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Performance of the Tensiometer Method for the Determination of Soil-Water Retention Curves in Various Soils

Reference

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ABSTRACT

The soil-water retention curve (SWRC) describes the relationship between the soil matric suction and the water content of an unsaturated soil. It is an essential tool in geotechnical engineering and agriculture and is, for example, used in the analysis of unsaturated soil conditions such as those found in tailings dams and in analyzing the water retention capacity of agricultural land. Conventional methods used to obtain the SWRC are laborious and often rely on empirically derived equations to describe the curve. These test procedures can take weeks to complete and usually rely on indirect methods of measuring suction. Recent advances in the development of affordable high-capacity tensiometers (HCTs), the only devices capable of producing a direct and continuous measurement of high matric suctions, enable the introduction of the tensiometer method for the rapid determination of continuous SWRCs. The method requires an HCT, a digital laboratory balance, and a means of sample volume measurement if volume changes are relevant. The method involves continuously monitoring the mass and matric suctions generated in a naturally desaturating soil sample. The method has thus far seen limited implementation owing to the need for measuring specimen volume change to describe the hydraulic and volumetric behavior fully. The performance of the tensiometer method was investigated by determining SWRCs of five different soil types and then comparing them to the SWRCs determined from the filter paper method. A novel method, based on photogrammetry, was adopted for volume change measurement to produce SWRCs for soils that undergo shrinkage during drying. Excellent agreement between the methods was found for both the nonplastic soils and plastic soils tested.

Keywords

soil-water retention curve, matric suction, volume change, high-capacity, tensiometer, unsaturated soil, laboratory testing

Introduction

Fundamental to the understanding of unsaturated soil mechanics is the concept of soil suction, which contributes strength to unsaturated soils and alters their volumetric and hydraulic behavior. A key stumbling block limiting the advancement and implementation of these concepts is the lack of simple methods of measuring soil matric suction. An increased interest in the use of high-capacity tensiometers (HCTs), devices capable of measuring high values of soil matric suctions directly, has inspired more studies into and confidence in the application of unsaturated soil mechanics around the world.

HCTs

HCTs are capable of measuring negative pore water pressures below 100 kPa, but only after a rigorous saturation process. The first successful HCT was introduced by Ridley and Burland (1993), who continued to advance the technology and were able to raise the range of matric suction measurement to about 1,500 kPa. Since then, the research area has rapidly advanced to produce HCTs proven capable of measuring suctions over 1,500 kPa for more extended periods in a laboratory environment (Ridley and Burland 1996; Guan and Fredlund 1997; Tarantino and Mongioví 2003). Notably, HCTs have been successfully used for long-term in situ suction measurement as well (Cui et al. 2008). Mendes et al. (2019) developed the first ultra-high-capacity tensiometer (UHCT) capable of measuring water tensions up to 7 MPa in air. The UHCT has yet to be applied to measuring suction in soils but has the potential to lead to the replacement of indirect high suction measurement techniques with further advancement. Implementation of HCTs as a routine method to measure suctions in the 0–1,500 kPa range remains of great interest for the use in unsaturated soil testing scenarios where extreme desaturation is infeasible, such as in centrifuge modeling or seepage studies.

SOIL-WATER RETENTION CURVES

The soil-water retention curve (SWRC), which describes the relationship between the soil matric suction and the water content of an unsaturated soil, is an essential tool in the practical application of unsaturated soil mechanics. The SWRC is a basis for modeling various unsaturated soil parameters such as hydraulic conductivity and shear-strength functions (Vanapalli, Sillers, and Fredlund 1998). It is, therefore, vital that an accurate characterization of the SWRC of a soil be made (Fredlund and Xing 1994). If the complexities involved with the accurate measurement of matric suction and the determination of the SWRC could become routine, development in the field of unsaturated soil mechanics will accelerate.

CONVENTIONAL METHODS FOR DETERMINING SWRCs

The conventional determination of SWRCs involves the measurement of discrete points of water content and soil suction with empirical equations fitted to the data to define the SWRC between these point measurements. Each point on the SWRC is determined by testing different specimens taken from the same sample assumed to be identical.

The axis translation technique using the pressure plate apparatus is a direct method for controlling soil suction offered as the standard method in ASTM D6836-16, *Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge*. The technique measures pore water tension referenced to a raised air pressure, which does not represent natural conditions (Standing 2012). The technique also suffers from slow response times and provides low accuracy in the low suction range (<1,000 kPa) (Ridley and Burland 1993).

Other commonly used and accessible methods for measuring suction are usually indirect. The simplest indirect methods are the chilled mirror hygrometer offered as the standard method in ASTM D6836-16, and the filter paper method (FPM) as offered in ASTM D5298-16, *Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper*. These methods calculate suction based on the exchange of humidity rather than direct measurement of pore water tension. The chilled mirror hygrometer can fairly rapidly measure suctions, but it is typically only used to determine the portion of the SWRC corresponding to higher suctions (>1,000 kPa) and lower water contents. The FPM applies to the entire range of the SWRC suctions and water contents but does not provide high precision at low suctions and high water contents (Leong et al. 2020). The long equilibration times required makes the FPM a slow procedure. Although independent calibration of the filter paper to other conventional methods for measuring soil suction is recommended, variability between published calibration curves is typically low (Bicalho, Cupertino, and Bertolde 2013; Bicalho et al. 2015).

CONTINUOUS DRYING METHODS FOR DETERMINING SWRCs

The advancement of HCTs in the last decade and a half has led to the introduction of continuous drying methods or "the tensiometer method" for measuring SWRCs as an alternative to the conventional point measurement methods traditionally employed. The tensiometer method was introduced by Toker (2002) and Toker et al. (2004) as a rapid method for determining continuous SWRCs using an HCT and a digital laboratory balance. The method involves the concurrent measurement of matric suction via an HCT and the corresponding decrease in mass of a specimen because of the evaporation of pore water under controlled conditions. The SWRCs of various fine sand and uniform glass bead samples could be repeatably determined between the suction range of 0–100 kPa. The most notable limitation of the study was on the type of soil tested. The ideal samples of fine sand and uniform glass beads do not necessarily represent common problem soils (Standing 2012). Specifically, these samples do not exhibit any shrinkage or swelling behavior. However, Toker (2002) has suggested that rapid advances in unsaturated soil mechanics can be achieved if dimensional change measurement can be readily introduced into the method to provide insight into the relationship between soil matric suction and swelling and shrinking behavior.

Since the introduction of the tensiometer method, researchers have successfully implemented versions of the tensiometer method, usually using a proprietary HCT design capable of measuring suctions in excess of 100 kPa. These studies are presented by Lourenço et al. (2011), Toll, Lourenço, and Mendes (2013), and Chen et al. (2015).

Marinho and Teixeira (2009) showed that point measurements of suctions using an HCT in various clayey soils were unaffected by equilibration time and showed no appreciable difference from SWRCs determined from the axis translation and FPMs up to 500 kPa. Li and Standing (2014) investigated one-dimensional shrinkage of a silty sand and a silt sample using on-specimen dimensional change measurement via a linear variable differential transformer (LVDT). Toll et al. (2015) investigated the volumetric dimensional change of a sandy clay sample using LVDTs to measure the height and diameter of specimens. Altogether, few investigations into dimensional change measurement techniques have been made for different soil types.

