Field and Laboratory Test Methods

Forward

One of the important steps in the evaluation and design of a stormwater retention pond is the determination of the type of field and laboratory tests and how many tests should be conducted at a particular site or for a particular retention pond system. Typically, a soil boring and a hydraulic conductivity test are conducted for each stormwater retention pond. The number of soil borings and hydraulic conductivity tests performed are usually based on local experience, regulatory criteria, site topography, subsurface hydrogeologic conditions, size of pond, pond geometry and other factors. In some areas, the regulatory agencies have established criteria for a minimum number of soil borings and hydraulic conductivity tests. However, judgment and experience are usually applied in the decision making process. In this course, methods for estimating the required number of soil borings and hydraulic conductivity tests are presented which will allow for a consistent and reproducible approach to characterize the shallow aquifer system for retention pond designs. These methods should be used as a general guide and more or fewer tests may become necessary based on local experience and knowledge, regulatory criteria and/or site hydrogeologic conditions.

Objective

The objective of this course is to introduce a systematic methodology to a designer of a stormwater retention pond to select the minimum number of soil borings and hydraulic conductivity tests needed for a particular site and to present the applicability of the various tests for stormwater retention pond design. The course will be presented in two parts. The first part will present the soil borings that are typically used to characterize the subsurface conditions and the second part will present the hydraulic conductivity test methods and their applicability for a particular subsurface condition. The course will conclude with the proposed methods to select the number and type of soil borings and the number and type of hydraulic conductivity tests needed for a particular site or for a particular retention pond system.

The proposed testing methods and selection of number of tests presented in this course are intended for the design of stormwater retention ponds in unconfined shallow aquifer systems.

Soil Borings

To explore the subsurface soil and groundwater table conditions within an area proposed for a stormwater retention pond, a variety of soil borings, soil penetration tests and/or ground penetrating radar tests can be performed. Perhaps the most widely used methods to investigate subsurface conditions within the shallow depths of an unconfined aquifer, typically conducive for stormwater retention ponds design, are the Standard Penetration Test (SPT) borings (ASTM D-1586) or auger borings (ASTM D-1452). Other tests are also used as supplemental data for the SPT and auger borings. These include cone penetration tests, ground penetrating radar, and the hand penetrometer.

SPT Borings

Standard Penetration Test borings provide a reasonable soil profile and an estimate of the relative density of the soils. The soil profile is typically developed by continuously sampling for the first 10 feet and at intervals of 5 feet thereafter. The SPT borings measure soil density using a split spoon sampler advanced by a 140-pound hammer, which is repeatedly dropped 30 inches. The relative density is reported as the "N-value", which is the number of blows by the hammer required to advance the split spoon sampler one (1) foot. The change in relative density of the soil can be indicative of the change of soil hydraulic conductivity (the denser the soil the lower the hydraulic conductivity), which can help with the characterization of the effective aquifer system. However, the measurement of groundwater table depth in SPT borings is usually less accurate than in auger borings due to the effects of drilling fluid (bentonite mud) used during the drilling process. The drilling fluid is typically used to stabilize the open hole while drilling and sampling in sandy aquifer systems. Although hollow stem auger can be used to advance the SPT borehole, the drilling fluid method is typically employed to advance the SPT boreholes in areas of sandy soil and high groundwater table conditions, which generally occur in areas where stormwater retention ponds are used for storm water infiltration.

The drilling fluid forms a poorly permeable lining of the borehole walls and can prevent accurate measurement of the groundwater table, which is an important factor in the design of stormwater retention ponds.

Auger Borings

Auger borings generally provide a more accurate soil profile and a better estimate of the depth to the groundwater table. The soil profile is developed by advancing a flight auger at a slow spin rate that preserves the natural soil profile and then extracting the auger without spinning. This method allows generating a complete soil profile that can be visually observed on the flight augers and collection of representative soil samples at any depth. The drilling method does not introduce any drilling fluids or other substances into the borehole which is important for measurement of the groundwater table. The groundwater level stabilizes in the open borehole after drilling and can be measured accurately. It is important that a sufficient amount of time is allowed for the stabilization of the groundwater level in the borehole. Typically, a minimum period of 24 hours is required for fine sand and silty fine sand soils. For clayey fine sand and clay soils a longer stabilization time may be required.

For shallow depths, 15 feet or less, the auger borings can also be drilled using a hand auger, which is also known as a bucket auger. The hand auger typically consists of a 3-inch diameter tube with cutting blades attached to extendable metal rods and a cross bar. It is manually advanced into the soil and soil samples are retrieved every 4 inches of the soil profile. This drilling method allows for a very accurate characterization of the soil profile and continuous soil sampling.

Selection of Type and Depth of Borings

For best aquifer characterization, both SPT borings and auger borings can be drilled to provide an accurate soil profile with soil density data and a reliable measurement of the groundwater table. However, if only one method is to be selected, the auger boring method would provide better data for subsurface characterization of the aquifer system and measurement of the groundwater table.

Whenever possible, the soil borings shall be extended to the confining layers of the effective aquifer system. For practical purposes, the effective aquifer confining layer can be defined as the first low permeability soil layer. Typical material of confining layers consists of clay, sandy clay, consolidated silt, hardpan, rock, impervious limestone or other material with a hydraulic conductivity of 0.1 feet per day or less. In groundwater hydrology, the effective hydraulic influence of a retention pond is approximately one width of the pond as measured below the groundwater table. For example, if the average pond width is 45 feet and the groundwater table is 10 feet below ground surface, the effective hydraulic influence of the retention pond will be 55 feet below ground surface. Therefore, when selecting the minimum depth for the soil borings, it is helpful to know the size and geometry of the pond and an approximate depth of the groundwater table.

When planning the soil investigation program for retention ponds, the soil borings should be extended to the first confining layer (poorly permeable soil with permeability of 0.1 feet per day or less) or to the effective hydraulic influence depth of the pond, whichever is less. For small retention ponds or for areas of highly permeable aquifer systems, often the retention ponds can adequately perform without utilizing the full depth of the aquifer system. In such cases, the soil borings should be drilled to a sufficient depth to demonstrate the presence and continuity of the aquifer, to measure the depth of groundwater table and to verify sufficient depth of the aquifer for adequate operation of the pond. If a confining layer is not encountered within the drilled depth of the soil borings, then the bottom of the soil borings shall be used as the confining layer (bottom of effective aquifer).

Selection of Number of Borings

The complexity of subsurface soil conditions and the variability of aquifer systems across the world make it very difficult to establish a single criteria to select the number of soil borings needed to adequately characterize the aquifer system for stormwater retention ponds. In general, the more variable the subsurface conditions and the more variable the surface topography, the more soil borings will be required to characterize the aquifer system. Local knowledge and experience generally drives the selection of the minimum number of soil borings for a particular stormwater retention pond. The other factors that can influence the minimum number of soil borings needed are the amount and intensity of rainfall, the sensitivity of the downstream drainage systems, the physical and political consequences of a failed retention system, the regulatory criteria and enforcement action for a failed retention system, and other related factors.

The designer is typically required to conduct an adequate investigative and testing program to design an effective retention system, while maintaining the cost of such investigations within the locally accepted levels. For example, in areas where a failure of a retention pond can create significant flood damage or significant water quality impacts, the level of investigation and testing will be higher than in areas where a potential pond failure will have minimal impact and can simply be repaired.

The engineering approach to developing a methodology for selecting a minimum number of soil borings for a retention pond can be described as follows:

- Minimum number = 1
- Maximum number = between 1 and X

Where,

X = function of pond size, site complexity, drainage area sensitivity, regulatory criteria, and other locally sensitive factors.

To develop an effective method of selecting the minimum number of soil borings for a particular area, it is best to draw upon the local knowledge and local data to create an equation or a matrix that best fits the local practice and regulatory criteria. The following general equation is provided for a typical unconfined aquifer system in fine sand formation with medium level of environmental sensitivity and regulatory control:

$$NB = 1 + \sqrt{2A} + \frac{L}{2\pi W}$$

Where,

NB = Minimum number of soil borings, rounded to the nearest whole number (i.e., 2.3 = 2; 3.65 = 4)
A = Average area of retention pond (acres)
L = Average length of retention pond (ft)
W = Average width of retention pond (ft)

This empirical equation was developed from actual data of a geotechnical engineering consulting firm in Central Florida (Jammal & Associates, Inc.) and was presented in the "Stormwater Retention Pond Infiltration Analyses in Unconfirmed Aquifers, Permitting Guidelines for Southwest Florida Water Management District, 1989" (Andreyev & Wiseman, 1989). By design the empirical equation has the following three components that affect the selection of the minimum number of soil borings needed for the design and infiltration analysis of retention ponds.

1. The first component forces the equation to produce a minimum of one (1) soil boring for each pond. This was based primarily on the local regulatory criteria but also serves as minimum data needed to understand the site conditions and to measure site specific depth to the groundwater table.
2. The second component provides for additional soil borings for larger ponds. The larger the pond, the more soil borings are needed to identify variability of subsurface conditions and to measure an average depth to the groundwater table, which can significantly vary over larger areas.
3. The third component allows for additional soil borings based on geometry of the pond area. For a given pond area, the larger the length to width ratio the more soil borings are needed to characterize the variability of subsurface conditions and to measure the average depth to groundwater table.

Additional components to this equation can be added to account for the other influencing factors, such as environmental sensitivity, flood sensitivity, downstream damage potential, local regulatory criteria, and other factors. However, the equation presented herein is a good starting point to a consistent and reproducible method to select the minimum number of soil borings needed to investigate a stormwater retention pond.

Hydraulic Conductivity

The hydraulic conductivity (interchangeably referred to as permeability) can be defined as the discharge rate through a unit area under a unit hydraulic gradient. If the seepage rate, perpendicular flow area and hydraulic gradient are known, the hydraulic conductivity can be calculated for any flow condition in a laboratory test or in the field. Likewise, for any situation where the seepage velocity is known at a point at which the hydraulic gradient and soil porosity are also known, hydraulic conductivity can be calculated. Although the hydraulic conductivity is usually constant throughout a given material, the magnitude may vary depending on several factors such as:

1. The viscosity and quality of the water
2. Grain size distribution of the soils
3. The size and shape of the soil particles
4. Density of the soil
5. Cementation of the soil
6. Degree of soil saturation

All of these factors strongly influence the hydraulic conductivity. The relationship between the hydraulic conductivity and these factors can be expressed by the following equation (Darcy 1856):

$$K = \frac{2g}{vC_s} D^2 \frac{e^3}{1+e}$$

Where:

K = hydraulic conductivity
g = the acceleration due to gravity
v = the kinematic viscosity of water
C_s = particle shape factor
D = the weighted or characteristic particle diameter
e = the void ratio

The characteristic particle diameter D is obtained from a grain size distribution analysis using the following equation:

$$D = \frac{\sum Mi}{\sum [Mi/Di]}$$

Where:

Mi = the mass retained between two adjacent sieves
Di = the mean diameter of the two adjacent sieves

Typical hydraulic conductivity values for granular soils and consolidated materials are summarized in **Table 1**. Typical values of hydraulic conductivity for various soil types in unconfined fine sand and silty fine sand aquifers are presented in **Table 2**. There are several direct methods of hydraulic conductivity measurement which can be performed in the laboratory or in the field. In general, laboratory tests will yield the most accurate results due to better control of the test procedures and more accurate measurements of physical parameters of the soil sample and the water flow rates. Typically, it is possible to obtain relatively undisturbed soil samples at shallow depths (less than 10 feet) by excavating a pit and driving a thin-wall, short "Shelby tube" by hand. Obtaining relatively undisturbed tube samples of sand at more than 10 feet below ground surface or below groundwater table is generally very difficult.

