Development and Testing of a Multiflow In Situ Permeameter

Clifton B. Farnsworth[1]; Steven F. Bartlett[2]; and Evert C. Lawton[3]

[1]Assistant Professor, Brigham Young Univ., Construction Management, 230 SNLB, Provo, UT 84602.
[2]Associate Professor, Univ. of Utah, Civil and Environmental Engineering, 110 Central Campus Dr., Suite 2000, Salt Lake City, UT 84112.
[3]Professor, Univ. of Utah, Civil and Environmental Engineering, 110 Central Campus Drive, Suite 2000, Salt Lake City, UT 84112.

Abstract: The horizontal permeability of thinly bedded foundation soils is one of the primary factors that controls the time-rate of consolidation during embankment construction. This paper explores using a tri-element water source housed in a push-in CPT permeameter device to measure the in situ horizontal permeability of thinly bedded sediments. As constant water pressure is applied, horizontal radial flow is achieved in the middle element because its flow is constrained by the parallel flow from the above and below elements. This effect eliminates any tendency for immediate vertical flow from the middle element and allows for direct measurement of the horizontal permeability using the flow equations derived for steady-state radial flow to a fully penetrating well. Although this paper explores the use of this concept for obtaining design properties for time-rate of consolidation calculations for low permeability soils with prefabricated vertical drains, this concept may also be utilized for any thinly bedded sediments where obtaining the true horizontal permeability of the soil is required, such as environmental and ground water assessments.

INTRODUCTION

Constructing large embankments, or other heavy structures, atop soft, thick compressible soils can introduce large primary consolidation settlement with lengthy settlement durations. For urban environments, rapid construction techniques are often used to lessen the construction time, thus minimizing public impacts and generally decreasing the overall cost of the project. Prefabricated vertical (PV) drains are often used to accelerate the rate of primary consolidation settlement in low permeability soils. PV drains are pushed into the foundation soils and allow for the relief of excess pore pressure due to drainage that occurs primarily in the horizontal direction. Because the drainage path has been shortened, the elapsed time to reach end of primary consolidation settlement is greatly accelerated. Therefore, characterization of the horizontal drainage properties of the foundation soils is vital for estimating the settlement duration for PV drain treated soils. This paper introduces a new in situ technique for directly measuring the horizontal permeability of the soil using a tri-element CPT permeameter device.

IN SITU PERMEABILITY DEVICES

Measuring soil permeability has a number of limitations. While standard laboratory tests measure the permeability in a single direction (typically vertical), CPTU and other in situ tests tend to measure the permeability in a spherical direction. In situ permeability tests often measure higher than laboratory tests because in anisotropic soils in situ tests more closely measure horizontal permeability, which is usually higher due to the soil fabric. Also, permeability measured in the laboratory is often influenced by the small size of the specimen (Andresen 1981). However, in situ devices are not without their limitations. Soil disturbance can occur from the drilling or direct-push process. In addition, the initial state and boundary conditions of such tests are less understood; thus, they can be theoretically more difficult to interpret.

Several types of devices have been developed for measuring soil permeability in situ. Pore pressure probes were developed by both Torstensson (1975) and Wissa et al. (1975). These allowed for estimating permeability continuously with depth, by the application of the analytical solution for the rate of excess pore pressure dissipation (Andresen, 1981). Later this type of device was coupled with the standard CPT, now commonly known as the piezocone. The pore pressure probe has largely been superseded by the piezocone (Meigh, 1987), and the resulting test is identified as the CPTU pore pressure dissipation test. This test is a common in situ technique for estimating soil permeability and there is a great deal published on this method.

