Infiltration Testing at Depth

Recommendations provided by the Groundwater Committee of the
New Jersey Section of the American Water Resources Association (AWRA)

Abstract:

The New Jersey Department of Environmental Protection (NJDEP) released the Soil Testing Criteria (Appendix E of the New Jersey Stormwater Best Management Practices Manual) in September of 2009. Based on this guidance, infiltration tests are often required at substantial depths below the existing ground surface. To comply with OSHA regulations, adequate side slopes and stepping of test pits to these depths often result in an extremely large excavation which may be impractical. The NJDEP has acknowledged this issue and requested that the Groundwater committee of the New Jersey Section of the AWRA investigate and provide recommendations on techniques for conducting infiltration testing at depths where typical test pit observations are not safe or practical.

Committee Background:

The Groundwater Committee is working group within the New Jersey Section of the AWRA (NJ-AWRA). The committee members have a wide variety of experience and professional backgrounds which includes participants from both the private and public sectors. Members include professional engineers, professional geologists, professional planners, groundwater hydrologists, and NJ State regulators. Many committee members have technical expertise and substantial experience with the determination of soil and aquifer hydraulic conductivity for stormwater design and other related purposes. Specific experience includes stormwater design, infiltration testing, hydrogeology, geotechnical engineering and planning among other related fields. The committee has previously provided guidance to the NJDEP in the development of guidelines for groundwater mounding analyses for stormwater infiltration practices.

Preface:

The purpose of this document is to provide general summaries of test techniques applicable at depths which preclude the use of a standard test pit. An effort has been made to provide supplemental references where possible, this document is intended to be used in conjunction with those references and not as a standalone reference. A brief definition list of some relevant terminology has been provided at the end of this document.

The determination of hydraulic conductivity is a complex subject; especially when in-field tests are conducted in the unsaturated zone (above the groundwater table). The practitioner who wishes to apply these testing techniques should have a general understanding of groundwater hydraulics. There are many complicating factors that can significantly influence test results and their application in design. Hydraulic conductivity often varies widely from one location to another. This is a natural characteristic that the practitioner should understand in the context of the site geology when determining appropriate test locations and interpreting test results. The scale of the test is also an important consideration. Some test methods provide a more area-averaged result while others methods only evaluate a very small sample volume.

The physics governing the flow of groundwater are considerably different above and below the groundwater table (the unsaturated and saturated zones respectively). These differences should be understood by the practitioner and reference is made to these differences as they apply to the tests summarized herein. Further complicating the application and analysis of these testing techniques is the potential for macropore flow in the sample soil; this is especially true for laboratory test methods. Macropore flow may occur when there are relatively large void spaces (in comparison to soil void spaces) that are in contact with ponded water or otherwise saturated soil conditions. The presence of macropores will always result in an overestimate of the hydraulic conductivity and therefore efforts should be made to avoid the presence of such conditions. While the previously mentioned conditions are often the most significant, test results are also influenced by the temperature of the water as the viscosity of water is temperature dependent. Efforts should be made to use water that is at a temperature that is representative of typical field conditions or test results should be corrected for the difference in water temperature.

Test Methods:

The following sections summarize various five different test techniques that are useful where infiltration testing is required at significant depths. References are provided at the end of each section for the benefit of the reader.

Cased Borehole Infiltrometer:

The Cased Borehole Infiltrometer test is essentially a single ring infiltration test which is conducted at depths that are not easily accessed by standard test pit excavation methods. While this test method was originally developed for analysis in saturated soils (below the water table), it has been successfully applied in the analysis of soils above the water table in the unsaturated zone. In the unsaturated zone, the test method involves the collection of falling head data over time.

A typical test setup consists of a borehole completed to the depth in question. The borehole can be completed by typical hollow-stem auger methods or with the use of a hand auger where conditions permit. A solid casing, often PVC pipe, is set at the base of the borehole and is gently set (pressed) into the relatively undisturbed soil surface at depth. The casing is then supported and maintained in a vertical position in the borehole. The annular space is filled with several inches of granular bentonite which is then wetted and allowed to hydrate and seal the base of the annular space. The remainder of the annular space is backfilled with native soil and lightly compacted. Several inches of coarse sand or fine gravel are added to the inside of the casing to protect the soil surface prior to the addition of water.

