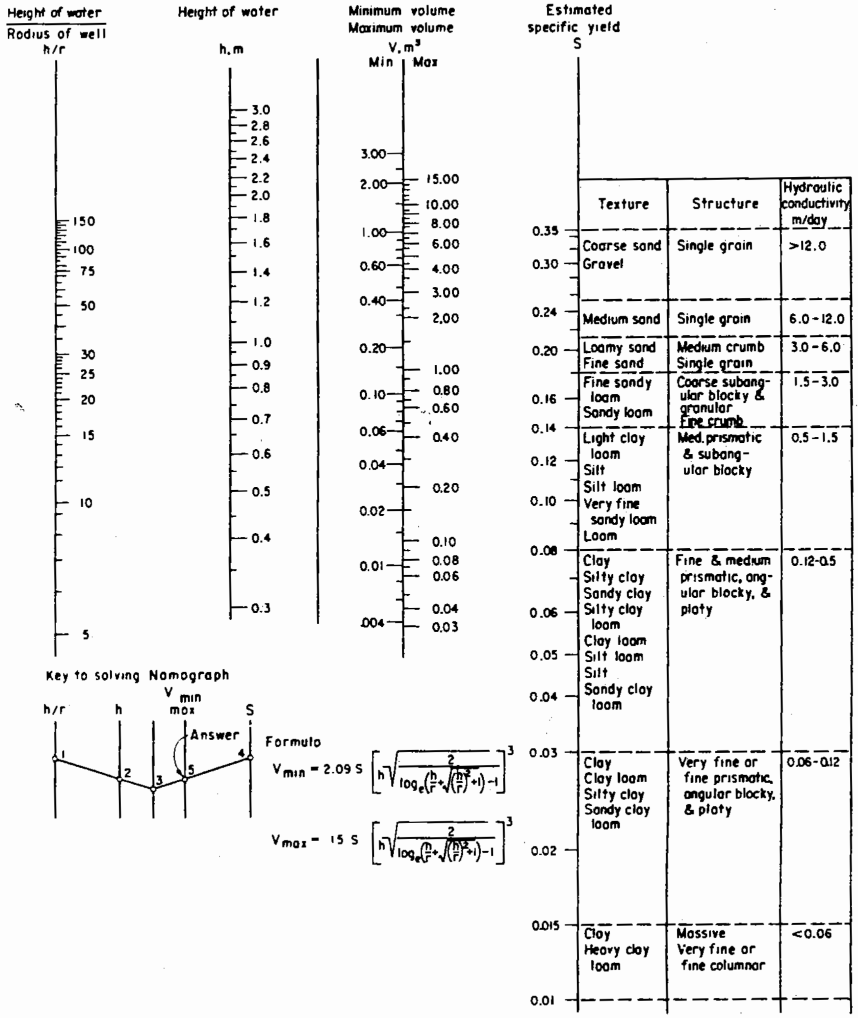
$$V_{min} = 2.09\,S\left[h\sqrt{\frac{2}{\log_e\left(\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2+1}\right)-1}}\right]^3$$

$$V_{max} = 15\,S\left[h\sqrt{\frac{2}{\log_e\left(\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2+1}\right)-1}}\right]^3$$

S	Texture	Structure	Hydraulic conductivity in/h	cm/sec ×10⁻⁴
0.35–0.24	Coarse sand Gravel	Single grain	>20.0	140
0.24	Medium sand	Single grain	10.0-20.0	70-140
0.20	Loamy sand Fine sand	Medium crumb Single grain	5.0-10.0	35-100
0.16	Fine sandy loam Sandy loam	Coarse subangular blocky & granular Fine crumb	2.5-5.0	
0.14–0.08	Light clay loam Silt Silt loam Very fine sandy loam Loam	Med. prismatic & subangular blocky	0.8-2.5	
0.08–0.03	Clay Silty clay Sandy clay Silty clay loam Clay loam Silt loam Silt Sandy clay loam	Fine & medium prismatic, angular blocky, & platy	0.2-0.8	1.4-5.6
0.03–0.015	Clay Clay loam Silty clay Sandy clay loam	Very fine or fine prismatic, angular blocky, & platy	0.10-0.2	0.7-1.4
0.015–0.01	Clay Heavy clay loam	Massive Very fine or fine columnar	<0.10	0.7

Figure 3–15.—Nomograph for estimating the minimum and maximum volume of water to be discharged during a pump-in hydraulic conductivity test (U.S. customary units). 103–D–1631.

$$\frac{in}{hr} \times \frac{1\,hr}{3600\,sec} \times \frac{2.54\,cm}{in} \times \frac{10{,}000}{10^{-4}}$$



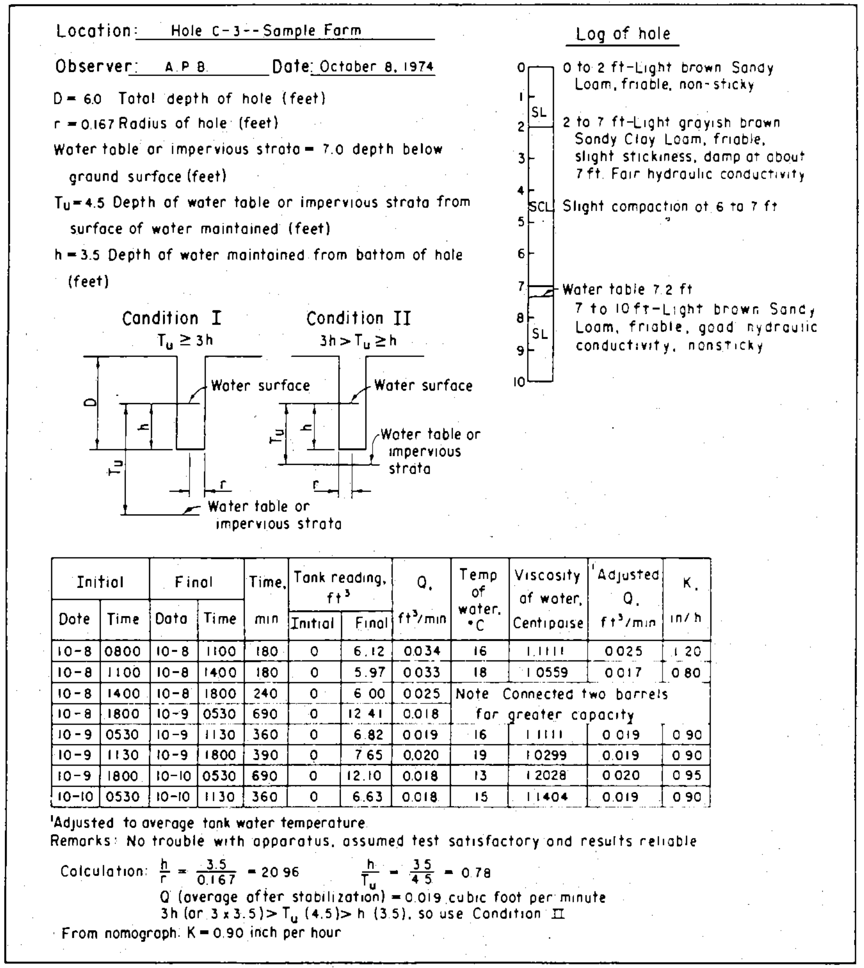
Formula

$$V_{min} = 2.09\,S\left[h\sqrt{\frac{2}{\log_e\left(\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2+1}\right)-1}}\right]^3$$

$$V_{max} = 15\,S\left[h\sqrt{\frac{2}{\log_e\left(\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2+1}\right)-1}}\right]^3$$

S	Texture	Structure	Hydraulic conductivity m/day
0.35–0.24	Coarse sand Gravel	Single grain	>12.0
0.24	Medium sand	Single grain	6.0-12.0
0.20	Loamy sand Fine sand	Medium crumb Single grain	3.0-6.0
0.16	Fine sandy loam Sandy loam	Coarse subangular blocky & granular Fine crumb	1.5-3.0
0.14–0.08	Light clay loam Silt Silt loam Very fine sandy loam Loam	Med. prismatic & subangular blocky	0.5-1.5
0.08–0.03	Clay Silty clay Sandy clay Silty clay loam Clay loam Silt loam Silt Sandy clay loam	Fine & medium prismatic, angular blocky, & platy	0.12-0.5
0.03–0.015	Clay Clay loam Silty clay Sandy clay loam	Very fine or fine prismatic, angular blocky, & platy	0.06-0.12
0.015–0.01	Clay Heavy clay loam	Massive Very fine or fine columnar	<0.06

Figure 3–16.—Nomograph for estimating the minimum and maximum volume of water to be discharged during a pump-in hydraulic conductivity test (metric units). 103–D–1193.