With this in view, the performance of the tensiometer method for SWRC measurement in various soil types was investigated. A newly developed HCT was used to measure SWRCs for nonplastic (coarse-grained) soils and plastic (fine-grained) soils. A method for indirectly measuring the shrinkage of the plastic soils was incorporated into the investigation.

Materials and Methods

MATERIALS

Continuous drying tests via the tensiometer method were performed on five different nonplastic and plastic soils. Because the magnitude of soil matric suction that can be developed is directly related to the effective particle size of a soil (Yang et al. 2004), the soils were selected to represent soils with different particle size distributions (PSDs) and effective particle sizes (D_{10}). The PSDs of each soil were produced by the laser diffraction method and are presented in **figure 1*A*** and **1*B***.

Two nonplastic soils were tested, comprising a fine silica sand and gold mine tailings, which are classified as a poorly graded sand (SP) and a silty sand (SM) as per the Unified Soil Classification System (ASTM D2487-17e1, *Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System)*). Additionally, three

FIG. 1

Particle size distributions of soils tested in the present study; (*A*) particle size distributions; (*B*) cumulative particle size distributions.

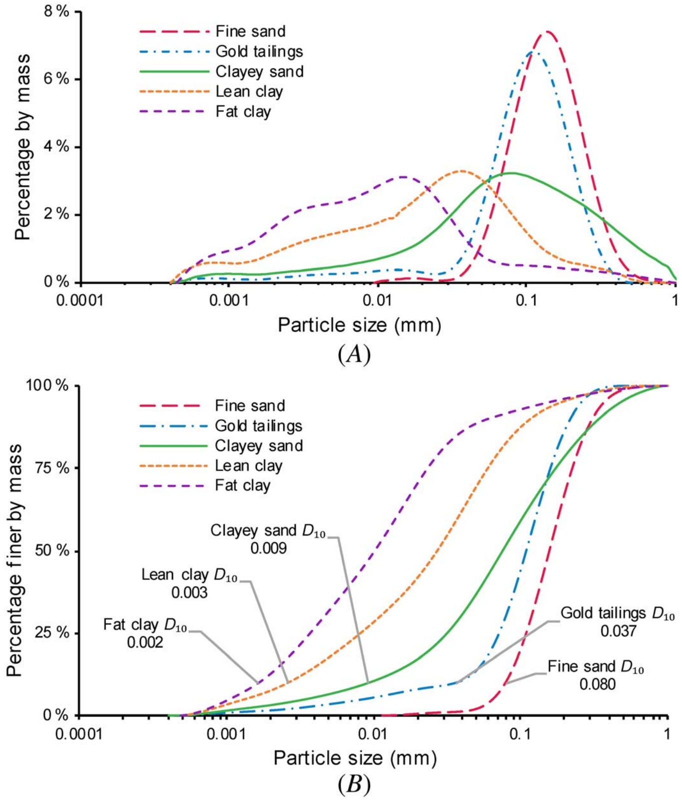


TABLE 1

Properties and classification of the soils test in the present study

	Particle Size			Atterberg Limits			
Material	D_{10}, mm	D_{50}, mm	G_s	w_L, %	w_P, %	I_P, %	Unified Soil Classification Symbol (USCS)
Fine sand	0.080	0.159	2.70	…	…	NP	SP
Gold tailings	0.037	0.11	2.70	…	…	NP	SM
Clayey sand	0.009	0.075	2.69	29	21	8	SC
Lean clay	0.003	0.027	2.68	32	22	10	CL
Fat clay	0.002	0.01	2.65	53	18	35	CH

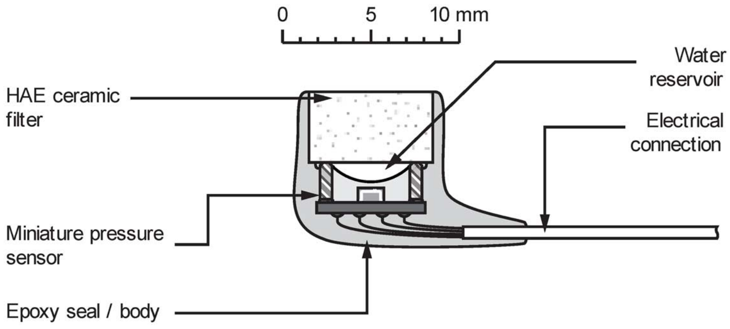
Note: CH = clay of high plasticity; CL = clay of low plasticity; D_{10} = effective particle size; D_{50} = average particle size; G_s = specific gravity; I_p = plasticity index; NP = nonplastic; SC = clayey sand; SM = silty sand; SP = poorly graded sand; w_L = liquid limit; w_p = plastic limit.

plastic soils of increasing plasticity were tested, comprising a clayey sand (SC), an inorganic lean clay (CL), and an inorganic fat clay (CH).

An accurate value of the specific gravity (G_s) of a soil is essential for determining the mass-volume relationships, particularly for high plasticity soils that undergo volume change during drying. The G_s of each of the soils tested was determined by gas pycnometer as per the standard method (ASTM D5550-14, *Standard Test Method for Specific Gravity of Soil Solids by Gas Pycnometer*). The properties and classification of the soils as per the standard methods (ASTM D4318-17e1, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*) are listed in **Table 1**.

FIG. 2

Diagram of HCT used in the present study.



HCT

A new low-cost HCT was recently developed for this study at the University of Pretoria (unit cost approximately 27 USD) (Jacobsz 2018). The HCT consisted of a high air-entry ceramic disc of 5 or 15-bar (500 or 1,500-kPa) nominal air-entry value (AEV) bonded to a miniature pressure sensor. A small gap in between forms the water reservoir. A structural epoxy was used to bond the components and form the external body of the instrument. The HCT in this form was able to measure suctions up to 1,150 kPa in this study. A cross section of the HCT is shown in **figure 2**. The design was further advanced to improve its measurement range and reliability for other unsaturated soil studies (Jacobsz 2019).

SATURATION AND CALIBRATION OF HCTs

The procedure adopted for reliably saturating and calibrating the HCTs is described in Jacobsz (2018). A two-stage saturation procedure consisting of initial saturation followed by prepressurization was used, similar to Tarantino and Mongiovì (2003). Prior to saturation, the HCTs were oven-dried overnight at 60°C. The HCTs were then subjected to a high vacuum in the absence of water, after Take and Bolton (2003). The tensiometers were subsequently submerged in high-quality deaired water and the vacuum was released, allowing water to be drawn into the ceramic and water reservoir until the tensiometer registered atmospheric pressure. Prepressurization was applied overnight, which forced any remaining traces of air into solution through the application of high pressure. The vacuum and prepressurization pressures were applied in a modified high-capacity triaxial cell, as depicted in **figure 3**. Pressures of up to 1,700 kPa were applied, adequate to prepressurize ceramics with AEVs of up to 15 bar. Calibration was carried out by the stepwise application of positive pressure in the cell referenced to a standard test gage. The positive pressure calibration was linearly extrapolated to the negative pressure (or suction) range. The validity of this extrapolation was demonstrated by Jacobsz (2018).

