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Profiling hydraulic conductivity using a Permeafor

Profilage de la conductivité hydraulique à l'aide d'un Permeafor

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ABSTRACT: The emerging need in geotechnical and geoenvironmental engineering to more quickly and accurately profile hydraulic conductivity in situ has led to further developments of a tool known as the Permeafor. An instrument originally developed in France to measure relative permeability in situ, the Permeafor has since been adapted to directly estimate hydraulic conductivity. The instrument, fabricated at the University of New Hampshire, consists of a cylindrical probe approximately 0.75 m long and 50 mm diameter with a 50 mm long recessed perforated section used to inject water into the soil as the probe is driven into the ground. At specific test depths, the probe is stopped and water is allowed to percolate into the soil at controlled pressure head or flow. Measurements made during a 15 to 30 minute test period can be used to establish a relationship between the rate at which water flows into the soil and the applied effective hydraulic head. This relationship, expressed as a ratio, can be correlated to hydraulic conductivity using a theoretical shape factor. This paper presents the Permeafor design, the supporting equipment and control software, the typical test method, and an example of results obtained from use at a test site in New Hampshire, USA.

RÉSUMÉ : Le besoin émergent en génie géotechnique et géoenvironnemental de connaître plus rapidement et plus précisément le profil de la conductivité hydraulique in situ, a conduit à de nouveaux développements d'un outil connu sous le nom de Permeafor. Instrument développé à l'origine en France pour mesurer la perméabilité relative in situ, le Permeafor a depuis été adapté pour estimer directement la conductivité hydraulique. L'instrument, fabriqué à l'Université du New Hampshire, se compose d'une sonde cylindrique d'environ 0,75 m de long et 50 mm de diamètre avec une section perforée en léger retrait de 50 mm de long utilisée pour injecter de l'eau dans le sol lorsque la sonde est enfoncée dans le sol. À des profondeurs d'essai spécifiques, la sonde est arrêtée et l'eau peut s'infiltrer dans le sol à une pression ou un débit contrôlé. Les mesures effectuées pendant une période d'essai de 15 à 30 minutes peuvent être utilisées pour établir une relation entre la vitesse à laquelle l'eau s'écoule dans le sol et la charge hydraulique effective appliquée. Cette relation, exprimée sous forme d'un rapport, peut être corrélée à la conductivité hydraulique à l'aide d'un facteur de forme théorique. Cet article décrit la conception du Permeafor, la méthode d'essai typique, l'équipement complémentaire et le logiciel de contrôle, et un exemple de résultats obtenus à partir d'une utilisation sur un site d'essais au New Hampshire, USA.

KEYWORDS: Hydraulic Conductivity, In Situ Testing, Permeafor.

1 INTRODUCTION

Assessment of soil permeability using the Permeafor is a relatively recent development in the field of in situ testing. The instrument, originally built and tested in Strasbourg, France in the early 1980s, was designed to measure relative horizontal hydraulic conductivity profiles.

The tool consists of a hollow perforated probe equipped with a conical tip that is driven into the ground while water is simultaneously injected into the surrounding soil. 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. Figure 1 outlines the fundamental configuration and intended use of the Permeafor.

The Permeafor is essentially a borehole permeability test but driven into the ground and with flow restricted to the horizontal direction. At the depth of water injection, measurements of flow and water pressure through the soil are used to estimate permeability by relating flow to the applied effective head at the depth of the screen. This relation is expressed using a ratio of flow to the applied effective head, or Q/H', where Q is the measured flow and H' is the effective head

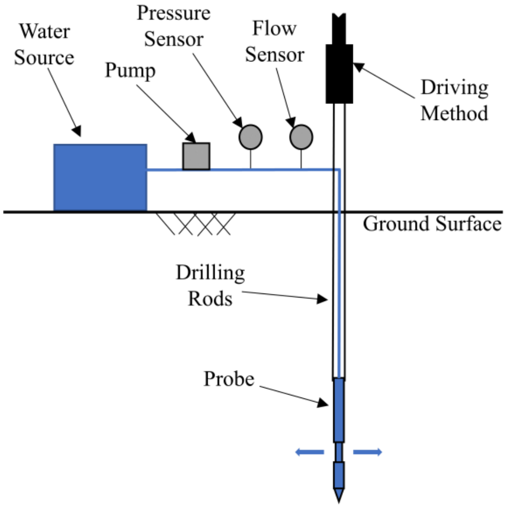

Figure 1. UNH Permeafor test schematic.