Location: Hole C-3--Sample Farm

Observer: A.P.B. Date: October 8, 1974

$D = 6.0$ Total depth of hole (feet)

$r = 0.167$ Radius of hole (feet)

Water table or impervious strata = 7.0 depth below ground surface (feet)

$T_u = 4.5$ Depth of water table or impervious strata from surface of water maintained (feet)

$h = 3.5$ Depth of water maintained from bottom of hole (feet)

Log of hole

0 to 2 ft–Light brown Sandy Loam, friable, non-sticky

2 to 7 ft–Light grayish brown Sandy Clay Loam, friable, slight stickiness, damp at about 7 ft. Fair hydraulic conductivity

Slight compaction at 6 to 7 ft

Water table 7.2 ft

7 to 10 ft–Light brown Sandy Loam, friable, good hydraulic conductivity, nonsticky

Initial		Final		Time,	Tank reading, ft³		Q,	Temp of water,	Viscosity of water,	[1]Adjusted Q,	K,
Date	Time	Data	Time	min	Initial	Final	ft³/min	°C	Centipoise	ft³/min	in/h
10-8	0800	10-8	1100	180	0	6.12	0.034	16	1.1111	0.025	1.20
10-8	1100	10-8	1400	180	0	5.97	0.033	18	1.0559	0.017	0.80
10-8	1400	10-8	1800	240	0	6.00	0.025	Note Connected two barrels for greater capacity			
10-8	1800	10-9	0530	690	0	12.41	0.018				
10-9	0530	10-9	1130	360	0	6.82	0.019	16	1.1111	0.019	0.90
10-9	1130	10-9	1800	390	0	7.65	0.020	19	1.0299	0.019	0.90
10-9	1800	10-10	0530	690	0	12.10	0.018	13	1.2028	0.020	0.95
10-10	0530	10-10	1130	360	0	6.63	0.018	15	1.1404	0.019	0.90

[1] Adjusted to average tank water temperature

Remarks: No trouble with apparatus, assumed test satisfactory and results reliable

Calculation: $\frac{h}{r} = \frac{3.5}{0.167} = 20.96$ $\frac{h}{T_u} = \frac{3.5}{4.5} = 0.78$

Q (average after stabilization) = 0.019 cubic foot per minute

$3h$ (or 3×3.5) $> T_u$ (4.5) $> h$ (3.5), so use Condition II

From nomograph: K = 0.90 inch per hour

Figure 3–17.—Data and computation sheet on shallow well pump-in test for hydraulic conductivity. 103–D–647.

(5) Two calibrated 50-gallon head tanks.

(6) Two wooden platforms to keep head tanks from rusting.

(7) Two 1-inch-diameter pipes 4 feet long, driven into the ground to keep tanks upright.

(8) Sufficient ⅜-inch i.d. rubber tubing to connect tanks to constant-level float valves (carburetors).

(9) Two constant-level float valves (carburetors).

(10) Adjustable rods to hold the carburetors at the desired elevation and threaded bolts which fasten to the steel cylinder and support the adjustable rods.

(11) Two ½-inch i.d. piezometers, 18 inches long, rigid copper tubing, and a small driving hammer to fit over the ½-inch tubing.

(12) A 7/16-inch wood auger for cleaning out piezometers and clean sand to fill cavities in piezometers.

(13) Bentonite to seal tensiometers and piezometers.

(14) Two mercury manometer-type tensiometers and mercury for them.

(15) Distilled water to fill tensiometers initially. (Distilled water is desirable but unnecessary after initial filling.)

(16) Small air syringe to fill tensiometers and expel air after filling.

(17) A 1-inch wood auger for installing tensiometers.

(18) Thermometer, Celsius preferred.

(19) Filter tank and filter material.

(20) Tiling spade to clean the hole, and a rope bucket for removing soil from hole.

(21) A 10-foot ladder (needed only for deep layer testing).

(22) Washed sand of uniform size, passing the No. 14 sieve and retained on the No. 28 sieve.

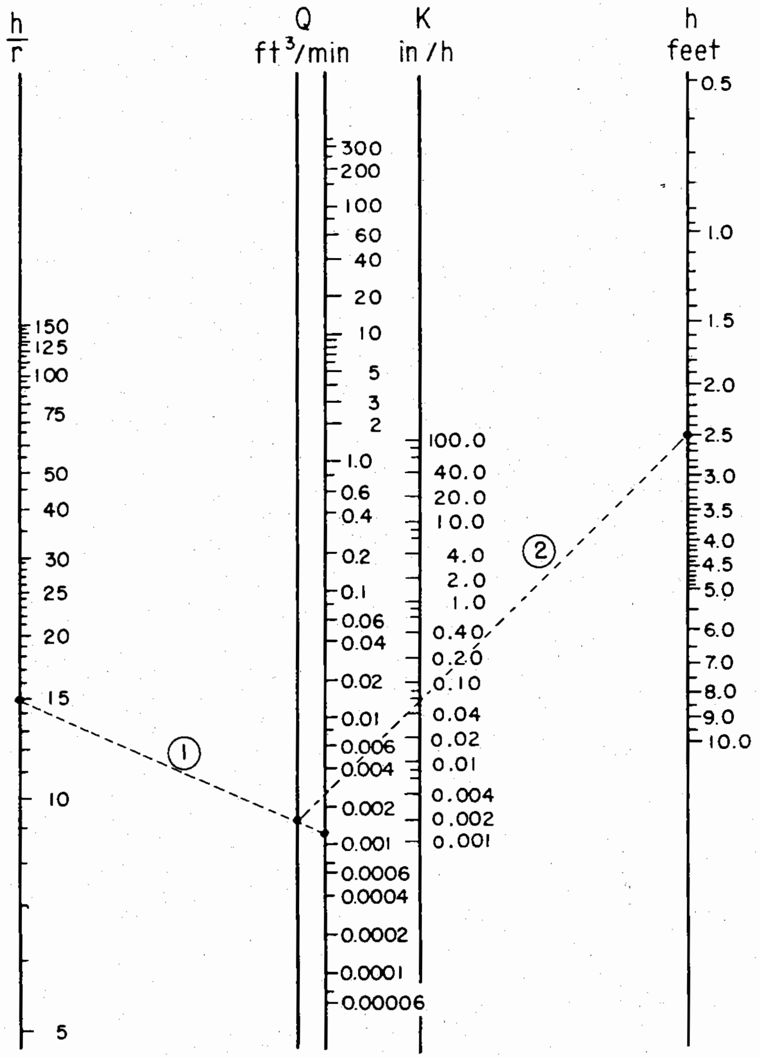
(23) Cover for the 18-inch cylinder to reduce evaporation and keep out debris.

(24) Steel fenceposts with post driver. (Four required per site and needed only when site must be fenced.) Wire for fencing site, approximately 85 feet.

(25) A 10-foot steel tape, 24-inch carpenter's level, white chalk, clawhammer, wire-cutting pliers, clipboard, and reference sheets.

Figure 3–22 shows the equipment set up for this test.