CONTINUOUS DRYING TEST SETUP AND EQUIPMENT

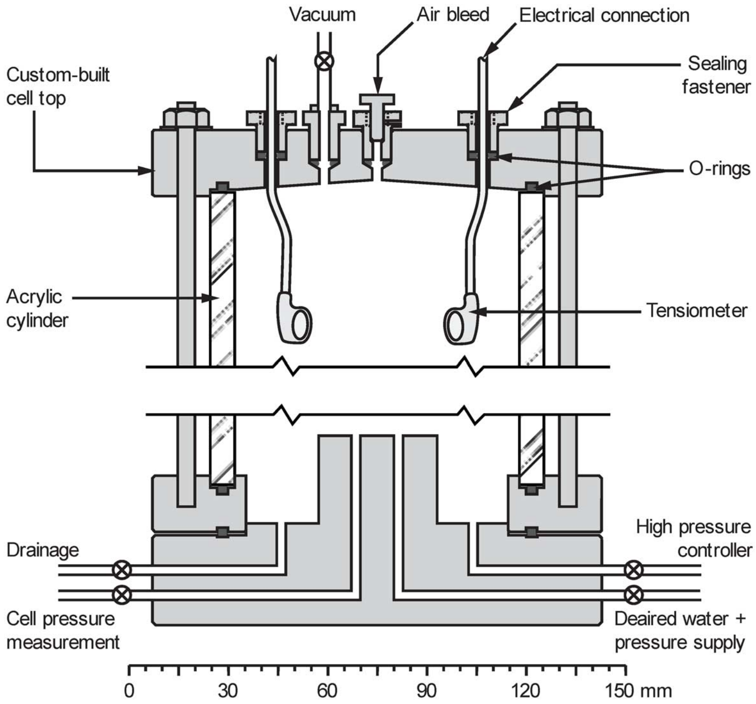
The test setup for the continuous drying tests consisted of a *Radwag* P600.R2 high-precision digital laboratory balance with data recording capabilities, two HCTs embedded in a soil specimen, and a digital camera monitoring the specimen dimensions.

The tests were performed in an insulated enclosure. A thermistor was placed near the specimen to monitor the temperature in the enclosure. An incandescent light bulb was used to raise the temperature of the test environment, increasing the potential for the pore water to evaporate. A small fan was used to extract humidity and regulate the temperature of the test environment. The setup could be adjusted to maintain an average temperature of 40°C ± 2°C. The full setup is illustrated in **figure 4*A***.

A transparent acrylic container was used to hold the specimen, which had a removable bottom with a centrally located opening through which to fit the HCTs. The dimensions of the specimen container were 23.3 mm in height and 71.6 mm in diameter, although larger specimen dimensions were also tested.

FIG. 3

Modified high-capacity triaxial cell for high-pressure saturation of HCTs.



The HCTs were inserted from the bottom of the container to help limit cracks forming in the specimen. This arrangement also allowed the camera an unobstructed view of the specimen. The specimen's diameter could be monitored directly, whereas a precisely angled mirror gave a view of the specimen's height.

The cable was stripped of its external insulation, leaving only the thin wire connections to the HCTs. A centering pedestal raised the container for the wires to be routed underneath to a data acquisition system. The wires were securely fixed nearby to limit instability in the mass readings because of their weight or relaxation with time, as shown in figures 4*B* and 5.

CONTINUOUS DRYING TEST METHODOLOGY

Each soil sample was sieved and oven-dried at 60°C. A specimen was then prepared by mixing the sample with freshly prepared de-aired water above the liquid limit to a uniform slurry consistency. Alternatively, the specimen was prepared to target a gravimetric water content and dry density. Air entrained and entrapped from mixing was removed by vacuum to ensure the void ratio of the prepared specimen could be accurately determined. Two saturated HCTs were placed inside the specimen container and sealed in with modeling clay. The faces of the HCTs were continually wetted with de-aired water to prevent premature cavitation in air. The prepared specimen was placed and leveled smooth to the top of the specimen container. The specimen was then placed on the balance and covered with a small amount of free water added to its surface to prevent initial moisture loss.

Data acquisition of the HCT output, mass readings, enclosure temperature, and time-lapse photography of the specimen dimensions were started. While keeping the specimen covered with enough free water, the specimen and test equipment were allowed to equilibrate to the enclosure temperature until all readings had stabilized. This step allowed any temperature offset of the HCTs or the balance to be mitigated and allowed the wires to reach their full relaxation. The specimen was then uncovered and allowed to desaturate in the enclosure.

The test was concluded when both HCTs had reached their maximum suction measurement and cavitation had occurred, or the specimen had dried to near-zero water content. The specimen was then carefully removed,

FIG. 4

Diagrams of the continuous drying test setup (*A*) in the environmental enclosure and (*B*) on the lab balance showing the test specimen and tensiometers.

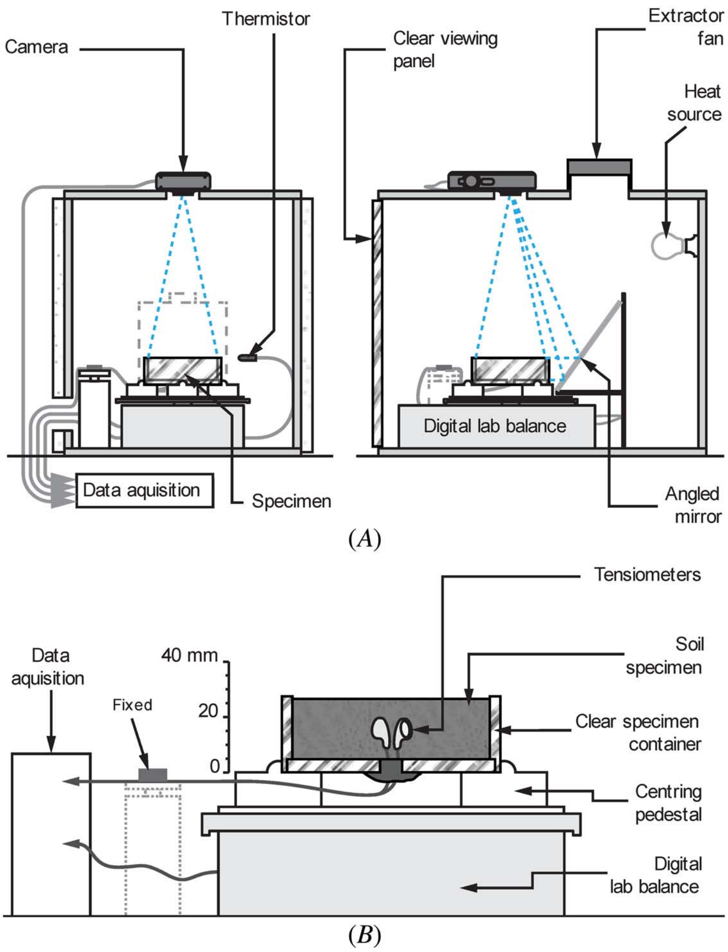
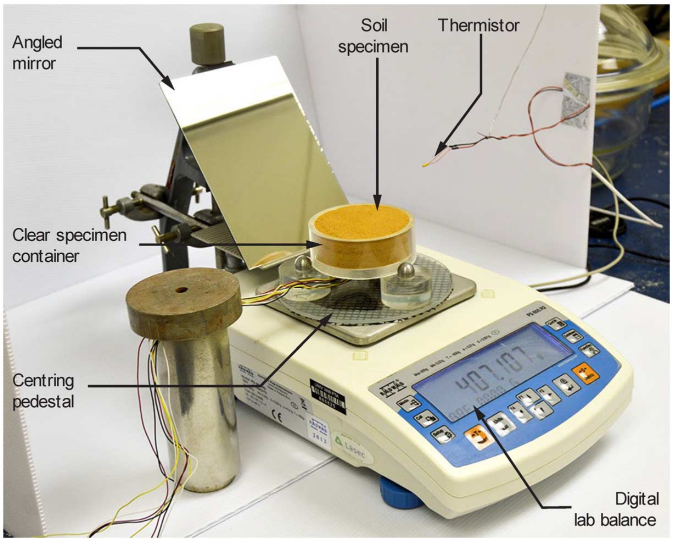


FIG. 5

Continuous drying test setup and equipment.



and the outer dimensions of the specimen were recorded using a digital caliper. The HCTs were then removed from the specimen, taking care to collect the entire specimen for weighing.

