A review of methods for characterization of site infiltration with design recommendations

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ABSTRACT

This paper presents a comparison of in-situ infiltration testing and correlations of hydraulic conductivity at three sites in southern California. Data includes short-term infiltration rates determined by the pilot infiltration test (PIT) (Washington State Department of Ecology, 2005); the double-ring infiltrometer test (ASTM D 3385-03); borehole tests (County of San Bernardino, 1992, and California test 750, 1986); and hydraulic conductivity estimated indirectly from correlations with grain-size distribution and cone penetrometer test data. Based on the results of the in-situ testing and correlations, the authors consider the PIT a preferred method, project and site constraints permitting. The authors also consider the approach for performing infiltration studies presented in the *Stormwater Management Manual for Western Washington* (Washington State Department of Ecology, 2005) to be transferable southern California. This paper presents procedures for characterizing a given site and estimating design infiltration rates. Guidance is provided on scoping multi-phased infiltration studies.

Keywords: infiltration, hydraulic conductivity, pilot infiltration test, double-ring infiltrometer

INTRODUCTION

A renewed interest in sustainable development has raised awareness of the environmental impact of uncontrolled storm water runoff as well as the need to recharge local aquifers. This has led to increased regulation of storm water runoff which has, in turn, required many development projects to incorporate some sort of on-site infiltration system in design. The design infiltration rate is an essential parameter in the design of such systems and is generally determined by the geotechnical engineer-of-record during their site investigations. The increased importance of on-site infiltration systems has significantly raised the standard-of-care to which geotechnical engineers are being held. However, there is currently little guidance provided to engineers in determining the design infiltration rate, and regulatory guidance is sparse and often conflicting. Methods for determining infiltration rates, both direct and indirect, are neither well documented nor well researched. Many of the common in-situ tests being used are designed for other purposes such as septic systems or clay liners for landfills.

Geotechnical engineers are relied upon to evaluate infiltration of storm water as an approach to aquifer recharge and mitigation of increased storm water runoff caused by new development and redevelopment. Geotechnical engineers often misjudge the uncertainties associated with determining infiltration rates. This is likely due to the engineers' unfamiliarity with infiltration test methods and a lack of appreciation for the variability of hydraulic conductivity of soils which is much greater than the variability of other common geotechnical design parameters such as undrained shear strength or compressibility. Often, the geotechnical engineer mistakenly views an infiltration study as simply performing a field or laboratory test (e.g. in-situ or laboratory falling head test, grain size analysis, etc.) and calculating an infiltration rate or hydraulic conductivity as some sort of index property similar to water content or unit weight without regard to what sort of infiltration system will be designed and how the design will use the infiltration rate provided. It is essential that the geotechnical engineer understand what sort of infiltration system will be designed before providing a recommendation for infiltration values. This is no different from other geotechnical recommendations such as allowable bearing stress. No reasonably prudent geotechnical engineer would even start to prepare a recommendation for allowable bearing stress without first knowing what type of structure and foundation system were being considered. The same concept applies to providing recommended infiltration rates.

Evaluation of infiltration systems to determine whether or not they will work at a given site can be complex. The range of uncertainty can vary based on the soil characteristics, stratigraphy or site variability, groundwater elevation, type of infiltration system, and the long-term maintenance of the system once it is constructed. In many cases, the range of uncertainty varies from an order of magnitude to several orders of magnitude. Selection of appropriate test methods coupled with a suitable level of site investigation is essential and requires knowledge of the types of systems being proposed.

INFILTRATION PROCESS

When precipitation reaches the ground, it can infiltrate into the ground, be stored as soil moisture eventually to be released back into the atmosphere through evapotranspiration, or if the soil profile has reached capacity, become runoff and enter the surface hydrological system. Whether the precipitation percolates into the soil or runs off the surface is dependent on the physical parameters associated with the following factors:

- The precipitation regime – intensity, type (rain or snow), frequency, primary season;
- Site attributes – slope, surface roughness, soil hydraulic conductivity;
- Cover – type and density of vegetation, percent of surface covered;
- Practices – structural improvements constructed to control surface water.

Several of these factors remain unchanged with site development (e.g. rainfall intensity and duration); others are subject to drastic alteration. These factors can include the complete removal of all vegetation, changes to the slope and surface roughness, changes to the soil's hydraulic conductivity from mixing and re-grading, and the installation of water control structures.

RUNOFF/EROSION EVALUATION VS. INFILTRATION SYSTEM EVALUATION

The primary difference between evaluating infiltration for storm water management systems versus runoff/erosion evaluation is how infiltration rates are considered. Determination of infiltration rates for evaluation of runoff/erosion generally consider saturated soil durations of only minutes to hours. Therefore, the short-term infiltration rate (IR_S) is appropriate for runoff/erosion. Infiltration rates for evaluating storm water management systems generally consider saturated soil conditions of days, weeks, or months. Therefore, the long-term infiltration rate (IR_L) is appropriate for selection, sizing, and locating infiltration systems. The IR_L used for design of infiltration systems typically includes additional reduction factors to account for repeated wetting/drying, maintenance, siltation, biofouling and soil variability. Additionally, IR_L is greatly dependent on the hydraulic gradient and the height of the water temporarily stored in the infiltration system whereas hydraulic gradient is not considered for IR_S and evaluation of runoff/erosion.

