New Hampshire DOT

Research

Improved Practices for Determining the Infiltration Characteristics of Soils for Design of Stormwater BMPs

Final Report

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16. Abstract

There are currently several in situ and laboratory methods of determining hydraulic conductivity of soils, however, it remains a difficult parameter to obtain accurately and economically. To characterize hydraulic conductivity for the design of stormwater best management practices (BMP's), the New Hampshire Department of Transportation currently uses a traditional field test, the borehole infiltration testing. The interpretation method of this test uses general assumptions and lacks vigorous analysis due to its development in the 1950's.

The proposed solution to these issues is to use a Permeafor, an instrument originally developed in France to measure horizontal hydraulic conductivity in situ. This property is determined by means of flowing water into the soil at any given depth, then obtained through the relation of applied hydraulic head and resulting flow. The tool has been designed, built, and tested at the University of New Hampshire. Using knowledge acquired during preliminary testing, several modifications in the testing procedure have been made, simplifying, and improving the method as well as the equipment used. The tool has been used extensively on 7 different sites across New Hampshire where the soil varied in characterization from coarse to silty sands. The results from more than 120 field tests demonstrated the potential of the Permeafor to rapidly hydraulically characterize soils at different depths to generate profiles of hydraulic conductivity. The Permeator is a useful tool in bridging the gap between time consuming testing at few locations and efficient broad scale permeability testing.

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Improved Practices for Determining the Infiltration Characteristics of Soils for Design of Stormwater BMPs

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FINAL REPORT

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Executive Summary

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The proposed solution to these issues is to use a Permeafor, an instrument originally developed in France to measure horizontal hydraulic conductivity in situ. This property is determined by means of flowing water into the soil at any given depth, then obtained through the relation of applied hydraulic head and resulting flow. The tool has been designed, built, and tested at the University of New Hampshire. Using knowledge acquired during preliminary testing, several modifications in the testing procedure have been made, simplifying, and improving the method as well as the equipment used. The tool has been used extensively on 7 different sites across New Hampshire where the soil varied in characterization from coarse to silty sands. The results from more than 120 field tests demonstrated the potential of the Permeafor to rapidly hydraulically characterize soils at different depths to generate profiles of hydraulic conductivity. The Permeafor is a useful tool in bridging the gap between time consuming testing at few locations and efficient broad scale permeability testing.

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Table of contents

List of Tables

List of Figures

1. Introduction

Soil infiltration data are used by the NH Department of Transportation (NHDOT) to assess the suitability of a site for various stormwater best management practices (BMPs) and to properly size and design a treatment area. With the recent issuance of EPA's final Municipal Separate Storm Sewer System (MS4) permit rules, the need for such testing is expected to increase. In order to estimate infiltration rates, the NHDOT currently utilizes a variation of the borehole infiltration test prescribed in the NH Department of Environmental Services (NHDES) Alteration of Terrain (AoT) rules using conventional geotechnical drilling equipment. This borehole infiltration test consists of measuring the rate at which water flows out of a borehole and into the soil under a certain hydraulic head. The boreholes are typically cased to the test depth where a filter pocket is created to facilitate flow into the soil formation. Existing testing protocols are labor intensive and time consuming, often taking 4 hours or more to complete a single test interval (depth). This is particularly inefficient if multiple depths require testing, e.g. if the preferred "bottom of practice" has not been established. In addition, the existing test method may not replicate field conditions and is prone to missing important features in the soil profile. The analysis still relies on methods developed in the 1950s which are based on several simplifying assumptions.

In spite of the number of in situ and laboratory methods currently available to determine hydraulic conductivity, it still remains a very difficult parameter to obtain accurately and economically. Laboratory tests typically provide results that are subject to sample disturbance, especially in granular materials, and only represent a small segment of the site and profile. Grain size analyses of field samples can also be used in various empirical relationships to determine hydraulic conductivity; however they are approximate as they rely on a minimal number of parameters. In situ tests which relate test measurements to hydraulic conductivity are also commonly subject to empirical or semi-empirical relationships based on various test assumptions or large-scale averaging.

The University of New Hampshire in partnership with the New Hampshire Department of Transportation has proposed to evaluate alternative methods and improve the NHDOT practices to allow for more effective design of BMPs. The proposed solution is to use the Permeafor, an instrument originally developed in France in the early 1980s to estimate horizontal hydraulic conductivity in situ. The test uses a cylindrical probe equipped with a screened section that is driven into the ground. As the probe advances into the soil, water is continuously injected through the screened section and into the soil. The penetration is then stopped at specific depths where a pressure head is applied and changes in flow are observed. The pressure and flow rate of the water is measured and regulated using a mobile support system located at the surface. The relationship between applied hydraulic head and resulting flow is used to assess hydraulic conductivity using more rigorous analytical methods.

The work conducted by UNH had the following objectives:

1. Review available permeafor drawings, adapt design features to be compatible with NHDOT equipment and operations, and fabricate a prototype for further evaluation in the field.

2. Compare the performance of the permeafor alongside existing test method.

3. Recommend and implement design modifications as a result of initial testing.

4. Provide a workable permeafor device suitable for implementation on NHDOT projects.

To accomplish these objectives several tasks were undertaken which included probe design changes to ensure compatibility with geotechnical drilling equipment operated by the NHDOT, fabrication of two permeafor devices with pumps, flowmeters, and other ancillary equipment, testing at a minimum of three sites, calibrate the permeafor with grain-size analyses and permeability water tests performed in the laboratory, review existing formula(s) used to convert field data to the Design Infiltration Rate needed for BMP design and recommend modifications to those formula(s) based on this research effort.

2. Permeafor Permeability Testing

The Permeafor consists of a hollow perforated probe that is driven into the ground with water simultaneously injected into the surrounding soils as shown in Figure 1. The probe has a conical tip to facilitate penetration into most soils by percussive drilling using conventional geotechnical drilling tools. Water is supplied to the probe during driving and testing using a flexible tube that runs inside the drill rods. For testing, driving is halted, and the flow of water is allowed to occur during the injection test. The probe is designed with tapered sections above and below the recessed perforated section to isolate the flow to occur primarily in the horizontal direction, preventing flow up or down along the soil-probe interface. The probe is supported by a system at the ground surface that regulates and measures the flow and pressure of the water supplied to the perforated section as shown in Figure 2. This water is supplied from the surface to the probe using a tank open to atmospheric pressure.

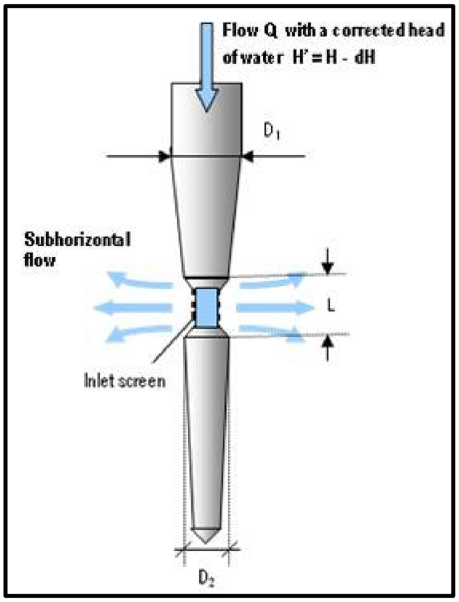


Figure 1. Schematic of Permeafor Probe

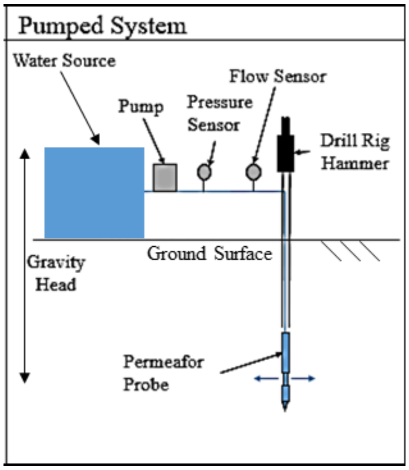


Figure 2. Permeafor System Configuration

2.1 Relation of Q/H' to Hydraulic Conductivity

The Permeafor is essentially a borehole permeability test but driven into the ground and with flow restricted to the horizontal direction. At the test depth, the measurements of flow and pressure through the soil are used to estimate permeability by relating flow to the applied head at the depth of the screen. This relation is expressed using a ratio of flow to the applied head, or Q/H', where Q is the measured flow and H' is the effective head at the screen. The effective head takes into account all head losses in the system. Practically, this relation may be thought of as the amount of pressure required to push a certain volume of water through the soil over a given time. Therefore, it becomes clear how Q/H' may be used to estimate the permeability of soil, where a larger or smaller Q/H' would indicate a more or less permeable soil, respectively.