The test procedure involves repeatedly filling the borehole with water to a depth of approximately two feet or less and measuring the decline of the water level in the borehole over a set depth range until the rate of water level decline in the well becomes essentially constant. The final measurement is taken once the readings stabilize (time required for the water level to drop the set depth range approaches a constant value). This test assumes that the contribution of unsaturated soil moisture potential of the surrounding soil is insignificant, as the wetting front becomes increasingly large and the readings stabilize. This test often requires a substantial number of readings or "presoak" before a constant reading is achieved.

Although no singular and comprehensive reference is available for this test, Hvorslev documents this analysis and provides a summary in a publication from 1951. This publication provides an "intake shape factor" of 2.75 for a solid well casing with an open bottom. These shape factors originate from earlier works dated to the 1930s. While originally developed and used as a slug test for analysis of soils of extremely low hydraulic conductivity below the water table (recovery), later publications reference its use above the water table (recession).

References:

Hvorslev, M., J., 1951, "Time Lag and Soil Permeability in Ground-Water Observations" Bulletin No. 36, Waterways Experiment Station, Corps of Engineers, U.S. Army, Vicksburg Mississippi

American Society for Testing and Materials, 1979, "Permeability and Groundwater Contaminant Transport" ASTM Publication Code Number 04-746000-38

ASTM International, 2006, "ASTM D6391-06 Standard Test Method for Field Measurement of Hydraulic Conductivity Limits of Porous Materials Using Two Stages of Infiltration from a Borehole"

Undisturbed Core Sample with Laboratory Analysis:

This test method involves the determination of hydraulic conductivity in a controlled laboratory setting on an undisturbed sample. In some instances, sampling is required at depths greater than those accessible via open excavations. In order to collect undisturbed samples at greater depths, specialized equipment is required.

A Shelby Tube Sampler (also generically referred to as a thin-walled push tube or Acker thin-walled sampler) uses a thin-walled metal tube to recover relatively intact cohesive soils for laboratory analysis of soils properties, including hydraulic conductivity. It may be difficult to obtain an undisturbed sample of non-cohesive soils (such as loose sands) with a Shelby Tube Sampler. These sample tubes normally have an outside diameter of 3 to 5 inches. This sampling method is limited to soils that can be penetrated by the thin-walled tube, and is not recommended for sampling soils containing rock fragments (gravel or cobbles) as the sample tube can be damaged resulting in an unrepresentative sample. The procedure for collecting undisturbed samples with the Shelby Tube Sampler is described in detail in ASTM Method D1587.

Typically, the Shelby Tube is attached to a drill rod and is lowered into the borehole to the top of the desired sampling horizon, where the sampler is then pressed into the undisturbed material by hydraulic force. After retrieval to the surface, the tube containing the sample is then removed from the sampler head. When the sample is collected for hydraulic conductivity testing, the tube should be capped, maintaining the sample in its relatively undisturbed state, and shipped to a qualified geotechnical laboratory with care taken to maintain the sample in a relatively undisturbed condition. The qualified geotechnical laboratory should be consulted to coordinate the appropriate sample size and sampling procedures required for permeability testing. The length to diameter ratio of the final sample used in the laboratory analysis should be between 1:1 to 2:1. The sample should have a minimum diameter of three inches. Prior to and after analysis the integrity of the sample should be inspected, specifically the sample should be inspected for evidence of macropore flow, especially along the walls of the sample tube.

References:

ASTM International, 2006, "ASTM D1587 Standard Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes"

ASTM International, 2006, "ASTM D2434 Standard Test Method for Permeability of Granular Soils (Constant Head)"

USEPA Region 4, 2011 "Soil Sampling Operating Procedure"

Direct-push Hydraulic Profiling:

Continuous hydraulic property profiles of unconsolidated sediments can be generated using a Hydraulic Profiling Tool (HPT). As the tool is driven into unconsolidated sediments by direct-drive, clean water is pumped through a screen on the probe and the resulting injection pressure is recorded. Relative hydraulic properties are determined by evaluation of injection pressure and flow rate: a formation with lower hydraulic conductivity would have a higher pressure response and a lower flow response than a more hydraulically conductive formation. The pressure response of the system is calibrated and tested before and after each log. Additional details regarding the operation and interpretation of results obtained from the commercially available HPT system manufactured by Geoprobe Systems are detailed in Knobbe (2006) and Geoprobe Systems (2007). Logs from Geoprobe's HPT system and similar research devices have been utilized in a wide variety of hydrogeologic site investigations (Dietrich and others, 2008; Kalibus and others, 2008; McCall and others, 2009; Reilly and others, 2010; McCall, 2011). Methods have been developed to estimate saturated hydraulic conductivity from the results of HPT logs by correlating them to co-located direct-push pneumatic slug tests (Butler and others, 2007; Dietrich and others, 2008; Lessof and others, 2010; McCall, 2010). This approach is directly applicable to the collection of subsurface hydraulic conductivity data prior to the construction of stormwater BMPs. Several drilling contractors in New Jersey own and operate the equipment necessary to conduct HPT testing and have experience interpreting results to provide clients with estimates of saturated hydraulic conductivity.

Considerations should be made for site access. The HPT requires the use of a direct-push machine. These machines are approximately the same size as a full-size pickup truck. They are either truck or track mounted and are designed to be easily maneuverable. They can be operated anywhere with reasonable vehicle access. The HPT injects water into the formation via small diameter tubes. Operation of this equipment in near or below freezing temperatures is problematic.

As the HPT requires the use of a direct-push machine, the other capabilities of direct-push sampling techniques can be employed in concert with HPT testing. These could include, but are not limited to, the collection of continuous soil cores, installation and pneumatic slug-testing of temporary or permanent monitoring wells, and auguring holes for cased borehole infiltration tests.

References:

Butler, J.J. Jr., Dietrich, P., Wittig, V., Christy, T., 2007. Characterizing Hydraulic Conductivity with the Direct-Push Permeameter. Groundwater, V.45, N.4, 409-419.

Dietrich, P., Butler, J.J.Jr., Faiß, K., 2008. A Rapid Method for Hydraulic Profiling in Unconsolidated Formations. Groundwater, V.46, N. 2, 323-328.

Geoprobe Systems, 2007. Geoprobe Hydraulic Profiling Tool (HPT) System Standard Operating Procedure. Geoprobe Technical Bulletin MK3137. http://geoprobe.com/sites/default/files/pdfs/hpt_sop.pdf

Kalbus, E.; Schmidt, C., Molson, J. W., Reinstorf, F., Schirmer, M., 2008. Groundwater-surface-water interactions at the contaminated mega-site Bitterfeld, Germany. IAHS-AI SH Publication, vol . 324, pp.491-498.

Knobbe, S., 2006. Hydrostratigraphic Characterization using the Hydraulic Profiling Tool (HPT). Geoprobe Technical Bulletin MK3099.

Lessoff, S.C., Schneidewind, U., Leven, C., Blum, P., Dietrich, P., Dagan, G., 2010. Spatial characterization of the hydraulic conductivity using direct-push injection logging. Water Resources Research, 46, W12502, doi:10.1029/2009WR008949.

McCall, W., Christy, T.M., Christopherson, T., Issacs, H., 2009. Application of Direct Push Methods to Investigate Uranium Distribution in an Alluvial Aquifer. Ground Water Monitoring and Remediation, V.29, N. 4, 65-76.

McCall, W., 2010. Tech Guide for Calculation of Estimated Hydraulic Conductivity (Est. K) Log from HPT Data. http://geoprobe.com/sites/default/files/pdfs/tech_guide_estk_v5.pdf

McCall. W., 2011. Application of the Geoprobe HPT logging system for geo-environmental investigations. Geoprobe Technical Bulletin MK 3184. http://geoprobe.com/sites/default/files/pdfs/mk3184_application_of_hpt_for_geo-environmental_investigations.pdf

Reilly, T.J., Romanok, K.M., Tessler, S., and Fischer, J.M., 2010, Assessment of physical, chemical, and hydrologic factors affecting the infiltration of treated wastewater in the New Jersey Coastal Plain, with emphasis on the Hammonton Land Application Facility: U.S. Geological Survey Scientific Investigations Report 2010–5006, 59 p.