Other methods for measuring in situ permeability have also been developed. Andresen (1981) performed in situ permeability testing for soft clays using hydraulic piezometers. The piezometer is directly pushed through the soil to the desired depth and a permeability test conducted. A self-boring permeameter was developed by Jezequel and Mieussens (1975) to further minimize disturbance resulting from pushing the piezometer through the soil. A similar device is described in Hawkins and Whittle (2012). Konrad and Frechette (2000) developed a peizocone-permemeater probe to obtain in situ hydraulic conductivity profiles in sands and silty sands. This device included a small injection zone located in the steel rod behind the piezocone filter element to conduct falling and constant head permeability tests. Unfortunately, the in situ values of hydraulic conductivities measured with this device were on average an order of magnitude lower than those obtained from field pumping tests or laboratory tests on reconstituted samples. The U.S. Department of Energy (2002) developed the Cone Permeameter™ for environmental restoration projects, a device based on assumed spherical flow geometery (Lowry et al., 1999). Fluid was injected into the surrounding soil and a spherical flow field developed as the fluid moved away from the rod. Measuring the pressure gradient at a distance from the injection point produced adequate information to infer the permeability (U.S. Department of Energy, 2002).

The inherent problem with many of the devices briefly introduced above is that isotropic soil conditions must be assumed. It is recognized that most of the testing described has been for environmental applications in porous media where isotropic conditions may be more prevalent. Unfortunately, these devices would not adequately capture the true horizontal drainage properties due to the presence of vertical drainage exhibited at the boundary of the flow regime. Although in situ permeability testing is not a new concept, it is also not currently a standard test available from the direct push CPT platform. Previous research has primarily focused on measuring the permeability in sands, thus assuming isotropic soil conditions, or maintaining a long injection zone so that vertical drainage effects are negligible.

The method for measuring in situ horizontal permeability proposed in this paper is to use a tri-element multiflow permeameter, as shown in Fig. 1. The top and bottom elements are fed by a different water supply, thus eliminating the edge effects for the center element and constraining the flow to a near horizontal direction. This concept has the capability of being utilized in conjunction with the CPT platform, and this research was conducted on such a device. The two major benefits of using a tri-element device are: 1) true horizontal permeability of the soil is measured directly in situ and 2) by constraining the flow in the center element to true horizontal flow, a fairly small soil layer may be targeted. This becomes valuable when characterizing thinly bedded layered deposits of alternating clays, silts, and sands.

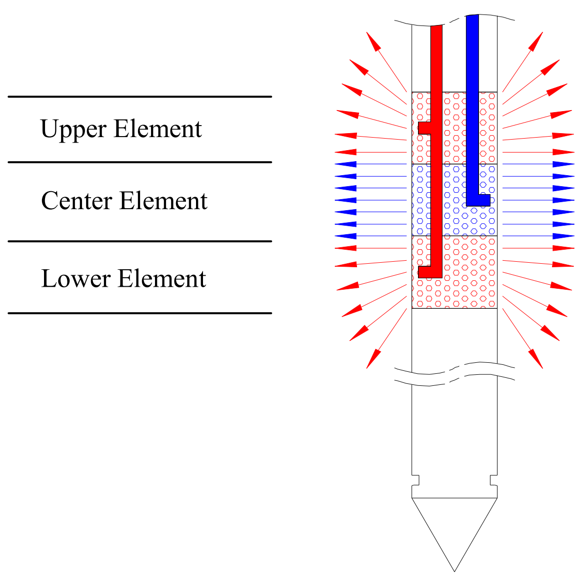

FIG. 1. Conceptual in situ permeameter with dual water sources.

MEASURING HORIZONTAL PERMEABILITY

Permeability tests conducted on soil generally include the constant and falling head tests. The constant head test assumes that a steady state condition has been reached, whereas the falling head test is for transient flow conditions. The constant head permeability test is easier to interpret, but achieving steady state conditions in a low permeability soil requires time. The permeability calculation for a constant head test is based on Darcy's law. When dealing with in situ radial flow, the distribution of the hydraulic gradient changes spatially from the element, because the contributing flow area increases with increasing radius. However, if the element is the same thickness as the layer and the layer is confined on top and bottom, then the horizontal permeability, k_h, is calculated from:

$$k_h = q \ln(R_o / r_w) / 2 \pi L H_c \tag{1}$$

where q is the flow rate, R_o is the effective radius of influence at constant head, r_w is the radius of the filter, L is the length of the filter element, and H_c is the constant piezometric head. This equation is used to represent confined flow to a fully penetrating well. Although the flow from the center element remains confined for a certain distance, the flow regime from all three elements behaves more like the flow from an in situ pressure test using packers. Therefore, the equation governing this type of flow would better estimate the horizontal permeability of the soil. The U.S. Bureau of Reclamation (1968) identified formulas used to compute the permeability from in situ pressure test data:

$$k_h = q \ln(L / r_w) / 2 \pi L H_c \qquad \text{for } L \geq 10r_w \tag{2}$$

$$k_h = q \sinh^{-1}(L / 2r_w) / 2 \pi L H_c \qquad \text{for } 10r_w > L > r_w \tag{3}$$