After determining Q/H' for a given test, the values can be related to hydraulic conductivity using a shape factor that describes the geometry and extent of flow through the soil. As the Permeafor is driven into the ground, it creates a cylindrical cavity in the soil of equal dimension as the probe. The perforated section of the probe then provides water flow to the pocket created by the penetration. The flow out of this pocket may be described using a modification of Darcy's law to represent flow out of a cavity as shown in equation 1.

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

where: k = hydraulic conductivity (cm/sec)
H' = applied hydraulic head (cm)
C = shape factor (cm)

Several solutions and modifications have been proposed to represent this shape factor. They have been found through analytical, experimental, and numerical solutions. While variance between proposed shape factors can be observed, they were all developed using the same basic Laplace equation for flow in an infinite medium. Using this equation and assuming the shape of the flow around the perforated section it can be simplified to a sphere or an ellipse. From those assumptions it is possible to solve for the shape factor (Cassan, 1980; Silvestri et al., 2012). Using these simplified flow shapes, Hvorslev (1951) proposed some of the most commonly used shape factors. The primary effect on the shape factor is the length to diameter ratio, (L/D) of the cavity. In general, as L/D increases, the distribution of hydraulic head around the cavity elongates and can be described as an ellipsoid shape. This is the case for L/D greater than five, while for L/D equal to one, the shape of the equipotential lines is more spherical. To represent a cylindrical cavity that has an impermeable base, and only allows for horizontal flow, the shape factor was developed by Chapuis (1989) as shown in Table 1, along with several other shape factors primarily based on borehole permeability tests. The shape factor with the permeable base represents the case of horizontal flow from the cavity only.

Table 1. Proposed Shape Factors for Cylindrical Cavity

Proposed by	**Normalized Shape Factor (C/D)**	**Cavity Shape**	**Applicable Range (L/D)**
Hvorslev (1951)	$\dfrac{2\pi\left(\frac{L}{D}\right)}{\ln\left(\left(\frac{L}{D}\right)+\sqrt{\left(\frac{L}{D}\right)^{2}+1}\right)}$	Ellipse	1.2-10
Hvorslev (1951)	$\dfrac{2\pi\sqrt{\left(\frac{L}{D}\right)^{2}-1}}{\ln\left(\left(\frac{l}{D}\right)+\sqrt{\left(\frac{L}{D}\right)^{2}-1}\right)}$	Ellipse	1.2-10
Cassan (1980)	$\dfrac{2\pi\left(\frac{L}{D}\right)}{\ln\left(2\left(\frac{L}{D}\right)\right)}$	Ellipse	>10
Cassan (1980)	$\pi\sqrt{4\left(\frac{L}{D}\right)+1}$	Sphere-Cylinder	0.7-1.2
Cassan (1980)	$\frac{\pi}{\sqrt{2}}\sqrt{4\left(\frac{L}{D}\right)+1}$	Half Sphere-Cylinder	0.5-0.7
Silvestri et al. (2013)	$2.8+3.79\left(\frac{L}{D}\right)^{0.725}$	Cylinder	0-16
Chapuis (1989)	$\frac{C_{Original}}{D}-2.75$	Cylinder with Impermeable Base	-

Using these shape factors hydraulic conductivity can be estimated with the Permeafor using equation 2.

$$k=\frac{Q}{H'}\left(\frac{1}{C}\right) \tag{2}$$

This equation is only applicable for saturated conditions and laminar flow. The degree of saturation of soil during an in-situ test is difficult to ascertain, however the Q/H’ data may be used to evaluate when a relatively saturated value has been reached, primarily by observing when it has reached a steady state flow.

2.2 Effective Pressure Head H’

Pressure and flow measurements are used to find a ratio of flow and effective head (Q/H’) with time. Flow rate at probe level can be determined by direct measurement because water flows as a continuum and therefore the rate is equal throughout the system. The pressure applied at the probe, the effective head, H’, is a function of the total head and the head losses. Total head includes the gravity head from the top of the water source tank to the depth of the probe as well as the additional head supplied by the pump. A pressure sensor located close to the system outlet is used to measure the head from the height of water in the supply tank as well as the head contributed by the pump. This sensor measures effective head directly and without the need to consider head losses upstream from the pressure sensor. The remaining total head is due to gravity only and is equal to the height difference between the location of the pressure sensor and the flow outlet at probe level in the ground, or, if the probe is below the water table, the difference is to the water table. The effective head is determined by subtracting the head losses due to the flexible tubing and the probe. For tests in unsaturated soil, above the water table, the effect of capillary action is not considered in the calculation of effective head. These pressures are not present after the soil has been saturated though they may influence the applied effective head during saturation of the zone. Furthermore, the degree of saturation required to prevent capillary action may be difficult to achieve when testing in fine grained soils. The accumulation of effective head throughout the process for each water level condition is described in Figure 3.

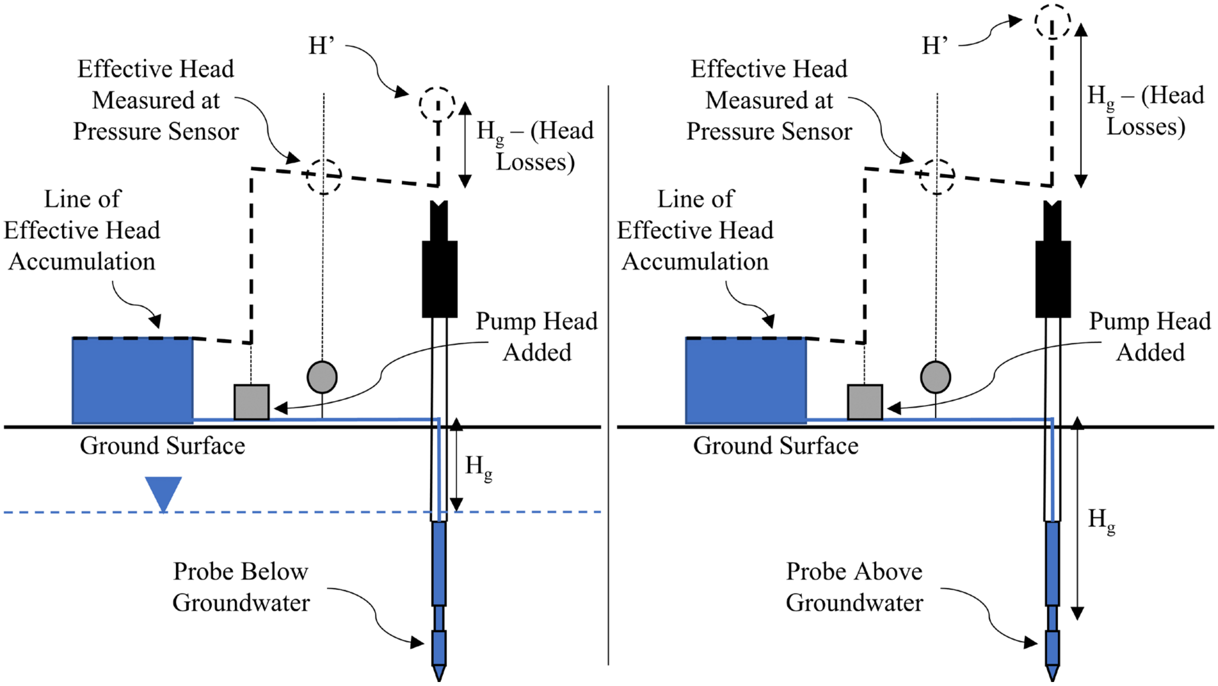


Figure 3. Accumulation of Effective Head During Permeafor Test

2.3 Permeafor Probe and Support System

This section presents the UNH Permeafor probe and supporting equipment.

Probe: The UNH Permeafor probe, designed after the 1988 French Permeafor version, is about 700 mm long with a maximum and minimum diameter of 70 and 44 mm, respectively. The length of the screen and diameter of the test cavity is 50 and 52 mm, respectively, resulting in an aspect ratio of about one. The end of the probe includes a threaded removable conical tip. Much of the UNH probe design is similar in dimensions but incorporates more modularity by machining the probe in several sections along its length. This approach was used to allow for potential future improvements and easy replacement of damaged sections. The modular pieces allow for two different probe designs, one with the screen located at the center of the probe and the other with the screen located at the tip. The middle screen configuration is similar to the original French design while the tip screen was an experimental modification first tested by Reiffsteck et al. (2009).

An additional screen giving an L/D of 2 was also evaluated during this test program. The various screen configurations and their dimensions are shown in Figure 4 with screen dimensions resulting in aspect ratios of approximately 1, 2 and 0.7, respectively. The individual middle and tip screen sections are also shown in Figure 5 A and B, respectively.