TABLE 1

Typical Values of Hydraulic Conductivity for Various Soils (Bouwer, 1978)

Type of Soil	***Hydraulic Conductivity (meters/day)****
Clay soils (surface)	0.01 to 0.20
Deep clay beds	10^{-8} to 10^{-2}
Loam soils (surface)	0.1 to 1.0
Fine sand	1 to 5
Medium sand	5 to 20
Coarse sand	20 to 100
Gravel	100 to 1,000
Sand and gravel mixes	5 to 100
Clay, sand and gravel mixes (till)	0.001 to 0.1
Sandstone	0.001 to 1.0

Carbonate rock with secondary porosity	0.01 to 1.0
Shale	10^{-7}
Dense, solid rock	$<10^{-5}$
Fractured or weathered rock (aquifers)	0.001 to 10
Fractured or weathered rock (core samples)	0 to 300
Volcanic rock	0 to 1,000
To convert to feet/day, multiply by 3.281 To convert to inches/hour, multiply by 1.64	

TABLE 2

Typical Values of Hydraulic Conductivity for Various Soils
In Unconfined Sand Aquifers in Florida, USA (Andreyev & Wiseman, 1989)

Type of Soil	***Hydraulic Conductivity (feet/day)****
Clayey fine soils and silty fine sands (SM-SC)**	0.01 to 0.5
Slightly silty fine sands (SP-SM)	0.5 to 5
Clean fine sands (SP)	5 to 50
Fine to medium sands (SP)	20 to 100
To convert to meters/day, divide by 3.281 To convert to inches/hour, divide by 2.0	
**** SM = Unified Soil Classification System**	

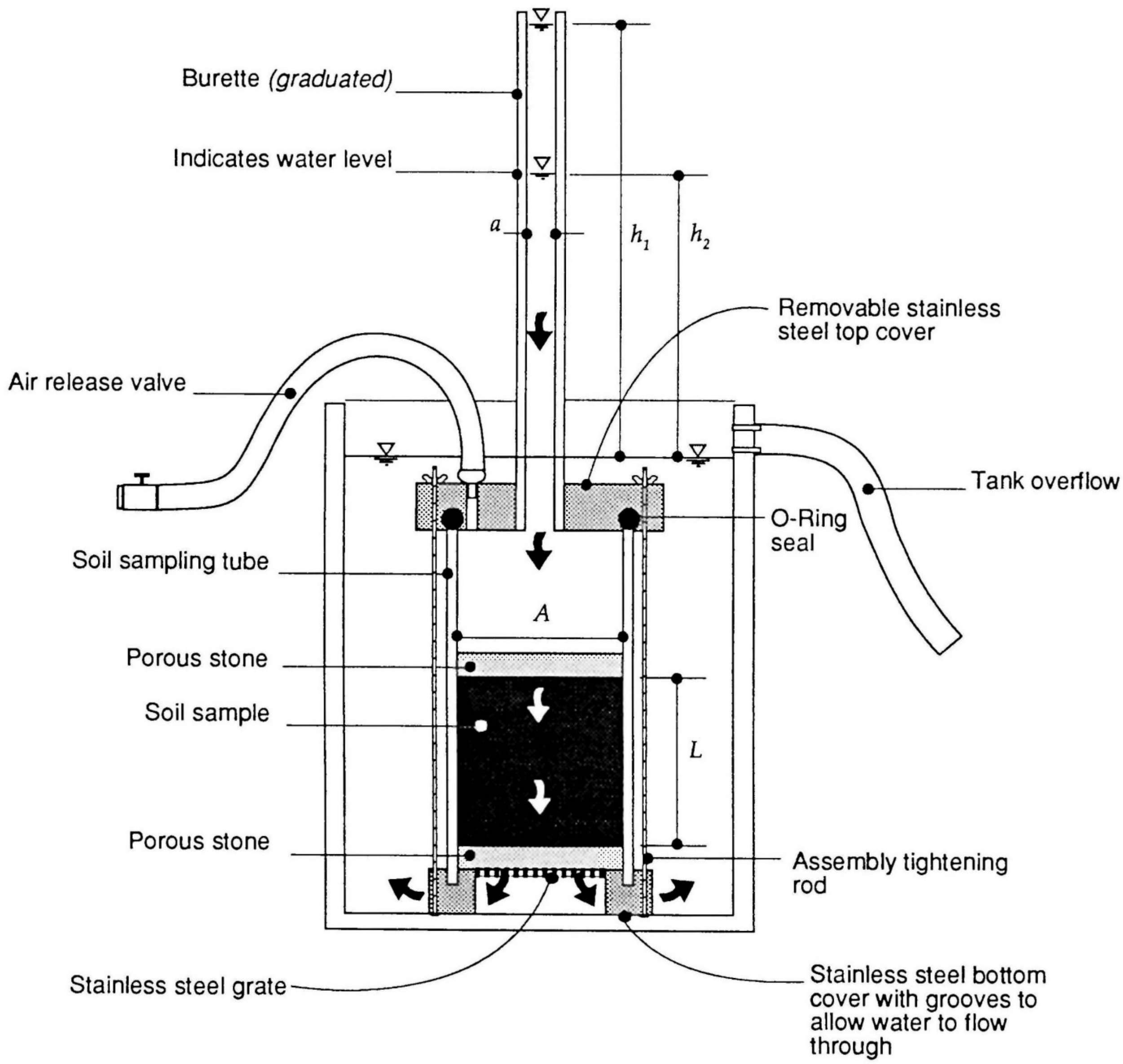
Laboratory Methods

There are two standard types of laboratory hydraulic conductivity measurements. The first type involves the collection of an undisturbed Shelby tube soil sample (ASTM D-1587). The sample is either collected in the horizontal or vertical direction using a Shelby tube soil sampler and transported to the laboratory for preparation and testing. The sample can be analyzed using either a falling head or a constant head method in a laboratory permeameter. A variety of laboratory permeameters are commercially available. However, the most effective laboratory permeameter for undisturbed sandy soil samples is the type that does not require extraction of the soil samples from the Shelby tube. In such a permeameter, the Shelby tube itself is inserted into the permeameter (without extracting the soil sample) and the hydraulic conductivity test is conducted. This minimizes the opportunity for soil sample disturbance during sample extraction from the Shelby tube and sample preparation. Such a “field-to-lab” permeameter was designed by Nicolas Andreyev in 1989 and has been successfully used to measure hydraulic conductivity of loose, sand soil samples for 20 years. A schematic of this permeameter (not requiring soil sample extraction) is presented on **Figure 1**.

Figure 1

Laboratory Permeameter for Undisturbed Tube Soil Samples

(Andreyev, 1989)



The second method of laboratory hydraulic conductivity measurement involves re-molding a disturbed soil sample, compacting the sample to an estimated in-

place density and then placing it either in a regular laboratory permeameter or a triaxial shear machine. The triaxial shear machine is generally used for low hydraulic conductivity soils such as silts, clayey sands and clays. This is primarily due to the ability of a triaxial shear machine to induce a high hydraulic head across a soil sample.
Regardless of the equipment used to measure hydraulic conductivity, the falling head test equation can be expressed as follows:

$$K = \frac{aL}{At} \ln \frac{h_f}{h_i}$$

Where:

a = area of the stand pipe
L = length of the soil specimen
A= cross sectional area of the sample
h_f = final effective head through the sample
hi = initial effective head through the sample
t = difference in time between initial head (h_i) and final head (h_f) readings

For the constant head method, a constant hydraulic gradient is applied through the soil sample and the discharge rate is measured. The equation for constant head hydraulic conductivity test can be written as follows:

$$K = \frac{VL}{Aht}$$

Where:

V = volume measured after flow through the soil for time, t
L = length of the soil sample
A = cross sectional area of the soil sample
h = effective hydraulic head applied through the soil sample
t = time duration for which flow through volume, V, was measured.

In general, the falling head laboratory permeameter appears to yield more reliable results when used with undisturbed sand soil samples (Shelby tubes). For well-drained sand soils, only permeameters that do not require sample extraction should be used. Laboratory test methods, when applied to undisturbed soil samples, generally provide very consistent and reliable results for soil samples collected at shallow depths above the groundwater table. For deeper deposits of saturated sands, it is difficult to obtain an undisturbed soil sample and, therefore, this method of hydraulic conductivity measurement becomes ineffective.

Field Methods

There are generally three types of field hydraulic conductivity tests, namely:

1. Auger hole or tube tests
2. Piezometer tests
3. Pumping tests

Auger-hole tests (also referred to as cased borehole tests) generally involve drilling an auger hole to the desired depth (cased or uncased) and performing either a slug test (falling head) or a constant head test. Disturbance of auger hole walls and setting the casing at a proper depth with a good seal around the casing are the major concerns for these types of tests.

The piezometer tests usually involve drilling and installing a piezometer (perforated or slotted well casing) in the drilled bore-hole, with sand or gravel filling the annular space between the casing and the open hole walls. A variable head test (slug test) or a constant head test can be used to measure the hydraulic conductivity. For the slug test, a slug of water is either added or removed (pumped out) from the piezometer, then the rate of water level recovery in the well is measured and the hydraulic conductivity is calculated. For the constant head test, a constant water level is maintained in the casing and the amount of water applied is recorded over known time periods. Appropriate equations are then used to calculate hydraulic conductivity. Proper installation and development of the piezometer play a key role in the accuracy of the hydraulic conductivity measurement in piezometers.

Steady state or unsteady state pumping tests involve installing a minimum of two piezometers (or wells) at some measured distance apart, one piezometer is pumped and the drawdown is measured in the other (observation) piezometer.

To enhance the accuracy of this method, a second or third observation piezometer can also be installed. This method is less dependent on installation and development techniques than the piezometer hydraulic conductivity methods. In the pump test method, the shape of the drawdown curve and the magnitude of drawdown at the observation piezometer are a function of hydraulic conductivity and the pumping rate at the pumping piezometer.

