



# Soil Water Retention Surface Determination Using a New Triaxial Testing System

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**Abstract.** The soil water retention curve has been widely used to characterize the relationship between the water content and the soil water potential. The conventional pressure plate method for the soil water retention curve determination is very time consuming. Also, soil volume change during testing is not available. Recently, a new triaxial testing system has been developed for unsaturated soil characterization. In this study, this new system was utilized to determine the soil water retention surface through a series of constant water content consolidation tests on unsaturated soils with different moisture contents. Results from these tests indicate that the new triaxial system is a time-efficient option for soil water retention surface determination.

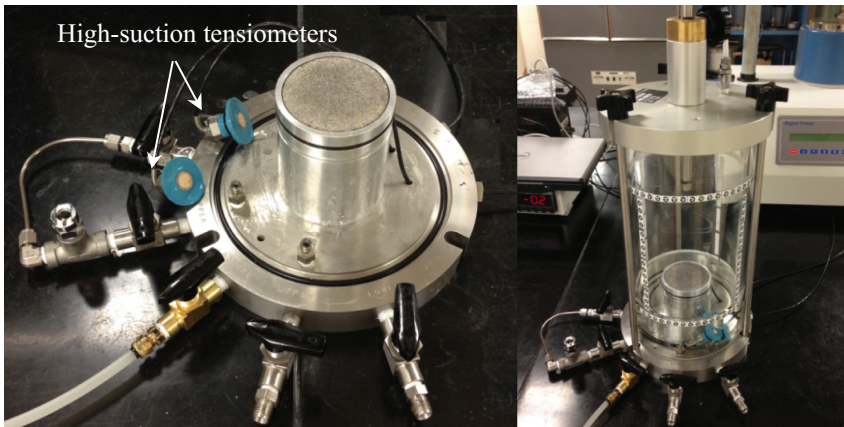
**Keywords:** Soil water retention surface · Triaxial test  
High-suction tensiometer

## 1 Introduction

The soil water retention curve is the relationship between the water content and the soil water potential. In the past, the soil water retention curve was commonly used to estimate in situ soil suctions by measuring the unsaturated soil water content. Several models (Williams et al. 1983; Hutson and Cass 1987; Rossi and Nimmo 1994; Assouline et al. 1998) were proposed to predict the soil water retention curves for unsaturated soils based upon their physical properties. A review of the existing soil water retention curve models was presented by Sillers and Fredlund (2001). In the past, based on principle of axis-translation technique, the pressure plate equipment has been commonly used for the soil water retention curve determination (i.e. ASTM C1699 2009; Richards 1941; and Péron et al. 2007). However, for the pressure plate test, due to the low permeability of unsaturated soils, several weeks are required for the soil water retention curve determination of one soil. Also, during testing, soil volume change, which is required for calculation of soil void ratio or degree of saturation, cannot be measured. Many research efforts (Lourenço et al. 2011; Padilla et al. 2005) have been dedicated to rapid and accurate determination of soil water retention curve. In Padilla et al. (2005), the Fredlund SWCC device was adopted soil water retention

curve determination. Vertical load was applied to the tested sample which guaranteed the contact between the sample and oedometer wall. As a result, volume change due to suction change could be determined simply by monitoring the axial displacement of the top plate. In Lourenço et al. (2011), a high-suction tensiometer was used to measure soil suction during drying process from which the soil water retention curve was extracted. However, the soil volume content cannot be measured during testing.

In Li and Zhang (2015), a new triaxial testing system was developed based on modifications on a conventional triaxial test apparatus which is for saturated soils. In the new triaxial testing system, high-suction tensiometers were equipped to measure soil suction during triaxial testing which is different from the suction-controlled triaxial test in which the axis-translation technique is adopted to control soil suction (Bishop and Donald 1961). To install the tensiometers, two holes are drilled in the base of the triaxial cell as shown in Fig. 1a. In this study, the high-suction tensiometers developed in Li and Zhang (2014) were used for soil suction measurement. The tensiometers were saturated and saturated in the triaxial chamber as shown in Fig. 1b. In this triaxial testing system, the photogrammetry-based method developed in Zhang et al. (2015) is adopted for soil volume change measurement during testing. A series of constant water content tests were performed on unsaturated soils with different moisture contents. A soil water retention surface, proposed by Salager et al. (2010), was then extracted to characterize soil water retention behavior with consideration of the effect of both suction and soil deformation.



(a) Modification on cell pedestal; (b) High-suction tensiometer saturation

**Fig. 1.** Modification for soil suction measurement

## 2 Constant Water Content Test on Unsaturated Soils

### 2.1 Sample Preparation

Locally available Fairbanks silt was used to fabricate several unsaturated soil specimens (71 mm in diameter and 142 mm in height) using the static compaction method (Ladd 1978) as shown in Fig. 2a. The properties of the used soil are summarized in Table 1. The soil cylinders were compacted in 10 layers. The surface of each soil layer was scarified to ensure good contact between adjacent soil layers as shown in Fig. 2b. Before testing, the soil specimen was completely sealed in the plastic cup for two days to reach matric suction equilibrium as shown in Fig. 2c. After suction equilibrium, the constant water content consolidation tests were conducted.