(c) Procedure.—A two-man team can efficiently install the equipment and conduct the ring permeameter test. After the site has been selected and the zone of critical hydraulic conductivity determined, a 42-inch-diameter hole is excavated to within 3 inches of the test zone. The last 3 inches are excavated when the equipment is ready to be installed, taking care not to walk on the area to be tested. The testing area, which will be inside the 18-inch cylinder, is checked with a carpenter's level to assure that it is level before the cylinder is placed. The cylinder is marked with chalk 6 inches from the bottom edge and driven 6 inches into the soil with the driving disk and hammer. The cylinder should be kept level during driving and the blows should be as powerful and steady as practicable. After the cylinder has been driven to the desired depth, the soil immediately against its inside and outside wall is tamped lightly to prevent channeling along the sides. About 1 inch of clean, uniform, permeable sand is spread over the area inside the cylinder to minimize puddling of the soil surface during the test. The outside periphery of the cylinder is also tamped to keep water from channeling down along the sides and causing erroneous readings in the tensiometers.



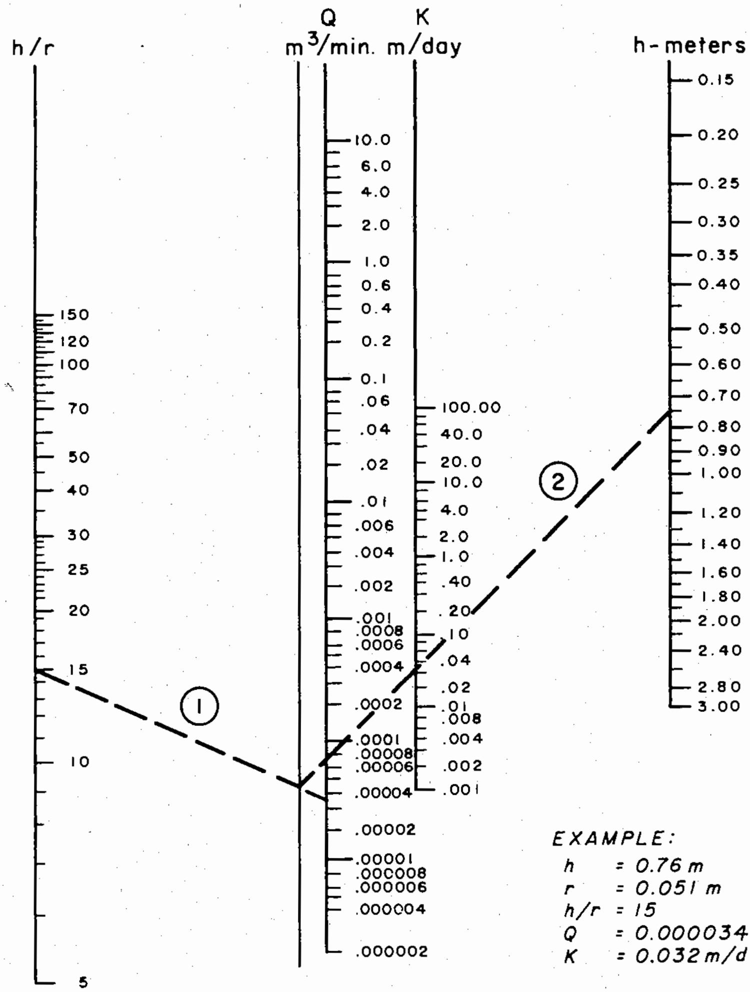
Example:
h = 2.5 ft
r = 0.167 ft
h/r = 15
Q = 0.0012 ft³/min
K = 0.06 in/h

CONDITION I

$$T_u \geq 3h$$

$$K = \frac{720\left[\log_e\left(\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2+1}\right)-1\right]Q}{2\pi h^2}$$

Figure 3–18.—Nomograph for determining hydraulic conductivity from shallow well pump-in test data for condition I (U.S. customary units). 103–D–656.



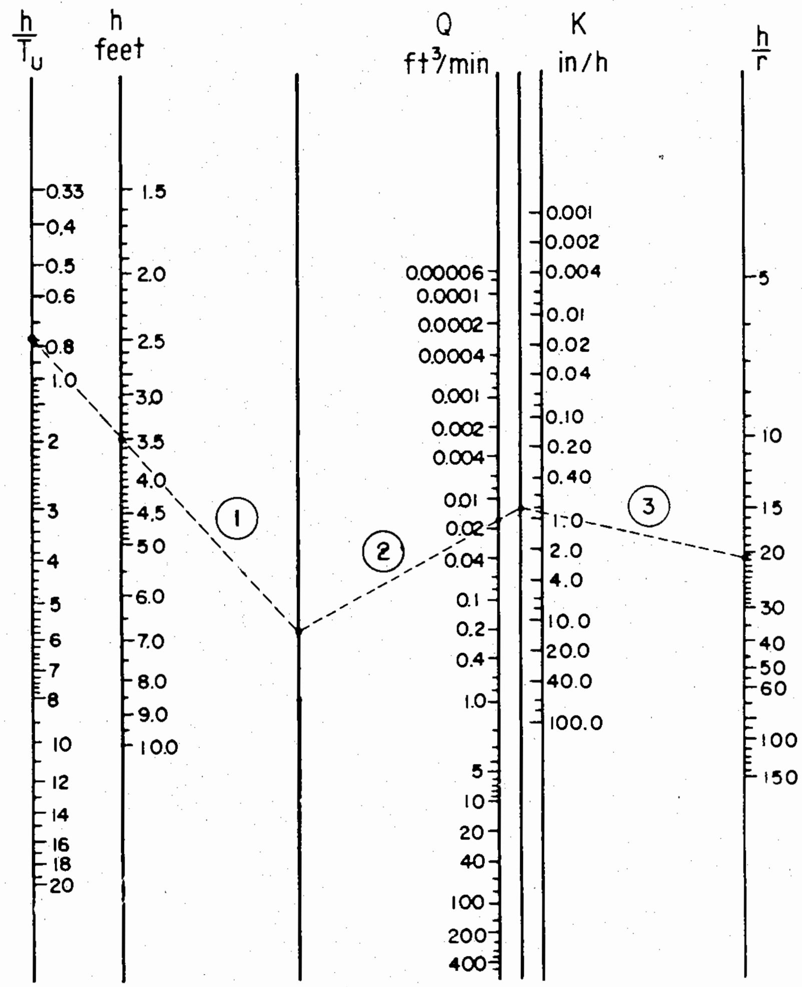
EXAMPLE:
h = 0.76 m
r = 0.051 m
h/r = 15
Q = 0.000034 m³/day
K = 0.032 m/day

CONDITION I

$$T_u \geq 3h$$

$$K\,(\text{m/day}) = 1440\,\frac{\left[\log_e\left(\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2+1}\right)-1\right]}{2\pi h^2}\,Q$$

Figure 3–19.—Nomograph for determining hydraulic conductivity from shallow well pump-in test data for condition I (metric units). 103–D–1191.