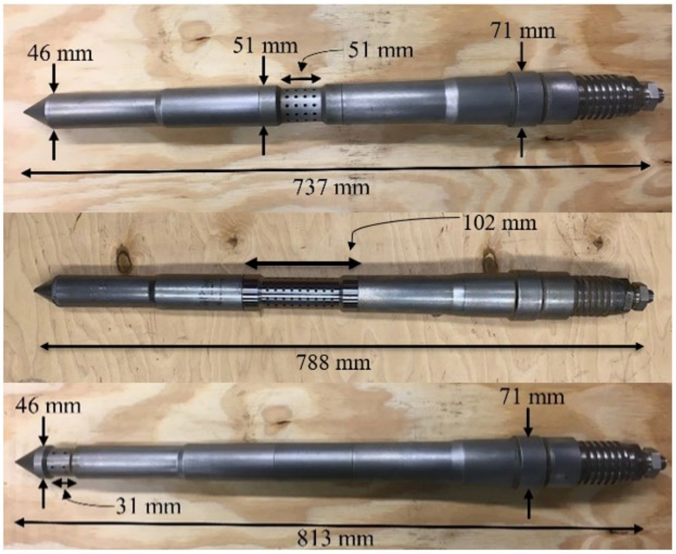


Figure 4. Probe Configurations; (a) Shorter Middle Screen, (b) Longer Middle Screen, (c) Tip Screen

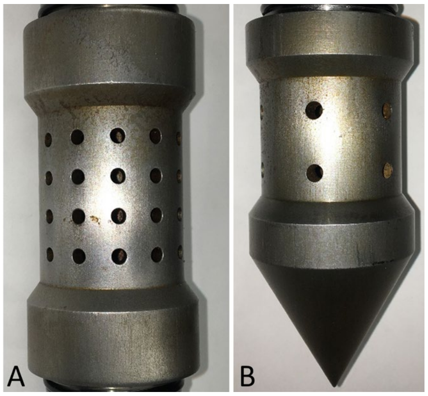


Figure 5. Probe Screens (A, Short Middle Screen and B, Tip Screen)

All pieces are hollow allowing for water to flow throughout. The pieces are assembled together by threaded connections. Each section is machined with an O-ring groove to prevent water loss between sections. The top of the probe is equipped with a Swagelok fitting that connects to the flexible tubing that supplies water to the screen. The tubing runs inside the rods to keep it protected from damage during driving and exits at the ground surface through a short, slotted rod as shown in Figure 6. The tubing is pre-strung through the rods before making connections to either end. The pre-strung rods are laid down and added or removed as needed. The probe is connected to drill rods using an NW sub adaptor.

Figure 6. Slotted Drilling Rod

Measurement and Control System: The system to regulate and measure test parameters was developed based on the principles established for the French Permeafor. The system, annotated in Figure 7, consists of four main components; a pump (1), flowmeter (2), pressure sensor (3), and data acquisition device (DAQ) located within a water resistant housing behind the flowmeter. The pump, made by Grundfos, is controlled by a variable frequency drive (VFD) which allows for precise speed adjustments. This version was selected so that pressure and flow could be increased, decreased, or maintained constant as needed and in real time during testing. A 1 in. diameter hose connects a 100 gallon heavy duty plastic tank, shown in Figure 8, to the system inlet using quick connection fittings (4) at either end. At the system outlet, a Swagelok fitting (5) facilitates the connection to the probe using flexible tubing.

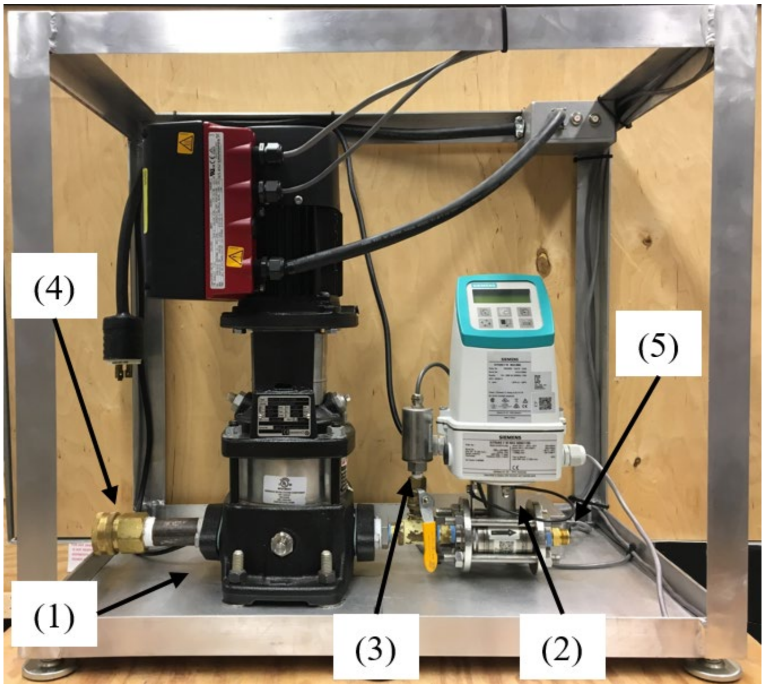
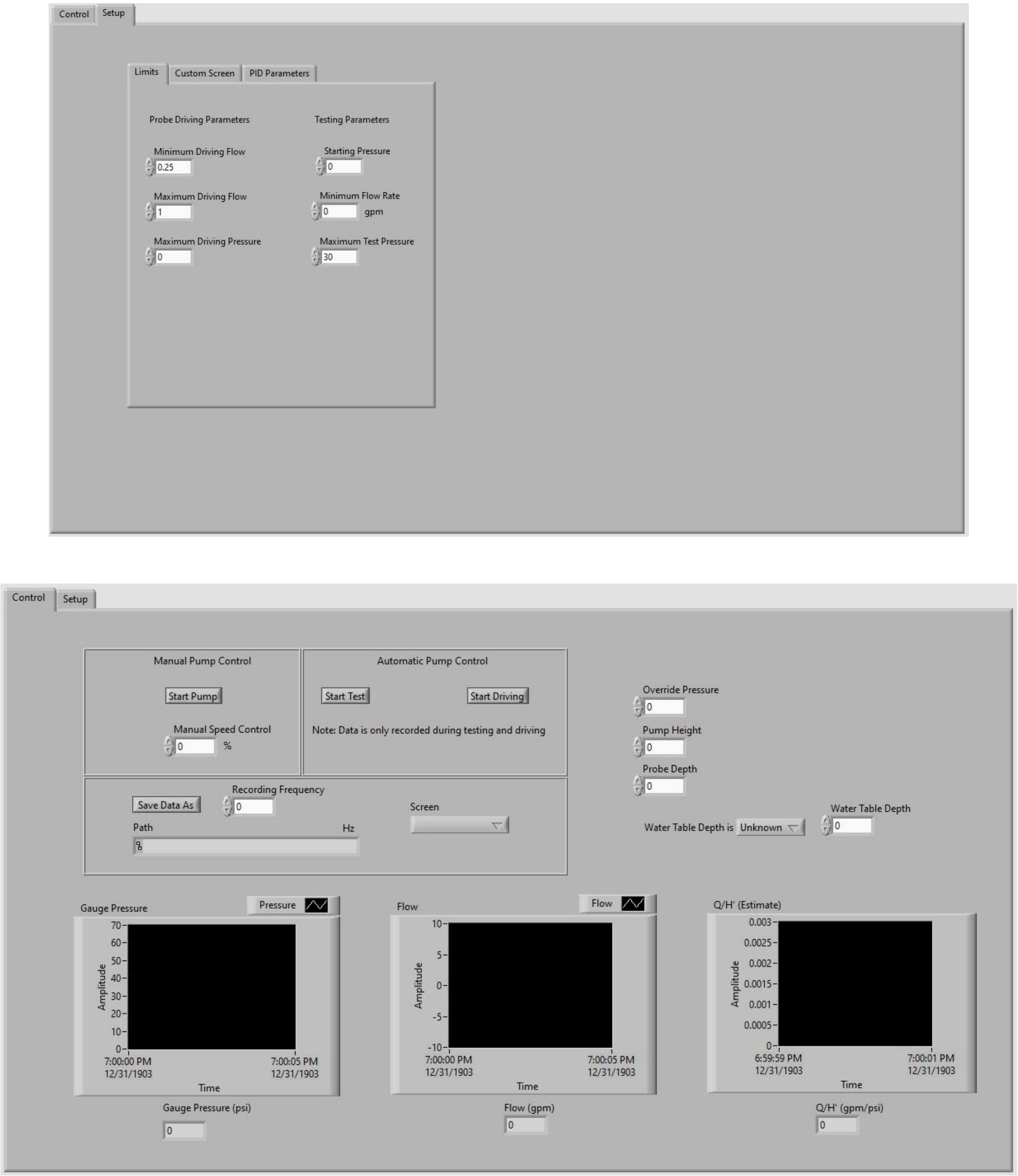