The specimen mass was used to calculate the gravimetric water content and plotted against the measured matric suction to produce gravimetric water content SWRC (ψ_m-w).

For nonplastic soils, the mass measurements were converted to degree of saturation to obtain the degree of saturation SWRC (ψ_m-S) if the specimen does not change in volume. For plastic soils that undergo volume change upon drying, volumetric strain must be measured to convert the mass measurements to the degree of saturation.

The average specimen diameter and height of a plastic soil specimen were measured directly with a digital caliper at the start of the test, $d_{m,0}$ and $h_{m,0}$, and at the end of the test when the specimen was taken off the balance, $d_{m,n}$ and $h_{m,n}$. Observations of the same dimensions were also made at the start of the test, $d_{o,0}$ and $h_{o,0}$, and the end of the test, $d_{o,0}$ and $h_{o,0}$, by measuring the dimensions on the time-lapse photography (in units of pixels).

The interpolated specimen dimensions (mm) were then calculated as $d_{m,i}$ and $h_{m,i}$ by

$$d_{m,i} = \left(\frac{d_{o,i}}{d_{o,0}}\right)\left(\frac{h_{o,i} - h_{o,n}}{h_{o,0} - h_{o,n}}\right)d_{m,0} + \left(\frac{d_{o,i}}{d_{o,i}}\right)\left(\frac{h_{o,i} - h_{o,0}}{h_{o,h} - h_{o,0}}\right)d_{m,n} \tag{1}$$

$$h_{m,i} = \left(\frac{h_{o,i}}{h_{o,0}}\right)\left(\frac{d_{o,i} - d_{o,n}}{d_{o,0} - d_{o,n}}\right)h_{m,0} + \left(\frac{h_{o,i}}{h_{o,i}}\right)\left(\frac{d_{o,i} - d_{o,0}}{d_{o,h} - d_{o,0}}\right)h_{m,n} \tag{2}$$

where $d_{o,i}$ and $h_{o,i}$ are the observed dimensions on the time-lapse photography for $i = 1$ to $n-1$ observations.

Equations (1) and (2) relate the observed dimensions to actual direct measurements before and after the test and account for an amount of scaling distortion that occurs as the specimen shrinks and the measured surface moves further from the lens.

FILTER PAPER METHODOLOGY

The FPM was used to compare the results obtained from the tensiometer method. *Whatman* No. 42 ashless filter paper was used to determine a series of suction measurements for each soil at different water contents. The Greacen, Walker, and Cook (1987) calibration curve for *Whatman* No. 42 ashless filter paper, as given in the standard method (ASTM D5298-16), was used to compare the tensiometer method with the FPM without independent calibration.

Specimens were prepared to target a range of degrees of saturation by mixing the oven-dried samples with varying amounts of water and compacting the specimens into small retaining rings. The specimens and filter paper were allowed to equilibrate for at least one week as recommended with greater precision achieved for equilibration times of up to three weeks.

AN EMPIRICAL EQUATION FOR THE SWRC

The Fredlund and Xing (1994) equation can be used to construct an SWRC through a set of suction measurement points. A graphical construction can be used to estimate the residual suction ψ_r, whereas a nonlinear computational technique is employed to derive the best-fit curve-fitting parameters a_f, m_f, and n_f to achieve a least-squares error. The SWRC expressed in terms of gravimetric water content w is given by

$$w = \frac{w_s C_r}{\left[\ln\left(e + \left(\frac{\psi}{a_f}\right)^{n_f}\right)\right]^{m_f}} \tag{3}$$

where ψ is the soil matric suction and w_s is the saturated water content. A shape correction function C_r is used to fit the curve over the entire theoretical range of soil suction (from 0 kPa at full saturation to 10^6 kPa at zero water content) and is given by

$$C_r = \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \tag{4}$$

AN EMPIRICAL EQUATION FOR THE SHRINKAGE CURVE

The shrinkage curve describes the shrinkage of a soil desaturating from beyond its liquid limit in terms of void ratio e. The Fredlund, Wilson, and Fredlund (2002) best-fit shrinkage curve equation is given by

$$e = a_{sh}\left[\frac{w^{c_{sh}}}{b_{sh}^{\ c_{sh}}} + 1\right]^{1/c_{sh}} \tag{5}$$

where a_{sh} is the minimum void ratio, b_{sh} is the slope of the saturation line, and c_{sh} is a curve-fitting parameter.

The ratio $a_{sh}/b_{sh} = G_s/S$ is constant for a specific soil, where G_s is the specific gravity of the soil and S is the degree of saturation. The value of c_{sh} is also derived using a computational technique to minimize the least-squares error between the observed shrinkage and the curve fit.

The combination of equations (3) and (5) can be used to fully describe most unimodal SWRCs, even when shrinkage change occurs as suctions are generated (Fredlund and Houston 2013).

Experimental Results

SWRCs OF NONPLASTIC SOILS

Five tests on the two nonplastic soils were performed using the continuous drying and tensiometer method. The specimens were tested from an initially "over-saturated" slurry by mixing the soil uniformly with de-aired water to a water content of around 30 %.

The soil particles would resediment in the specimen container, releasing excess free water and compacting while remaining saturated, similar to how tailings are deposited on the surface of a tailings storage facility (TSF) in the case of the gold tailings. The resulting initial specimen preparation parameters are summarized in **Table 2**. The fine sand had final dry densities of 1.65 and 1.71 g/cm^3 with saturated water contents of 23.4% and 21.3% for the two tests, respectively. For the gold tailings, the final dry densities of each test were 1.63, 1.66, and 1.64 g/cm^3, with saturated water contents of 24.2%, 22.9%, and 24.6%, respectively.

The tensiometer method produced a continuous record of the suctions, starting from very low suctions up to ultimate values of suction that correspond to cavitation, or the ceramic of the HCT experiencing air-entry. Each test was concluded within 24 to 60 h depending on the thickness of the specimen.

Suctions measured via the HCT were compared to the point measurements of the filter paper suctions from compacted specimens prepared at different water contents with average dry densities of 1.58 g/cm^3 for the fine sand and 1.57 g/cm^3 for the gold tailings. These measurements were used with equation (3) to produce the gravimetric water content SWRC for each soil.

TABLE 2

Initial specimen preparation

Material	Test	Initial Specimen Dimensions: Height, mm	Initial Specimen Dimensions: Diameter, mm	Initial Density ρd, g/cm^3	Saturated Water Content w_s, %	Preparation Method
Fine sand	#1	25.4	73.4	1.65	23.4	Resedimented
	#2	25.4	73.4	1.71	21.3	Resedimented
Gold tailings	#1	18.5	116.8	1.63	24.2	Resedimented
	#2	50.6	77.2	1.66	22.9	Resedimented
	#3	25.5	73.5	1.64	24.6	Resedimented

The resulting gravimetric water content SWRCs for the fine sand and gold tailings are shown in **figure 6*A*** and **6*B***, respectively.