Other field methods of hydraulic conductivity measurement include tracer studies and double ring infiltrometer tests. While ***in-situ*** tracer or dye studies can yield accurate hydraulic conductivity measurement, the time and cost to perform these types of tests are usually prohibitive. Even in highly transmissive aquifers the test can take as long as two to six months to detect the tracer in a down-gradient observation well. Double ring infiltrometer tests are typically used to estimate soil infiltration or runoff potential. The infiltration rates measured during a double ring infiltrometer test approximates the vertical hydraulic conductivity only if the driving hydraulic gradient is 1.0. However, field setups of double ring infiltrometer tests will generally result in effective hydraulic gradients of more than 1.0. Therefore, the double ring infiltrometer tests can only be used for a limited purpose and need to be well understood when using the results to estimate hydraulic conductivity.

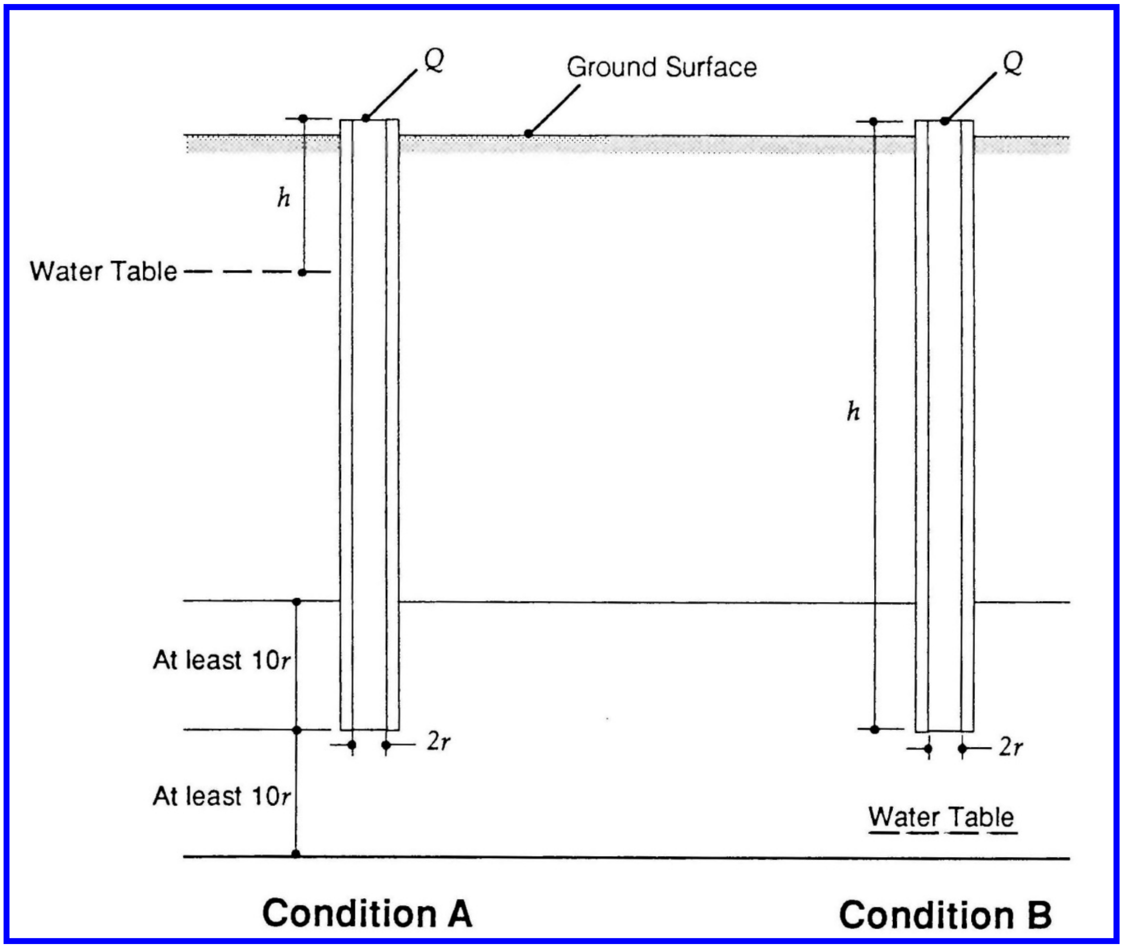
Auger-Hole and Piezometer Tests

Prior to conducting a slug test in an auger hole or a piezometer, the stratigraphy at the test location should be determined by drilling a soil boring. If it is desired to determine the hydraulic conductivity of the soil at or above the water table, water must be added to the piezometer instead of being pumped out of the piezometer. One of the more widely used methods of analyzing permeability under these conditions has been developed by the U.S. Bureau of Reclamation (1974). This test method is referred to as the open-end test. The open-end test (U.S.B.R. designation E-18) consists of installing a casing in the ground to a desired depth, carefully cleaning out the soil from the casing, leaving the prepared soil level and flush with the bottom of the casing, then adding water to the casing at a known rate to maintain a constant water level. The required data for analysis includes the hydraulic head maintained under a constant rate of flow, the diameter of the casing, and the average rate of recharge under saturated conditions, **Figure 2**.

Figure 2

Open End Pipe Hydraulic Conductivity Test

(U.S. Bureau of Reclamation, 1973)



Hydraulic conductivity is calculated from the following equation for both conditions:

$$K = \frac{Q}{5.5rh}$$

Where:

Q = flow rate at saturation

r = radius of the casing

h = the hydraulic head differential

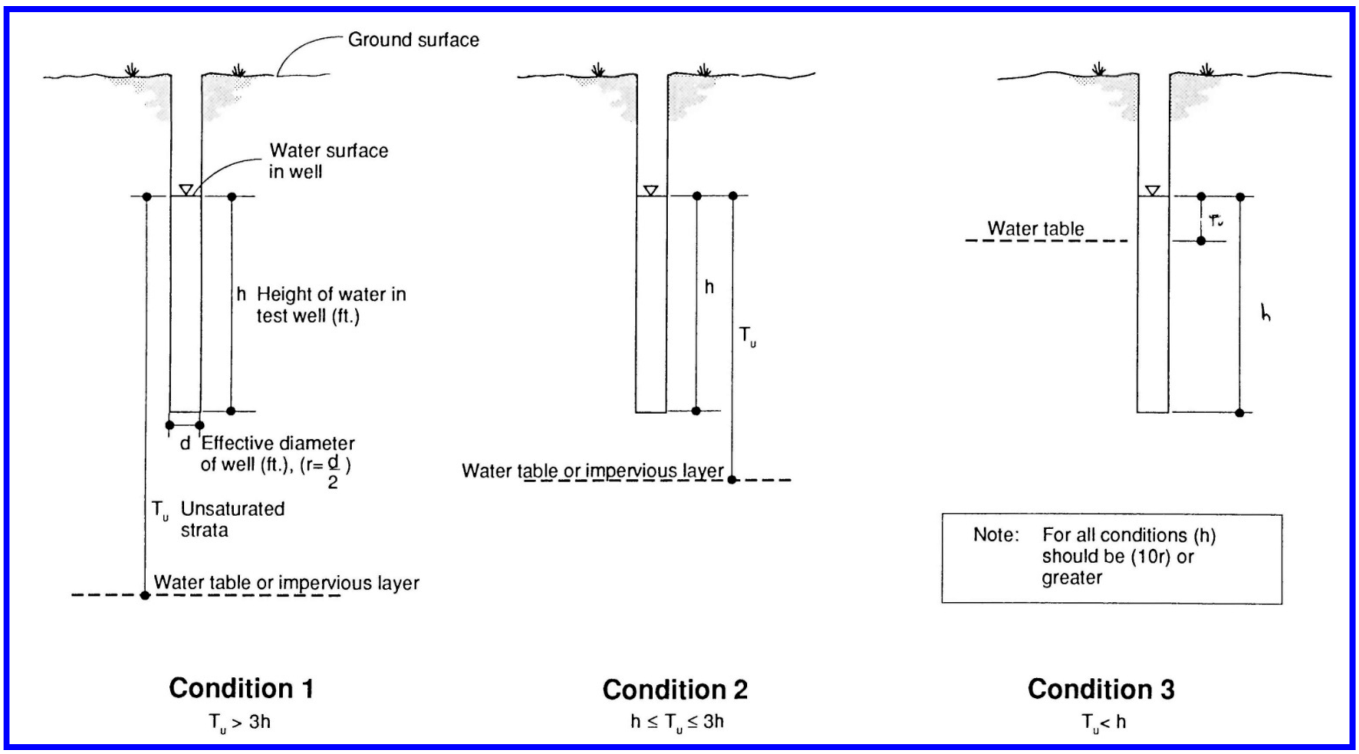
Any consistent units may be used in computing hydraulic conductivity.

Several other steady and non-steady flow methods are used in determining in-situ hydraulic conductivity. The Bureau of Reclamation (1974) also recommends a method where an uncased borehole (or borehole stabilized by fully perforated piezometer) is used to conduct constant head field hydraulic conductivity test. This method is also known as the well permeameter method. **Figure 3** presents the schematics for calculating hydraulic conductivity using the Bureau of Reclamation constant head well permeameter method (Designation E-19). A discharge time curve and a sample hydraulic conductivity calculation are presented on **Figure 4**.

Figure 3

Open-Hole or Piezometer Permeameter Test for Constant Head

(U.S. Bureau of Reclamation, 1974)



Condition 1

$$K = \frac{\left(\sinh^{-1}\left\langle \frac{h}{r} \right\rangle - 1\right)\frac{Q}{2\pi}}{h^2} \times \frac{\mu_T}{\mu_{20}}$$

Condition 2

$$K = \frac{\log_e\left\langle \frac{h}{r} \right\rangle \frac{Q}{2\pi}}{h^2 \left\langle \frac{1}{6} + \frac{1}{3}\left\langle \frac{h}{T_u} \right\rangle^{-1} \right\rangle} \times \frac{\mu_T}{\mu_{20}}$$

Condition 3

$$K = \frac{\log_e\left\langle \frac{h}{r} \right\rangle \frac{Q}{2\pi}}{h^2 \left\langle \left\langle \frac{h}{T_u} \right\rangle^{-1} - \frac{1}{2}\left\langle \frac{h}{T_u} \right\rangle^{-2} \right\rangle} \times \frac{\mu_T}{\mu_{20}}$$