Figure 7. Acquisition and Control System (Pump, Flowmeter, Pressure Sensor, Inlet Quick Connect, and Outlet Swagelok Fitting, respectively)

Figure 8. 100 Gallon Supply Tank and System Connection Hose

For proper operation all equipment and piping up to the outlet must be filled with water prior to testing. This is essential as the pump turbine spins at high speeds on bearings lubricated and cooled only by water running through the pump. If water is not flowing or there are air pockets within the system, severe damage to the pump can occur due to overheating. Additionally, if there is too much air in the lines the pump will no longer effectively move water. The presence of air will also change the effectiveness of the flow sensor as it is specifically designed to measure flow in saturated conduits. The saturation procedure consists of applying several feet of head to the system inlet to ensure the pump does not create air pockets. This can be achieved by raising the water supply tank and using a short, large diameter hose to connect the tank to the system, minimizing head losses. To evacuate the system of all air before use, the lines need to be bled using a valve on the pump while the outlet valve is closed. Finally, all connections located upstream from the pump must be watertight as suction pressures generated by the pump will pull air into the system.

The pump operates on 240 VAC while the remaining system runs on 120 VAC. A portable generator with voltage options of 240 VAC and 120 VAC and a capacity of at least 15 Amps was used to power the system. A 15 Amp breaker, as shown on the top right corner of the metal frame in Figure 8, protects the pump from overcurrent damage. The pump has a built-in AC to DC converter that provides the excitation voltage for the Omega pressure sensor. This sensor can measure from 0 to 100 psia as an analog voltage signal from 1 to 11 VDC. The Siemens flow sensor calculates flow by measuring the velocity of water passing through a known cross-sectional area. A digital display provides real time flow rate as well as a means to choose measurement and output settings. Screen shots of data acquisition for Permeafor testing are shown in Figure 9. The measured flows can be set to any range within 0 to 10 gal/min. Voltage signals received by the



Probe Driving Parameters

Minimum Driving Flow 0.25

Maximum Driving Flow 1

Maximum Driving Pressure 0

Testing Parameters

Starting Pressure 0

Minimum Flow Rate 0 gpm

Maximum Test Pressure 30

Manual Speed Control 0 %

Note: Data is only recorded during testing and driving

Recording Frequency 0 Hz

Path

Override Pressure 0

Pump Height 0

Probe Depth 0

Water Table Depth is Unknown

Water Table Depth 0

Gauge Pressure (psi) 0

Flow (gpm) 0

Q/H' (gpm/psi) 0

Figure 9. Input parameters, control and data acquisition screens

DAQ are converted by LabVIEW. Each set of flow and pressure is then recorded as a function of time. Flow and pressure information is also used to operate a proportional-integral-derivative (PID) controller. This controller allows for the pump to regulate pressure or flow at a specific level by increasing or decreasing its speed depending on an analog DC signal. The signal generated by the controller is adjusted according to its PID gain settings, the requested flow or pressure setpoint, and the actual flow or pressure values being measured at that time. Therefore, the PID controller operates as a closed loop, as the measured flow and pressure input are a result of the pump speed controlled by its output. In addition to pressure or flow regulation, the pump speed may also be set manually using the program. Flow, pressure, and several user input constants are also used to estimate Q/H' in real time to observe its changes over the duration of a test. More details of the system and DAQ can be found in Wuebbolt (2020).

Calibrations: To determine the effective applied hydraulic head, head losses need to be considered and subtracted from the total measured head. Head losses occur from the 100-foot flexible tubing and the probe itself. Since the probe can be assembled in different configurations, a separate head loss calibration is needed for each probe setup. Two sets of information are needed to complete a calibration; head loss under different constant heads and measured flow under the same applied heads. The first set of values are found by applying different hydraulic heads and measuring the vertical height of ejected water from the outlet of the flexible tubing. The pressure sensor measures the actual effective pressure throughout the system, simplifying the expression to find the head loss to Equation 3. This process was completed by fixing the outlet of the tubing, and then using the pump to apply different hydraulic heads for simple measurement of the different ejection heights, shown in Figure 10 and schematically in Figure 11 (Wuebbolt, 2020).

$$H_L = (H_m + H_g) - H_e \tag{3}$$

where: H_L = head loss due to tubing (cm)

H_m = effective head measured at pressure sensor (cm)

H_g = total head attributed to height difference between sensor and tube outlet (cm)

H_e = vertical height of ejected water (cm)

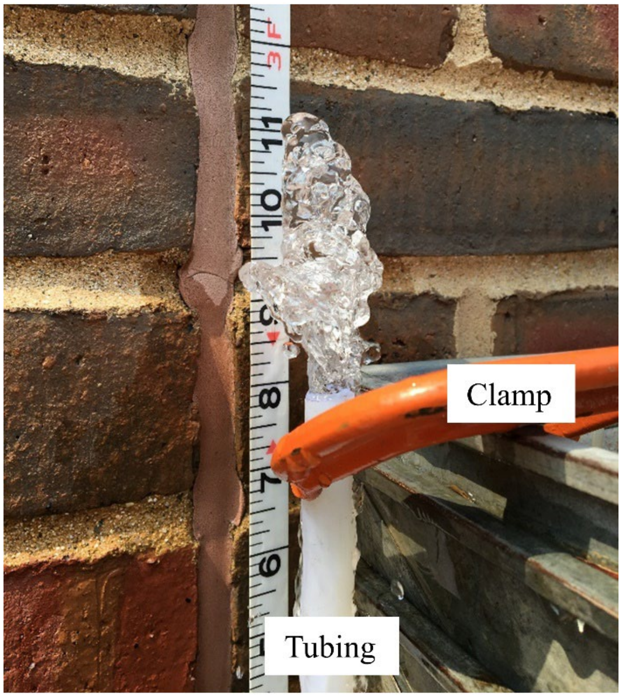


Figure 10. Measurement of Ejected Water (Wuebbolt, 2020)

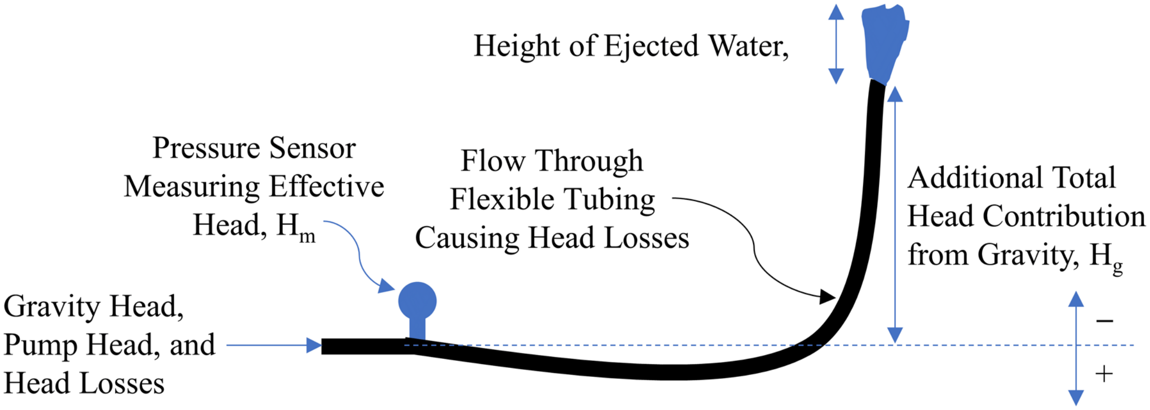


Figure 11. Head Loss Measurements (Wuebbolt, 2020)

The second set of values is found by connecting the probe and measuring the flow rates that occur under the same head levels. This can be completed by using the pump to vary H_m while the gravity head is maintained by submerging the probe in an overflowing bucket of water to keep the head constant, as shown in Figure 12.