POINT A TO POINT B CONCEPT

When preparing to perform an infiltration study, it is important to first consider a simple concept prior to developing a site investigation, in-situ testing, and laboratory testing program—the Point A to Point B concept. The intent of an infiltration system is to increase infiltration at certain locations of a site in order to keep total runoff at or below predevelopment conditions. This is generally accomplished by selecting an area of the site to initiate infiltration (Point A). This location is often in an undevelopable area of the site, a zone below pavements, or an area of planned landscaping. Point A is often obvious; however locating Point B, the place where the water migrates to, requires a little more thought and often an expanded view of the project and surroundings. Only in rare circumstances will the infiltrating water flow vertically downward to a perfect sink. More often the vertical flow of water will be affected by depth to existing groundwater, historic high groundwater elevations, proximity of slopes, existing soil stratigraphy (uniform soil conditions vs. alternating layers of fine and coarse grain soils), predevelopment surface gradients and post development surface gradients.

It is also important to consider the difference between infiltration rate and hydraulic conductivity when considering the Point A to Point B concept. Infiltration rate (also termed percolation rate) is defined as the volume of water crossing the air-soil interface into a unit area of soil per unit time. Infiltration rate depends upon the physical condition of the soil and the hydraulics of water in the profile, both of which change with time. Hydraulic conductivity (k) refers to the soil's intrinsic ability to transmit fluid (also termed permeability). In general, hydraulic conductivity of soil horizontally (k_h) is much higher than hydraulic conductivity of soil vertically (k_v). The rate of infiltration is generally a function of hydraulic conductivity (k), hydraulic gradient (i), and infiltration area (A), as expressed empirically by Darcy's Law for one-dimensional saturated flow (Darcy, 1856).

$$Q = kiA \tag{1}$$

Where Q = the flow rate; k = hydraulic conductivity i = the hydraulic gradient; and A = the wetted area of soil

Because k_v is often half or less than half of k_h, the direction that water flows is seldom straight down. Also, hydraulic gradient (i) can be considered to be equal to 1 so long as the wetting front moves vertically downward. This will be true only when depth to groundwater or low hydraulic conductivity soil layer is sufficient (20 feet or more depending on the type and size of infiltration system). When the wetting front encounters the groundwater table or a soil layer with low hydraulic conductivity the vertical hydraulic gradient can rapidly approach zero, resulting in greatly reduced infiltration and groundwater mounding. The Point A to Point B concept requires the engineer to consider not just where the infiltration process starts, but also where it ends.

CONSIDERATIONS FOR INFILTRATION SYSTEM USE

Soil characteristics, soil stratigraphy and site variability, and groundwater conditions play important roles in the successful design and implementation of infiltration systems.

Soil characteristics

Storm water infiltration systems are best suited for sites having sandy soils with IR_L or saturated hydraulic conductivities of at least ½ inch per hour (generally loose to medium dense sandy soils with $D_{10} \geq 0.02$ mm and $D_{20} \geq 0.06$ mm). Silty and/or clayey sites, including many silty sand and clayey sand gradations, generally are not suitable for storm water infiltration for several reasons, including:

- The potential for volumetric change of expansive soils due to cyclic wetting and drying;
- Softening of soil due to cyclic wetting, which has greater impact on fine-grained soils; and
- Large variations in the magnitude of infiltration rates characteristic of some fine-grained soils (discussed below).

Soil stratigraphy and site variability

The variability and range of uncertainty of infiltration rates depends greatly on the site stratigraphy. Sites with uniform subsurface conditions will have relatively low variability, whereas sites underlain by landslide debris, buried stream channels, fine-grained alluvial deposits, and sites that have had previous earthwork activities (cuts and fills) will have a much higher variability. Thin layers of impermeable or low permeablility soils will have significant impacts on the actual infiltration rate as well as the direction in which the water migrates. Consequently, understanding of the bedding direction and inclination of fine-grained layers is very important when considering whether a proposed infiltration system could adversely impact adjacent properties, especially properties down gradient.

Groundwater conditions

Infiltration at sites with a shallow groundwater table can result in groundwater mounding. If the wetting front below the infiltration system reaches the groundwater table, the vertical hydraulic gradient will immediately drop to zero and the local groundwater level will rise or mound. Any further infiltration will be due to horizontal groundwater flow and the infiltration rate will slow dramatically. If the infiltration system is not large enough, water can continue to enter the system resulting in overflows and subsequent flooding (system failure). Groundwater mounding can also negatively impact structures, slopes, and other areas adjacent to the infiltration system, especially if mounded groundwater intercepts a laterally pervious layer. Because of this potential for groundwater mounding, the authors do not recommend using infiltration systems at sites where groundwater is less than 10 feet below the bottom of the proposed infiltration system. In some cases, depending on the site conditions, scope of the project, and conditions of adjacent properties, even a 10-foot distance between groundwater and the base of the infiltration system may not be sufficient.

METHODS FOR CHARACTERIZING SITE INFILTRATION

It is common practice to determine infiltration rates using two general methods:

- Direct in-situ infiltration tests (borehole, double-ring infiltrometer, pilot tests, and others)
- Correlations with index properties or indirect in-situ tests (grain size distribution, CPT, resistivity and others)

Both methods have pros and cons, and neither method is necessarily superior to the other. Ideally, the geotechnical engineer should use both methods in their evaluation of soil infiltration rates.