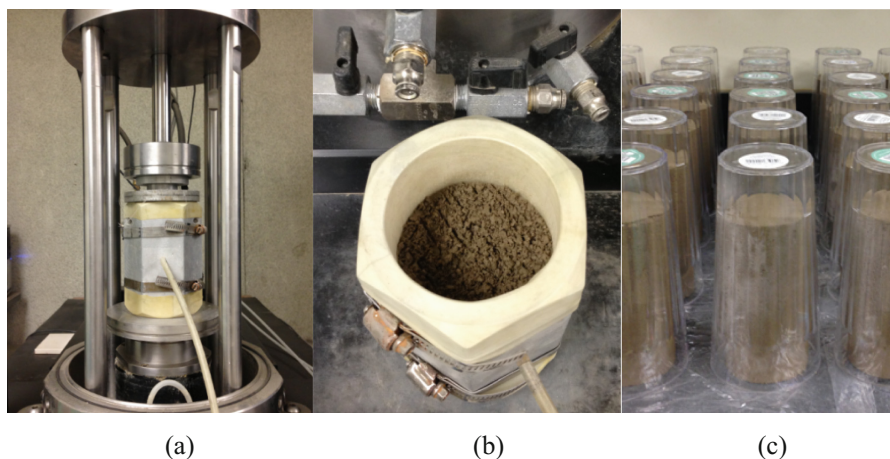


Fig. 2. Specimen preparation using the static compaction method

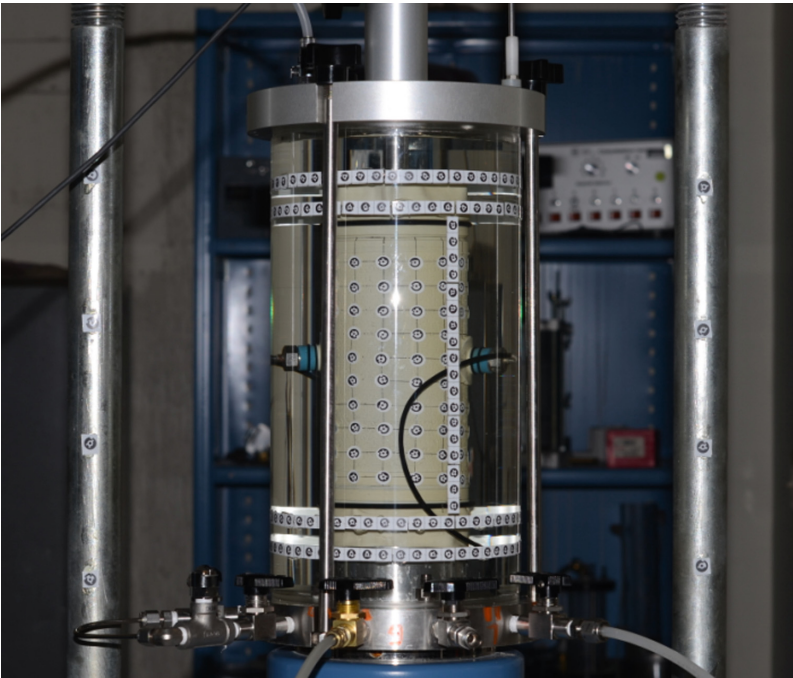
Table 1. Soil properties of the used soil mixture

Soil properties	Value
Maximum dry density	1.836 g/cm <sup>3</sup>
Optimum moisture content	15%
Specific gravity	2.7
Plastic limit	18.2
Liquid limit	19.7
Plastic index	1.5

### 2.2 Undrained Consolidation Tests

After saturation and calibration, tensiometers can then be used for matric suction measurement. Before sample installation, two holes were cut on the membrane, which would be used to cover the soil specimen during testing. The specimen was mounted on

the pedestal of the triaxial cell and carefully sealed with O-rings. A small suction ( $-5$  kPa) was applied to the inside of the soil specimen after this. Vacuum grease was smeared on the back of the grommet, which was used to hold the tensiometer. By carefully stretching the membrane, the tensiometer can be placed on the sample surface through two holes on membrane. Two saturated tensiometers were placed at the middle of the specimen (see Fig. 3). The use of vacuum grease ensured a good seal between the grommet and the membrane, and a negative pressure was applied to the inside of the soil specimen held the sensor in place during tensiometer installation. Some measurement targets were posted on the membrane surface after this with the help of vacuum grease. A series of images around the specimen were then captured to determine the volume of the soil specimen before any load was applied. The triaxial cell was installed and filled up with water after this as shown in Fig. 3.