Figure 12. Measurement of Flow Given Different Applied Heads

Using at least four sets of measurements, a trend of head loss with respect to flow can be established either by using curve fitting methods or by solving equation 4 for constants a, b, and c to develop equation 5. Any negative head loss values calculated at low flows are set to zero as it is likely that the losses are small enough to be negligible and cannot physically be negative.

$$\begin{bmatrix} \sum Q^4 & \sum Q^3 & \sum Q^2 \\ \sum Q^3 & \sum Q^2 & \sum Q \\ \sum Q^2 & \sum Q & N \end{bmatrix} * \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum Q^2 * H_L \\ \sum Q * H_L \\ \sum H_L \end{bmatrix} \tag{4}$$

where: Q = measured flow with probe attached at each head level (cm^3/sec)

N = number of sets of data acquired

H_L = head loss measured during calibration (cm)

$$H_L = aQ^2 + bQ + c \tag{5}$$

where: Q = flow through system (cm^3/sec)

H_L = head loss in system (cm)

Calibrations were completed, for the short middle screen probe configuration and for the tip, both attached to the same 100 ft length of 3/8 in. inside diameter tubing. The calibration results are summarized in equations 6 and 7, with flow in units of in.^{3}/min and head loss in inches. The results are also graphed in Figure 13 for the middle and the tip. These results are compared to reported head loss values for the same diameter tubing. As can be seen, the difference between calibrations and the reported values is small, though losses incurred by the tip screen are slightly larger. This difference is likely due to the smaller permeable area of the tip screen in comparison to the middle, causing a larger exit velocity and therefore more turbulent flow. The equations can then be used to determine head loss at any flow measured throughout a Permeafor test. For example, for the middle screen configuration and a flow of 231 in.^{3}/min (1 gal/min), equation 6 can be used to determine that approximately 190 in. (16 ft) of head loss would be incurred.

$$H_{L_{mid}} = 0.00196Q^2 + 0.567Q - 44.853 \tag{6}$$

$$H_{L_{tip}} = 0.00214Q^2 + 0.483Q - 29.210 \tag{7}$$

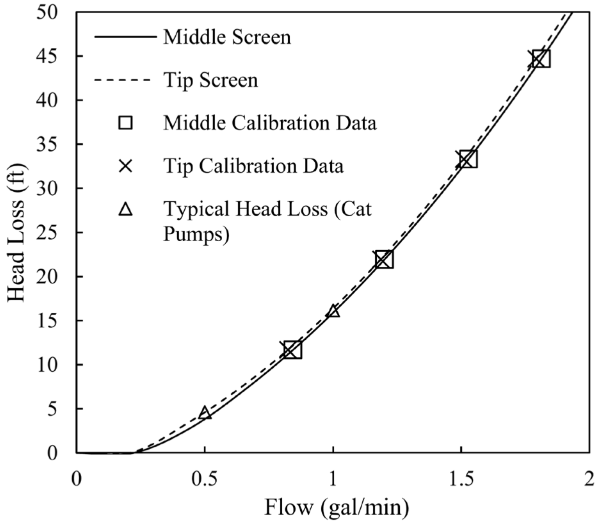


Figure 13. Flow vs Head Loss Calibration for Middle and Tip Screen Probe Configuration

In addition to the physical calibration of the permeafor, the flow of water through the soil must be laminar for proper evaluation of the hydraulic conductivity. The procedure and verification based on the effective grain size and Reynold's number are outlined in Wuebbolt (2020).

3. Data Reduction

To conduct a permeability test, probe advancement is stopped and total head at the probe is maintained constant while flow and pressure measurements are made. These measurements are typically continued for 15-30 minutes before removing the probe or continuing to the next test depth. Data collected at each test depth can then be used to determine Q/H' and ultimately estimate soil permeability.

3.1 Q/H' with Time

The first step of determining Q/H' at each recorded time interval is to convert measured pressure into head using equation 8.

$$H_m = \frac{P}{\gamma_w} \tag{8}$$

where: H = pressure head (cm)
P = measured water pressure (N/cm^2)
γ_w = unit weight of water (N/cm^3)

The effective head at time, t, can then be defined using equations 9, 10, 11, and 12 depending on the depth of the probe screen relative to the depth of the water table, d_w, as shown in Figure 14.

Case I: Probe above water table, $d - d' < d_w$

$$H(t,d) = H_m(t) + (d_s + d - d') \tag{9}$$

where: H_m (t)= measured pressure at each time step, converted to head (cm)

d = depth of probe tip from ground surface (cm)

d_s = distance between pressure sensor and ground surface (cm)

d' = distance between probe tip and middle of permeable screen (cm)

d_w = depth of groundwater table from ground surface (cm)

Case II: Probe below water table, $d - d' \geq d_w$

$$H(t, d) = H_m(t) + (d_w + d_s) \tag{10}$$

Using the applicable case:

$$H' = H(t, d) - H_L(t) \tag{11}$$

where: $H(t,d)$ = total head at time, t, and probe depth, d (cm)

$H_L(t)$ = head loss at time, t (cm)

$$H_L(t) = aQ(t)^2 + bQ(t) + c \tag{12}$$

where: a, b, and c = head loss coefficients

$Q(t)$ = measured flow with units corresponding to a, b, and c (cm^3/sec)

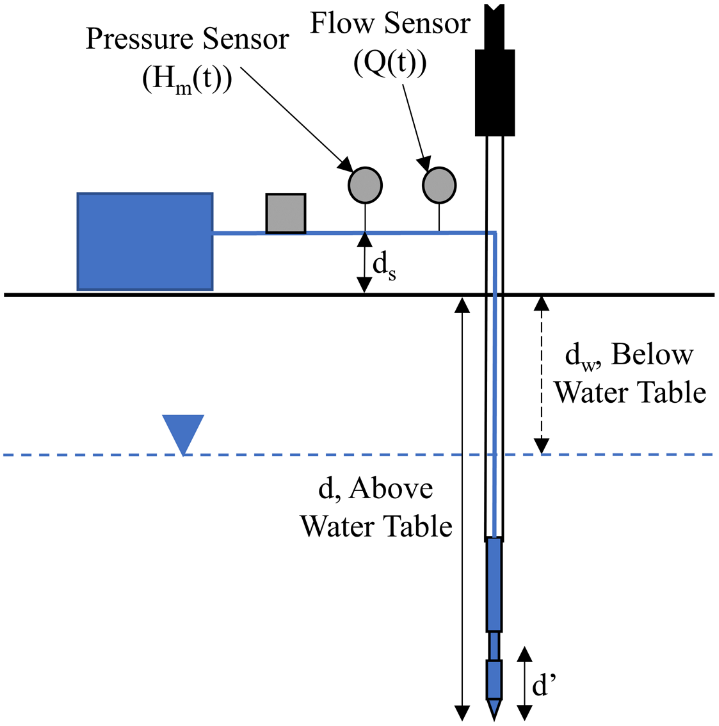


Figure 14. Head Measurements Needed to Determine Q/H'

The ratio of flow to effective head may then be determined using those values, with proper units, at each time step. Graphing these values allows for the changes in Q/H’ to be observed over the test duration. The two major characteristics that indicate a successful test are that the ratio Q/H’ becomes approximately constant over time, and that changes in applied head do not significantly affect the ratio as it stabilizes with time. If these characteristics are observed the constant Q/H’ value may be related to hydraulic conductivity using the methods discussed later in this report. A typical response of the recorded flow (Q) and effective head (H’) can be seen in Figure 16, which was recorded from the Kingston test site using the shorter middle screen permeafor configuration at 1.9 ft below the ground surface. The corresponding Q/H’ response over the duration of the test is also shown in Figure 15. The effective head typically increased over time because it is a function of the amount of flow, where head losses decrease as the flow decreases with time. Thus, the resulting response of Q/H’ typically followed a descending asymptotic trend.

3.2 Modification of Shape Factor

As previously discussed, the methods used to determine the shape factor for a Permeafor test were re-examined to assess which solution would be most applicable to the Permeafor test conditions. Unlike the borehole infiltration tests, the cavity created by the Permeafor does not have a permeable bottom as this face is blocked by the probe which continues beneath the cavity. Consequently, water can only flow out of the sides of the cylindrical cavity. As a result, the traditional formulas need to be adapted to this flow configuration by applying the modification proposed by Chapuis (1989). The shape factor modification can be used to represent a cylindrical cavity with an impermeable base by subtracting 2.75 from the original normalized shape factor, C/D. Furthermore, the method by Silvestri et al. (2013) is a more accurate representation of the actual shape factor for flow through a cylindrical cavity. This method uses an exact representation