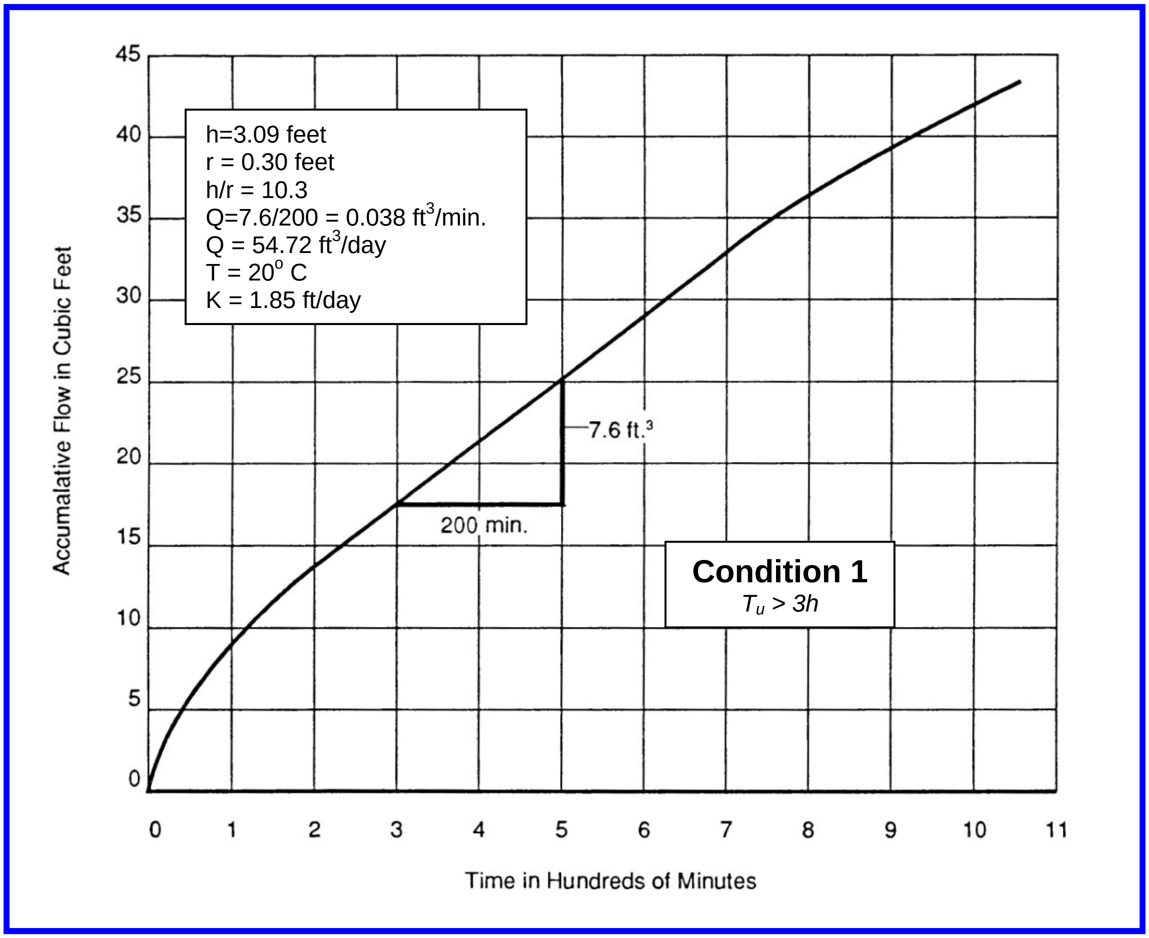
Where,

K = Hydraulic conductivity, in any consistent units (feet per day, cm/sec)
h = Hydraulic head in open hole or well as depicted on **Figure 3**.
r = Radius of open hole or well.
T_u = Unsaturated strata as depicted on **Figure 3**.
Q = Saturated flow rate of water to maintain constant head in test hole.
μ_τ = Viscosity of water at temperature *T*.
μ_{20} = Viscosity of water at 20^o C.

Figure 4

Example of Discharge-Time Curve for Well Permeameter Test

(U.S. Bureau of Reclamation, 1974)



The U.S. Department of the Navy, Naval Facilities Engineering Command (1974) has standard methods of performing variable head tests to estimate the in-situ hydraulic conductivity by means of cased and uncased holes. **Figure 5** **s**ummarizes the methods of calculating hydraulic conductivity using the U.S. Department of the Navy methods.

Figure 5

Variable Head Field Test Methods for Hydraulic Conductivity

(U.S. Dept. of Navy, Naval Facilities Engineering Command, 1974)

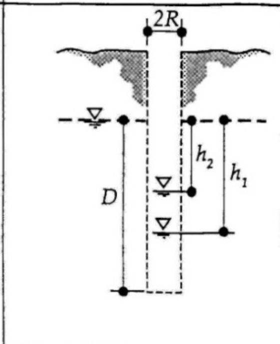
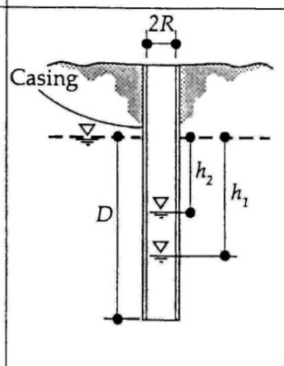
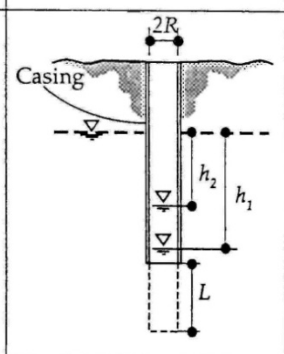
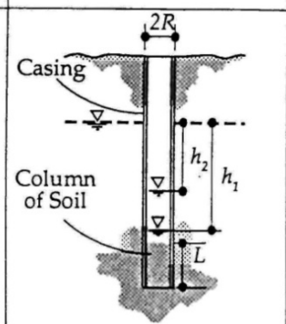
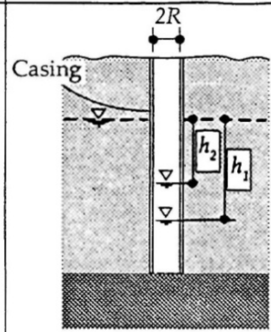
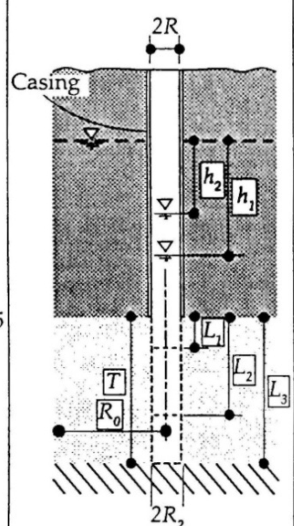
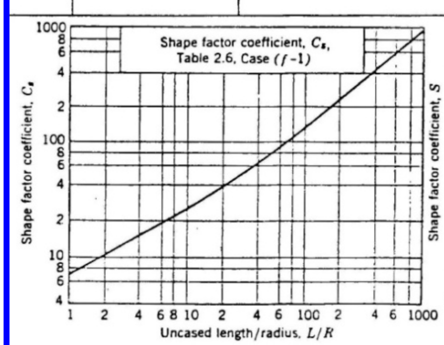
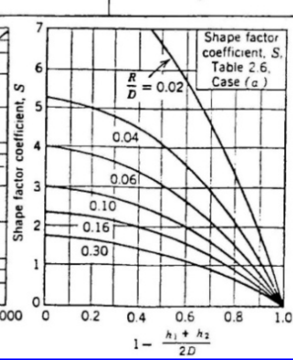
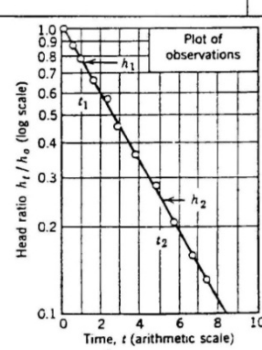
	Condition	Diagram	Shape Factor, F	Permeability, k by variable head test	Applicability
Observation well or piezometer in saturated isotropic stratum of infinite depth	a) Uncased hole		$F = 16\pi DSR$	$k_h = \frac{R}{16DS} \times \frac{(h_2-h_1)}{(t_2-t_1)}$ for $\frac{D}{R} < 50$	Simplest method for permeability determination; not applicable in stratified soils.
	b) Cased hole, soil flush with bottom		$F = \frac{11R}{2}$	$k_v = \frac{2\pi R}{11(t_2-t_1)} \ln\left(\frac{h_1}{h_2}\right)$ for $6\ in. \le D \le 60\ in.$	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		$F = \frac{2\pi L}{\ln(L/R)}$	$k_h = \frac{R_1^2}{2L(t_2-t_1)} \ln\left(\frac{L}{R_2}\right) \ln\left(\frac{h_1}{h_2}\right)$ for $\frac{L}{R} > 8$	Used for permeability determinations at greater depths below the water table. R_1 = Radius of casing R_2 = Radius of open hole
	d) Cased hole, column of soil inside casing to height L		$F = \frac{11\pi R^2}{2\pi R^2 + 11L}$	$k_v = \frac{2\pi R + 11L}{11(t_2-t_1)} \ln\left(\frac{h_1}{h_2}\right)$	Principal use is for permeability in vertical direction in anisotropic soils.

Figure 5 (continued)

	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		$F = 4R$	$k_v = \frac{\pi R}{4(t_2 - t_1)} \ln\left(\frac{h_1}{h_2}\right)$	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) $\frac{L_1}{T} \leq 0.20$ 2) $0.2 < \frac{L_2}{T} < 0.85$ 3) $\frac{L_1}{T} = 1.00$ Note: R_0 equals effective radius to source at constant head		1) $F = C_s R_1$	$k_h = \frac{\pi R_1}{C_s(t_2 - t_1)} \ln\left(\frac{h_1}{h_2}\right)$	Used for permeability determination at depths greater than about 5 feet
			2) $F = \frac{2\pi L_2}{\ln(L_2/R_2)}$	$k_h = \frac{R_1^2 \ln(L_2/R_2)}{2L_2(t_2 - t_1)} \ln\left(\frac{h_1}{h_2}\right)$ for $\frac{L_2}{R_2} > 8$	Used for permeability determination at greater depths and for fine grained soils using porous intake point of piezometer.
			3) $F = \frac{2\pi L_3}{\ln(R_0/R_2)}$	$k_h = \frac{R_1^2 \ln(R_0/R_2)}{2L_3(t_2 - t_1)} \ln\left(\frac{h_1}{h_2}\right)$	Assume value of $\frac{R_0}{R} = 200$ for estimates unless observation wells are made to determine actual value of R_0





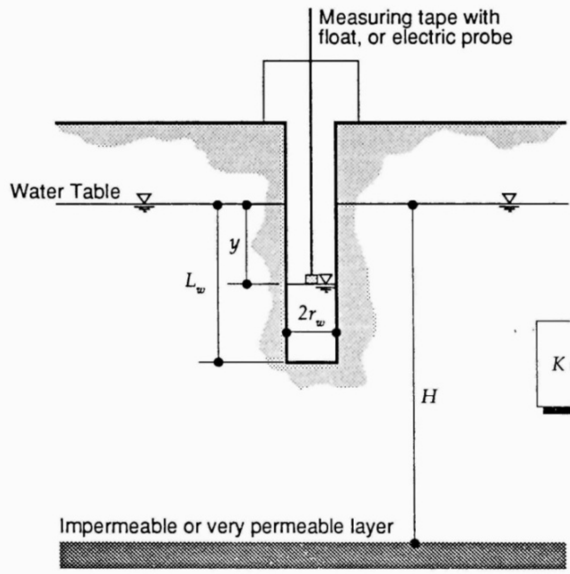


Bouwer (1978) presented an auger-hole method for field hydraulic conductivity measurement. The diagram for the test method, the hydraulic equation and the associated dimensionless parameters table are presented in **Figure 6**.