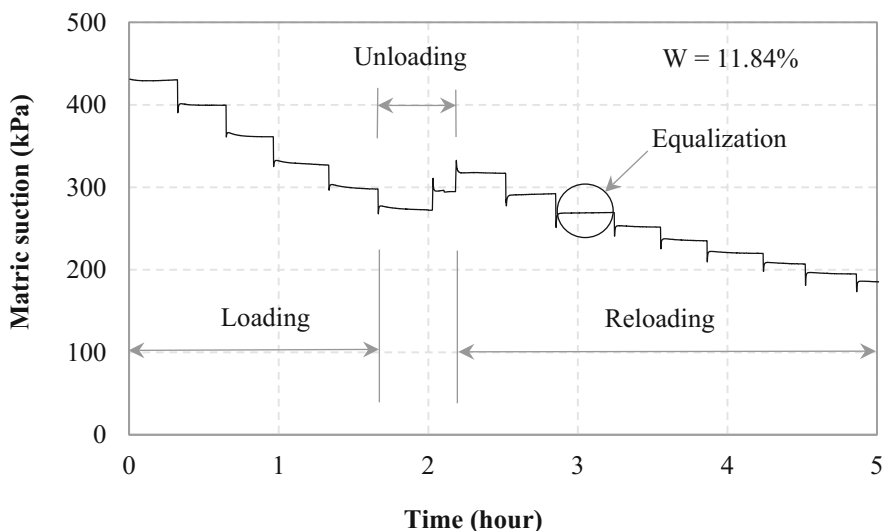
**Fig. 3.** System setup for the constant water content consolidation test

A confining pressure of 50 kPa was then applied to hold the tensiometer in place, and the applied suction inside of the soil specimen was released simultaneously. The reading of the tensiometers required a certain time to reach equilibrium. After the equilibrium, isotropic load was applied in steps to a maximum net confining load of 600 kPa for the water retention surface determination. Usually, approximately 20 min, dependent on soil suction, were required to ensure the stabilization of the high-suction tensiometer readings. Once suction stabilized, the volume of the soil specimen was

measured by using the photogrammetry-based method. Then, isotropic compression test was performed. Confining pressure was gently increased (i.e. loading) or decreased (i.e. unloading) to a target value and followed by another suction stabilization period. The time required for new suction equilibrium also depends on soil suction level. After suction equilibrium, the volume of the soil specimen was measured again.

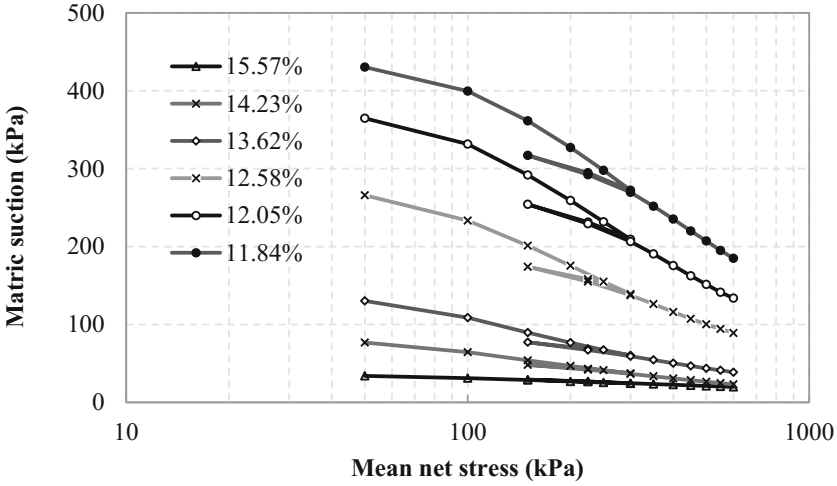
### 2.3 Experimental Results

During isotropic compression test, matric suctions of the test specimen under different net confining stresses was monitored via high-suction tensiometers. A typical matric suction variation for the soil specimen with water content of 11.84% due to isotropic load was presented in Fig. 4. During isotropic loading, there was an immediate drop of suction associated with the increase of isotropic load, followed by a small increase in suction with time and finally reached equilibrium. The entire isotropic loading process lasted for approximately 5 h.