at the screen, accounting for all head losses. 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 this relationship may be used to estimate the permeability of soil, where a large flow and small pressure would indicate a permeable soil and a small flow and large pressure would indicate a less permeable soil. Results from research completed in France by Reiffsteck et al. (2009) have shown that the Permeafor is especially useful in detecting variations of soil permeability with respect to depth, where the tool was shown to be capable of obtaining a profile of relative soil permeability with good resolution in a relatively short amount of time. However, all iterations of the French Permeafor design have aimed to determine a relative indication of soil permeability rather than the soil property of hydraulic conductivity (Wuebbolt 2020).

Work completed at the University of New Hampshire (UNH), USA, aimed to investigate the ability of the Permeafor to accurately and consistently assess hydraulic conductivity. In 2008 a small scale model of the French Permeafor was constructed and tested in the laboratory and in situ at UNH by Larrabee (2010). Work completed using the small scale probe was useful in verifying the principles of the Permeafor as well as to identify potential issues for future work (Larrabee et al. 2012). In 2018 a full scale Permeafor similar to the French model was constructed and tested at three sites in New Hampshire, USA, by Wuebbolt (2020). Analysis and comparison of the test results from these sites to commonly accepted laboratory and in situ methods of measuring hydraulic conductivity suggested that the Permeafor model used in this research is capable of assessing the horizontal hydraulic conductivity of soils. Further verification testing of the Permeafor is currently being completed at UNH.

2 PERMEAFOR

The Permeafor built at UNH in 2018 was based on the existing French Permeafor probes and supporting equipment. The UNH instrument and support system was constructed considering several important design features. The tool needed to be simple to use in daily geotechnical testing practice as well as reliable and adaptable to various soil conditions.

2.1 *Probe*

The Permeafor probe is a hollow metal cylindrically shaped tube that consists of a conical tip and recessed perforated screen. The conical tip facilitates penetration of the probe into most soils using conventional geotechnical drilling methods. The probe is designed with tapered sections above and below the recessed perforated section to isolate flow to primarily the horizontal direction by preventing flow up or down along the soil-probe interface. Various probe configurations have been used, most commonly with variations of the diameter of the permeable screen: for example probes with screens of 40 mm, 50 mm, and 70 mm diameter (Ursat and Hervé 2002). A more recent design by Reiffsteck et al. (2009) also allowed the injection of water at the tip, with later iterations by Reiffsteck et al. (2010) incorporating a CPT cone to aid in soil classification.

The probe is approximately 700 mm long with a maximum and minimum diameter of 70 mm and 44 mm, respectively. The length of the screen and diameter of the test cavity is 50 mm and 52 mm, respectively, and the end of the probe includes a threaded removable conical tip. Much of the UNH probe design is similar in dimensions to the French version 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 another 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). The middle and tip screen configurations are shown in Figures 2 and 3, respectively.

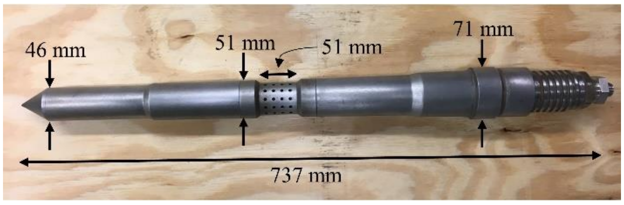

Figure 2. Middle screen configuration with dimensions.

Figure 3. Tip screen configuration with dimensions.

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 quick connect Swagelok fitting that connects the flexible tubing which directs supplied water to the probe screen. The flexible tubing runs inside the drilling rods to keep it protected from damage during probe advancement and exits at the ground surface through a short slotted section of rod. 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. (Wuebbolt 2020).