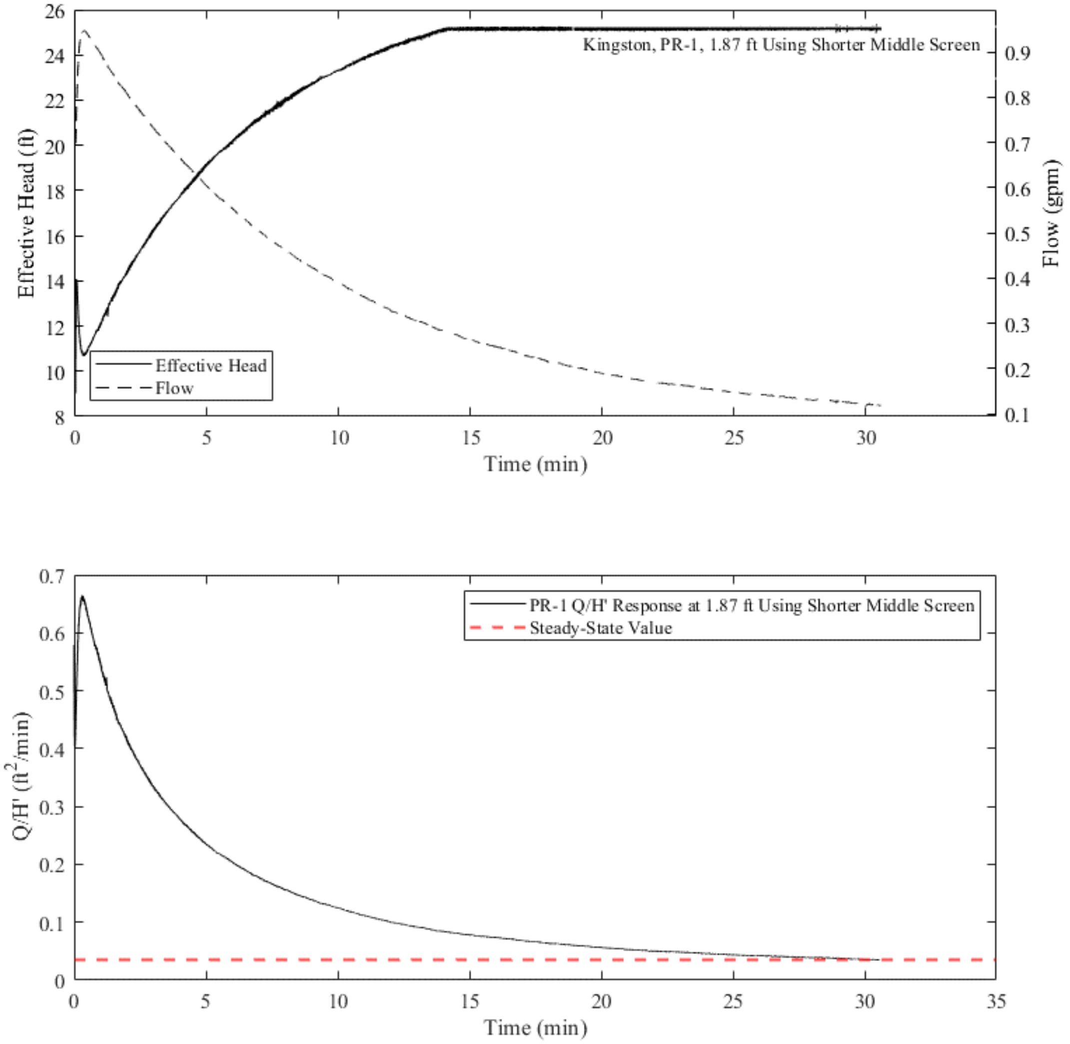


Figure 15. Example Flow and Effective Head, Kingston, PR-1, 1.9 ft Using Shorter Middle Screen and Corresponding Typical Q/H' Response, Kingston, PR-1, 1.9 ft Using Shorter Middle Screen

of the cylindrical shape instead of an approximated solution using an ellipse or sphere. By combining this expression with the modification for an impermeable base, a more appropriate normalized shape factor can be determined using equation 13. A modification of 2.8 instead of the 2.75 as suggested by Chapuis (1989) was used to reflect that the shape factor should be equal to zero when the aspect ratio (L/D) is equal to zero, as if the cylinder length is zero there is no permeable area for flow to occur. The resulting shape factor is defined in equation 14 and the normalized factor with respect to aspect ratio is shown in Figure 16.

$$\frac{C}{D} = \left(\frac{C}{D}\right)_A - \left(\frac{C}{D}\right)_B = \left(2.8 + 3.79\left(\frac{L}{D}\right)^{0.725}\right)_A - (2.8)_B \tag{13}$$

where: $(C/D)_A$ = original normalized shape factor by Silvestri et al. (2013)

$(C/D)_B$ = modification of normalized shape factor for impermeable bottom

$$C = 3.79D\left(\frac{L}{D}\right)^{0.725} \qquad 0 < \frac{L}{D} < 16 \tag{14}$$

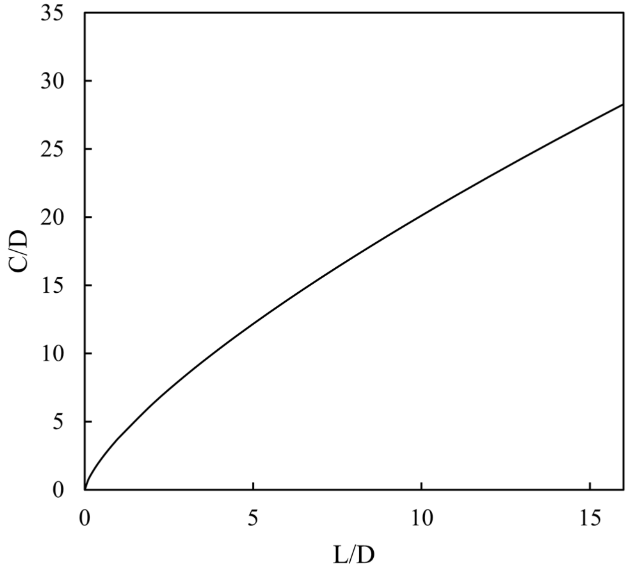


Figure 16. Modified Normalized Shape Factor for Determination of Hydraulic Conductivity

4. Testing Program

During the summers of 2019 and 2020, permeafor testing was conducted at six locations across New Hampshire: Newington, Ossipee, Merrimack (two different sites), Kingston, and Rochester.

For each test site, different test methods and probe configurations were used to evaluate the capability of the permeafor to estimate hydraulic conductivity. This includes the perforated screen configuration and location (mid-probe, L/D of screen and tip) and the test time. A summary with the geometric characteristics of each testing configuration is shown in Table 2.

4.1 Site Characterization

Various tests were conducted to classify the subsurface material present at each site. In situ samples were obtained through standard penetration testing (SPT), allowing for sieve analyses to be conducted in the laboratory. Specimens were created with these in situ samples, and laboratory constant head tests were performed using a custom mold. Details of these tests are described in further detail in Wuebbolt (2020) and Lefebvre (2021).

4.2 Soil Classification

The primary soil type tested across the six different test sites was sandy material, however, the amount of fines and coarse material varied across each site. These soil types ranged from silty sand (SM) to poorly graded sand (SP) with traces of gravel using the USCS classification. Figure 17 shows the combined grain size distribution for all six test sites. The average classification parameters for these sites are shown Table 3. It can be seen that the Ossipee site has the finest material with an average fines content of about 37%. The Merrimack sites had the coarsest material with an average fines content of about 5%. The majority of the test sites can be classified as poorly graded sand (SP) according to the USCS.

Table 2. Testing Characteristics for the Test Program

Site	Profile ID	Number of Tests	Screen Configuration	L/D	Maximum Depth (ft)
Ossipee	PR-3	4	Middle	1	23
Ossipee	PR-4	4	Middle	1	13.5
Ossipee	PR-5	1	Middle	1	13.5
Ossipee	PR-6	3	Middle	1	13.5
Ossipee	PR-7	6	Tip	-	13.5
Ossipee	PR-8	6	Tip	-	13.5
Merrimack- RT. 101A	PR-1	9	Middle	1	19.5
Merrimack- RT. 101A	PR-2	8	Middle	1	19.5
Merrimack- RT. 101A	PR-3	8	Tip	-	19.5
Merrimack- RT. 101A	PR-4	9	Tip	-	19.5
Merrimack- FE Everett	PR-1	6	Middle	1	13
Merrimack- FE Everett	PR-2	6	Middle	1	13
Merrimack- FE Everett	PR-3	6	Middle	2	13
Merrimack- FE Everett	PR-4	6	Tip	-	13
Kingston	PR-1	8	Middle	1	17
Rochester	PR-1	6	Middle	1	20.5
Rochester	PR-2	6	Middle	1	20.5

Table 3. Combined Average Site Classification Parameters

	Average Classification Indices					
Test Site	**Percent Fines (%)**	**D_{10} (mm)**	**D_{30} (mm)**	**D_{60} (mm)**	**C_U**	**C_C**
Ossipee	36.6	0.074	0.091	0.136	2.8	0.9
Merrimack- RT. 101A	3.4	0.178	0.350	0.633	3.5	1.5
Merrimack- FE Everett	6.3	0.144	0.260	0.503	3.4	0.3
Kingston	35.3	0.110	0.117	0.211	3.1	1
Rochester	22.9	0.071	0.177	0.757	6.5	1.1