Example:

h = 3.5 ft

T_U = 4.5 ft

$h/T_U = 0.78$

Q = 0.019 ft³/min

r = 0.167 ft

h/r = 20.96

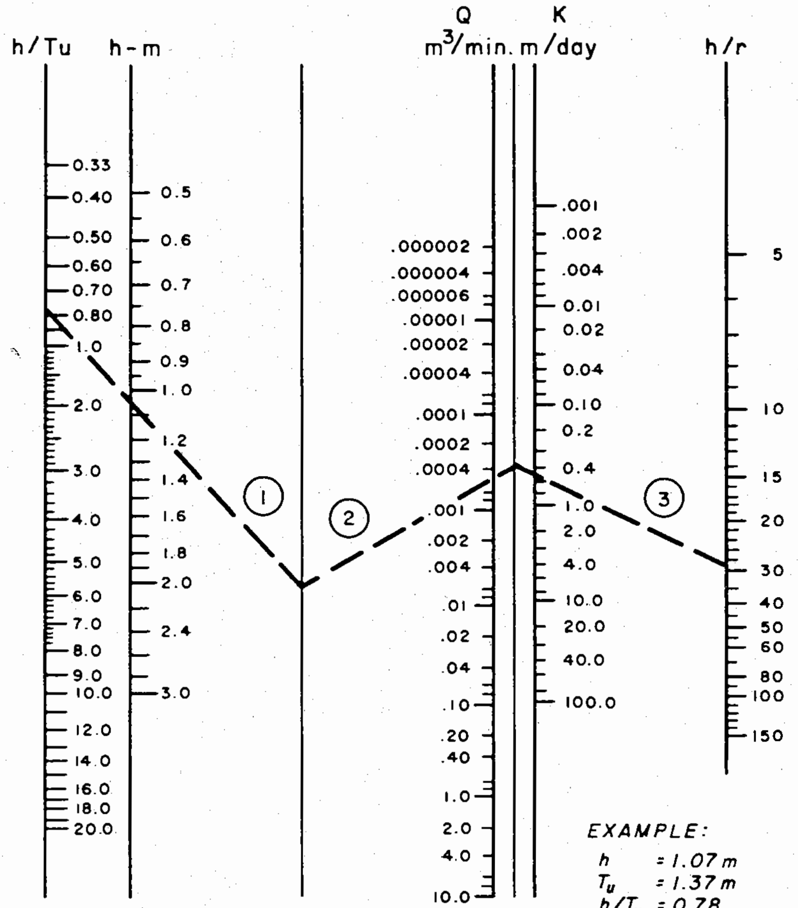
K = 0.90 in/h

CONDITION II

$3h \geq T_U \geq h$

$$K = 720\left[\frac{3\log_e \frac{h}{r}}{\pi h(h+2T_U)}\right]Q$$

Figure 3-20.—Nomograph for determining hydraulic conductivity from shallow well pump-in test data for condition II (U.S. customary units). 103-D-657.



EXAMPLE:

h = 1.07 m

T_u = 1.37 m

h/T_u = 0.78

Q = 0.00054 m³/min.

r = 0.051 m

h/r = 20.96

K = 0.55 m/day

CONDITION II

$3h \geq T_u \geq h$

$$K = 1440\left[\frac{3\log_e \frac{h}{r}}{\pi h(h+2T_u)}\right]Q$$

Figure 3-21.—Nomograph for determining hydraulic conductivity from shallow well pump-in test data for condition II (metric units). 103-D-1192.

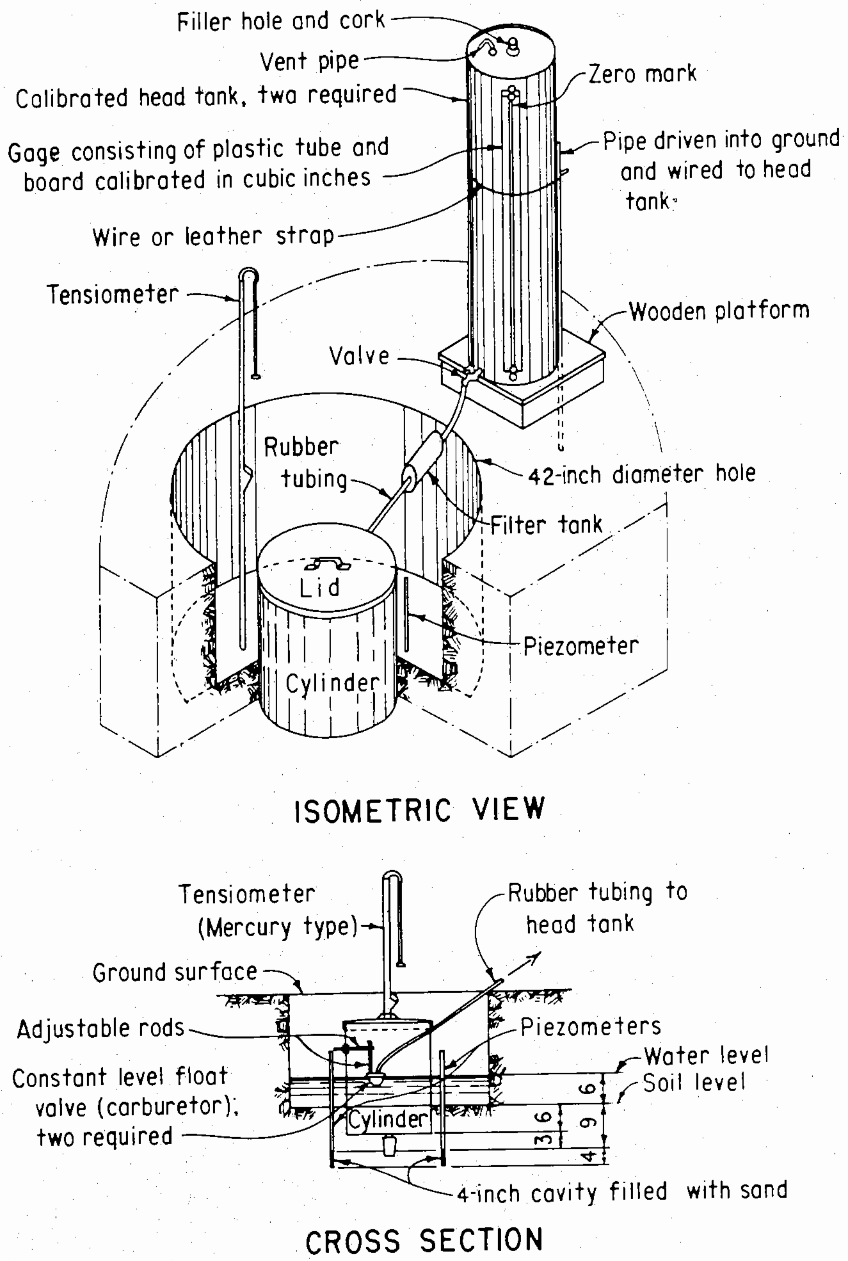


Figure 3-22.—Equipment setup for the ring permeameter hydraulic conductivity test. 103-D-658.

Next, the two 18-inch piezometers are marked 9 inches from the sharpened bottom and installed on opposite sides of the cylinder and about 3 to 4 inches distant from it. The piezometers are installed by driving them 2 or 3 inches into the soil with a driver and then augering out the core. This process is continued until the 9-inch mark is at ground level. Care should be taken that the piezometers do not turn or come up with the auger during installation. A 4-inch long cavity is then augered below each piezometer and filled with clean fine sand. As an additional means of preventing channeling along the sides, a 1-to-1 bentonite-soil mixture is tamped around the piezometers. Caution should always be exercised when using bentonite to assure that none of it falls into the piezometers or into the testing ring. The piezometers are filled with water and checked to assure that they are functioning properly. If the water falls in the piezometers, the installation is satisfactory. A small can should be placed over each of them to keep out dirt and water during the remainder of the installation. If the water does not fall, the piezometers should be flushed with a stirrup pump and reaugered if flushing does not clear them.

The two calibrated and tested tensiometers are then installed on opposite sides of the cylinder and 3 to 4 inches from it on a line at right angles to that of the piezometers. The calibration and testing should be done in the laboratory. Instructions for calibrating and testing can be obtained from the manufacturer. During the calibration, 100 on the scale should be set at zero tension so that pressures caused by a rising water table can be observed if the water table rises above the tensiometer cup. The holes for the tensiometers are excavated with a 1-inch soil auger to a depth of 9 inches. A small amount of dry soil is then dropped into the hole, followed by a small amount of water. The tensiometer is then placed in the hole, with the glass tubes facing away from the sun, and worked up and down in the mud to obtain good contact between the porous cup, the mud, and the undisturbed soil. The annular space around the tensiometer is filled and tamped with dry soil to within about 1 inch of the soil surface. A 1-to-1 bentonite-soil mixture is then added to prevent channeling. Mercury is placed in the reservoir cup and the tensiometer tubes filled with water. A small air syringe is used to remove air from the tensiometer tube by forcing water through the system.