In addition to the location of the screen, the ratio of screen length to test cavity diameter (L/D) is also different. This aspect ratio defines the geometry and extent of flow through the soil, and therefore it is important when determining the shape factor which relates test measurements to hydraulic conductivity.

2.2 *Testing procedures*

To complete a Permeafor test, the probe must first be advanced to a given depth using either percussion or direct push drilling methods. Throughout the advance, water is directed to the probe at a pressure sufficient to maintain flow through the perforated screen to prevent potential clogging of the screen from accumulated soil particles. This water is supplied from the surface to the probe using a tank open to atmospheric pressure. Pressure and flow rate are controlled and measured as water is directed down to the probe through the flexible tubing that runs inside the drilling rods. After probe advancement has been halted, permeability may be estimated by observing water infiltration into the soil through a screened section mid-probe or at the tip. Testing completed by Wuebbolt (2020) demonstrated that a single hydraulic conductivity test could typically be completed in 15 to 30 minutes. Therefore, a profile of hydraulic conductivity with depth may be quickly generated by simply advancing the probe to the next desired depth and repeating the test.

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. The accumulation of effective head throughout the process for the below water level condition is described in Figure 4.

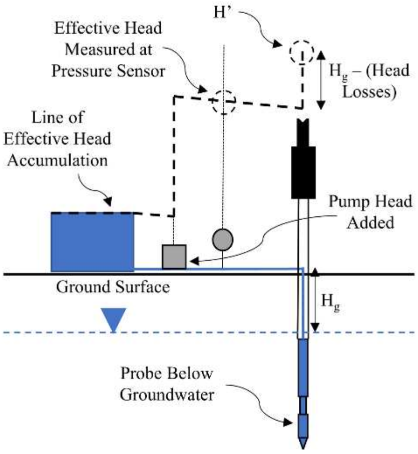

Figure 4. Accumulation of effective head throughout Permeafor system

For both the middle and tip screen configurations, soil is displaced as the probe is driven or pushed, with its tapered shape creating zones of disturbed and expanded soil conditions. The diameter of the upper tapered section of the probe is such that it creates a cavity of approximately double the cross-sectional area of the smallest diameter of the probe, at the tip. This doubling of cavity area is associated with the limit pressure of the soil (a threshold commonly used in pressuremeter practice), and therefore the layer of soil immediately surrounding the probe is densified and the permeability of that soil potentially decreases, forcing the flow to remain at and below the screened section. Due to this, when the screen is located at the center, flow out will be primarily in a horizontal radial direction as vertical flow along the probe is less likely. However, when water flows out of the probe close to the tip, less restrictive soil displacement below the cavity is likely to have occurred. Therefore, water is more free to travel horizontally and vertically, in a fan-like shape (Wuebbolt 2020).

2.3 *Supporting Equipment*

The system to regulate and measure test parameters that was built at UNH in 2018 was developed based on the principles established for the French Permeafor. The system, annotated in Figure 5, 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.

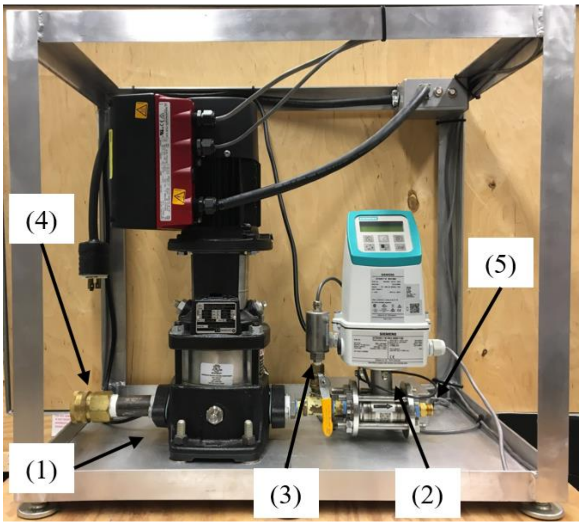

Figure 5. Acquisition and control system (pump, pressure sensor, inlet quick connect, and outlet quick connect, respectively).