Slug Test:

Slug tests can be used to measure hydraulic conductivity in saturated (below the water table) conditions to characterize aquifer properties. Slug tests are conducted within a well installed in the location of interest. A limitation of slug testing for this application is that the data will be collected for the saturated zone whereas the stormwater infiltration occurs in the unsaturated zone. Slug tests are conducted by artificially raising or depressing the static water level in a well by the introduction or removal of a slug. The slug may consist of a solid object, water, or air. The removal of a slug to depress the water level in the well is used to measure the rebound to static and is called a rising head test. The introduction of a slug to artificially elevate the water level then measure its fall to static is called a falling head test. Water levels are measured over time using a water level meter or pressure transducer until they return to static. Slug tests are typically conducted in wells composed of a surface riser connected to an intake consisting of slotted well screen. The well intake is designed for both slot size and length based on field (aquifer) conditions. Care must be taken to utilize a slug of sufficient volume to influence more than the filter pack both surrounding and above the screen (if any) and to understand the potential of storage volume in the filter pack (for a falling head test). A slug of insufficient volume may lead to over-estimating aquifer hydraulic conductivity. Therefore, rising head tests are preferred.

Slug tests should be conducted and analyzed by qualified personnel following industry-standard practices that are outlined, for example, in one or more of the following American Society of Testing and Materials (ASTM) standards. Care must be taken to use an appropriate analytical (mathematical) solution when analyzing slug-test data to ensure simplifying assumptions are appropriate for the site conditions. An estimate of aquifer thickness is required when using the Bouwer and Rice (1976) solution for a slug test in an unconfined aquifer or for calculating hydraulic conductivity when using a solution that yields the transmissivity of the aquifer (transmissivity = hydraulic conductivity x aquifer thickness: $T = Kb$). Inputting a smaller saturated thickness to the calculation will yield a larger estimate of hydraulic conductivity, so assumption of a large saturated thickness may be more conservative.

References:

ASTM International, "ASTM D4044 Test Method for (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers"

ASTM International, "ASTM D7242 Standard Practice for Field Pneumatic Slug (Instantaneous Change in Head) Tests to Determine Hydraulic Properties of Aquifers with Direct Push Groundwater Samplers"

ASTM International, "ASTM D4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)"

ASTM International, "ASTM D5912 Test Method for (Analytical Procedure) Determining Hydraulic Conductivity of an Unconfined Aquifer by Overdamped Well Response to Instantaneous Change in Head (Slug)"

Bouwer, H. and Rice, R.C., 1976, "A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells" Water Resources Research, vol. 12, p. 423-428.

Domenico, P.A. and Schwartz, F.W., 1990, "Physical and chemical hydrogeology" John Wiley and Sons, New York, N.Y., 824 p.

Fetter, C.W., 2000, “Applied Hydrogeology”, 4th ed.: Prentice Hall, Inc., Upper Saddle River, N.J., 598 p.

Halford, K.J. and Kuniansky, E.L., 2002, “Documentation of spreadsheets for the analysis of aquifer-test and slug-test data” U.S. Geological Survey Open-File Report 02-197, 51 p.

Kruseman, G.P. and de Ridder, N.A., 1991, “Analysis and evaluation of pumping test data”, 2nd ed.: International Institute for Land Reclamation and Improvement Publication 47, Wageningen, The Netherlands, 375 p.

Aquifer (Pumping) Test:

Aquifer tests affect (test) a larger area of aquifer than the other outlined tests and, therefore, provide a more comprehensive measurement of the ability of the aquifer to transmit water away from the source of the infiltration. A limitation of aquifer testing for this application is that the data will be collected from the saturated zone whereas the stormwater infiltration initially occurs in the unsaturated zone. Aquifer tests vary in scope and complexity. For a public-supply well withdrawing hundreds of gallons per minute, a 72-hour test with water levels monitored in multiple observation wells with automatic data loggers may be needed. For assessing stormwater recharge, a smaller test is suitable. A small pump in a small-diameter piezometer with water levels monitored in the pumped well by hand for a few hours may be sufficient. Aquifer tests conducted to estimate the transmissivity of the aquifer in the vicinity of a stormwater infiltration BMP are assumed to withdraw water from any diameter well (for example 1-, 2-, or 4-inch diameter screen) for a sufficiently long time period to stress the aquifer (typically less than 8 hours) with accurately measured water levels measured manually or with a pressure transducer and data logger (calibrated with manual measurements). The pumping rate should be sufficient to substantially stress the aquifer, lowering water levels in the pumped well on the order of a foot or more and in observation wells (if any) on the order of a tenth of a foot or more.

