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Modification of triaxial apparatus for permeability measurement of unsaturated soils ☆

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Abstract

Both the shear strength and the permeability of unsaturated soils are important engineering properties that are required in numerous geotechnical designs. Many studies on the shear strength of unsaturated soils have been reported; however, only a limited number of studies on the permeability of unsaturated soils have been presented. This might be due to the fact that the time and the costs associated with unsaturated permeability measurements are excessive. The purpose of this paper is to introduce the modification of a triaxial apparatus for the direct measurement of permeability in conjunction with shear strength tests on unsaturated soils under multiple cycles of drying and wetting. Detailed designs and modifications are carried out to allow the unsaturated permeability and the shear strength of a soil to be measured for the same soil specimen. The test results are found to be more consistent as both measurements are conducted on the same specimen. A series of unsaturated permeability tests and then a series of unsaturated consolidated drained (CD) triaxial tests, under multiple cycles of drying and wetting, are conducted on three different soils, and the results are shown to be compatible with the theory reported in literature.

Keywords: Permeameter; Hysteresis; Permeability; Shear strength; Multi-cycle; Drying; Wetting; Unsaturated soils

1. Introduction

Many geotechnical and geoenvironmental problems involving unsaturated soils require an understanding of the unsaturated permeability of the soils. These problems include the stability of slopes, road and railway embankments, earth dams, clay barriers for the containment of contaminated soils, water management structures, contaminant transport in unsaturated soil zones and many more. The permeability of soil is a soil property which expresses the rate of water flow through the soil. It refers to the Darcy's coefficient of permeability, k, or the simplified term, coefficient of permeability, in civil engineering (Holtz and Kovacs, 1981). The permeability of a saturated soil, with respect to the water phase, is a function of the void ratio of the soil. However, in unsaturated soil, the permeability of the soil, with respect to the water phase, is a function of both the void ratio and the water content of the soil (Fredlund and Rahardjo, 1993). Various studies have shown that the

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water in soil can only flow through the voids that are filled with water in a continuous path. As a result, the permeability of an unsaturated soil is dependent on two stress state variables, i.e., the net normal stress and the matric suction, which control the water content of an unsaturated soil.

The matric suction has a dominant influence on the amount of water in a soil. The permeability of an unsaturated soil decreases significantly as the water content decreases when the matric suction of the soil increases. The coefficient of permeability of soil can vary by several orders of magnitude when the matric suction varies in the range of practical interest to engineers. The unsaturated permeability of a soil has been described to have a close relationship to the Soil–Water Characteristic Curve (SWCC) of the soil during the drying and wetting processes (Fredlund et al., 1994). In other words, the unsaturated permeability of a soil is hysteretic as it depends on the soil properties associated with either the drying or wetting paths (Fredlund and Rahardjo, 1993; Fredlund, 2006; Gallage et al., 2013). The shear strength of unsaturated soils is also a crucial engineering property in various geotechnical problems. Many studies have been carried out in order to understand the shear strength behavior of unsaturated soil (Han et al., 1995; Vanapalli et al., 1996; Rahardjo et al., 2004).

Numerous permeability and shear strength results of unsaturated soils have been reported in the literature. However, these results were obtained using different specimens and different apparatuses. Furthermore, most of the results were limited to the initial drying and/or wetting paths. Therefore, it is appropriate to develop an apparatus that can perform direct measurements of both the shear strength and the permeability of unsaturated soil using the same specimen in order to achieve cost effectiveness and to shorten the time needed for both tests. The test results would be more meaningful if both the permeability and the shear strength results could be directly obtained from the same specimen. The objective of this paper is to describe the modification of a triaxial apparatus for both the permeability and the shear strength testing of unsaturated soils under multiple cycles of drying and wetting.

2. Determination of permeability for unsaturated soil

There are two approaches for obtaining the permeability of an unsaturated soil, i.e., direct and indirect approaches (Leong and Rahardjo, 1997a). Direct permeability measurements can be conducted in a laboratory or in the field. Although field measurements are always considered to be more representative, laboratory measurements are usually preferred due to the lower costs and fewer uncertainties involved in laboratory measurements (Benson and Gribb, 1997). On the other hand, the indirect approach to the permeability determination of an unsaturated soil refers to the use of a permeability function associated with particular soil properties, e.g., SWCC, to estimate the permeability of the unsaturated soil.

The laboratory permeability measurements of an unsaturated soil can be performed using a steady-state method or an unsteady-state method. The steady-state method (also called constant-head method or constant-flow method) is performed by maintaining a constant hydraulic head gradient across a specimen (Fredlund and Rahardjo, 1993). A steady-state water flow across the specimen is created while the matric suction and the water content of the specimen are maintained as constants. Benson and Gribb (1997) commented that more accurate results can be produced by the steady-state method using Darcy's law, although it is always more time-consuming, as compared to the unsteady-state method. The unsteady-state methods (i.e., variable–head method, infiltration techniques, instantaneous techniques, etc.) can be used either in the laboratory or in-situ. The unsteady-state methods have several variations. The differences are mainly found in the flow process and in the measurement of the hydraulic head and the flow rate (Fredlund and Rahardjo, 1993; Krisdani, et al., 2009). The flow process can be a wetting process, where water flows into the specimen, or vice versa. When using the variable-head method to measure the permeability, difficulties are often encountered in maintaining the stress state of the specimen during the test (Agus et al., 2003)

In general, there are two types of permeameters used to measure the unsaturated permeability of soil, i.e., the rigid wall permeameter and the flexible wall permeameter. Klute (1965), Gan and Fredlund (2000), Lu et al. (2006), Vanapalli et al. (2007) and Gallage et al. (2013) developed rigid wall permeameters to measure the unsaturated permeability of soil. On the other hand, Barden and Pavlakis (1971), Huang et al. (1998), Agus et al. (2003) and Moncada and Campos (2010) developed flexible wall permeameters to measure the unsaturated permeability of soil. The main advantage of using a flexible wall permeameter over a rigid wall permeameter is that the changes in the volume of the soil, during consolidation, drying and wetting processes, can be monitored and determined. Another advantage of a flexible wall permeameter is that the shrinkage of specimens during drying does not affect the accuracy of the permeability measurement.

Generally, the permeability of soil remains relatively constant at matric suctions below AEV and starts to decrease significantly at matric suctions beyond AEV. The shape of the permeability function is similar to the shape of SWCC (Fredlund et al. 1994; Gan and Fredlund, 2000). Numerous permeability functions for unsaturated soils, e.g., Richards (1931), Brooks and Corey (1964), Mualem (1976), Kunze et al. (1968), van Genuchten (1980) and Leong and Rahardjo (1997a), have been introduced to estimate the unsaturated permeability of soil. Most of the equations were developed based on the relationship among permeability, SWCC, pore sizes and the pore-size distribution of the soil.

The permeability functions are able to provide a quick approximation of the permeability of soil; however, the estimations using some of the permeability functions may significantly underestimate the actual unsaturated permeability of certain types of soil (van Genuchten, 1980; Fredlund et al., 1994; Chiu and Shackelford, 1998). Therefore, it is always recommended that the direct permeability measurement of an unsaturated soil be conducted, even though it is more time-consuming (Fredlund and Rahardjo, 1993).

3. Modified triaxial apparatus for unsaturated soil tests

A modified triaxial apparatus has been developed for the direct measurement of unsaturated permeability before a