The pump, made by Grundfos, is controlled by a variable frequency drive (VFD) which allows for precise speed adjustments. The pump was selected so that pressure and flow could be increased, decreased, or maintained constant as needed and in real-time during testing. 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 has been used to power the system. A 1-inch (25.4 mm) diameter hose was used to connect a 380 liter heavy duty plastic water supply tank to the system inlet using quick connection fittings (4) at either end. At the system outlet, a Swagelok fitting (5) was used to facilitate the connection to the probe using flexible tubing. Supporting system instrumentation specifications are summarized in Table 1 (Wuebbolt 2020).

Table 1. Permeafor instrument specifications.

Instrument	Flow Sensor	Pressure Sensor	DAQ
Output	Frequency Signal	Analog Voltage	N/A
Output Range	0-500 Hz	1-11 VDC	N/A
Measurement Range	0.129-7.6 l/min	0-690 kPa	N/A
Error (±)	0.032 l/min	6.9 kPa	0.61 mVDC

Voltage signals received by the DAQ are converted by LabVIEW, a system development platform produced by National Instruments. The incoming signal is sampled at a rate of 5000 Hz over a duration of 0.2 seconds, obtaining groups of 1000 samples. From each group of samples, a frequency rate from the flow sensor output is determined using fast Fourier transform methods. From those samples, an average signal from the pressure sensor is also determined. These reduced frequency and voltage measurements are then converted to flow and pressure at a rate of 5 Hz. Each set of flow and pressure is then recorded as a function of time. Concurrently to this, test events are recorded according to the orientation of switches located on the graphical interface of LabVIEW, indicating the times at which probe driving or testing begins and ends. 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. Figure 6 outlines this flow of data (Wuebbolt 2020).

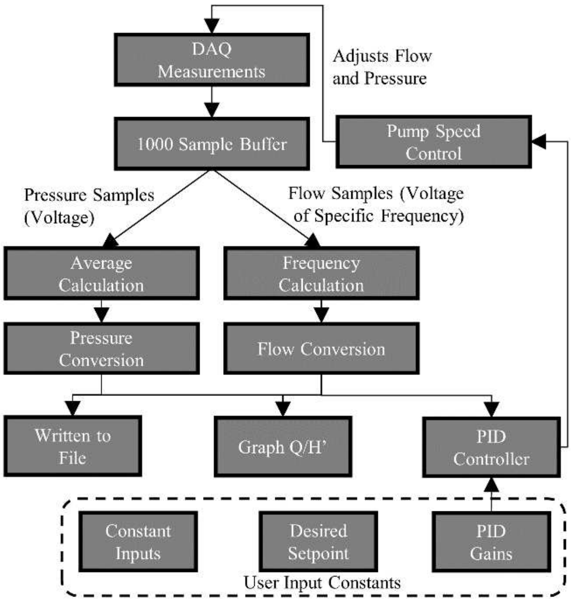

Figure 6. Permeafor test data logic.

2.3.1 *Calibration*

To determine the effective head measurement needed for the assessment of hydraulic conductivity, a calibration must be completed to determine system head losses throughout testing. Head losses through the system are primarily due to the pump, the long and small diameter tubing that directs water to the probe, and the probe itself. However, head losses through the entire system can be simplified to only those downstream of the pressure sensor, as this sensor directly measures effective head at that point.

The calibration is completed by obtaining two sets of four measurements; head loss under different constant heads and, measured flow under the same applied constant heads. Head loss under a constant head may be determined in the laboratory by measuring the height that water is ejected from the flexible tubing under any four applied hydraulic heads. In this situation, if head losses from flow through the tubing were equal to zero the height of ejected water would be equal to the applied hydraulic head. Therefore, the difference between the applied hydraulic head and the ejected height of water will provide the amount of head lost from flow through the tubing. An example Permeafor head loss calibration is provided in Figure 7 (Wuebbolt 2020).