In-situ infiltration tests

In-situ infiltration testing provides an estimate of IR_S that is generally representative of the infiltration rates at a specific location at the site. Several tests at several locations are typically necessary to obtain a range and statistically valid values for average IR_S.

The pilot infiltration test (PIT), (Washington State Department of Ecology, 2005) is considered a preferred approach for in-situ infiltration testing by the authors. A PIT includes:

- Excavating a large test pit with the bottom located at the proposed elevation of the base of the infiltration facility or a minimum of 5 feet below proposed finished grade for permeable pavements. The typical area of the excavation bottom is approximately 10 feet x 15 feet. Smaller excavations can be used, but with a consequent decrease in accuracy and precision.
- Placing a highly permeable geotextile in the bottom of the excavation to reduce disturbance of soils during test.
- Placing a measuring staff in the middle of the excavation (a 4- to 6-inch diameter PVC pipe with 0.1 foot increments marked on it works well), driven into the ground or otherwise secured so that it does not move during the test.
- Rapidly filling the excavation with water approximately 2 to 4 feet deep to establish a constant head (2 feet is sufficient for finer grained materials, while 4 feet is more appropriate for coarser grained materials).
- Adjusting the water flow as necessary to maintain a constant water level in the excavation for approximately 24 hours (minimum 16 hours).
- Measuring the water flow rate necessary to maintain a constant water level.
- At the end of the constant head test, turning off the water and conducting a falling head test (measuring the water level at regular time intervals during water level decline until the excavation is dry).
- Analyzing the data for both constant head and falling head conditions.

The PIT is one of the few testing approaches that 1) assures adequate soil presoaking and 2) provides for a sufficient infiltration period to assure a stabilized infiltration rate, which could be expected to occur during a storm. However, because logistical constraints may arise that would preclude the use of the PIT (e.g., little or no water for testing, extreme depth of the proposed infiltration system, difficult access, project scope and budget, etc.), other approaches warrant consideration.

The most common in-situ infiltration test alternatives to the PIT include the double-ring infiltrometer test (ASTM D 3385-03) and the borehole infiltration tests (i.e., California Test 750, 1986; EPA, 1980, and others). These tests have significant technical weaknesses when applied to infiltration of storm water, as the double-ring infiltrometer test was originally developed for relatively low hydraulic conductivity infiltration media (pond and landfill liners), and the borehole tests were primarily developed as empirical methods for sizing septic systems. Both of these tests saturate a very small amount of soil at the test location. Consequently, when interbedded fine-grained sediments and/or changes in hydraulic conductivity within the infiltration media exist below the tested area, these methods can provide erroneous and overly optimistic (higher) infiltration rates for a site. These tests are limited by the amount of material that they saturate. They may be appropriate for design of septic systems where the quantity of infiltrate is expected to be low, however, for storm water infiltration systems, where the volume of infiltrate is substantially higher, these in-situ test methods should not be used alone. These tests do, however, provide value for preliminary assessments when performed in conjunction with grain-size distribution correlations.

A second weakness of in-situ infiltration tests is that they measure short-term infiltration rates which apply only to the initiation of the infiltration process. Factors such as infiltrate quality, frequency of infiltration system maintenance and site variability will affect long-term (design) infiltration rates. These factors are generally accounted for by reducing short-term infiltration rates by factors ranging from 5 to 50. For example, dividing a measured short-term infiltration rate of 5 inches per hour, depending on the factors considered, would result in a design infiltration rate ranging from 0.1 to 1 inch/hour.

Grain size analysis

Estimates of hydraulic conductivity can be made using a variety of empirical correlations and formulas based on a soil's grain-size distribution. One of the most commonly used correlations is the Hazen (1892, 1911) empirical formula for predicting hydraulic conductivity of saturated soils. The estimates of hydraulic conductivity using the Hazen and other methods should be considered as order-of-magnitude approximations. Correlations do not generally account for the in-situ compaction and/or density of the soil being infiltrated.

Geotechnical engineers can also use several other methods for determining infiltration rates based on grain-size distributions from sieve analysis and hydrometer data. These include approaches employing the traditional soils characterizations developed by the United States Department of Agriculture (USDA) Soil Conservation Service and analysis of grain-size distribution based on ASTM D-422. Washington State Departments of Ecology and Transportation have developed empirical and analytical relationships between grain-size and infiltration rates (Washington State Department of Ecology, 2005). Geotechnical engineers outside of the State of Washington can typically employ these approaches modified based on local experience and knowledge of soil and infiltration conditions.

COMPARISON OF METHODS AT THREE SITES IN SOUTHERN CALIFORNIA

This section describes fieldwork performed at three sites in southern California, summarizes the data collected, and presents a discussion of the results. Data was collected and/or generated using the following test procedures.