Figure 6

Variable Head Auger-Hole Method for Field Hydraulic Conductivity

(Boast & Kirkham, 1971)



$$K = C_a \frac{(dy/dt)}{864}$$

C_a Values in Table below

.Geometry and Symbols for Auger Hole Method

		$(H-L_w)/L_w$ for impermeable layer								$H-L_w$	$(H-L_w)/L_w$ for infinetly permeable layer			
L_w/r_w	y/L_w	0	0.05	0.10	0.20	0.50	1	2	5	∞	5	2	1	0.5
1	1.00	447.00	423.00	404.00	375.00	323.00	286.00	264.00	255.00	254.00	252.00	241.00	213.00	166.00
	0.75	469.00	450.00	434.00	408.00	360.00	324.00	303.00	292.00	291.00	289.00	278.00	248.00	198.00
	0.50	555.00	537.00	522.00	497.00	449.00	411.00	386.00	380.00	379.00	377.00	359.00	324.00	264.00
2	1.00	186.00	176.00	167.00	154.00	134.00	123.00	118.00	116.00	115.00	115.00	113.00	106.00	91.00
	0.75	196.00	187.00	180.00	168.00	149.00	138.00	133.00	131.00	131.00	130.00	128.00	121.00	106.00
	0.50	234.00	225.00	218.00	207.00	138.00	175.00	169.00	167.00	167.00	166.00	164.00	156.00	139.00
5	1.00	51.90	48.60	46.20	42.80	38.70	36.90	36.10		35.80		35.50	34.60	32.40
	0.75	54.80	52.00	49.90	46.80	-	41.00	40.20		40.00		39.60	38.60	36.30
	0.50	66.10	63.40	61.30	58.10	53.90	51.90	51.00		50.70		50.30	49.20	46.60
10	1.00	18.10	16.90	16.10	15.10	14.10	13.60	13.40		13.40		13.30	13.10	12.60
	0.75	19.10	18.10	17.40	16.50	15.50	15.00	14.80		14.80		14.70	14.50	14.00
	0.50	23.30	22.30	21.50	20.60	19.50	19.00	18.80		18.70		18.60	18.40	17.80
20	1.00	5.91	5.53	5.30	5.06	4.81	4.70	4.66		4.64		4.62	4.58	4.46
	0.75	6.27	5.94	5.73	5.50	5.25	5.15	5.10		5.08		5.07	5.02	4.89
	0.50	7.67	7.34	7.12	6.88	6.60	6.48	6.43		6.41		6.39	6.34	6.19
50	1.00	1.25	1.18	1.14	1.11	1.07	1.05			1.04			1.03	1.02
	0.75	1.33	1.27	1.23	1.20	1.16	1.14			1.13			1.12	1.11
	0.50	1.64	1.57	1.54	1.50	1.46	1.44			1.43			1.42	1.39
100	1.00	0.37	0.35	0.34	0.34	0.33	0.32			0.32			0.32	0.31
	0.75	0.40	0.38	0.37	0.36	0.35	0.35			0.35			0.34	0.34
	0.50	0.49	0.47	0.46	0.45	0.44	0.44			0.44			0.43	0.43

Hvorslev (1951) conducted studies for the U.S. Corp of Engineers, Waterways Experiment Station, to measure the hydraulic conductivity from soil borings, cased boreholes and piezometers. Whenever a boring is drilled or a piezometer is installed, the initial water level (hydrostatic pressure) measured in the borehole/piezometer seldom reflects the true ambient water level. The groundwater must flow to or from the borehole or piezometer until the measured water level matches the ambient level. The flow of water to or from the borehole/piezometer will occur until the hydrostatic pressure gradient approaches zero and the time in which the flow occurs is referred to as "time lag". This time lag is related to the permeability of the soil and configuration of the piezometer /borehole. A basic differential equation for time lag can be written as follows:

$$\frac{dy}{z - y} = \frac{dt}{T}$$

Where:

- z = initial water level difference at time equals 0 (at the stop of pumping)
- y = water level above the datum z at some time t
- T = time lag

A diagram presenting these parameters is represented in **Figure** 7. In the field, the basic time lag is determined by raising or depressing the head in the piezometer/borehole and recording the head at a number of time intervals. A plot is then made with time on an arithmetic scale and the head ratio (h/ho) on a log scale. The basic time lag is the time at which the head ratio equals 0.37. The equalization ratio is defined as (I-h/ho); thus when the head ratio is 0.37 the equalization ratio is 0.63. An equalization ratio of 0.90, which corresponds to a time lag of 2.3 x the basic time lag is considered by Hvorslev to be adequate for many practical purposes. The basic time lag T corresponds to H = 0.37ho: that is,

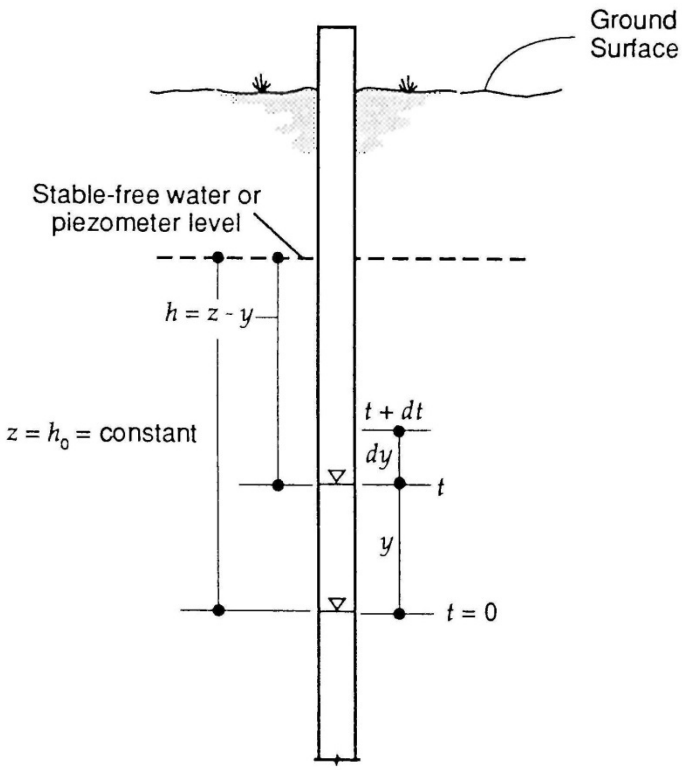
$$\frac{\ln(h_o)}{h} = \frac{\ln(\mathrm{h_o})}{0.37h_o} = \ln(2.7) = 1.0$$

Figure 8 presents a summary of formulas compiled by Hvorslev (1951) for the determination of hydraulic conductivity by constant head, variable head and basic time lag tests.

Figure 7

Diagram of the Time Lag Field Method for Hydraulic Conductivity

(Hvorslev, 1951)



Differential Equation

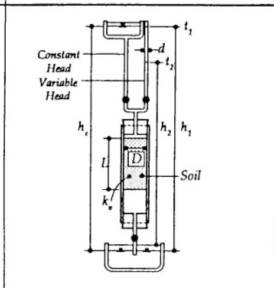
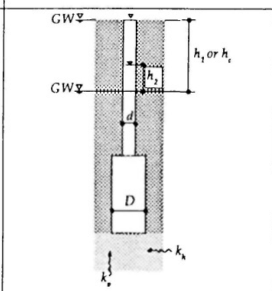
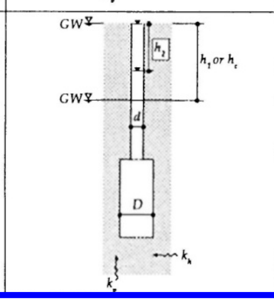
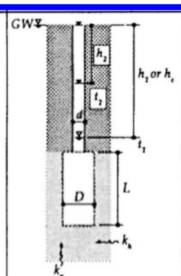
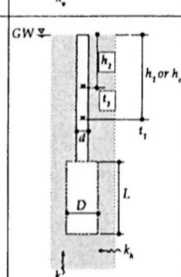
$$\frac{dy}{z-y} = \frac{dt}{T}$$

T = Basic time lag

Figure 8

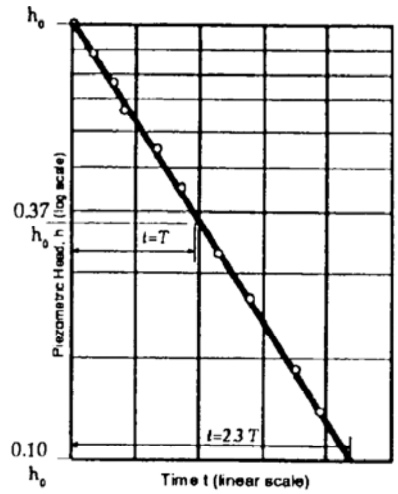
Constant & Variable Head & Time Lag Hydraulic Conductivity Equations

(Compiled by Hvorslev, 1951)