The SWRCs for nonplastic soils were typically normalized with respect to the water content parameter to enable a direct comparison of different SWRCs. The degree of saturation (*S*) is one such normalization and is easily determined for soil samples not undergoing volume change. The degree of saturation SWRCs for both soils are shown in **figure 7**.

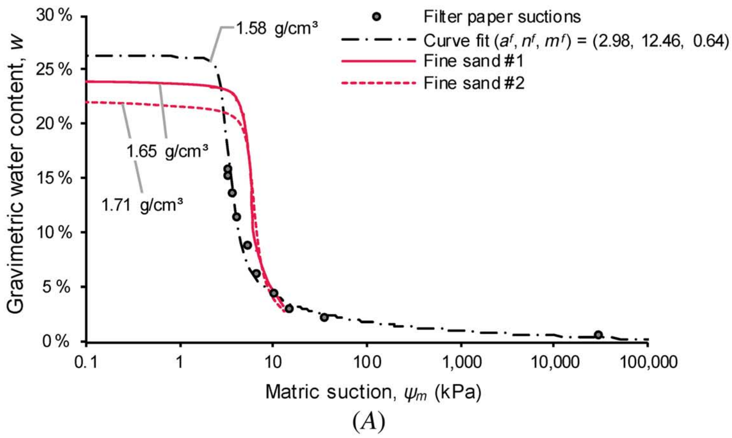
Initial density is one of the most significant contributors to the form of the SWRC (Mercer, Rahardjo, and Satyanaga (2019). This property is evident from the starting points on each of the gravimetric water content SWRCs where desaturation starts.

When comparing the results for the fine sand, it is shown that the tensiometer method delivered near-identical degree of saturation SWRCs for matric suctions between 0 and 13 kPa and very consistent SWRCs for matric suctions between 0 and 320 kPa in the gold tailings.

The relatively low ultimate values of suction measured on the SWRC via the tensiometer method is attributed to the breaking of the hydraulic link between the ceramic and the pore water below a certain water content near the residual suction value. Beyond this point, the measurement system would no longer be in equilibrium with the pore water and would register desaturation of the ceramic rather than matric suction of the specimen. The measured negative pressure would then increase until cavitation occurred in the water reservoir or the pores of the ceramic, identified by an abrupt return to the cavitation pressure. This portion was excluded from the SWRC plot. This break occurred at lower values of suction for the coarser fine sand with a larger average pore size than for the finer gold tailings.

FIG. 6

Gravimetric SWRCs (ψ_m-*w*) of (*A*) fine sand and (*B*) gold tailings specimens.



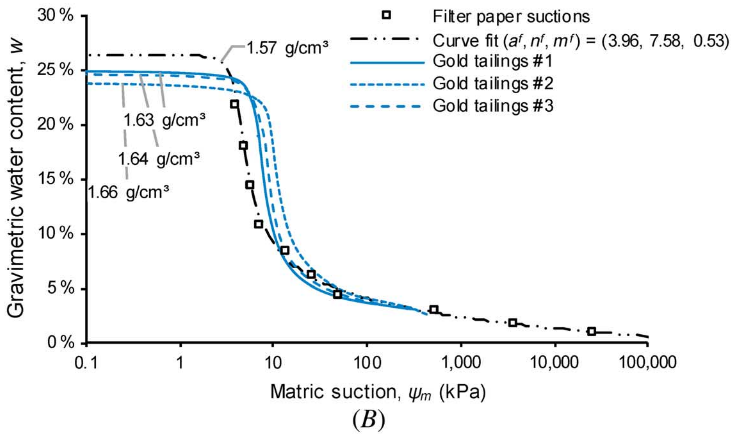
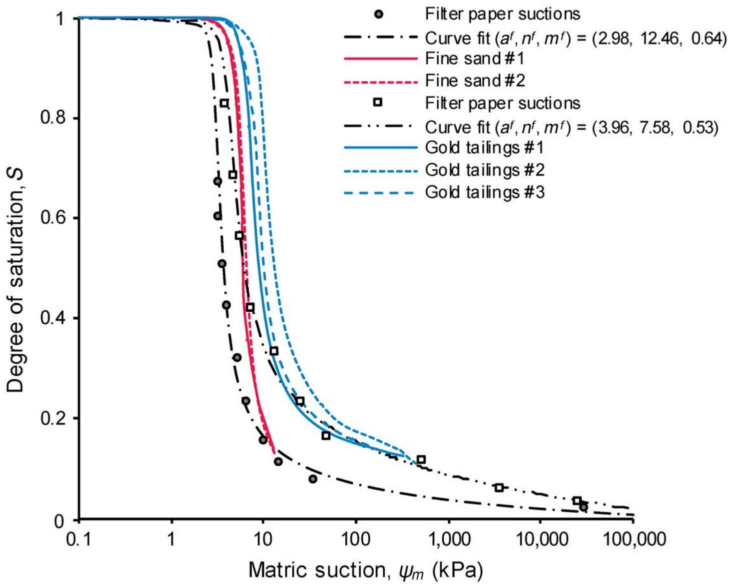


FIG. 7

Degree of saturation SWRCs (ψ_m-S) of fine sand and gold tailings specimens.



Good agreement between the filter paper and tensiometer methods was found for the range of suctions measured. For water contents above 5 %, the tensiometer method tended to measure higher values of suction when compared to the FPM. The SWRCs determined from the tensiometer method are primary drying curves (PDCs). Because of the method in which the specimens were prepared, the SWRCs determined from the FPM represent scanning curves, occurring between the PDCs and the primary wetting curves (PWCs). Hysteresis between the curves is expected.

The agreement between the methods might be improved by independent calibration of the filter paper rather than using the Greacen, Walker, and Cook (1987) calibration curve as is.

The tensiometer method additionally fully showcases the early stages of the PDCs, which cannot be determined by the FPM for degrees of saturation above 90% or suctions below the air-entry value. The FPM serves as a valid method for extending the SWRC into the range of suctions that are beyond the range of the HCT.

SHRINKAGE CURVES OF PLASTIC SOILS

After SWRCs were successfully determined for nonplastic soils using the tensiometer method, the experimental procedures were applied to plastic soils that undergo shrinkage during drying. Nine tests on the three plastic soils were performed using the continuous drying and tensiometer method, incorporating dimensional change measurement. The initial specimen preparation parameters are summarized in **Table 3**.

TABLE 3

Initial specimen preparation

		Initial Specimen Dimensions		Initial Density	Saturated Water Content	
Material	Test	Height, mm	Diameter, mm	ρd, g/cm^3	w_s, %	Preparation Method
Clayey sand	#1	22.8	71.6	1.31	36.4	Reconstituted
	#2	22.8	71.6	1.54	27.0	Re-compacted
	#3	22.9	71.6	1.50	28.4	Re-compacted

TABLE 3 *Continued*

		Initial Specimen Dimensions		Initial Density	Saturated Water Content	
Material	Test	Height, mm	Diameter, mm	ρd, g/cm^3	w_s, %	Preparation Method
Lean clay	#1	23.3	71.6	1.09	54.2	Reconstituted
	#2	21.8	71.6	1.18	47.4	Reconstituted
	#3	22.7	71.6	1.15	49.6	Reconstituted
Fat clay	#1	22.8	71.6	0.95	64.5	Reconstituted
	#2	22.8	71.6	0.97	62.5	Reconstituted
	#3	22.8	71.6	1.02	58.2	Reconstituted
	#4	26.7	70.0	1.34	35.5	Re-compacted

FIG. 8

Specimen dimensions before and after shrinkage of (*A*) clayey sand, (*B*) lean clay, and (*C*) fat clay specimens.