- Double-ring infiltrometer test (ASTM D3385-3);
- Borehole test (County of San Bernardino, 1992)
- Borehole test (California test 750, 1986);
- Grain-size distribution testing (ASTM D422-63);
- Correlation using the Hazen (1892, 1911) empirical formula (Hazen equation):

$$k = C_H D_{10}^{\ 2} \tag{2}$$

  where k = hydraulic conductivity, D_{10} = diameter at which 10 percent of soils is finer, C_H = an empirical coefficient

- Correlation using Kozeny-Carman empirical formula, Kozeny (1927), Carman (1938,1956) and Carrier (2003):

$$k = \left(\frac{\gamma}{\mu}\right) \cdot \left(\frac{1}{C_{K-C}}\right) \cdot \left(\frac{1}{S_0^{\ 2}}\right) \cdot \left(\frac{e^3}{(1+e)}\right) \tag{3}$$

where γ = unit weight of water, μ = viscosity of water, $C_{K\text{-}C}$ = an empirical coefficient, S_0 = specific surface area per unit volume, and e = void ratio

- Correlation using Massman and others (2003) empirical formula:

$$Log_{10}(k) = -1.57 + 1.90D_{10} + 0.015D_{60} - 0.013D_{90} - 2.08F_{fines} \tag{4}$$

where D_x = diameter at which x percent of soils is finer and F_{fines} = percent of soil finer than the #200 sieve size.

- Pilot infiltration test (PIT) (Washington State Department of Ecology, 2005); and
- Cone penetration test (CPT) using correlations with soil behavior type.

The data presented herein was collected from three sites in southern California (Site A, B, and C). Site A surface soils generally consist of silty sand and are sparsely vegetated with weeds. The subsurface soils generally consist of near-surface silty sand overlying alternating layers of sandy, silty, and clayey soils to depths explored of approximately 50 feet below ground surface (bgs). Groundwater was encountered in a sand layer at approximately 30 feet bgs.

Site B surface soils generally consist of silty sand to sandy silt and are sparsely vegetated with weeds. The subsurface soils generally consist of approximately five feet of silty sand to sandy silt underlain by fine- to medium-grained sand and fine- to coarse-grained sand with varying amounts of gravel. Groundwater is assumed to be approximately 150 feet bgs.

Site C is currently a vacant field covered with shrub and grass vegetation. Surface soils generally consist of silty sand and poorly graded sand. Subsurface soils consist of layers of clayey sand, silty sand and sandy silt. Groundwater was not encountered in any of the 41 borings and 32 test pits advanced. The maximum depth of the borings was approximately 56½ feet bgs and the test pits were excavated to depths on the order of 5 feet bgs. Groundwater beneath the site is anticipated to be deeper than 80 feet bgs.

The results of field and laboratory tests performed for Sites A through C are summarized in Tables 1 through 3. The sections that follow describe the test procedures and results in further detail.

Table 1. Summary of In-Situ Testing and Empirical Correlations – Site A

Depth (ft)	Soil Type	Borehole Test (California Test 750, 1986) (in/hr)	Double Ring #1 ASTM D 3385-03, (in/hr)	Double Ring #2 ASTM D 3385-03, (in/hr)	Double Ring #3 ASTM D 3385-03, (in/hr)	Double Ring #4 ASTM D 3385-03, (in/hr)	CPT Correlation, k_{sat} (in/hr)
0-2	SM	4	2		2		20
2-3.5	SM						0.2
3.5-4	ML-CL			1		1	0.002

Table 2. Summary of In-Situ Testing and Empirical Correlations – Site B

Depth, (ft)	Soil Type	D_{10} (mm)	Borehole Tests EP-1 and EP-2 (County of San Bernardino,1992), approx. 5 ½-in diameter boreholes, (in/hr)	Double Ring #1 ASTM D 3385-03, (in/hr)	PIT #1 and #2 † (in/hr)	Hazen k_{sat} (in/hr)	Kozeny-Carman k_{sat} (in/hr)	Massman et. al. k_{sat} (in/hr)	CPT Correlation (generalized) k_{sat} (in/hr)
0	--	--	15 and 28			--	--	--	1.4 to 14
2.5	SP, SP/SW, and SW	0.093 to 0.121		21	5 and 4	12.76 to 21.26	23* to 58	49 to 56	
5	SP, SP-SM, SP/SW, and SW	0.08 to 0.145				8.5 to 29.76	8.8* to 100*	27 to 62	
7.5	SP, SW-SM, and SW	0.094 to 0.121				12.76 to 21.26	28* to 63*	28 to 55	
8.5	SP	0.095				12.76	28*	45	
9	SP	0.096				12.76	31*	40	
10	SW	0.154				34.02	130*	31	14 to 140

* Hydrometer analysis was not performed; silt/clay fraction was estimated based on comparison to similar grain-size distribution shapes and visual classification.

† Performed following guidelines in Washington State Department of Ecology, 2005.

Table 3. Summary of In-Situ Testing and Empirical Correlations – Site C

Depth, (ft)	Soil Type	D_{10} (mm)	Borehole Tests P-1 and P-3 (County of San Bernardino,1992), approximately 8-inch diameter boreholes, (in/hr)	Borehole Tests P-2 and P-4 (County of San Bernardino,1992), approximately 8-inch diameter boreholes, (in/hr)	Hazen k_{sat} (in/hr)	Kozeny-Carman k_{sat} (in/hr)	Massman et. al., k_{sat} (in/hr)	CPT Correlation (generalized) k_{sat} (in/hr)
0	SM	--	14.7 and 2		--	--	--	1.4 to 14
5	SP-SM and SM	0.025 to 0.075		12.1 and 5.8	0.9 to 8	2.1 to 5.2*	8.2* to 32.5	
10	SP-SM, SW-SM, and SM	0.012 to 0.17			0.2* to 56.7	0.65* to 29*	4* to 70	0.14 to 14
15	ML and SM	0.002 to 0.045			0.006 to 2.9	0.02 to 5.2	1 to 8.2	0.014 to 1.4

*Hydrometer analysis was not performed; silt/clay fraction was estimated based on comparison to similar grain-size distribution shapes and visual classification.