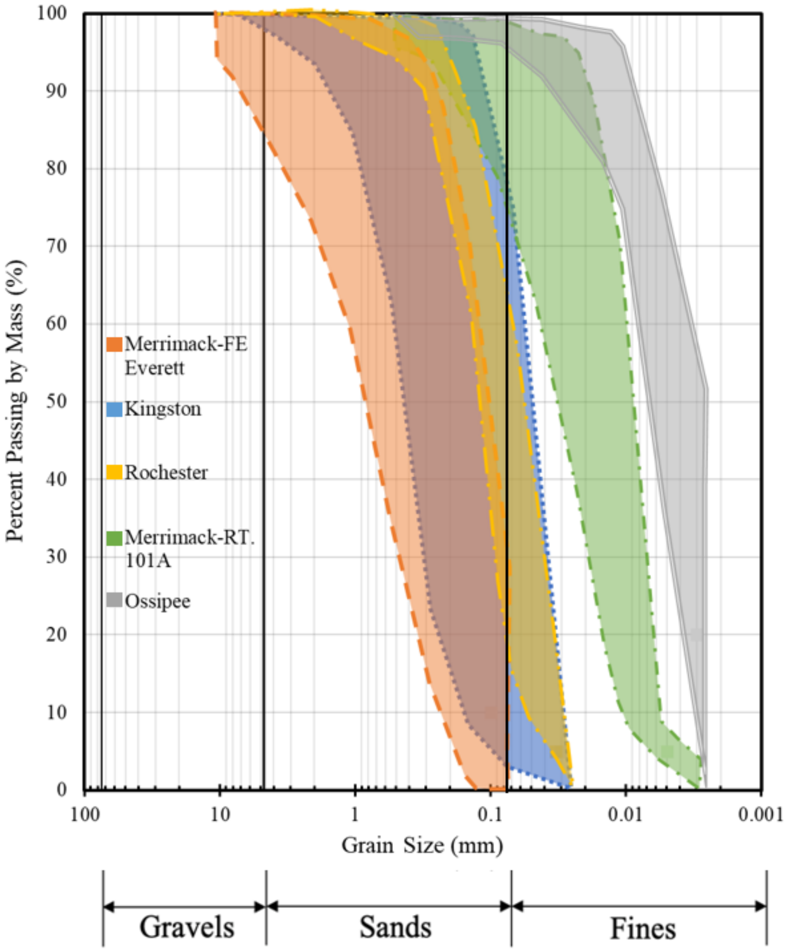


Figure 17. Combined Grain Size Distribution at Permeafor Test Sites

4.3 Test Method and Data Acquisition

In order to ensure that soil is not entering the probe or clogging the perforated section during penetration, flow of water is kept at a constant value of 0.2 gal/min during driving. Once the test depth has been reached, the pump control is switched from constant flow to constant pressure, at an initial value of 10 psi. The pump is capable of maintaining a constant pressure within ± 0.02 psi over the duration of the test. The beginning of the test is considered to be when the pressure reaches that initial value. Depending on the in-place deposit, the initial value is reached about 20 seconds after reaching the test depth. Once reached, the flow and effective head can be observed as shown in Figure 16. The graphs showed an initial spike which corresponds to the time it took for the initial pressure to stabilize.

Flow and effective head are recorded for approximately 10 to 30 minutes, with a typical test duration of about 15 minutes. The test is terminated when the response of Q/H' is nearly constant with time. This constant value is considered the steady-state flow condition and is used in evaluating the hydraulic conductivity.

4.4 Data Analysis

The flow to effective head ratio (Q/H') responses can be used to estimate hydraulic conductivity. The value at steady-state conditions suggests that the test cavity and the surrounding soil have been fully saturated, in cases above the water table, and have reached a constant state of flow, representing the in-situ flow characteristics of the soil. For tests below the water table, the steady-state condition represents equilibrium under the applied pressure. The graphs of Q/H' are used to estimate the asymptotic value and were shown as a red dashed line on Figure 16. Using this steady-state value, the hydraulic conductivity can be estimated using the relationship between Q/H', hydraulic conductivity, and the theoretical shape factor previously discussed in Section 3.2. and given in Equation 14. Using this shape factor, Equation 2 is used to estimate the hydraulic conductivity.

The tests presented on Figure 18 were obtained using the shorter middle screen, with the length to diameter ratio equal to one. This results in a shape factor for this configuration equal to 0.629 ft. For the typical Q/H' response shown on that Figure, the steady-state Q/H' value was found to be 0.036 ft^2/min, which resulted in an estimated hydraulic conductivity of 0.057 ft/min or 0.029 cm/sec. This estimated hydraulic conductivity aligns well with what is expected for that soil type at that test depth. These expected results were also found in cases where the Q/H' response did not follow a typical response, as long as steady-state condition was reached during the test.

Figure 18 shows Q/H' responses for all configurations of the permeafor screen at the same depth in adjacent boreholes. Each test used the same procedure where the pressure was kept constant at 10 psi, while the flow and effective head changes were observed for a time period between 14 and 20 minutes.

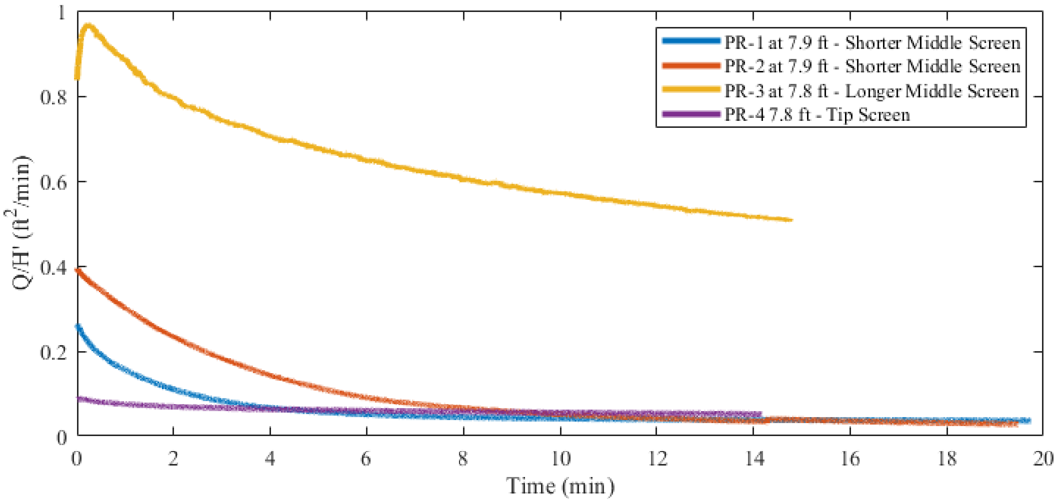


Figure 18. Merrimack-FE Everett, PR-1 through PR-4 Q/H' Response

It can be seen that all four screen configurations produced typical Q/H’ responses, consisting of a decreasing Q/H’ with time approaching a steady-state value. However, for the longer middle screen where the length to diameter ratio is equal to two, a steady-state value is not reached within the 14-minute test period. This larger perforated area requires a longer time for saturating the surrounding soil and reach equilibrium. Other tests with the longer screen produced similar trends with longer times to reach a steady-state Q/H’ value.

It can be observed that for the tip screen configuration there is minimal change of Q/H’ values over time suggesting that steady-state condition is approached almost immediately. While the tip screen configuration suggests a shorter required test time, the flow occurs mostly downward, and in a zone that is highly remolded from the advancing probe. Therefore, using the middle screen configurations allow for horizontal flow into the soil that is less influenced by the penetration and likely providing conditions more appropriate for evaluating hydraulic conductivity with the permeafor.

When observing the estimated hydraulic conductivity values based of these Q/H’ responses, the shorter middle screen and tip screen estimated similar values. However, all configurations are still within one order of magnitude of each other. When looking at the value estimated with the longer middle screen compared to the others, the value is higher due to the overestimation of the steady-state Q/H’ value. Due to this overestimation and the amount of time required to reach a steady-state condition, the use of longer middle screen with the length to diameter ratio equal to two was discontinued.

4.5. Results

Figure 19 shows a profile of hydraulic conductivity with depth using the estimate from the steady-state Q/H' value from each test. The range of values estimated from permeafor testing is outlined by the solid shaded region and the average of these values is represented by the solid black line. Also seen in this figure, are values other hydraulic conductivity estimates, such as the results from laboratory constant head testing and the range of hydraulic conductivities shown in the hashed region which were found from empirical grain size relationships. In addition, the graph on the right displays the permeafor driving resistance and is compared to the recorded SPT hammer strikes per 6 inches obtained from adjacent boreholes conducted by the NHDOT. Overall, the resistance to penetration is greater for the permeafor in part due to the larger projected area the permeafor and the longer soil contact with drill string above the probe.