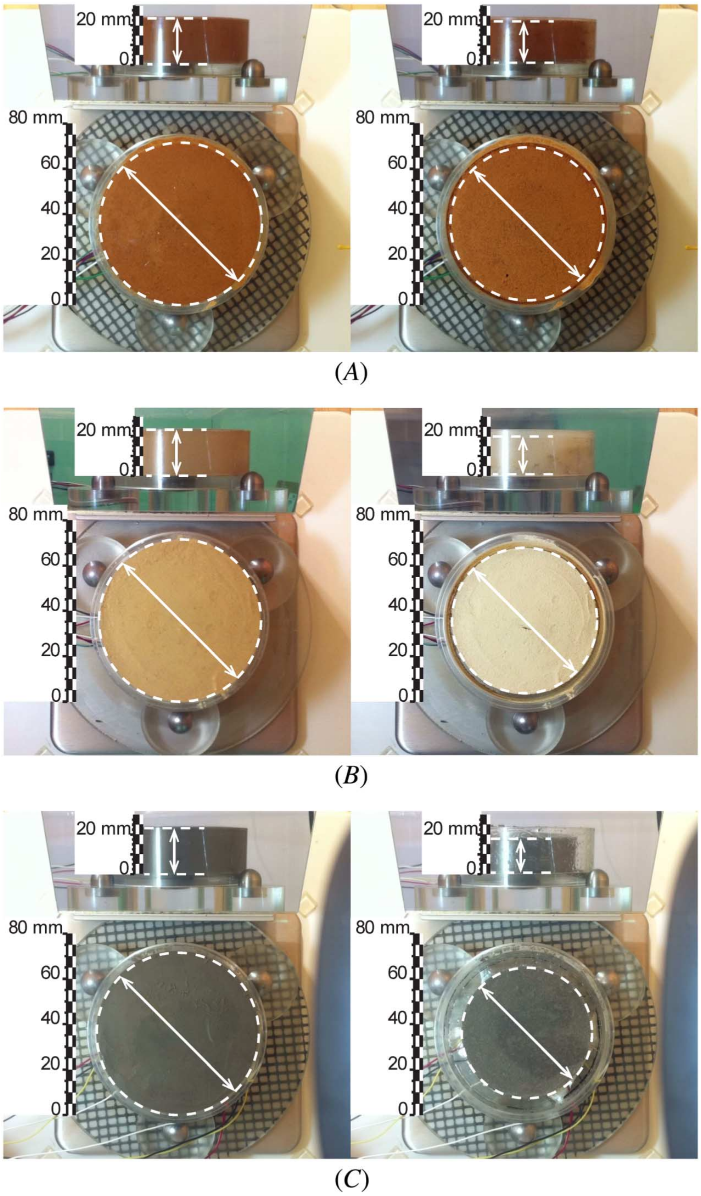


Figure 8*A*–*C* shows how the average specimen dimensions were measured for each of the plastic soils. Equations (1) and (2) were used to relate the observations to the actual specimen dimensions and interpolate measurements for several images taken in between.

The interpolated measurements were sufficiently accurate to calculate the void ratio of each specimen during drying. A curve fit for the shrinkage curve of each specimen was constructed using equation (5).

The clayey sand specimen for test 1 was prepared fully saturated at an initial water content of around 40 % to obtain the primary shrinkage curve for the soil. The specimens for test 2 and test 3 were prepared as recompacted specimens at higher initial densities. The effect of initial density on the shrinkage curve (**fig. 9*A***) is not immediately evident because of the degree of scattering in the observed measurements. However, for the clay specimens, all prepared well above the liquid limit, the shrinkage curves of each soil were near-identical for the lean clay (**fig. 9*B***) and fat clay (**fig. 9*C***).

SWRCs OF PLASTIC SOILS

The gravimetric water content SWRCs determined for the three plastic soils are shown in **figure 10*A*–*C***. The initial dry density, saturated water content w_s, and the ultimate value of measured suction for each specimen via the HCTs are also indicated.

The clayey sand specimen for test 1 was prepared as an over-saturated slurry to obtain the PDC, whereas the specimens for test 2 and test 3 were prepared as recompacted specimens at higher initial densities, the effect of which can be seen in the starting point of the gravimetric water content SWRCs in **figure 10*A***.

FIG. 9 Shrinkage curves (*e*-*w*) of (*A*) clayey sand, (*B*) lean clay, and (*C*) fat clay specimens.