Lowe and Zaccheo (1991) acknowledge that these formulas only provide approximate values of k, because they are based on several simplifying assumptions. However, they further note that the formulas give values that are suitable for practical purposes. Eq. (3) then best represents the steady state flow condition established in the center element with a tri-element multiflow permeameter.

NUMERICAL MODELING OF MULTIFLOW PERMEAMETER

Finite element modeling was performed to explore the theoretical flow paths of the multiflow permeameter and to establish that the multiflow concept was capable of establishing purely horizontal flow through the center element. A finite element software program developed specifically for analyzing groundwater seepage within porous materials (such as soil) was utilized. A two-dimensional axisymmetric finite element model was created to analyze the permeameter for the proposed prototype dimensions and testing conditions. Initially the model was used to explore how the magnitude of applied pressure affected the distance of horizontal flow in a soil profile with a vertical hydrostatic gradient. The lengths of the proposed filter elements were 50 mm for the center element and 25 mm for the top and bottom elements, with a 3-mm separation gap included between each element.

Modeling with a wide boundary showed that the achievement of perfect horizontal radial flow is only necessary for several centimeters beyond the probe to provide an accurate calculation of the horizontal permeability for fine grained soils. The length of the effective radius of influence at constant head, R_o, is predominantly a function of the applied pressure. At very low head (e.g., 0.7 kPa), the effective radius of influence for fine-grained soils is approximately 100 mm. As the applied pressure increases the effective radius of influence also increases, such as 430 mm at 70 kPa. However, the practical radius of influence for dissipation of at least 85% and 90% of the applied pressure occurs at radial distances of approximately 50 mm and 70 mm, respectively, for fine-grained soils. This means that the effective radius of influence for dissipation of at least 85% of the applied pressure in fine-grained soils occurs at a radial distance approximately equal to the length of the filter element. Therefore, the effective radius of influence, R_o, can be approximated as being equal to the length of the center filter element. Beyond this distance, any component of vertical flow from the hydrostatic gradients does not significantly affect the calculation of permeability. This is because in radial flow, the amount of flow per cross-sectional area greatly decreases at increasing distance from the probe face. Thus, the contributing area for the equipotential lines becomes increasingly larger with increasing distance from the probe. Therefore, the soil's calculated horizontal permeability is predominately governed by the flow that is discharged near the permeameter face. Additionally, the measured flow in a sufficiently large laboratory test chamber would not be greatly affected by the no-flow boundary condition caused by the chamber boundaries.