The carburetor float apparatus is installed and adjusted to hold a constant 6-inch head in the cylinder, and the carburetor is connected to the head tank with rubber tubing. If the test water contains suspended material, a filter tank should be installed with the tubing as described in section 3–6. The tank should always be anchored and the gage should always face away from the sun. The cylinder is then filled with water to the 6-inch mark, and the tank valve opened. The hole outside the cylinder should also be filled with water to a depth of 6 inches and should be kept to this 6-inch depth during the entire test period. The extra tank and carburetor are used for this purpose. When all adjustments have been made and the tensiometers are full, the time and water content of the tank are recorded.

The head tank should be checked at least two or three times a day, depending upon the percolation and hydraulic conductivity rates, and filled as necessary. Each time the site is visited, a record should be made of the time, volume of water in the tank, gage readings of the tensiometers and piezometers, temperature, and the hydraulic conductivity. When the tensiometer gages read approximately 100 (zero tension), no water shows in the piezometer, and water is moving through the 6-inch test layer at a constant rate, the requirements of Darcy's law may be assumed to have been met and valid test results can be obtained for calculating hydraulic conductivity. Tensiometer readings sometimes fluctuate when the soil is at or near saturation, and it is not always possible to get the 100 reading. If the gages fluctuate between 100 and 105, they are probably indicating saturated conditions for that particular soil. Also, it is not necessary for both tensiometers to have the same reading providing they both read in the 100 to 105 range.

If the saturated front should reach a zone less permeable than the layer being tested before the requirements of Darcy's law are met, a mound of water will build up into the test zone. When this happens, the hydraulic gradient will be less than unity, and the base of the soil column being tested will be at greater than atmospheric pressure. This condition will be shown by both the piezometers and tensiometers. When the piezometers show that a mound has reached the bottom of the cylinder, the test will no longer give a true hydraulic conductivity value. When this happens, the test will either have to be stopped or the mound lowered below the bottom of the cylinder. When the material between the bottom of the cylinder and the less permeable zone has a fair rate of hydraulic conductivity, it is sometimes possible to lower the water table mound by augering a number of holes around the outside periphery of the cylinder approximately 10 inches from the sides. These holes, when filled with sand, will act as inverted drainage wells and, under most conditions, will lower the mound. If the holes do not provide the necessary drainage, the testing equipment should be lowered to the less permeable zone and the test rerun.

At the close of the test, the soil is excavated from around the outside of the cylinder and cut for a short distance under the cylinder. A chain placed around the cylinder and pulled by a truck will usually break the soil across the bottom so it can be examined for root holes, cracks, and possible channeling.

(d) Calculations.—Hydraulic conductivity computations for the ring permeameter test are made using the Darcy flow equation:

$$K = \frac{VL}{tAH} \tag{3}$$

where:

K = Hydraulic conductivity in inches per hour,

V = volume of water passed through the soil in cubic inches,

A = cross-sectional area of the test cylinder in square inches,

t = time in hours,

L = length of the soil column in inches, and

H = height of the water level above the base of the ring in inches.

A sample data sheet and computations are shown on figure 3–23.

When fluctuations in the water temperature exceed 2°C, viscosity adjustments should be made. This usually results in more uniform hydraulic conductivity values. This adjustment is illustrated on the sample data sheet, figure 3–23.

(e) Limitations.—The principal limitation in this test is that the material directly below the test zone must have equal or greater hydraulic conductivity than the test zone. Also, it must extend to a sufficient depth below the test zone so that a steady state flow is reached for at least three consecutive hourly readings before any water mound builds up to the bottom of the cylinder. Another limitation is the presence of progressively tighter soils below the test zone. With this condition, a steady state flow is never reached, and the hydraulic conductivity apparently becomes less as the test proceeds.

Unreliable data may result when the test zone is immediately above a thick, very permeable material. A fairly steady state flow can be obtained, but the tensiometers in the very permeable material will never indicate zero tensions below the test zone and, thus, the requirements of Darcy's law are not met.

This test cannot be used in rocky or coarse gravel materials because the cylinder cannot be driven into such material without resulting in channeling along the inside periphery of the ring during the test.

3–8. Test Pit Method.—(a) *Introduction.*—There is no exact method for determining the hydraulic conductivity above a water table in soils of coarse gravel and cobbles with matrices of finer materials. The following procedure, equations, and sample computations describe one method which is considered sufficiently accurate to give a reasonable hydraulic conductivity when applied to field problems.

The test pit can be of three different shapes: (1) a circular test pit of diameter, *a*, (2) a square test pit with side dimensions of *a*, and (3) a rectangular test pit with side dimensions *a* by *2a*.

The test should be conducted in only one textural classification such as a cobbly, coarse gravelly, or loamy sand. A backhoe, power auger, or hand tools can be used to excavate down to the test zone. The test pit is then carefully excavated to the desired shape and depth by hand. For the different shaped pits, an *a* value of 1 foot should be adequate. Larger sizes can be used, but the larger the pit, the more water that will be required. Small cavities left when cobbles are removed or a few small cobbles sticking out into the test pit will cause little difference in the quantity of water entering the test pit or in the average diameter of a circular pit or in the side dimensions of a square or rectangular pit.

Matrices with textures such as fine sands, silts, silt loams, and very fine sands

ENGINEERING MONOGRAPHS No. 8

United States Department of the Interior
BUREAU OF RECLAMATION

THEORY AND PROBLEMS OF WATER PERCOLATION

By Carl N. Zangar

Denver, Colorado
April 1953 65 cents

large relative to T, Muskat[10] has shown that equation (24) may be applied to a radial gravity flow system if the driving head H is modified according to the equation

$$H_{(gravity)} = \frac{2TH - H^2}{2T} \quad .. \ (81)$$

Equation (81) defines a modified driving head which approaches H/2 as H approaches T and is almost equal to H as H becomes small relative to T.

Thus, a two-dimensional radial flow system is readily reproduced and analyzed if

1. Full penetration of the pervious layer by the pumping well can be achieved.

2. Observation wells are available for determining the driving head between successive radii.

The full penetration requirement makes the test cost excessive for deep pervious strata. However, the tests are ideally suited to relatively thin pervious strata already equipped with pumping or drainage wells where only the horizontal permeability is desired.

Three-Dimensional Radial Flow.

a. *Saturated Material.* Equations (54) through (57) give the mathematical development for three-dimensional radial flow. Equation (57) states that the quantity of flow from or to a spherical source or sink is directly proportional to the driving head, H, ($\phi_b - \phi_a$); the permeability of the surrounding material; and the radius of the source or sink. It is inversely proportional to one minus the ratio between the inner and outer radii used in measuring the differential head. The effect of the ratio of radii in the denominator is negligible if b is large relative to a. In most real cases b will be at least 20a, therefore, neglecting this term will change the results by about 5 percent or less. For determining the field permeability of soils, only hemispherical flow need be considered, and letting the outer radius b be large compared to radius a leads to the simplified form of equation (57)

$$Q = 2\pi HKa \ \ldots\ldots\ldots\ldots \ (82)$$

where

$$H = \phi_b - \phi_a.$$

This simplification immediately eliminates the need for an observation well if the ground water level is known and if no major obstacle, such as an impervious layer, is closer than 5a to the source.