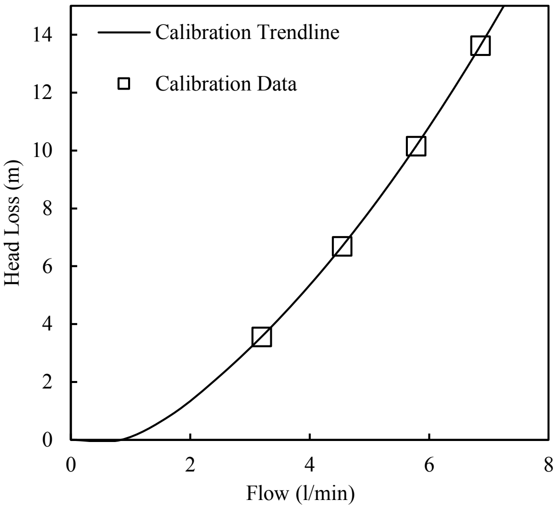

Figure 7. Permeafor head loss calibration.

3 PERMEAFOR TESTING

To complete a Permeafor hydraulic conductivity test, the probe must first be advanced to the desired depth. During probe advancement, the Permeafor control system is used to maintain a constant flow and the flow rate is monitored to ensure it does not go to zero. Once the test depth is reached, the control system is used to set a constant pressure value and approximately 25 to 30 seconds is allowed before recording the test response, while the system water pressure stabilizes. After the pressure has stabilized, measurements of flow and effective head are made for approximately 15 to 30 minutes. A typical test response can be seen below in Figure 8.

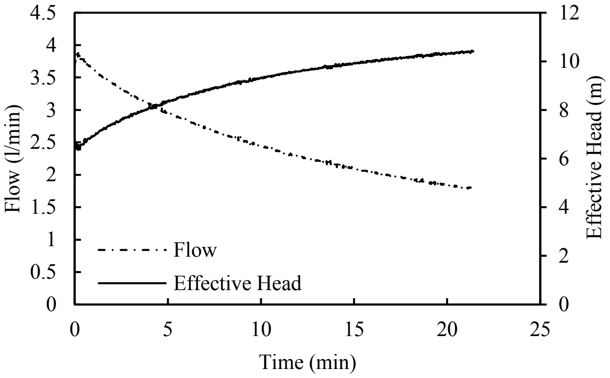

Figure 8. Typical flow and effective head response

As shown in Figure 8, measured flow decreases while effective head increases until each curve approaches an asymptotic steady-state value. A similar logarithmic response is observed when these two parameters are combined to determine Q/H', as demonstrated in Figure 9.

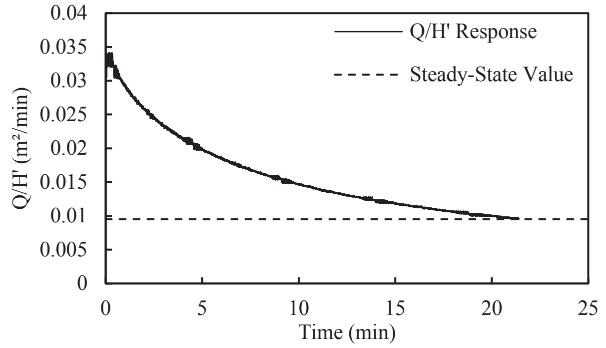

Figure 9. Typical Q/H’ response

Once a steady-state value of Q/H’ has been reached, this value and a theoretical shape factor based on the probe dimensions, C, can be related to hydraulic conductivity, k, according to Equation 1.

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

Field use of the Permeafor by Wuebbolt (2020) has shown that test responses typically follow this general trend. However, though the shape of these responses is typical, the change in magnitude from start to finish and the time required for that change to occur is less consistent. As suggested by Wuebbolt (2020), characterization of the general trend of Q/H’ may allow for a standardized method of determining a steady-state Q/H’ value. Standardization would lead to a less subjective result as well as the possibility that steady-state Q/H’ could be determined over a shorter test period using extrapolation of the trend.

Analysis and comparison of Q/H’ and hydraulic conductivity results by Ursat et al. (1989) and Wuebbolt (2020) has also demonstrated that the application of different injection heads during the same test will have little effect on Q/H’ values and associated hydraulic conductivities. As described by Darcy’s law, hydraulic conductivity is a soil property that should not be influenced by test conditions, given that flow occurs in the laminar region and soil structure and density is unchanged due to the flow. Therefore, this result should be expected when determining hydraulic conductivity experimentally.