Condition	Diagram	Constant Head	Variable Head	Basic Time Lag
a) Laboratory Permeameter (consolidometer)		$k_v=\frac{4\,q\,L}{\pi D^2 h_c}$	$k_v=\frac{d^2 L}{D_2\,(t_2-t_1)}\ln\frac{h_1}{h_2}$ $k_v=\frac{L}{t_2-t_1}\ln\frac{h_1}{h_2}$ for $d=D$	$k_v=\frac{d^2 L}{D^2 T}$ $k_v=\frac{L}{T}$ for $d=D$
b) Flush bottom at impervious boundary		$k_v=\frac{q}{2\,D\,h_c}$	$k_m=\frac{\pi\,d^2}{8\,D\,(t_2-t_1)}\ln\frac{h_1}{h_2}$ $k_m=\frac{\pi\,D}{8\,(t_2-t_1)}\ln\frac{h_1}{h_2}$ for $d=D$	$k_m=\frac{\pi\,d^2}{8\,D\,T}$ $k_m=\frac{\pi\,D}{8\,T}$ for $d=D$
c) Flush bottom in uniform soil		$k_v=\frac{q}{2.75\,D\,h_c}$	$k_m=\frac{\pi\,d^2}{11\,D\,(t_2-t_1)}\ln\frac{h_1}{h_2}$ $k_m=\frac{\pi\,D}{11\,(t_2-t_1)}\ln\frac{h_1}{h_2}$ for $d=D$	$k_m=\frac{\pi\,d^2}{11\,D\,T}$ $k_m=\frac{\pi\,D}{11\,T}$ for $d=D$
d) Well point filter at impervious boundary		$k_h=\frac{q\,\ln\left[\frac{mL}{D}+\sqrt{1+\left(\frac{2mL}{D}\right)^2}\,\right]}{2\,\pi\,L\,h_c}$	$k_h=\frac{d^2\ln\left[\frac{2mL}{D}+\sqrt{1+\left(\frac{2mL}{D}\right)^2}\,\right]}{8\,L\,(t_2-t_1)}\ln\frac{h_1}{h_2}$ $k_h=\frac{d^2\ln\left(\frac{4mL}{D}\right)}{8\,L\,(t_2-t_1)}\ln\frac{h_1}{h_2}$ for $\frac{2mL}{D}>4$	$k_h=\frac{d_2\ln\left[\frac{2mL}{D}\sqrt{1+\left(\frac{2mL}{D}\right)^2}\,\right]}{8\,L\,T}$ $k_h=\frac{d^2\ln\left(\frac{4mL}{D}\right)}{8\,L\,T}$ for $\frac{2mL}{D}>4$
e) Well point filter in uniform soil		$k_h=\frac{q\,\ln\left[\frac{mL}{D}+\sqrt{1+\left(\frac{mL}{D}\right)^2}\,\right]}{2\,\pi\,L\,h_c}$	$k_h=\frac{d^2\ln\left[\frac{mL}{D}+\sqrt{1+\left(\frac{mL}{D}\right)^2}\,\right]}{8\,L\,(t_2-t_1)}\ln\frac{h_1}{h_2}$ $k_h=\frac{d^2\ln\left(\frac{2mL}{D}\right)}{8\,L\,(t_2-t_1)}\ln\frac{h_1}{h_2}$ for $\frac{mL}{D}>4$	$k_h=\frac{d_2\ln\left[\frac{mL}{D}+\sqrt{1+\left(\frac{mL}{D}\right)^2}\,\right]}{8\,L\,T}$ $k_h=\frac{d^2\ln\left(\frac{mL}{D}\right)}{8\,L\,T}$ for $\frac{mL}{D}>4$

D=diameter of soil sample
d = diameter of standpipe
L = length of soil sample
h_c = constant piezometer head
h_1 = piezometer head for time t_1
h_2 = piezometer head for time t_2
q = flow rate of water
t = time
T = basic time lag
k_v = vertical hydraulic conductivity
k_h = horizontal hydraulic conductivity
k_m = mean hydraulic conductivity = $\sqrt{k_v k_h}$

m = transformation ratio = $\sqrt{\dfrac{k_h}{k_v}}$



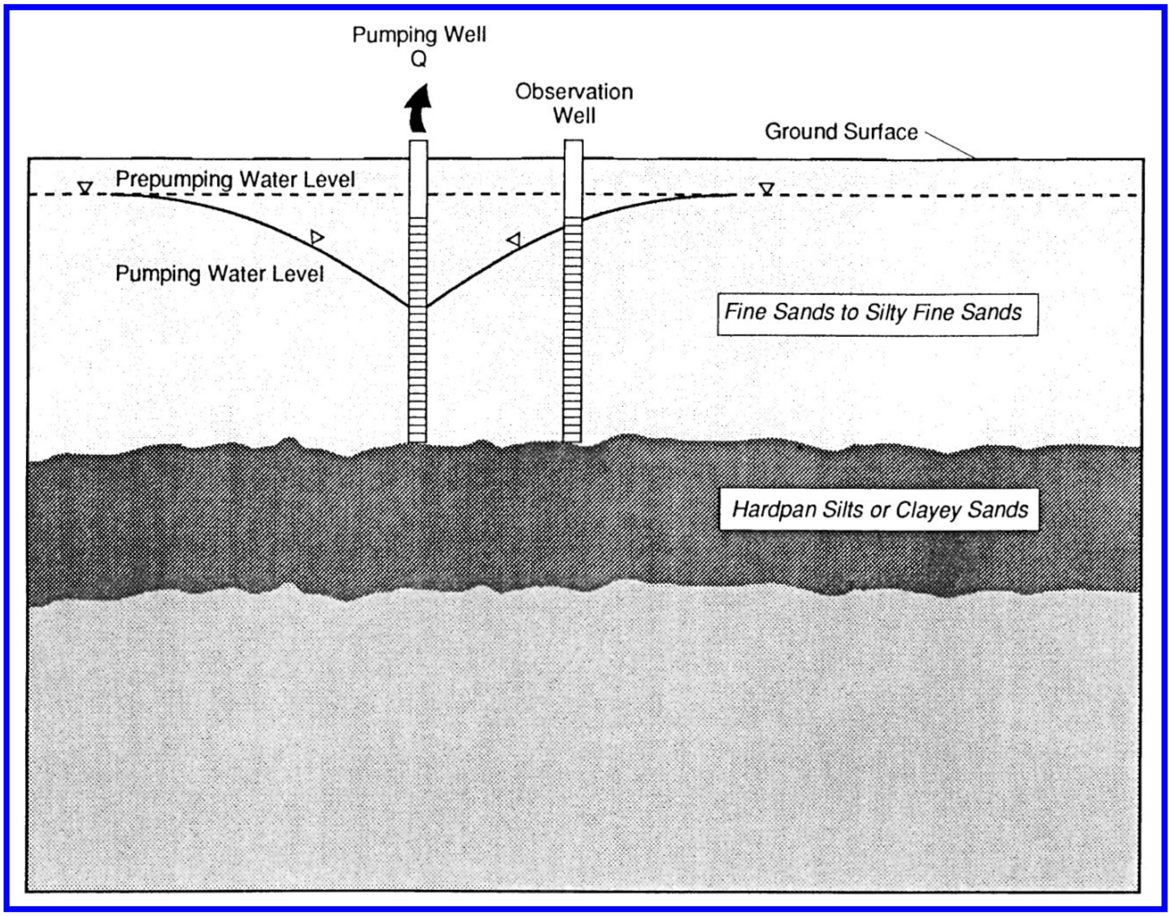
Determination Basic Time Lag T

Pumping Tests

The third method of measuring permeability in the field is to conduct a pumping test. Both short term and long term pumping times can be used depending upon the aquifer type being tested, the pumping rate and distance between wells. In general, a pumping test consists of installing a minimum of one pumping well and one observation well at some reasonable distance away from the pumping well, **Figure 9**. Typical (reasonable) distances of observation wells in sandy shallow aquifer system vary from about 5 to 30 feet. In general, it is desired to record a measurable drawdown in the observation wells. If the observation wells are installed too far from the pumping well, minimum or no drawdown would be measured and a reliable hydraulic conductivity value could not be calculated.

Figure 9

Pumping Test with Two Wells & Drawdown Profile



The pumping well and observation well should be installed with the same characteristics (same depth and screen interval). Prior to initiating pumping, the static water level below the top of the casing should be measured in all wells. Then one well should be pumped at as high a rate as possible (to stress the aquifer) and the drawdown below the static water level should be measured in the observation well(s).

For shallow unconfined aquifer pumping tests in sandy aquifers, the yield is generally low and the groundwater typically mixes with air. Therefore, the volume of water pumped should be measured using calibrated containers (i.e., 55 gallon calibrated drums) and the time to fill each container or a fraction should be recorded. This will yield a better estimate of the average pumping rate for the hydraulic conductivity calculation since the drawdown in the observation well is more a function of the total volume of water removed than the instantaneous flow rate. In highly transmissive aquifers where sufficiently high withdrawal rates are necessary to produce measureable drawdown, other methods such as installation of an in-line flow meter or an orifice is more appropriate. Minimum pumping time to produce reliable results is 8 hours for short-term unconfined aquifer pumping tests. However, longer pumping periods are preferable. For shallow unconfined aquifers (sand aquifers), the wells are typically placed no further than 5 feet apart for short duration pumping tests and no greater than 10 feet for long duration pumping tests. For highly transmissive aquifers (such as limestone or gravel aquifers) observation wells can be installed at distances of 100 to 300 feet away from the pumping well.

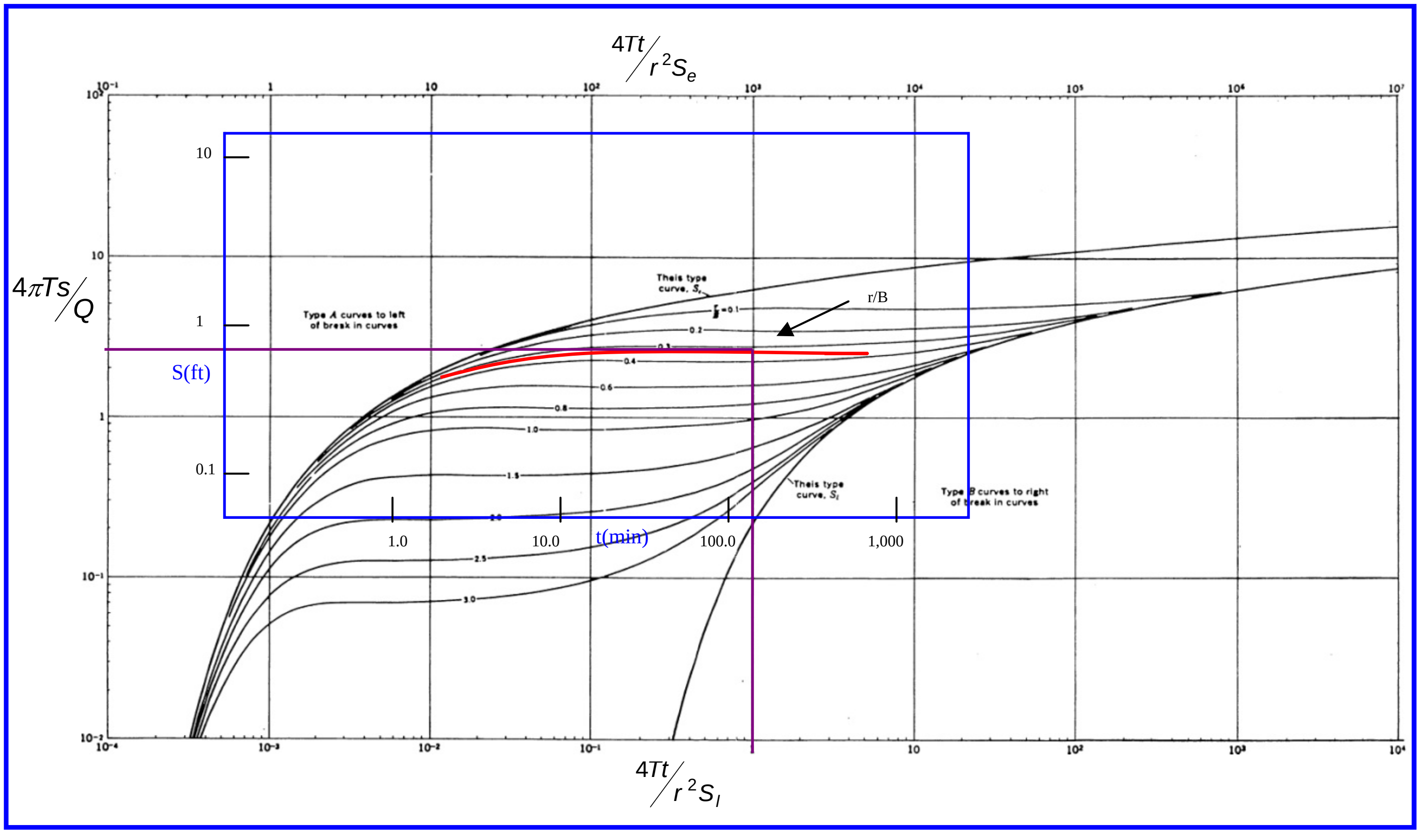
For unconfined aquifer short-term pump tests, very few methods are available to evaluate the data. One reliable method is the match-point method presented in Lohman (1972). This method consists of plotting the drawdown versus time in the observation well on a log-log scale paper and superimposing a family of type curves developed by Boulton (1963). This family of type curves, developed by Boulton, is presented in **Figure 10**.