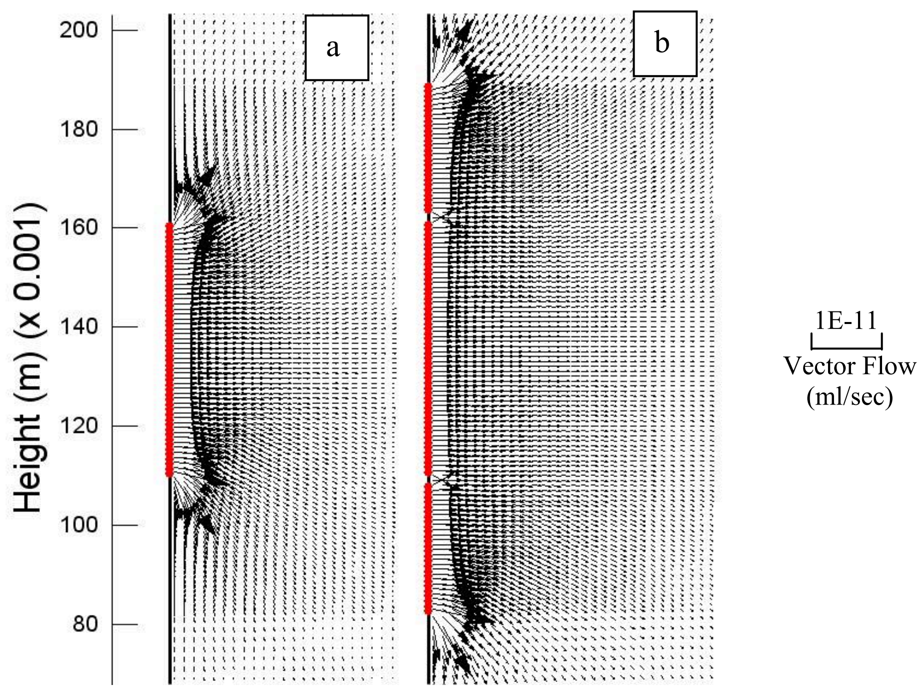

FIG. 2. Finite element modeling vectors for water discharged through the multiflow permeameter for a) center flow only, and b) multiflow conditions.

A second series of models considered the outer boundaries of the proposed laboratory test chamber conditions, with drainage at the top and bottom and a no-flow boundary along the side. As before, the flow remained nearly horizontal for a distance approximately equal to the center filter element when all three filter elements were discharging. Beyond this distance, the flow through the center element exhibited a greater vertical component. Most important is the initial pattern of the flow vectors at the top and bottom margins of the center filter element as discharge was occurring through the center element only, as shown by the flow vectors in Fig. 2a. In this case, the flow paths at the edges did not remain horizontal, because the flow was not constrained at these locations. However, as shown in Fig. 2b, when the flow was constrained by the upper and lower filter elements during the multiflow condition, the flow vectors remained nearly identical across the entire element face. These figures clearly show the edge effect, where a greater flow discharged in a spherical nature at the top and bottom edges of the center filter element for center filter element flow only. However, this edge effect was essentially eliminated for the center element during the multiflow condition, since the edge effects were shifted to the upper and lower filter elements. This demonstrates the idea that discharge from the upper and lower filter elements can confine the center flow in the horizontal direction. This modeling was performed with both sand and clay selected as the porous material. Although the magnitude of discharge values changed with material type, the shape of the flow vectors were similar for both material types. Fig. 2 shows the results for modeling in a clay material. Finally, note that because of the edge effects, the average flow was nearly 7 times larger for center flow only compared to the average center flow for the multiflow condition.

DEVELOPMENT OF PROTYPE DEVICE

A prototype device was constructed for testing the tri-element multiflow concept. Fig. 3 shows an illustration of the prototype device. A field direct push device would most likely be constructed with internal chambers for transferring and discharging water. However, for machining convenience, the prototype probe used for bench scale testing described herein was constructed with external chambers wrapped with a filter element. The tip of the probe was machined to create a standard 1,000 mm^2 area cone penetrometer tip, with the corresponding outer standard diameter equal to 35.7 mm. The length of the center filter element was machined to 50 mm, thus providing sufficient length to capture the permeability for an appropriate zone of soil, yet remain small enough to target reasonably thin layers. The lengths of the upper and lower filter elements were 25 mm, with a 3-mm section separating these filter elements from the center filter element. These dimensions were demonstrated in the modeling to provide sufficient flow to minimize the edge effects for the center element. The flow elements were placed 50 mm behind the cone shoulder. External channels were cut into each side of the probe to house the water feed lines, one for the upper and lower filter elements and a second on the opposite side of the probe for the center filter element. Small water transfer channels were cut into each of the filter sections to facilitate more uniform water transmittance throughout the filter.

The water lines (3.175 mm outer diameter nylon tubing) were placed within the channels, and a nonshrinking silicon caulk used to seal the filter elements and secure the water line. A small annulus was left at the end of each tubing as well as a small hole inserted into the tubing of the upper element for water discharge. Two layers of 1.59-mm thick porous polyethylene strips were used as the filter elements within each of the three filter zones encompassing the water channels. In reality, this type of material would be easily damaged in an actual field setting, and a more durable filter element system would need to be utilized. However, for bench scale testing, this type of material was sufficient.