Double-ring infiltrometer test (ASTM D3385-3)

Double-ring infiltrometer testing was performed in general accordance with the procedures of ASTM D 3385-3. Four tests were performed at Site A and one test was performed at Site B. The test areas at Site A were prepared by excavating test holes using shovels and other hand tools. The test area at Site B was prepared with the support of a backhoe.

The double-ring infiltrometer testing was found to be labor intensive and difficult to perform where the soils tested were sandy. It was imperative that set-up of the apparatus was performed with rigorous attention to detail. The apparatus was generally easy to obtain and assemble at a relatively low cost. For use on a regular basis and for implementation for professional work, one should be careful to select high quality materials. Significant difficulty was found in maintaining a constant water level within the rings due to valves that became plugged with contaminants in the water, valves that either stuck open or stuck closed, and valves through which it was difficult to regulate the flow of water.

In spite of the difficulties discussed above, when the tests were performed with proper care, the results were consistent with other in-situ tests and correlation methods performed as part of this study. The results of the double-ring infiltrometer tests performed for this study are presented in Tables 1 and 2. The infiltration rates from the double-ring infiltrometer tests were generally within an order of magnitude of those estimated using borehole tests and the correlations with grain-size distribution and CPT soil behavior type. At Site B, the infiltration rate from the double-ring infiltrometer test was approximately 4 to 5 times higher than that predicted by the PIT discussed later in this paper.

Borehole test (California test 750, 1986; and county of San Bernardino, 1992)

Falling head percolation testing was performed in general accordance with California Test 750, 1986 at Site A. The test method prescribes that at least 6 borehole tests be performed within the general area of one test location to generate an average infiltration rate. The testing for this study consisted of excavating four test holes by hand auger, approximately 5½ inches in diameter. A two-inch layer of gravel was then placed in the bottom of each completed hole. Perforated PVC pipe was then placed near center in each hole, and gravel was used to fill in the annular space to the surface. Each hole was presoaked at least 8 inches above the bottom of the hole. The test method prescribes presoaking for at least 18 hours prior to performing the test in order to provide saturation of fine-grained soil layers and allow for any potential swelling of the soils to occur. Presoaking for this study was abbreviated to approximately 4 hours. The borehole tests were performed adjacent to double-ring infiltrometer test DR1 at Site A. The result of the borehole infiltration tests are presented in Table 2.

Falling head percolation testing was also performed in general accordance with the procedures from *On-Site Wastewater Disposal System* (Pages 11-12), County of San Bernardino, Department of Public Health Division of Environmental Health Services, August 1992, at Sites B and C. Testing consisted of excavating two 5.5-inch-diameter hand auger borings (EP-1 and EP-2) for test holes at Site B. The borehole tests were performed adjacent to PIT No. 1 at Site B. Four borehole falling head tests (P-1 through P-4) were performed at Site C. The tests at Site C were performed in borings drilled using a Mobile B-61 truck-mounted drill rig equipped with 8-inch hollow stem augers.

Testing was found to be relatively easy to perform. Not only could the presaturation of multiple tests be performed simultaneously, but multiple tests could be performed at the same time. Additionally, the test materials (perforated drain pipe and gravel) were purchased from a local hardware store for less than $20. The average infiltration rate from these tests was approximately 3 to 7 times higher than that predicted by the PIT as shown in Tables 1-3. The infiltration rates from these tests were generally within an order of magnitude of those estimated using the double-ring infiltrometer test at Site B and the correlations with grain-size distribution and CPT.

Pilot infiltration test (PIT)

Two PITs were performed at Site B in general accordance with the Washington State Department of Ecology Western Washington Storm water Manual, February 2005. The tests consisted of digging a large excavation, rapidly adding water to a pre-established elevation, and measuring the flow rate required to maintain the water level at that elevation (constant head) over an extended period of time.

Excavations were performed with a rubber-tired backhoe to depths equivalent to the depth of a proposed infiltration system being considered for this site (approximately three feet bgs). Bottom dimensions of the excavations were approximately ten feet by ten feet with side slopes ranging from 2.4:1 to 2.9:1 (horizontal:vertical). Three piezometers were installed evenly spaced along a line perpendicular to one wall of each PIT to monitor the direction of the flow of water into the subsurface soils. The three piezometers were installed spaced approximately three feet apart, to depths of 8, 13 and 25 feet, respectively.

The excavations were rapidly filled to a pre-established level using water supplied from a water truck and a water holding tank. The water flow was regulated using a gate valve near the discharge point, and the flow rate was measured with an in-line flow meter. Calibration of the meter was performed by measuring the time required to fill a five-gallon bucket. The flow meter was replaced with a flow totalizer during the test, because the flow meter was found to be inaccurate, especially at low flow rates.

Measurements of the flow rate required to maintain the pre-established water level within the excavations were recorded at intervals of 15 to 20 minutes throughout the test. The initial measured flow rates during PITs 1 and 2 were 33 gallons per minute (gpm) and 52 gpm, respectively. The flow of water was reduced after approximately 14 hours as the infiltration of water approached a steady flow rate of approximately 20 gpm and 37 gpm during PITs 1 and 2, respectively, where they remained until the end of the tests. The infiltration rate for each of the PITs was computed by dividing the steady state flow of water into the excavation by the wetted area. The results of the PITs are presented Table 2.