Figure 10

Delayed-Yield Type Curves

U.S Department of Interior Geological Survey, Professional Paper 708

(Boulton, 1963)



For a pumping test in an unconfined aquifer the red curve above represents the best match of drawdown versus time data for a pump test observation well. The following aquifer conditions and pump test data produced the matching curve:

1. The pumping well and the observation well fully penetrate the unconfined aquifer with a total saturated thickness of 55.0 feet.
2. The observation well is located 18.3 feet away from the pumping well.
3. Average pumping rate for a 10-hour pump test was 16.5 gpm.

The drawdown results at the observation well are plotted on a log-log paper with the same scale as the "type-curve" graph presented above. Then the pump test data curve is matched to the one of the "type" curves. Once the test data is matched on the graph above, the hydraulic conductivity can be calculated as follows:

1. Select any point along the matched line and obtain the values on the left coordinates from both the "type-curves" graph and the drawdown (s) versus time (t) curve graph. For the above example, pick any point on the red line (drawdown line) and follow the purple line to the left to read the following values:

   s = 0.7 ft [from the s-t graph]

   $4\pi Ts/Q$ = 2.8 [from the type-curve graph]

2. Calculate transmissivity, T, by solving the above equations.

$$T = \frac{2.8Q}{4\pi s} = \frac{2.8(16.5gpm x 1440\,\text{min}/\,day x 0.134 ft^3\,/\,gal)}{4\pi(0.7ft)} = 1010.9ft^2\,/\,day$$

3. Calculate horizontal hydraulic conductivity, K, as follows:

   ***K*=** T/H=1010.9 ft^2/day/55.0 ft = **18.38 ft/day**

   Where, H is the effective saturated thickness of the unconfined aquifer.

Double-ring Infiltrometer Test

A popular method to estimate in-situ infiltration rate from stormwater retention ponds is the double-ring infiltrometer test (ASTM D-3385). This test involves the use of cylindrical devices in which an inner ring is placed within a larger outer ring. Typical diameters are 14 inches for the inner ring and 36 inches for the outer ring. Both rings are pushed or driven into the soil to a depth of 2 to 4 inches below grade.

A constant water level is maintained inside both rings and the amount of water added to maintain this constant head within the inner ring is measured versus time. The infiltration rate is then plotted on a log scale versus time on an arithmetic scale. Infiltration at various times can be predicted using Horton's equation as follows:

$$I_t = I_c + (I_o - I_c)\, e^{-kt}$$

Where:

I_t = infiltration rate as a function of time
I_c = final or ultimate infiltration rate
I_o = initial infiltration rate
k = recession constant
t = time

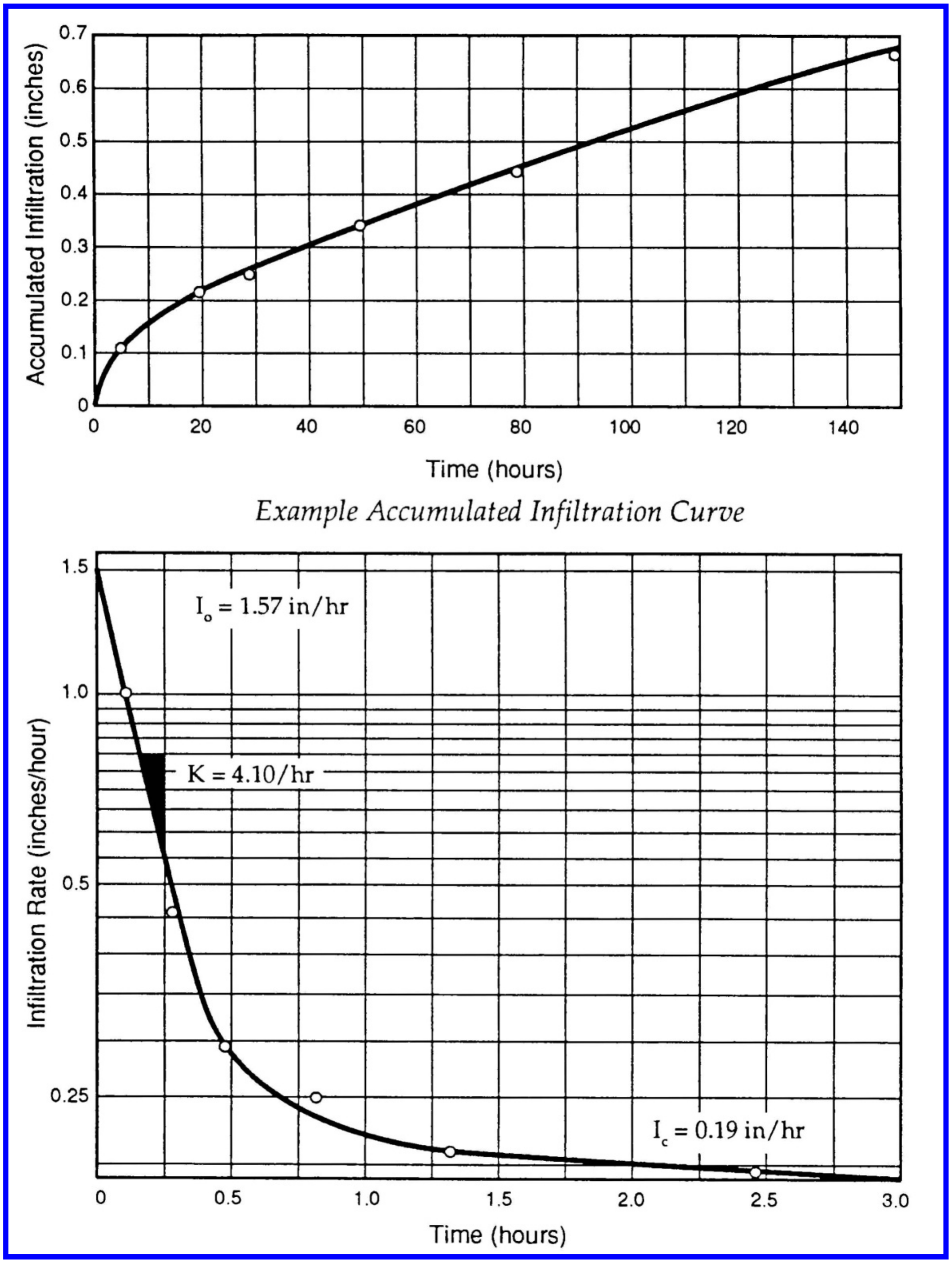
The total volume of infiltration using the Horton's equation is determined by integrating the area under the curve.

$$I_v = \int_o^t I(t) = I_c + \frac{(I_o - I_c)}{K}(1 - e^{-Kt})$$

Example terms of these equations are presented graphically in **Figure 11**. For most soils, k is not constant and it is difficult to obtain an average value. Horton's equation appears to be most suited for describing infiltration when the water is applied by rain or sprinkling systems, and then only for relatively short time periods (Bouwer 1978). It should be realized that field data (I, and t) for evaluation of the parameters in the empirical infiltration equation must be obtained for the same conditions as will occur for the infiltration systems to be predicted with equations. These conditions include duration of infiltration event, quality of water applied, depth of flooding, velocity of water above ground (ponded or flowing), soil conditions, and size and geometry of field tests (Bouwer 1978).

Figure 11

Example of Double Ring Infiltrometer Test Results &Horton's Infiltration Curve



The main source of error with this technique is lateral diversion of the flow below the cylinder, which may be due to unsaturated flow (Bouwer 1961; Swartzendruber and Olsen 1961; Talsma 1970) or to restricting layers in the soil (Evans et al., 1950). Since the amount of infiltration contributing to the diversions will be minimal, when infiltration takes place over a large area like a field or retention pond, the test results will lead to an over-estimation of infiltration rates.

Diversions of flow below the cylinder due to unsaturated flow can be minimized by increasing the diameter of the cylinder. However, flow diversions due to lateral flow above restrictive layers deeper in the profile can be avoided only by using full scale ponds for the infiltration measurements (Bouwer 1978).

When using double-ring infiltrometer test data to estimate stormwater infiltration from retention ponds, the following comments and suggestions shall be considered:

- If the test is conducted at the depth of the proposed pond bottom and the surface is representative of post-construction conditions, the test results are useful to estimate initial infiltration rates, prior to groundwater mounding conditions.
- Once the groundwater mound rises to the pond bottom or higher, the results of a double-ring infiltrometer test are not valid.
- In shallow aquifer conditions where the groundwater mound would intersect the pond bottom, the use of double-ring infiltrometer tests data shall be limited to the initial "unsaturated infiltration" analyses only.
- The small area of recharge from the double-ring infiltrometer cannot produce a significant groundwater mound during the test period. Therefore, the scale factor between the test area and the area of a retention pond should be realized when using the results of a double-ring infiltrometer test.
- The double-ring infiltrometer test data is useful only to estimate the initial unsaturated infiltration from stormwater retention ponds, except in deep groundwater conditions where groundwater mound does not intersect the pond bottom throughout the entire duration of the stormwater runoff and recovery period.

Evaluation of Field Hydraulic Conductivity Test Methods

All of the field hydraulic conductivity test methods presented in this course provide reasonably accurate results. Some of the test methods are easier to install and perform in the field while other test methods are almost impossible to install and/or perform in sandy unconfined aquifer systems. The following is a summary of various issues and/or concerns for field hydraulic conductivity tests:

- The field open borehole test or the piezometer test must be set up without significant disturbance to the surrounding soil.
- The open borehole shall not be allowed to collapse and/or the walls of the borehole to cave in during the test.
- If casing is installed into a borehole, the soil material in the casing needs to be removed to the exact depth (bottom of the casing or an exact known distance below the casing).
- If a piezometer is installed, it should be sufficiently developed to mitigate the installation soil disturbance effects.
- All assumptions and conditions of the test method and equation restrictions shall be satisfied. This is typically ignored and leads to significant errors in calculating the value of hydraulic conductivity.
- Field hydraulic conductivity test methods in open boreholes (without a piezometer to hold the open borehole walls) in well drained sandy soils are not appropriate and should not be used.
- Cased borehole methods generally provide reasonable results when used in measuring hydraulic conductivity of sandy soils above the groundwater table.
- Below the groundwater table, only piezometer methods (properly installed and sufficiently developed) or pump test methods provide reasonable results.