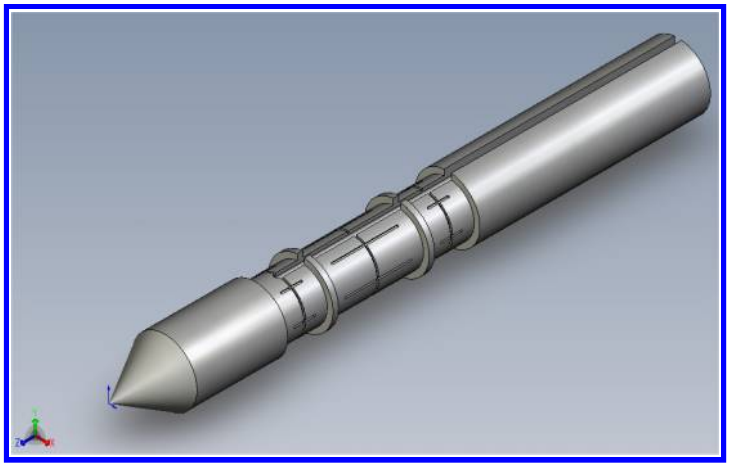

FIG. 3. Rendering of the prototype tri-element multiflow permeameter.

Two different flow pumps were utilized for pumping water through the multiflow permeameter, one supplying water to both the upper and lower filter elements and the other supplying water solely to the center filter element. The laboratory flow pumps each had a capacity of 250 ml water with the volume resolution measured to the nearest one-thousandth of a ml by the data acquisition system. The flow, q, out of the center filter element of the prototype multiflow permeameter was measured by simply monitoring the change in volume of the flow pump reservoir until steady state conditions were reached. That steady state flow rate was then used to calculate the horizontal permeability of the soil using Eq. (3).

To ensure that the chambers were completely sealed and could not hydraulically communicate with each another, three observation tests were performed at a discharge pressure of 70 kPa. Each included pumping colored water through the center element and ensuring that the dyed liquid did not discharge through the other two elements. These tests were performed first with atmospheric pressure, then submerged in a tank of water, and finally in a light-colored saturated sand. The first two tests demonstrated that the filter elements had indeed been isolated from each other. The latter test visually demonstrated the horizontal flow of the colored water through the sand.

BENCH SCALE TESTING

To bench scale test the multiflow permeameter in the laboratory, several important considerations had to be addressed. First, kaolin clay was selected as the test material because of its ease of placement and slightly larger permeability for a fine-grained soil. The clay was mixed from a dry powder form to a consistency easily placed in the test chamber without creating trapped air voids, and then fully consolidated under a load of 120 kPa in the test chamber. Second, the fluid pressure applied within the multiflow permeameter had to be less than the lateral earth pressure achieved in the chamber to ensure the water did not simply migrate along the surface of the rod. This was addressed by applying fluid pressures at levels much lower than the effective vertical stress. Likewise, the applied pressure had to be small enough to not hydraulically fracture the soil. Therefore, the applied fluid pressures selected for testing the prototype permeameter were 3.5 and 14 kPa. A further consideration was the time required to dissipate shear-induced pore pressures before testing could commence. Because excess pore pressures were much larger than the flow pressure planned, and because shear-induced pore pressure could not be easily accounted for during a multiflow test, the excess pressures were allowed to fully dissipate after pushing the probe and before testing.

The principal purpose of the testing was to compare the flow rate between the center element flow only and multiflow conditions and to calculate the corresponding horizontal permeability for the center element of the multiflow condition. For test 1, the clay material was placed and consolidated around the probe. For the other two tests, the probe was advanced to simulate being pushed in situ. Finally, the applied water pressure was increased for the third test. Table 1 shows the results of the bench scale testing. As indicated with the modeling, the flow rate was lower for the multiflow case. The calculated horizontal permeability is shown for the steady state flow of the center element for the multiflow condition of each test.

TABLE 1. Measured flow and calculated permeability through center element.