Equipment required for the PITs included two 4,000-gallon water holding tanks, two 2,200-gallon water trucks, pumps, hoses, and metered valves. Electronic water-level indicators were also used to check for the presence of water in each of the piezometers periodically throughout the tests. No water was encountered in any of the piezometers indicating there was no significant horizontal flow at least in the area where the piezometers were placed.

The PIT procedure requires significantly greater effort, time, and space than either the borehole or double-ring infiltrometer tests. However, the data obtained from the PITs better represents short-term infiltration rates than either the borehole tests or double-ring infiltrometer tests presented above. The infiltration rates estimated from the PITs were 4 to 5 times lower than those estimated by the double-ring infiltrometer test and 3 to 10 times lower than those estimated from the borehole tests. Infiltration rates from the PITs were also 3 to 10 times lower than those estimated using correlations with the grain-size distributions, see Table 2.

Grain-size distribution testing, ASTM D422-63

Grain-size distribution testing was performed on multiple samples of materials encountered at Sites B and C in order to classify the soils. Hydrometer analyses were also performed on several samples of materials sampled at the Sites B and C. The tests were performed in general accordance with ASTM Test Method D 422-63.

Correlations were made between the grain-size distributions and hydraulic conductivity based on the results of sieve analyses and hydrometer testing of the site soils. Correlations were made using the Hazen (1892, 1911), Kozeny-Carman (Carrier, 2003), and Massman and others (2003) empirical formulas for predicting the hydraulic conductivity of porous media. The results of the correlations to hydraulic conductivity are presented in Tables 2 and 3.

To simplify the correlations made using the Hazen equation, the empirical coefficient C_H in Equation 2 was assigned a value of unity. It was observed that for Site B soils, the correlations using the Hazen equation were two to three times and in some cases four times lower than correlations made with the Kozeny-Carman (Carrier 2003) and Massman and others (2003) empirical formulas. It was also observed that the Hazen equation, using $C_H=1$, predicted saturated hydraulic conductivities that were very close to *IRs* predicted/measured using double-ring infiltrometer and borehole tests.

It should be noted that the Massman and others (2003) empirical equation assumes minimal compaction, and therefore if the site soils are overconsolidated or exposed to heavy compaction, the equation could overestimate the hydraulic conductivity by approximately an order of magnitude (Washington State Department of Ecology Water Program, 2005). The correlation using the Massman and others (2003) equation is approximately 10 times higher than the measured *IRs* generated by the PIT testing at Site B.

The correlations using the Kozeny-Carman equation were generally consistent with the correlations using the Massman and others (2003) equation for Site B where the soils were characterized as poorly graded sands and well graded sands. The correlations using the Kozeny-Carman equation were generally consistent with the correlations using the Hazen equation for Site C where the soils were characterized as poorly graded sand with silt and silty sand. However, it should be noted that the D_{10} grain size was typically less than 0.1 mm at Site C which is smaller than the range where Hazen's equation is applicable.

Cone penetration test (CPT)

Cone Penetration Tests were advanced at all three sites. The major application of the CPT is soil profiling and classification (Robertson and Robertson, 2006). The advantages of the CPTs over soil borings include frequency of data collection (near continuous), repeatability, and the speed at which the sounding can be completed [a 60-foot sounding can be completed in about 30 minutes (Robertson and Robertson, 2006)].

CPT classification charts provide a repeatable index of the aggregate behavior of the in-situ soil in the immediate area of the probe (Robertson and Robertson, 2006). Prediction of soil type based on CPT is referred to as soil behavior type (SBT) (Robertson, 1989). Many soil properties, including hydraulic conductivity, have been correlated with SBT. The hydraulic conductivity correlation with SBT developed by Lunne and others (1997) was used for this study.

The values of hydraulic conductivity estimated from correlations with SBT are presented in Tables 1 through 3 for the three sites. These estimates provide an order of magnitude estimate of the saturated hydraulic conductivity and generally agree with the results of the in-situ testing and correlations with grain-size distribution. Because both the penetration resistance and sleeve friction increase with depth due to the increase in effective overburden stress, the CPT data requires normalization for overburden stress to properly predict soil behavior type. This is particularly important for very shallow and/or very deep soundings (Robertson and Robertson, 2006). The results presented in Table 1 are based on the normalized soil behavior type index SBT_n whereas the results presented in Tables 2 and 3 are based on non-normalized SBT because CPTs were performed by different companies which each reported data differently. At the depths of concern there is no significant difference between the normalized and non-normalized SBT values. . Based on review of the CPT logs and comparison with the borings and test pits from the three sites, it appears that the SBT is not entirely consistent within the first approximately five feet of penetration at the sites presented herein. Therefore at depths less than about five feet, the variability of the soil should be accounted for when estimating hydraulic conductivity using correlations with SBT.

SUMMARY OF IN-SITU TEST PROCEDURES

In-situ infiltration testing, such as PITs, borehole tests, and double-ring infiltrometers provide an estimate of IR_S that is generally representative of the actual infiltration rate at a specific location on the site. Several tests at several locations are typically required to obtain a range of statistically valid values for an average IR_S. Used in conjunction with correlations based on grain-size distribution and local knowledge and experience (including other correction factors accounting for maintenance, biofouling, etc.), in-situ tests can be used to obtain an order of magnitude estimation of IR_L.