Selection of Number of Hydraulic Conductivity Tests

Similar to the selection of the number of soil borings, it is difficult to establish a single criteria to select the number of hydraulic conductivity tests needed for adequate characterization of the aquifer system for stormwater retention ponds. Again, local knowledge and experience generally drives the selection of the minimum number of tests for a particular stormwater retention pond. The other factors that can influence the minimum number of tests include the total number of soil borings drilled for the retention pond evaluation and design, the sensitivity of the downstream drainage systems, the physical and political consequences of a failed retention system, the regulatory criteria and enforcement action for the retention system. The designer is typically required to conduct an adequate investigative and testing program to design an effective retention system, while maintaining the cost of such an investigation and testing within the locally accepted levels. For example, in areas where the failure of a retention pond can create significant flood damage or significant water quality impacts, the level of investigation and testing will be higher than in areas where a potential pond failure will have minimal impact and can simply be repaired.

The engineering approach to developing a methodology for selecting a minimum number of hydraulic conductivity tests for a retention pond can be described as follows:

- Minimum number = 1
- Maximum number = between 1 and X

Where,

X= function of the number of soil borings drilled, site complexity, drainage area sensitivity, regulatory criteria, and other locally sensitive factors.

To develop an effective method of selecting the minimum number of hydraulic conductivity tests for a particular area, it is best to draw upon the local knowledge and data to create an equation or a matrix that best fits the local practice and regulatory criteria. The following general equation is provided for a typical unconfined aquifer system in fine sand formation with a medium level of environmental sensitivity and regulatory control:

$$NK = 1 + \frac{NB}{4}$$

Where,

NK = Minimum number of hydraulic conductivity tests
NB = Number of soil borings drilled for the pond

This empirical equation was developed from actual data of a geotechnical engineering consulting firm in Central Florida (Jammal & Associates, Inc.) and was presented in the "Stormwater Retention Pond Infiltration Analyses in Unconfined Aquifers, Permitting Guidelines for Southwest Florida Water Management District, 1989" (Andreyev & Wiseman, 1989). By design the empirical equation has the following two components that affect the selection of the minimum number of hydraulic conductivity tests needed for the design and infiltration analysis of retention ponds.

1. The first component forces the equation to produce a minimum of one (1) hydraulic conductivity test for each pond. This was based primarily on the local regulatory criteria but also serves as minimum data needed for the critical soil layer below the retention pond.
2. The second component provides for additional hydraulic conductivity tests for larger ponds or for complex aquifer systems. This component is primarily driven by the number of soil borings that were drilled for the retention pond, which in itself is an indication of the pond size and/or complexity.

Conclusions

There are many field and laboratory test methods which can be used to explore and estimate hydrogeologic conditions and hydraulic parameters of an aquifer. In most instances, the limitations of the various methods are not clearly understood. It is essential to review and fully understand all the parameters and the assumptions of a particular test method. Often there are specific assumptions and limitations in the test methods. If these assumptions and limitations are ignored the test results could provide drastically different (erroneous) values.

Only two soil boring test methods were presented in this course. However, many other methods exist and are used to characterize the shallow aquifer system. Some are similar to the auger method or the standard penetration test (SPT) method, but others such as ground penetrating radar (GPR) and cone penetration methods are significantly different. The same conclusions can be drawn for similar test methods that provide results similar to those of the SPT method, while others can only provide supporting data to the tests described in this course, such as the GPR method. Regardless of the type of soil drilling or aquifer characterization methods used, the minimum depth of drilling, the number of soil borings needed and the methods of hydraulic conductivity testing presented in the course are still valid.

For best aquifer characterization, both SPT borings and auger borings (or other similar test methods) can be conducted to provide an accurate soil profile with soil density data and reliable measurement of the groundwater table. However, if only one method is to be selected, the auger boring method (or other similar technique) would provide better data for subsurface characterization of the aquifer system and measurement of the groundwater table. When planning the soil investigation for retention ponds, the soil borings should be extended to the first confining layer or to the effective hydraulic influence depth of the pond, whichever is less.

Laboratory permeability measurements on undisturbed samples generally yield accurate results. This is primarily due to the controlled laboratory conditions, where the diameter and length of the sample is known and the measurement of the flow rate of water through the sample is accurate. Provided that the undisturbed sample is properly collected and prepared, the test results will be accurate. However, the hydraulic conductivity value obtained in this method is usually representative of a discrete interval of the soil stratum within the aquifer. Thus, to characterize the entire aquifer system, undisturbed tube samples need to be collected in each soil strata comprising the effective aquifer system. The primary limitation of this method is the excessive number of tests required for full characterization of the aquifer system and the fact that undisturbed tube samples must be collected. Sometimes it is difficult to collect undisturbed tube samples at or below groundwater table or in loose soil strata. To control the number of tests and to reduce the cost of testing for stormwater retention ponds, the following guidelines can be used if only laboratory methods are used to test for hydraulic conductivity:

- Collect samples and test the **lowest** hydraulic conductivity soil layers between the pond bottom and groundwater level to calculate the weighted average **vertical** hydraulic conductivity. Estimate the values for the **higher** hydraulic conductivity soil layers from published data or from summary tables included in this course. This approach will produce the best estimate of average vertical hydraulic conductivity.

- Collect samples and test the **highest** hydraulic conductivity soil layers of the effective aquifer system (above and below groundwater table) for **horizontal** hydraulic conductivity. Estimate the values for the lower hydraulic conductivity soil layers from published data or from summary tables included in this course. This approach will produce the best estimate of average horizontal hydraulic conductivity.
- Calculate the weighted average hydraulic conductivity values for vertical and horizontal hydraulic conductivity using the following equations:

$$\text{Weighted Average } Kv = \frac{\sum L}{\frac{L_1}{Kv_1} + \frac{L_2}{Kv_2} + \frac{L_3}{Kv_3} + \ldots\ldots\ldots \frac{L_n}{Kv_n}}$$

$$\text{Weighted Average } Kh = \frac{Kh_1.L_1 + Kh_2.L_2 + Kh_3.L_3 + \ldots.Kh_n.L_n}{\sum L}$$

- To calculate the weighted average vertical hydraulic conductivity, all soil layers between the pond bottom and the groundwater level must be included.
- To calculate the weighted average horizontal hydraulic conductivity, all soil layers between the design water level of the pond and the bottom of the effective aquifer must be included.

To measure the horizontal hydraulic conductivity of the entire effective aquifer thickness, full depth piezometer tests or pumping tests can be used. These methods, if installed and tested properly, provide reliable results and eliminate estimating hydraulic conductivity for untested soil layers.

In general, the hydraulic conductivity testing should consist of a combination of laboratory and field tests that produce the most reliable results. These would include laboratory tests on undisturbed soil samples obtained from shallow depths, well permeameter tests in sandy soils and above the groundwater table, piezometer slug tests with properly installed and developed wells in deeper sandy deposits and below the groundwater table and short term or long term pump tests for multi-layer aquifer systems. A summary of recommended methods for the various exploration and testing techniques are presented in **Tables 3 and 4.**

It should be realized that the information contained in this course is intended for planning purposes. Good, sound engineering judgment is still needed to determine when and where a particular test method is applicable to assess the limitations of each method and the validity of its results.

TABLE 3

Recommended Soil and Aquifer Exploration Methods for Stormwater Retention Pond Infiltration Analyses

Conditions	Test Methods
< 10 feet	Hand or power auger borings
> 10 feet	Power auger borings
In-situ density needed (any depth)	Standard Penetration Test (SPT) or equivalent
Accurate groundwater level reading is critical	• Hand or power auger boring and allow water levels to stabilize for a minimum of 24 hours • Auger borings and piezometers to allow accurate groundwater level determination

TABLE 4

Recommended Laboratory and Field Methods Hydraulic Conductivity Testing for Stormwater Retention Pond Infiltration Analyses

Conditions	Test Methods
Above Groundwater Table (sandy soil):	
< 4 feet	Excavate test pit with post-hole digger or shovel, hand drive Shelby tube to collect soil sample and perform laboratory permeameter tests

> 4 feet and < 10 feet >10 feet and < 50 feet	Excavate test pit with backhoe or other mechanical equipment, collect Shelby tube soil sample by hand and perform laboratory permeameter tests Drill power auger or hollow stem auger to the desired depth. Install slotted or perforated casing in the desired test interval. Conduct field hydraulic conductivity test using well permeameter method (USBR Designation E-19)
Below Groundwater Table: < 30 feet (sandy soil) Average Aquifer Hydraulic Conductivity Determination (any depth & any aquifer type)	Drill power auger borings to define aquifer system. Install piezometers to desired depth, develop piezometers, and stabilize the groundwater level for 24 hours minimum. Conduct slug test or constant head test (Hvorslev 1951, US Navy, 1974 and Bouwer 1978) Install two or more wells into the desired test depth interval. Conduct a short term or a long term pumping test. Calculate average hydraulic conductivity using curve-matching method (Lohman, 1972)
Unsaturated Hydraulic Conductivity (sandy soil): Near the surface	Conduct Double Ring Infiltrometer (DRI) test and use average initial infiltration rate as unsaturated vertical hydraulic conductivity. Alternatively, obtain an undisturbed tube sample in the vertical direction, conduct a laboratory permeameter test and then estimate unsaturated hydraulic conductivity by empirical approximation.
Deep Soil Strata: Below Confining Unit and Groundwater Level Below Bottom of Restrictive Soil (sandy soil)	Install piezometer(s) to the desired depth and screen below confining unit. Grout from bottom of confining unit to land surface. Conduct slug test in piezometer(s). (Hvorslev, 1951; US Navy, 1974)
Deep Soil Strata: Below Confining Unit and Groundwater Level Above Bottom of Restrictive Soil (sandy soil)	Install two (2) piezometers to the desired depth and screen below confining unit. Grout from bottom of confining unit to land surface. Conduct long-term pumping test. (Lohman, 1972)
Restrictive Soil Strata: Confining layers at any depth (clayey sand, clay, hardpan, rock..)	Collect Shelby tube soil samples by hand or with a drill rig and conduct laboratory test using a triaxial machine.

Estimate of Hydraulic Conductivity after Drilling is Completed: Any depth	Remold sample collected during drilling program to the approximate *in-situ* unit weight and conduct laboratory test using a triaxial machine.
Unsaturated Vertical Infiltration (direct method): Near the surface	Conduct double ring infiltrometer test at the pond bottom level. Compact test surface to the approximate post construction density. Use final (Ic) infiltration rate determined during the test. Applicable to initial vertical infiltration from pond only. It is not valid for saturated flow and mounding period of pond infiltration.

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