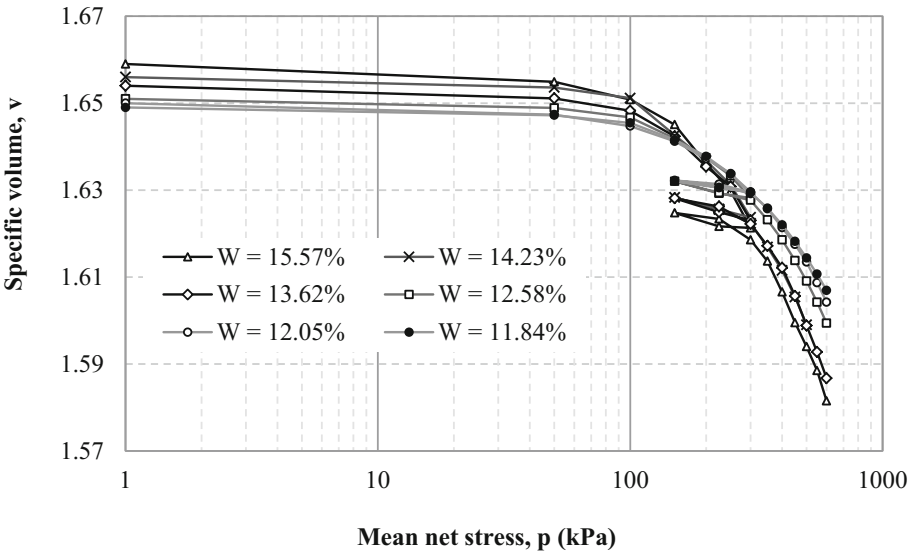


**Fig. 4.** A typical high-suction tensiometer response during isotropic loading

The representative soil suctions recorded by the tensiometers after each equalization stage were plotted in Fig. 5a. Generally, soil suction decreased with increasing isotropic load. Also, soils with low water contents had higher initial suction and experienced the larger reduction in suctions after the same loading procedure. When there is an unloading at the mean net stress of 300 kPa, there were irrecoverable suction changes due to the soil plasticity. The soil volume change was measured based on the measurement targets on soil surface. Details on the soil volume measurement method using the photogrammetry-based method can be found in Zhang et al. (2015) and Li et al. (2015). During isotropic loading, with increasing confining load, the soil volume,



(a) Soil suction variation during isotropic loading



(b) Soil volume change during isotropic loading

**Fig. 5.** Soil response during isotropic loading under undrained condition

continuously decreased as shown in Fig. 5b. The soil specimens with the highest water content experienced the highest volumetric reduction when subjected to the same loading procedure. This was because the moisture lubricated the soil particles and led to smaller modulus during the isotropic loading. The plastic soil deformation was also identified when there was an unloading as shown in Fig. 5b.

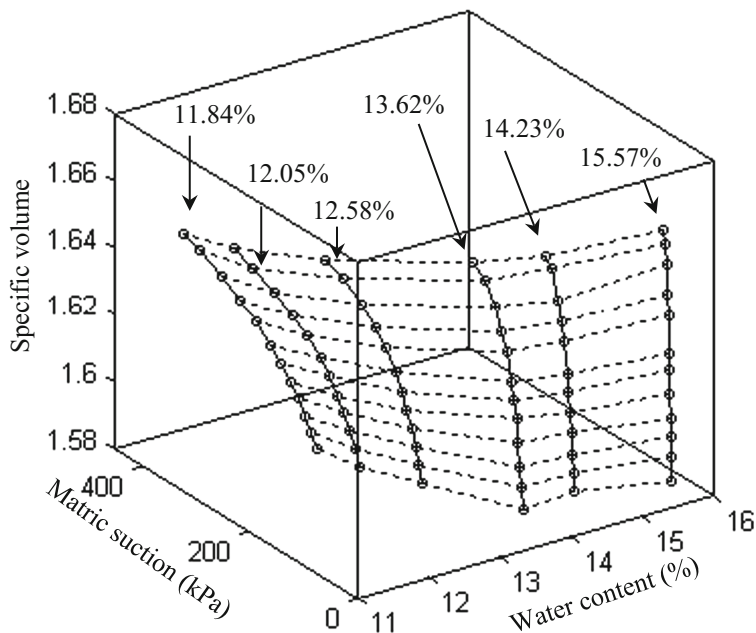


Fig. 6. Soil water retention surface

With the soil volume, suction, and water content, the soil water retention curves for six soil specimens were extracted and plotted in Fig. 6 in which the unloading and reloading was not included. With six soil water retention curves, a soil water retention surface could then be created as shown in Fig. 6 in which the significant influence of soil specific volume on the soil water retention capability was clearly shown. With this surface, the soil suction can be predicted with given specific volume and water content.

### 3 Conclusions

In this study, to determine the water retention surface of an unsaturated soil, a new triaxial testing system was adopted for the constant water content triaxial tests. During triaxial testing, soil suction and volume changes were measured using high-suction tensiometers and the photogrammetry-based method, respectively. Through a series of isotropic consolidation tests on the unsaturated soil, the soil water retention surface was determined. Compared with the conventional pressure plate method, the soil volume changes during testing could be recorded which makes the soil water retention curve more accurate and representative.

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