It is not necessary to make the test well for a three-dimensional radial flow system fully cased except for a hemispherical open end. Most test wells have cylindrical active lengths that are either screened, perforated, or uncased. To permit use of this type of test well, conductivity coefficients C_s, which give the equivalent hemispherical radius of a cylindrical well, have been determined. These dimensionless coefficients have been plotted against the ratio of cylinder length L_A to radius r_1 in figure 41. For a perforated cylindrical well, an effective well radius was found to be

$$r_{1(effective)} = r_1 \left(\frac{\text{area of perforations}}{\text{cylinder wall area}}\right)$$

In applying this result to a well with closed bottom, the effective C_s was that obtained from the curve on figure 41 at

$$L_s / r_{1(effective)}.$$

For an open bottom well,

$$4 \left[r_1 / r_{1\,(effective)} \right]$$

should be added to the above. The effective hemispherical radius can be computed directly from these coefficients as

$$r_{(effective)} = \frac{C_s r_1}{2\pi} \ \ldots\ldots\ \ (83)$$

The effective radius will always lie numerically between the cylinder length and the radius length. These conductivity coefficients were obtained from experimental and analytical results. The experimental results include field, sand model, and electric analogy values. The analytical results include a solution for partly penetrating cylindrical wells by Muskat[11] and a solution by F. E. Cornwell (see Appendix A) for flow from a cylindrical element to a plane potential surface. Cornwell's solution

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[10] Muskat, op. cit.

[11] Muskat, op. cit.

yields a very simple expression for the conductivity coefficient

$$C = \frac{L_A}{r_1} \frac{2\pi}{\ln \frac{L_A}{r_1}} \quad \ldots\ldots\ldots\ldots (84)$$

which fits the curve of figure 41 very well for values of $L_A \geqq 20r_1$, and shows that the shape of the outer boundary of the system is relatively unimportant in most three-dimensional flow systems. It should be pointed out here that equation (81) may be used to modify the head for gravity effects in three-dimensional flow as well as two-dimensional flow.

In some test areas, insufficient geological information may be available to define the boundaries of the pervious material. It is then impossible to decide whether two or three-dimensional radial flow is more nearly applicable to the problem. Solutions for both assumed ideal cases will yield values which define the limits between which the average permeability must lie. The value based on two-dimensional radial flow will always give the upper limit and, in horizontally arranged layers of material, will usually give conservative adequate results. The ratio of limiting permeabilities will be

$$\frac{K_{(2\text{-dim})}}{K_{(3\text{-dim})}} = \frac{\ln \frac{r_2}{r_1}}{\ln \frac{L_A}{r_1}} \quad \ldots\ldots\ldots (85)$$

b. Unsaturated Material. Three-dimensional radial flow from a cylindrical well in an unsaturated isotropic pervious bed requires some special treatment. R. E. Glover (see Appendix B) has developed a precise solution for the steady-state flow from a well into an infinite unsaturated medium. This solution is based on flow from an array of point sources in a uniform stream. The relation between Q, h_1, r_1, and K was found to be

$$K = \frac{Q}{2\pi h_1^2} \left[\sinh^{-1} \left(\frac{h_1}{r_1}\right) - 1 \right] \ldots (86)$$

where

h_1 = the depth of the water in the test well.

All of the developments given here have been applied to partially penetrating wells and to partly cased wells. Therefore, different limits of integration were applied to Glover's solution to yield the more general expression

$$K = \frac{Q}{2\pi L_A (2h_1 - L_A)} \left[\sinh^{-1}\left(\frac{L_A}{r_1}\right) - \left(\frac{L_A}{h_1}\right) \right] \ldots\ldots\ldots\ldots (87)$$

To reduce the labor involved in solving this equation, a set of coefficients, C_u, for a wide range of h_1/r_1 and L_A/h_1 ratios has been computed and plotted in figure 43. These values can be used with the familiar three-dimensional radial flow relation given by equation (82) with $2\pi a$ replaced by $C_u r_1$. Thus

$$K = \frac{1}{C_u r_1} \frac{Q}{h_1} \quad \ldots\ldots\ldots\ldots (88)$$

Applications to Soils Permeability. From the preceeding discussion it can be seen that preliminary permeability investigations can be made by very simple, rapid, and inexpensive field tests. The most accurate type of investigation employs the two-dimensional radial flow systems of Theim and Theis tests. Both tests require observation wells and a pump well which penetrates the aquifer by at least 85 percent of its depth. In the Theim test steady-state conditions are required. However, the drawdown at the well may be any percent of the total depth of aquifer. In the Theis type of test steady-state conditions need not be established. Drawdowns may be measured as a function of time. However, in the Theis test (often referred to as the nonequilibrium tests) the drawdown at the well should not exceed 10 percent of the depth of the aquifer. If the extra time and expense of these two-dimensional tests are not justified, then the simple three-dimensional radial flow test may be used, and the systematic error estimated by equation (85).

Examples 6, 7, and 8 give applications useful in determining the permeability of unsaturated soils, and Examples 9, 10, and 11 may be used in determining the permeability of saturated soils under artesian effects or where the drawdown at the well is not more than 10 percent of the depth of