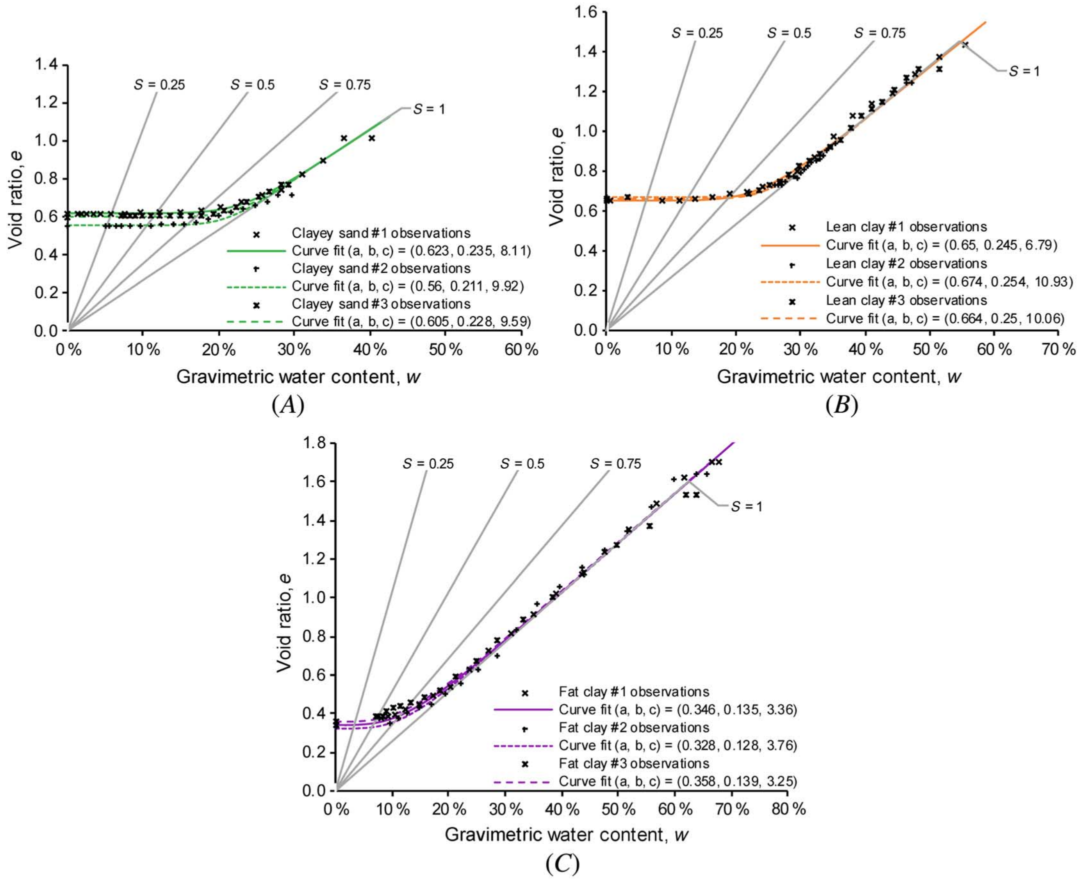
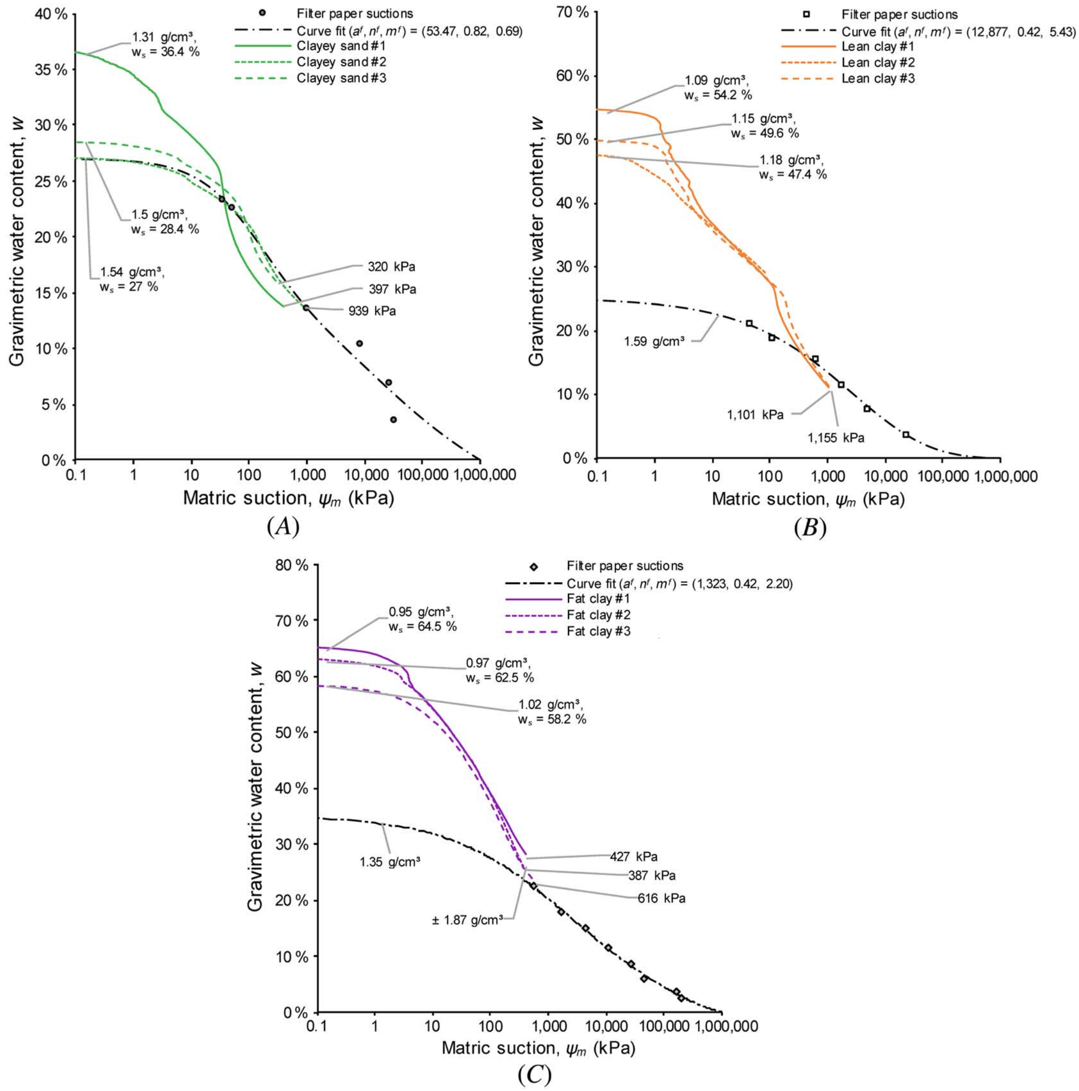


FIG. 10 Gravimetric water content SWRCs (ψ_m-w) of (*A*) clayey sand, (*B*) lean clay, and (*C*) fat clay specimens.



The best agreement between the filter paper and tensiometer methods was found for test 2 on the clayey sand up to around 940 kPa, where the initial density of the specimen and the average density of the compacted filter paper specimens were near 1.54 g/cm^3 each.

Suctions over 1,100 kPa were recorded via the HCTs for the lean clay. The finer soil texture is thought to allow the ceramic to remain hydraulically linked to the pore water for longer, resulting in higher suction measurements before cavitation occurs. All three specimens for the lean clay were prepared above the liquid limit, with initial densities varying slightly between 1.09 and 1.18 g/cm^3 and a final density consistently nearing 1.60 g/cm^3.

The filter paper measurements on the lean clay were taken from specimens prepared at an average dry density of 1.59 g/cm^3, the highest that could be achieved in the confining rings by compaction, rather than discrete drying of each specimen. Because the specimens for each method were prepared and tested differently, a direct comparison could not be made. However, it appears that the tensiometer measurements tended toward the suctions measured by the FPM at very low water contents, as shown in figure 10*B*. The second source of discrepancy stems from the hysteresis between PDCs determined from the tensiometer method and the scanning wetting curve determined from the FPM, which is expected to be between the PDCs and the PWCs.

Because of the high plasticity of the fat clay, extreme shrinkage took place during drying, particularly at the surface of the specimens where cracking would initiate. These cracks would propagate toward the tensiometers and are thought to have broken the hydraulic contact with the pore water, causing early cavitation. The ultimate values of suctions measured for the fat clay were lower than for the lean clay at between 380 and 620 kPa.

The filter paper measurements were taken from specimens of the fat clay prepared at an average dry density of 1.35 g/cm^3, whereas the HCT suctions were determined from the clay undergoing shrinkage during drying from around 1.00 to 1.87 g/cm^3. As with the lean clay sample, a direct comparison could not be made, particularly at the higher water content range.

The relatively quick drying (between 24 and 48 h prior to cavitation occurring) could potentially impact the measured SWRC because of a nonuniform suction distribution and long equilibration time required in each of the plastic soil specimens. However, two HCTs in each specimen measured identical values of suction, suggesting that the error was small within the for the range of the suctions measured.

A fourth and final continuous drying test, test 4, was conducted on a recompacted sample of the fat clay prepared at the maximum achievable density, reaching 1.34 g/cm^3 and shrinking to around 1.50 g/cm^3. This was done to verify the curve fit of the SWRC determined from the filter paper measurements from an initially compacted specimen. This test was in excellent agreement with the curve fit determined from the filter paper results, as shown in figure 11. A curve fit for the SWRC determined from the initially slurried specimen in test 3, combined with the filter paper measurements, was determined based on the assumption that the two methods would provide similar results at low water contents and is also shown.