Borehole tests are often misunderstood. In most cases, the falling head borehole test is not in the true sense a falling head test which was first introduced by Henry Ryon in the 1920s, and is an entirely empirical method for sizing septic systems. With an understanding of the limitations of the test and when properly performed, the results of the borehole tests are generally close to the results obtained from double ring infiltrometer testing.

In spite of the relative agreement between double-ring infiltrometer data and borehole tests, the double-ring infiltrometer should not be used for the purposes of evaluating infiltration for design of storm water infiltration systems for the following reasons.

- The test is designed to test fine-grained soils with relatively low infiltration rates. Soils suitable for infiltration systems are typically coarse-grained and therefore are not suitable for double-ring infiltrometer testing.
- Application of the test to coarse-grained soils requires rigorous attention to detail and experience with the test method in order to produce reliable and repeatable results.
- The effort to complete one test is greater than the effort to complete several borehole tests.

The PIT is currently the most rigorous method known by the authors for performing in-situ infiltration tests. It is a large-scale test run for long periods of time. The PIT allows for deeper saturation of the subsurface soils and reduces some of the scalability errors associated with the smaller double-ring infiltrometer and borehole tests.

SUMMARY OF HYDRAULIC CONDUCTIVITY CORRELATIONS

Saturated hydraulic conductivity can be estimated using a variety of empirical correlations that are typically based on grain-size distribution or CPT SBT. Estimates of hydraulic conductivity using grain-size distribution and CPT SBT should be considered order-of-magnitude approximations. Correlations do not generally account for the in-situ compaction and/or density of the infiltrating soils.

The Hazen equation, using $C_H=1$, is one of the most commonly used correlations to obtain saturated hydraulic conductivity, primarily because of its simplicity. The Hazen equation is typically applicable for soils with 0.1 mm $<D_{10}<$ 3 mm (Carrier, 2003). Based on the results of this study, the Hazen equation-generated values of saturated hydraulic conductivity for soils with D_{10} on the order of 0.025 mm were reasonably consistent with the results of in-situ testing.

RECOMMENDATIONS FOR DESIGN

Many sites are not conducive to the use of infiltration systems due to a fine-grained soil layer near the surface, a shallow groundwater table, or other site constraints. Therefore the first step in evaluating the applicability of a site for infiltration should be to perform a preliminary infiltration study. Design-level infiltration studies are not recommended until both the initial geotechnical investigation and a preliminary infiltration study have been completed.

Preliminary studies

The geotechnical engineer should perform a preliminary infiltration evaluation as part of the preliminary geotechnical investigation. The evaluation should include:

- Review of the intent of the infiltration system and identification of the proposed infiltration system to be used;
- Review the site setting including the depth to groundwater;
- Perform expanded sampling and grain-size distribution testing (including hydrometer); and if warranted,
- Perform small-scale field infiltration testing.

The primary benefit of a preliminary infiltration study is to avoid the cost of performing a full-scale infiltration study at a site that may not be suitable for infiltration. Another benefit of performing a preliminary study during the preliminary geotechnical investigation is that optimal selection and siting of an infiltration system is more likely to occur. The limitation of a preliminary infiltration study is that it is generally insufficient to provide design-level recommendations, and reliance on correlations and small-scale infiltration tests could result in underestimation or overestimation of IR_L. The following paragraphs present information that should be evaluated in a geotechnical investigation and preliminary infiltration study.

It is imperative to understand the scope of the proposed project, the client’s or owner’s needs, which infiltration system has been selected or is being considered for the project, and the depth of the proposed infiltration system. There are several factors that influence site suitability and long-term performance of infiltration systems. Such factors include depth to impermeable or low-permeability subsurface stratum, depth to groundwater, hydraulic conductivity of the infiltrating soils, volume of storm water to be infiltrated, and anticipated maintenance of the infiltration system once constructed. After understanding the infiltration system intended for the project, the following items should be accomplished.

- Perform a preliminary assessment as to whether the site can infiltrate between 0.5 and 2.5 inches/hour. Sites that infiltrate less than 0.5 inches per hour will not perform well. Sites that infiltrate greater than 2.5 inches/hour could require special agency approval depending on the depth to groundwater and whether groundwater is a local drinking water source.

- Evaluate whether the site is located adjacent to or within a landslide hazard area or hillside grading area.
- Evaluate whether the site has the potential for shallow groundwater mounding (i.e., sites with shallow, low hydraulic conductivity, or impervious soils and/or sites with shallow groundwater). The depth to first groundwater (current and historic high) or low or impermeable subsurface strata (silty/clayey sand, silt, clay, bedrock, etc.) should be at least 10 feet below the bottom of the proposed infiltration system.
- Evaluate whether the site is located within a liquefaction hazard zone or if there is a moderate or high potential for liquefaction.
- Evaluate whether the site soils (near surface) have a moderate or high expansion potential.
- Evaluate which direction the surface of the site is sloping (and if known, the direction and dip of bedding planes), and if there will be a negative impact from storm water infiltration on down-gradient sites that cannot be mitigated with practical solutions.
- Evaluate if the proposed infiltration system will be designed to allow overflow once the storage capacity has been reached and where the overflow will be directed and/or diverted (e.g., will a neighboring property be flooded once the infiltration system reaches capacity?).
- Evaluate if there is a potential for soil and/or groundwater contamination.
- Evaluate if the proposed infiltration system will impact future and/or existing use of the site (e.g., will softening of the near surface soils be caused by the infiltration system?).