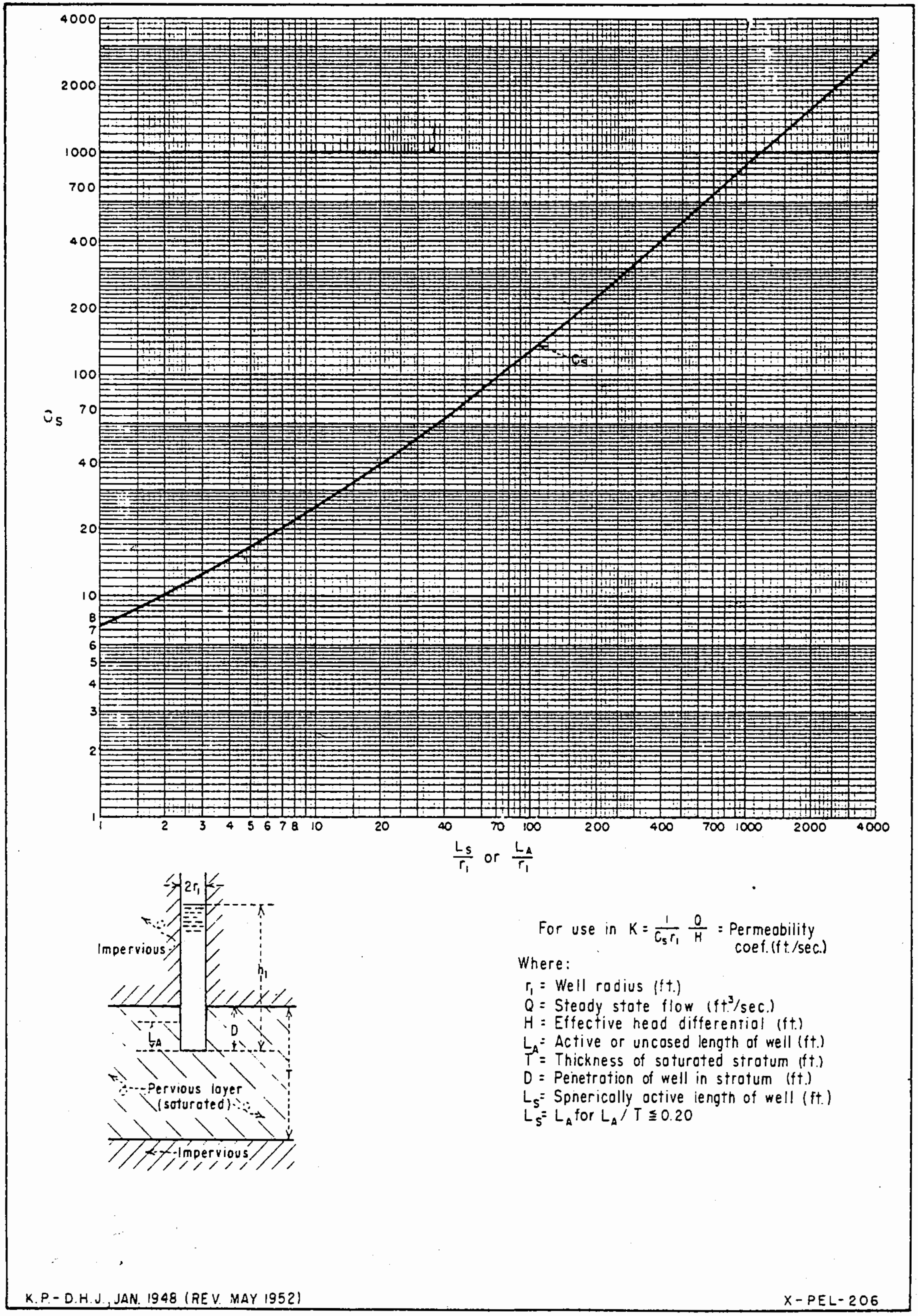
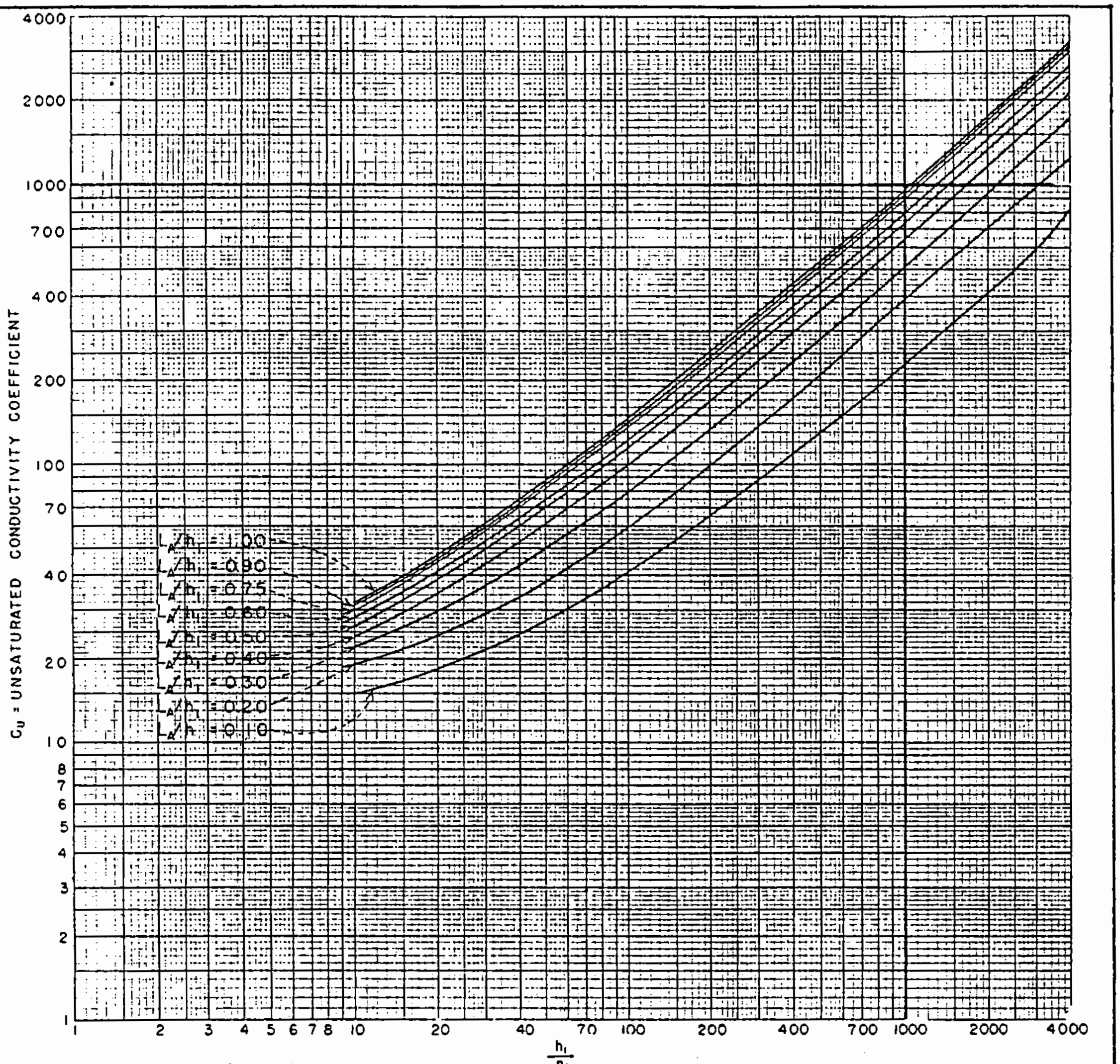
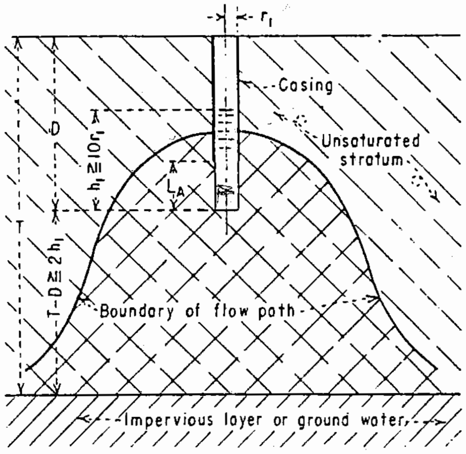


Figure 41 - Conductivity Coefficients for Semi-spherical Flow in Saturated Strata through Partially Penetrating Cylindrical Test Wells.





$K = \frac{1}{C_u r_1} \frac{Q}{h_1}$ = Permeability coef. (ft./sec.)

Where:

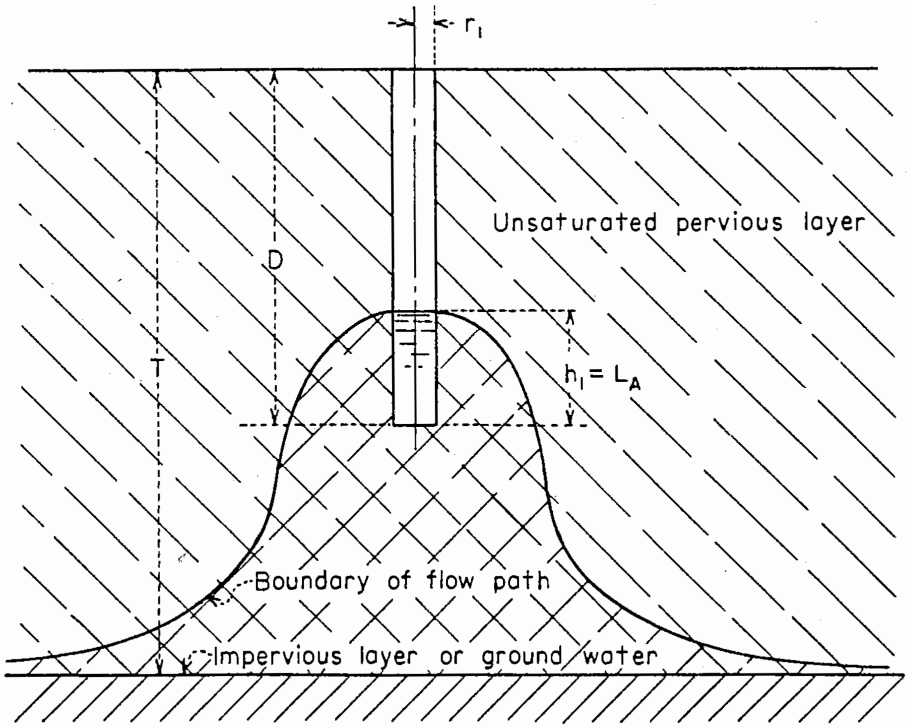
r_1 = Well radius (ft.)
Q = Steady state flow (ft./sec.)
h_1 = Head on well (ft.)
L_A = Active or uncased length of well (ft.)
T = Thickness of unsaturated stratum (ft.)
D = Penetration of well in stratum (ft.)

APPLICABILITY LIMITS:

$h_1 \geqq 10 r_1$ $\qquad$ $T - D \geqq 2h_1 \geqq 20 r_1$

K. P. - D.H.J., JAN 1948 (REV. MAY 1952) X-PEL-205

Figure 43 - Conductivity Coefficients for Permeability Determination in Unsaturated Strata with Partly Penetrating Cylindrical Test Wells.