By combining the gravimetric water content SWRCs with the continuous shrinkage curves, the degree of saturation SWRCs could be determined and directly compared, as shown in figure 12*A* and 12*B*. When comparing the three specimens of the clayey sand, the effect of volume change on the shape of the SWRC becomes

FIG. 11

Gravimetric water content SWRCs (ψ_m-w) of additional fat clay specimens.

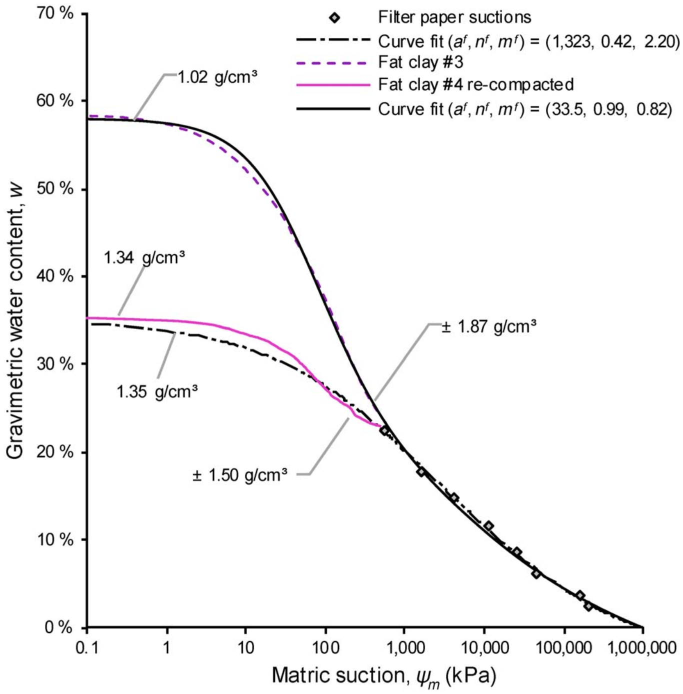
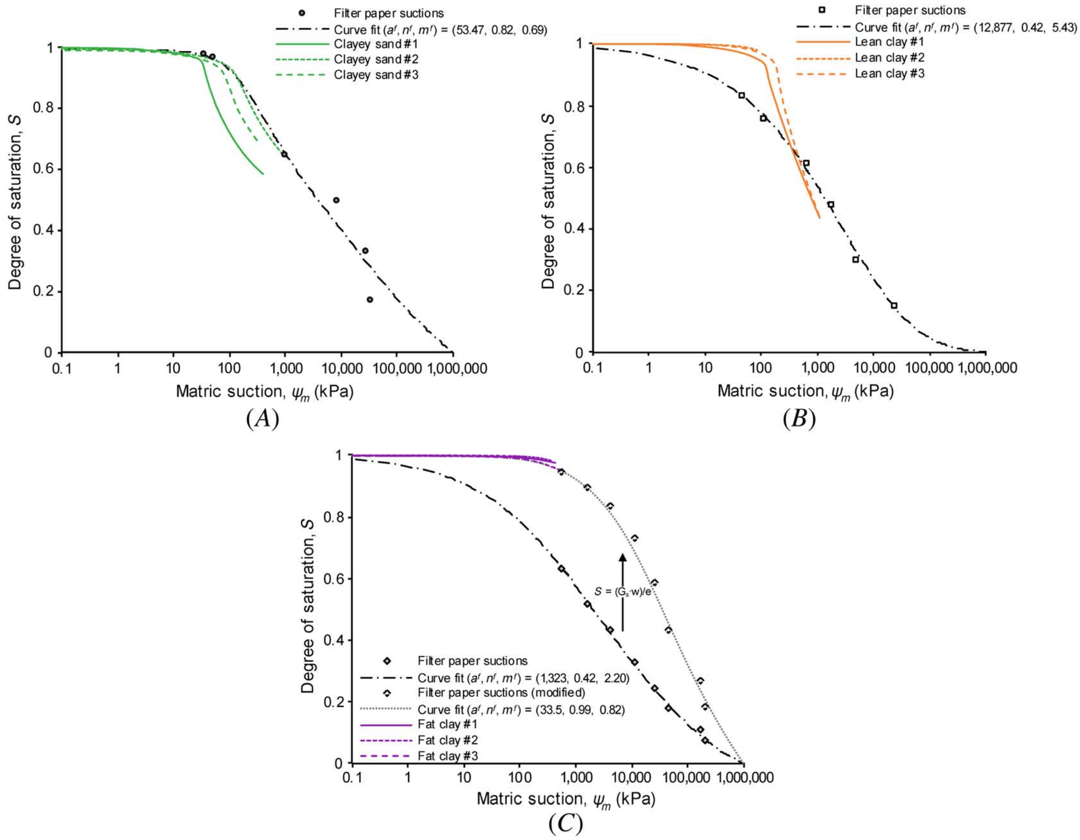


FIG. 12 Degree of saturation SWRCs (ψ_m-S) of (*A*) clayey sand, (*B*) lean clay, and (*C*) fat clay specimens.



evident. As the initial density of the specimens increased, the approximate air-entry suction, overall density, and values of suction measured increased as well.

The high plasticity of the fat clay led to considerably higher shrinkage than for the lean clay (**fig. 9*B*** compared to **fig. 9*C***), with the specimens remaining near the saturation point for the majority of the test, only reaching air-entry at a water content of around 20 %. Because of this high shrinkage and the high values of suction generated before cavitation occurred, only limited parts of the SWRCs were recorded for the fat clay specimen. The approximate air-entry pressures of the specimens, thought to occur around a water content of 20 % as interpreted from the shrinkage curves, could not be determined from the tensiometer method data directly. However, by translating the filter paper suctions and curve fit on the degree of saturation axis using the specimen's shrinkage curve and fundamental soil phase relationships, a reasonable estimation of the degree of saturation SWRC could be made as shown in **figure 12*B***.

Conclusions

The tensiometer method allows an uninterrupted continuous record of the SWRC to be obtained, starting from very low suctions and up to cavitation of the HCT. This continuous record cannot be obtained with the conventional methods described where only point measurements are obtained.

The low-cost HCT developed for this study places the tensiometer method within reach of most research groups. Saturation of the HCT is relatively simple, only requiring access to a standard triaxial cell, water deaerator, and a vacuum pump. The tensiometer method has the potential to become a routine method for the determination of the SWRC. Additionally, the HCT provides a direct measurement of the soil matric suction, where other standard methods used in SWRC determination rely on indirect measurement. The method is not limited to the tensiometer described in this article, as any other commercially available high-capacity tensiometers of small size should be equally suitable for SWRC measurement. However, for satisfactory performance, it is essential that the tensiometer be very well saturated.

The performance of the tensiometer method of a range of nonplastic and plastic soils was presented. In nonplastic soils, it is possible to measure suctions over nearly the entire range of the degrees of saturation with the tensiometer method. Because of the relatively low suctions occurring in these soils, almost the full SWRC can be obtained. This range of measurement is a crucial benefit for the tailings industry where soils often occur in the silt size range and where knowledge of the SWRC is essential.

In plastic soils, where high suctions are recorded early in the drying-out process, it is only possible to record a relatively limited part of the SWRC before cavitation of the HCT occurs. Therefore, additional means are required for the measurement of high values of suction, such as the FPM or dew point hygrometer. Results from the tensiometer method were found to compare very well with measurements from the FPM.

The test setup allows direct noncontact observation of the specimen dimensions such that the shrinkage of plastic soils can be determined. This observation is not possible for other methods that require specimens to be contained.

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