The soil at the site is primarily classified as poorly graded sand, with a combination of medium to fine particles. Traces of silt were observed towards the bottom of the profile and gravel towards the top of the profile. Based on this soil type, the expected values for hydraulic conductivity should be in the range of 1 to 10^{-2} cm/sec. The estimated hydraulic conductivities from permeafor testing aligned well with this expected range, where the maximum estimated value was 0.474 cm/sec and the minimum value was found to be 0.007 cm/sec, across all tests. Measurements throughout the depth of the profile varied within one order of magnitude. This variability in values can be expected based on variations in the stratigraphy and soil densities.

The estimated hydraulic conductivity found through the different empirical relationships fall within the range of estimated permeafor hydraulic conductivities, while the values found from laboratory testing are consistently lower than the permeafor and the empirical methods. The reason for these differences is most likely due to the use of a smaller custom permeameter and variations in specimen densities, as described in Wuebbolt (2020). The specimens were reconstituted from samples obtained from the SPT testing and duplicating a density similar to the field conditions were difficult. The samples were also too small for standard testing. In addition, the relative density of the specimen varied up to approximately three and a half times greater than that of the in situ. Nevertheless, it follows the same general trend.

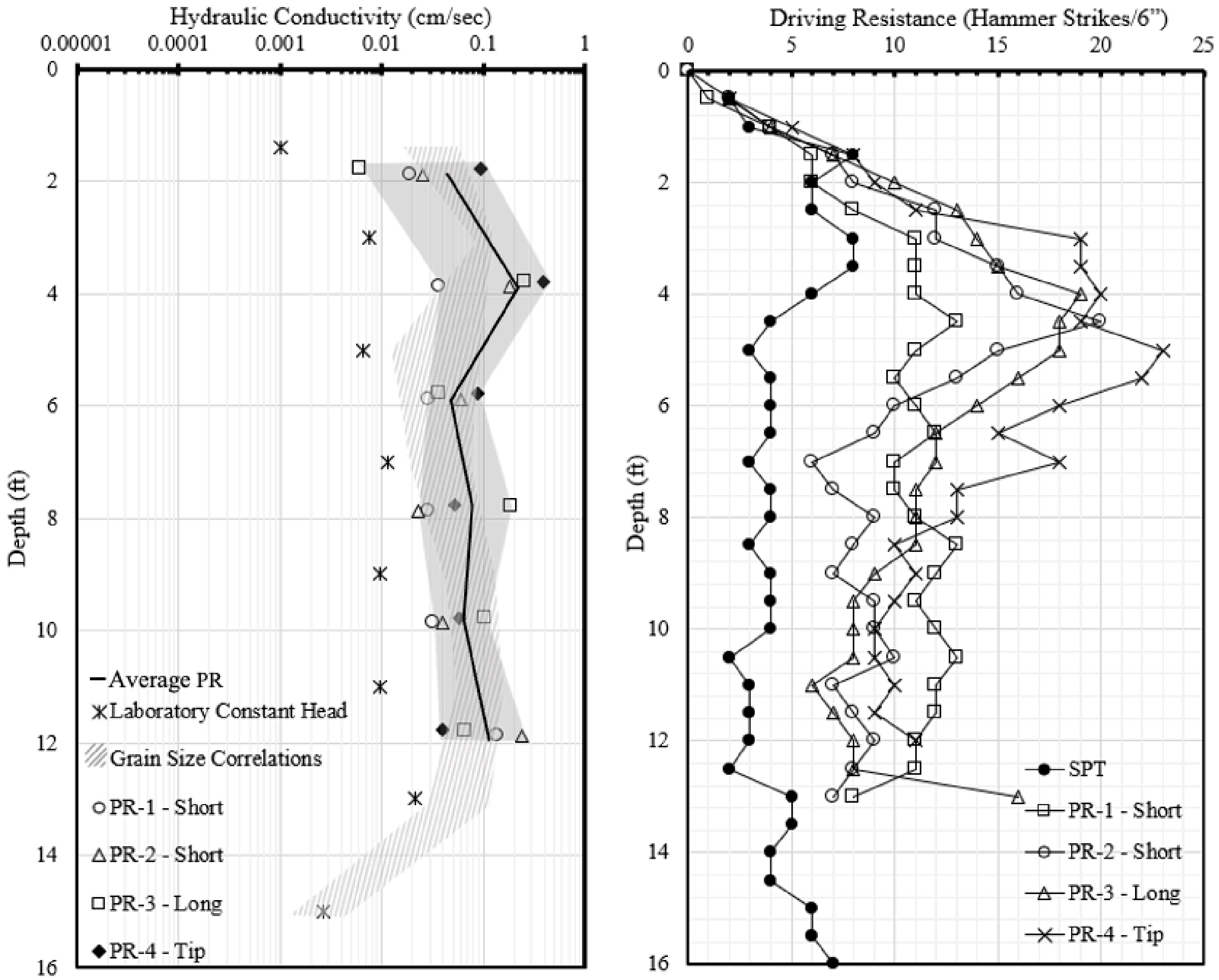


Figure 19. Merrimack-FE Everett, PR-1 through PR-4 Q/H' Response

5. Summary

The permeafor probe was originally designed in France to investigate relative permeability of soils in situ. Based on the existing design, a probe was built at the University of New Hampshire with some minor modifications to the equipment and test method. Using a conventional drill rig, the permeafor was evaluated at five sites across New Hampshire in profiles of granular soils. A total of 120 hydraulic conductivity tests in 20 profiles were completed by Wuebbolt (2020) and Lefebvre (2021) and used to develop a methodology to assess the permeability of soils in situ. Additional testing was carried out in 2021 in Dover, NH as training for the DOT personnel. The permeafor probe and supporting system used in this work was designed to withstand driving using an SPT hammer as well as being simple to use and operate in the field. Software was developed to perform the permeafor test and acquire pressure and flow data during penetration and testing. The system was designed to be user-friendly and to allow monitoring of all aspects of the permeafor test.

Using the ratio of measured flow to applied effective head (Q/H’), along with a theoretical shape factor, a relationship was developed to estimate the hydraulic conductivity. This ratio was obtained with the permeafor using an applied pressure and measuring the resulting flow with time until a steady-state condition was reached, indicating equilibrium and proper saturation of the surrounding test zone. Testing was conducted with three screen sections of varying length to diameter ratios to determine the optimal position for estimating the hydraulic conductivity. Tests were conducted in adjacent profiles at the same site to compare results from each probe configuration. Permeafor hydraulic conductivity estimates were compared to commonly used laboratory and in situ methods.

6. Conclusions

Based on the results from permeafor testing along with comparisons to other methods to measure hydraulic conductivity and finite element analyses, the following conclusions can be reached:

1. Hydraulic conductivity was successfully estimated through permeafor testing in silty sand (SM) to poorly graded sand (SP) where fines content varied from approximately 37% at the Ossipee site and about 5% at the Merrimack sites. The resulting permeabilities ranged from approximately 0.3 cm/sec to 1×10^{-3} cm/sec.
2. Results obtained from permeafor testing were in general agreement with estimates made using laboratory permeability tests and empirical relationships based on grain size and grain size distribution. Results aligned well with expected hydraulic conductivities based on soil classification.
3. Permeafor testing allows for faster and more reliable site estimates of hydraulic conductivity compared to the borehole infiltration test. A permeafor profile can be completed in a few hours while a profile completed using the borehole infiltration method can take several days.
4. Permeafor results with the three probe configurations compared well to each other with values within one order of magnitude. Results were shown to be repeatable regardless of probe configuration.
5. Values of Q/H’ with time showed similar responses during all tests consisting of a logarithmic path that approached an asymptotic steady-state value over time. While most tests approached an approximate steady-state condition, the longer middle screen with a length to diameter ratio of two, required a longer test interval to reach that state. It was determined that the middle screen with an L/D of 1 should be used based on the shorter test duration.

6. The shape factor proposed by Wuebbolt (2020), a combination of proposed factors by Silvestri et al. (2013) and Chapuis (1989), was determined to be the most appropriate for permeafor testing.
7. Permeafor testing designed to study the influence of injected hydraulic pressure on the resulting hydraulic conductivity did not seem to affect the resulting estimates. Increasing the injected hydraulic pressure through various increments over time at the Kingston site, and decreasing the hydraulic pressure at the Rochester site, did not appear to influence the estimated hydraulic conductivity.

The results of this research study suggest that the permeafor is capable of rapidly and accurately estimate hydraulic conductivity in situ. Other methods such as borehole infiltration testing are slow and provide limited data to support the required permeability measurements needed for design of BMPs.

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