FORMULA: $K = \frac{1}{C_u r_1} \frac{Q}{h_1}$

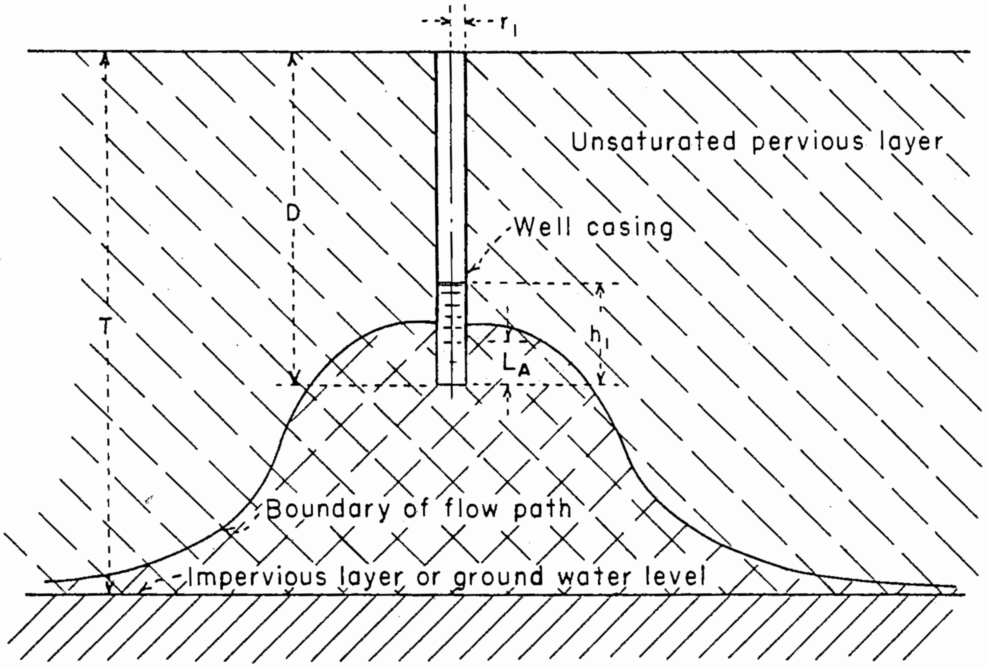
DEFINITIONS:
Q = Well discharge – steady state (ft.^{3}/sec.)
C_u - From figure 43 - Use curve for $\frac{L_A}{h_1} = 1.00$
Other values as shown

NUMERICAL EXAMPLE:

Let $T = 60$ ft., $D = 35$ ft., $h_1 = 10$ ft., Then $T - D = 25$ ft. $= 2.5\, h_1$
$Q = 0.10$ ft.^{3}/sec. $r_1 = 0.25$ ft.
$\frac{h_1}{r_1} = 40 \quad \therefore \quad C_u = 74.5$ (From figure 43)
$K = \frac{1}{(74.5)(0.25)} \; \frac{0.10}{10} = 0.00054$ ft./sec.

D.J.H., 11-26-47 (REV. MAY 1952) X-PEL-181

Figure 45 - Example 6: Outflow from an Uncased Cylindrical Well in an Unsaturated Stratum, $T - D \geqq 2h_1$, $\frac{h_1}{r_1} \geqq 10$.



FORMULA: $K = \frac{1}{C_u r_1} \frac{Q}{h_1}$

DEFINITIONS: Q = Well discharge - steady state (ft.³/sec.)
C_u = From Figure 43 use curve for nearest $\frac{L_A}{h_1}$

NUMERICAL EXAMPLE:

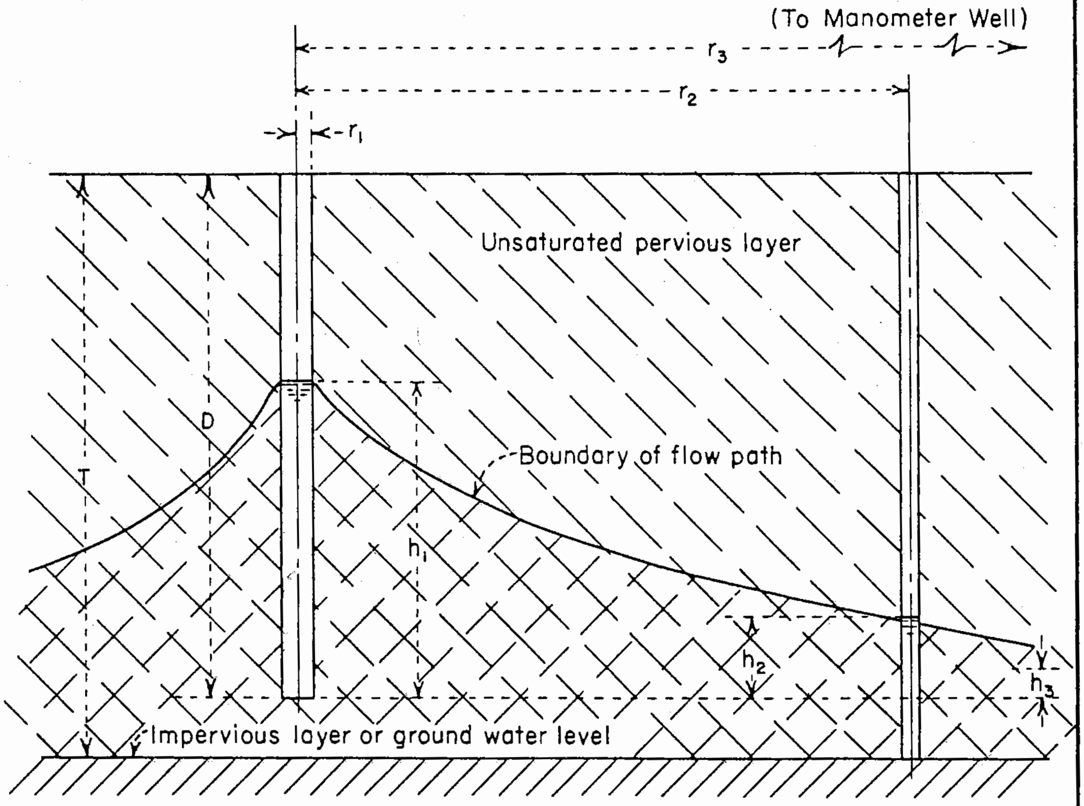
Let $T = 60$ ft., $D = 35$ ft., $h_1 = 10$ ft., Then $T - D = 25$ ft. $= 2.5 h_1$
$L_A = 5$ ft., $\frac{L_A}{h_1} = 0.5$, $r_1 = 0.25$ ft., $\frac{h_1}{r_1} = 40$, $C_u = 59$
$Q = 0.10$ (ft.³/sec.)

$$K = \frac{1}{(59)(0.25)} \frac{0.10}{10} = 0.00068 \text{ ft./sec.}$$

D.H.J. 11-28-47 (REV. MAY 1952) X-PEL-182

Figure 46 - Example 7: Outflow from a Partly Cased Cylindrical Well in an Unsaturated Stratum,

$$T - D \geqq 2h_1, \; \frac{h_1}{r_1} \geqq 10.$$



NECESSARY CONDITIONS:

(1) $$\frac{\left[35\, r_3^2 \;(\Delta h_1 + 2\Delta h_3)\right]}{Q} \leqq 10 \quad \text{(Steady state)}$$

(2) $$r_2 \geqq \frac{h_1 + (T-D)}{2}$$

FORMULA:

$$K = \frac{\ln\left(\frac{r_3}{r_2}\right)}{\pi} \; \frac{Q}{(h_2^2 - h_3^2)}$$

DEFINITIONS:

Q = Steady state well discharge (ft.³/sec.)

Q.H.J., 11-28-47 (REV. MAY 1952)

X-PEL-183

Figure 47 - Example 8: Outflow from a Cylindrical Well in an Unsaturated Stratum, $T - D < 2h_1$.