3.1 *Test Results from Ossipee, NH, USA*

Field and laboratory hydraulic conductivity test results from soils approximately 1 meter to 4 meters below the ground surface obtained by Wuebbolt (2020) at a site in New Hampshire, USA are shown in Figure 10. The site consisted of primarily granular soils and the groundwater table was located approximately 1.5 meter below the ground surface. Five Permeafor profiles of hydraulic conductivity with depth were obtained. Permeafor profiles 1, 2, and 3 were completed using the middle screen probe configuration, shown in Figure 2, and Permeafor profiles 4 and 5 were completed using the tip screen configuration, shown in Figure 3. The Permeafor results are also compared to two laboratory and one in situ method of assessing hydraulic conductivity; empirical grain size correlations to hydraulic conductivity, provided as a range of values, laboratory constant head testing, and two borehole infiltration tests, respectively.

As shown in the figure, Permeafor hydraulic conductivity estimations using the same probe configuration at the same depth generally differed by less than one order of magnitude, indicating good repeatability of the tool. Additionally, varied comparability between Permeafor, laboratory, and borehole infiltration test results may indicate that Permeafor hydraulic conductivity testing is, in spite of disturbance from probe insertion, more accurate and consistent than laboratory and borehole infiltration testing. As shown, the most significant difference between the Permeafor and comparison method results can be observed at depths above the water table, however field use of the Permeafor by Ursat and Hervé (2002) and additional use of the Permeafor by Wuebbolt (2020) have suggested that soil saturation has little effect on Permeafor results, provided the test is carried out to a steady-state Q/H’ value. The difference between the results can be better explained by considering that Permeafor testing is carried out in situ and therefore involves a much larger and less disturbed volume of soil than is used for laboratory testing. Furthermore, the test includes more instrumentation and potentially fewer sources of soil disturbance than commonly used borehole infiltration test methods.

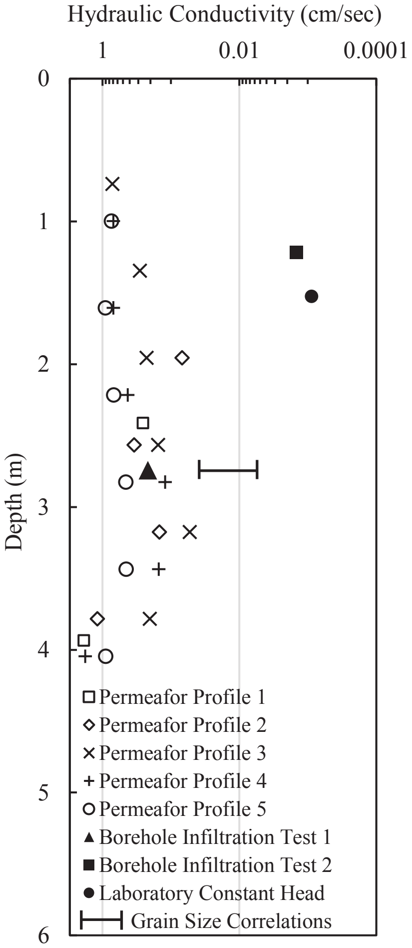

Figure 10. Example Permeafor hydraulic conductivity results.

4 CONCLUSIONS

Use of the Permeafor probe, supporting system, and operating software designed and built at UNH in 2018 has demonstrated that the tool is capable of obtaining profiles of hydraulic conductivity in a relatively short time. Repeated application of the tool has also demonstrated it to be reliable, rugged, and easy to use. Analysis of results obtained by Wuebbolt (2020) and Ursat et al. (1989) has demonstrated that Permeafor hydraulic conductivity measurements are independent of applied testing conditions and therefore are only influenced by the in situ conditions of the soil being tested. Comparison of results obtained by Wuebbolt (2020) to those of commonly used laboratory and in situ methods has also demonstrated that these hydraulic conductivity estimations are reasonable and repeatable. These conclusions demonstrate that work completed from the early 1980s to the present has established the Permeafor as a viable solution to consider when assessing the hydraulic conductivity of soils in situ.

5 ACKNOWLEDGEMENT

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