Test #	Applied Pressure (kPa)	Permeameter Condition	Steady State Flow (ml/sec)	Horizontal Permeability (mm/sec)
1	3.5	Center Only	4.6×10^{-4}	N/A
		Multiflow	2.1×10^{-4}	1.0×10^{-6}
2	3.5	Center Only	6.0×10^{-4}	N/A
		Multiflow	4.0×10^{-4}	1.9×10^{-6}
3	14	Center Only	5.4×10^{-3}	N/A
		Multiflow	1.9×10^{-3}	2.0×10^{-6}

By beginning with consolidating the clay around the probe and then pushing, an attempt was made to see if any significant smear effects could be observed. It was believed that the smear effect along the probe face should theoretically decrease the flow from the center element, thus underestimating the true undisturbed horizontal permeability. However, Test 2 produced an increase in permeability, despite every effort to minimize setup and apparatus errors. It was concluded that when the magnitude of flow is very small, slight differences in the testing procedure or test conditions could produce important differences. Despite this challenge the results are still reasonably consistent. Test 3 successfully demonstrated that the permeability could be replicated with a larger water pressure.

The horizontal permeability of the kaolin clay was also measured by a Rowe Cell with a radial consolidation test to verify the permeability measured by the multiflow permeameter probe. The test was performed at the same void ratio as the clay material placed in the test chamber. The horizontal permeability obtained with the Rowe Cell was 9.8×10^{-7} mm/sec. The permeabilities obtained in the test chamber were larger by factors of 1.0 to 2.1, without and with pushing, respectively. The differences in the these results can be attributed to 1) differences in test apparatuses, 2) variations in the samples due to sample preparation, 3) smear effects, 4) difficulties in measuring flow at very low differential pressure, 5) minor head losses in the permeameter, and 6) other experimental errors. However, despite these factors, we believe that the results are reasonable and reproducible. Therefore, based on the modeling and bench scale testing performed, we recommend further development of the tri-element multiflow permeameter as an in situ test device.

CONCLUSIONS

The tri-element multiflow permeameter uses three elements to create radial flow and measure the in situ horizontal permeability of a thinly bedded soil. The radial flow condition, coupled with Darcy's law, can be used to calculate the horizontal permeability for steady state theory conditions. The proposed method is simpler and requires fewer assumptions than most methods for measuring in situ permeability. However, there are several constraints to using this method. First, the applied pressure for discharging water through the multiflow permeameter must be kept well below the lateral confining pressure of the soil. Second, when pushing the multiflow permeameter to depth in cohesive soils, the shear induced excess pore water pressures must dissipate prior to performing the multiflow permeameter test. Finally, the flow is constrained only for a distance approximately equal to the length of the center filter element because of the size of the filter elements. Therefore, the zone of influence of the discharged flow must be approximated to this same zone.

Finite element modeling was used to establish the flow paths for the center element in single and multiflow conditions. The finite element modeling demonstrated that edge effects were essentially eliminated for the center filter element during the multiflow condition. Subsequently, a prototype device was constructed and tested in the laboratory. Radial consolidation testing was performed in a Rowe Cell to verify the chamber test results. Although the values estimated with the multiflow permeameter were somewhat different (i.e., up to 2.1 times) than Rowe Cell results, they were sufficiently close to conclude that the device shows promise for estimating the in situ horizontal permeability of low permeability soils.

The primary benefit of using the multiflow permeameter is that the horizontal permeability of a thinly bedded soil is measured directly without upper and lower edge effects. However, for thinly bedded soils, the length of the center filter element must be sufficiently small to target such zones. Ideally the multiflow permeameter should be positioned at some distance behind a standard CPT sleeve transducer, in a multitool configuration, thus allowing the thin zones to be pre-identified for targeted permeability measurements.

Although the primary purpose of this research was to establish the potential use of the multiflow permeameter for measuring horizontal permeability of cohesive soils for time of radial consolidation calculations, the device could also be used to determine the horizontal permeability of thinly bedded granular soils. Because of the larger permeability for such soils, permeability testing would probably require larger capacity tubing and larger flow pump reservoirs. Therefore, although not tested as part of this research, the multiflow permeameter may also be a valuable tool for estimating the true horizontal permeability of thinly bedded granular soils for environmental and groundwater contamination applications.

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