Aquifer tests should be conducted and analyzed by qualified personnel following industry-standard practices that are outlined, for example, in one or more of the references provided below. An estimate of aquifer thickness is required when analyzing aquifer test data to obtain an estimate of hydraulic conductivity. For example, the Theis nonequilibrium solution yields a transmissivity value and transmissivity = hydraulic conductivity x aquifer thickness (T = Kb). Inputting a smaller saturated thickness to the calculation will yield a larger estimate of hydraulic conductivity, so assumption of a large saturated thickness may be more conservative.

References:

ASTM International, “D4043 Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques”

ASTM International, “D4050 Test Method for (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems”

ASTM International, “D4105 Test Method for (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method”

ASTM International, “D4106 Test Method for (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method”

ASTM International, “D5269 Test Method for Determining Transmissivity of Nonleaky Confined Aquifers by the Theis Recovery Method”

ASTM International, “D5270 Test Method for Determining Transmissivity and Storage Coefficient of Bounded, Nonleaky, Confined Aquifers”

ASTM International, “D5920 Test Method (Analytical Procedure) for Tests of Anisotropic Unconfined Aquifers by Neuman Method”

ASTM International, “D4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)”

Domenico, P.A. and Schwartz, F.W., 1990, “Physical and chemical hydrogeology” John Wiley and Sons, New York, N.Y., 824 p.

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New Jersey Geologic Survey, 1992, Geological Survey Report GSR 29, Guidelines for Preparing Hydrogeologic Reports for Water-Allocation Permit Applications, with an Appendix on Aquifer-Test Analysis Procedures.

Definitions:

This list of definitions are paraphrased from Lohman and others, 1972, Definitions of Selected Ground-Water Terms: USGS Water-Supply Paper 1988

Aquifer: a formation that contains sufficient saturated permeable material to yield significant [economic] quantities of water to wells and springs.

Saturated Zone: Beneath the water table (including beneath perched water tables), all voids are filled with water under pressure greater than atmospheric.

Unsaturated Zone: Above the water table, includes the capillary fringe, where water in voids is under less than atmospheric pressure. Above the capillary fringe most pores contain some water and some air.

Capillary Fringe: the zone immediately above the water table in which most (if not all) voids [interstices/pore space] are filled with water that is under less than atmospheric pressure and that is continuous with the water below the water table.

Permeability, intrinsic, k: A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. Units of length squared (e.g. feet squared)

Hydraulic Conductivity, K: Related to permeability, but specific to water (vs. other fluids, such as oil). The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Units of length per time (e.g. feet/day, cm/sec, ...)

Transmissivity, T: The rate at which water of the existing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient. Units of length squared per time (e.g. ft2/day, m2/d). Equal to hydraulic conductivity times aquifer thickness (T = Kb). Traditionally units were rate of flow per unit width of aquifer (e.g. gallons per day per foot).

Confining Bed: A formation or part of a formation that has lower permeability than the overlying and/or underlying aquifer.

Perched Groundwater: unconfined groundwater separated from any underlying body of groundwater by an unsaturated zone.

Homogeneous: Synonymous with uniform. Hydrologic properties are identical everywhere. Although no known aquifer is homogeneous in detail, models based upon the assumption of homogeneity (for example, Hantush, 1967) have been shown empirically to be useful.

Heterogeneous: Synonymous with nonuniform. Hydrologic properties vary with location.

Isotropic: Hydrologic properties are the same in all directions. Similar to homogeneous, the assumption of isotropy yields useful results in many situations.

Anisotropic: Hydrologic properties change according to direction. For example, many materials have greater horizontal hydraulic conductivity (X, Y directions) than vertical hydraulic conductivity (Z direction).

Porosity, n: The volume of pore space (voids or interstices) divided by the total volume (Vp/Vt), dimensionless.

Effective Porosity, ne: Interconnected pore space available for fluid transmission. (Vpe/Vt), dimensionless.

Specific Retention (Sr): Similar to Field Capacity, the volume of water retained by soil/aquifer (after being saturated and then drained by the force of gravity) divided by the total volume (Vsr/Vt), dimensionless.

Field Capacity: Similar to Specific Retention, but measured after a defined period, often 24 hours.

Specific Yield (Sy): The volume of water yielded by soil/aquifer (after being saturated and then drained by the force of gravity) divided by the total volume (Vsy/Vt) dimensionless. Important in stormwater infiltration because it represents the available storage in the soil/aquifer after previous infiltration events that saturated the soil/aquifer have drained.

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