If there is the potential for a negative impact from implementation of a storm water infiltration system based on any of the above items, then use of an infiltration system at the site may not be successful and could be dangerous. In such conditions, advise the client/owner to consider alternative biofiltration and/or mechanical storm water management systems in lieu of an infiltration system.

Suitable geotechnical investigations should include an adequate number of explorations including a combination of borings, test pits, and CPTs, where applicable, to characterize the soils across the site and address the considerations presented above. Soil sample intervals in borings used for the preliminary infiltration study should be near-continuous within the zone located at least ten feet below the bottom of the proposed infiltration system. Sieve analyses should be performed on differing soil layers below proposed infiltration system locations. Additional sieve analysis of samples collected across the site at elevations consistent with proposed infiltration system grades and at depths of approximately five and ten feet below these proposed grades should be considered. This information will prove useful to identify areas that may provide better infiltration or areas to avoid.

Small-scale field infiltration tests such as the EPA 1980 Borehole Falling Head infiltration test or California Test 750, 1986 should be performed as index tests at various locations across the site. If the project will include a system of infiltration trenches (i.e. perforated stormdrains), the authors recommend tests be performed every 100 to 200 feet along the proposed alignment(s) depending on the uniformity of the infiltrating soils. If the project will include infiltration basins, the borehole index testing can be used to help with selection of an appropriate location.

It is critically important to understand that small-scale field infiltration tests cannot model the complexity of the effects of interbedded layering. When using the borehole test data to estimate infiltration rates, it is necessary to apply some type of correction factor for final design, which is usually based on the range of uncertainty. Common correction factors are discussed in Washington State Department of Ecology, 2005.

Sieve analyses based on ASTM D-422 (including the hydrometer portion of the test method) should be performed on each differing soil layer within 10 feet below the bottom of the proposed infiltration system. It is the authors' opinion that Hazen's equation using $C_H=1$ is appropriate for uniform coarse-grained soil profiles. Even though Hazen's equation and others are prone to significant error (10 times or greater for coarse-grained soils) and are not applicable for fine-grained soils, the objective of their use is to identify site locations that will infiltrate at rates greater than 0.5 in/hr (coarse-grained materials).

It is important to note that the hydrometer portion of the sieve analysis test needs to be performed, because many of the correlation equations available are dependent on knowing the D_{10} grain-size. For example, for silty sand with 15 percent passing the #200 sieve, D_{10} cannot be determined without the hydrometer portion of the sieve analysis. It is also important to note that final design using hydraulic conductivity will also require estimation of hydraulic gradient as well applying additional correction factors as discussed in the Washington State Department of Ecology, (2005).

Design-level infiltration studies

A design-level infiltration study should be performed only if infiltration systems appear to be appropriate based on the results of a preliminary infiltration study as presented above. The approaches to determining IR_L in Washington State Department of Ecology (2005), Section 3.3.6, are generally appropriate for implementation in geotechnical engineering practice in southern California with the following guidelines.

Washington State Department of Ecology (2005) recommends selecting one of the following three methods for evaluating IR_L.

1. USDA Soil Textural Classification;
2. ASTM Gradation Testing; and
3. In-situ Infiltration Measurements.

Either Methods 1 and 3 together or Methods 2 and 3 together should be selected when evaluating and developing recommendations for IR_L. Borehole tests, such as the EPA (1980) or California Test 750, 1986 tests, should only be used for preliminary infiltration studies and for infiltration measurements for design of perforated stormdrains and pervious pavements. PITs should be used for in-situ infiltration measurements for design of infiltration ponds.

The EPA recommends applying correction factors of 25 to 50 to data from borehole infiltration tests. Additional correction factors should be applied unless effective pretreatment (filtering fines from the influent or permeant) and reliable long-term maintenance can be guaranteed. The Washington State Department of Ecology (2005) recommends applying correction factors ranging from 5.5 to 18 to data from PIT tests to account for site variability and number of locations tested, degree of long-term maintenance and influent permeant/control, and potential for long-term clogging due to siltation and bio-buildup. For example, infiltration rates from the Site B borehole tests ranged from 15 to 28 in/hr. If a correction factor of 25 is applied to these results, the long-term infiltration rates would range from 0.6 to 1.1 in/hr. The infiltration rates from results of the PITs ranged from 4.1 to 4.9 in/hr. Using a correction factor of 5.5, the long-term infiltration rates from the PIT data would range from 0.75 to 0.9 in/hr. The correction factors recommended by both EPA and WWSWM seem to be appropriate, and the results are generally consistent with the testing presented herein.

CLOSING

There are many methods for measuring infiltration and determining hydraulic conductivity of soils. The approach for performing infiltration studies presented in Washington State Department of Ecology (2005), *Stormwater Management Manual for Western Washington,* are generally appropriate for implementation in geotechnical engineering practice in southern California; and the PIT is considered by the authors to be a preferred approach for in-situ infiltration testing (project and site constraints permitting).

Many sites are not conducive to the use of infiltration systems. The geotechnical engineer should view infiltration studies as phased investigations, beginning with simplistic desktop studies and progressing to more complex field investigations as appropriate to suit a given project. It is essential that the geotechnical engineer understand what sort of infiltration system will be designed before providing a recommendation for infiltration values and consider presenting a range of statistically valid values.

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