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TECHNICAL NOTE

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Impact of Single and Multiple Specimen Suction Control Oedometer Testing on the Measurement of the Soil–Water Characteristic Curve

Reference

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ABSTRACT

Devices that simultaneously facilitate controlling suction and applying a net stress on soil specimen provide soil–water characteristic curves (SWCCs) in terms of both the water content and degree of saturation, and volumetric deformations at various applied suctions. Such tests determine the water content of soil specimens based on the measured water volume changes at various applied suctions. However, studies have shown disagreements between the water volume–based calculated water content and the actual water content of soil specimens determined by the oven-drying method. Testing multiple soil specimens at predetermined suctions and measuring water content by the oven-drying method can overcome this but are a time-consuming approach. In this study, the impact of testing single and multiple soil specimens on the subsequently determined suction-water content and suction-degree of saturation SWCCs for the wetting process were studied. Statically compacted specimens of a sandy clay were used for establishing SWCCs using a suction control oedometer. Differences were noted between the calculated and measured water content and degree of saturation for an applied suction range of 0 to 95 kPa. Differences were noted between the SWCC fitting parameters obtained from the test results of single and multiple soil specimens. Statistical analysis suggested the differences between the results from single and multiple soil specimens testing were not significant. Corrections applied to the water volume change measurements were found to minimize these differences.

Keywords

laboratory testing, unsaturated soil, collapsible soil, soil–water characteristic curve

Introduction

Laboratory tests on soil samples subjected to an increase and a decrease in suction have enabled researchers to study the engineering behavior of unsaturated soils under predetermined stress and hydraulic boundary conditions (Escario and Sáez 1973; Pereira et al. 2005; Fredlund, Rahardjo, and Fredlund 2012). The soil–water characteristic curves (SWCCs) established from such tests provide various relevant parameters that are required for constitutive models of unsaturated soil behavior (Fredlund and Fredlund 2020). Laboratory suction control SWCC tests at a chosen applied stress are usually carried out on a single soil specimen that is taken through wetting and drying processes in a stepwise manner. Suction control odeometers measure the vertical deformation of soil specimens under K_0-condition. Problematic soils are known to exhibit significant shrinkage during the drying process, accompanied by changes in the lateral and axial dimensions. Therefore, the use of suction control oedometers is more appropriate for studying the volume change behavior of problematic soils during the wetting process, in which case the diameter of soil samples remains unchanged. The water content of a soil specimen at any applied suction is usually determined based on the water volume change measurement and either the initial or final water content of the soil specimen. The water content and volumetric changes of the specimen are considered for determining the degree of saturation at various applied suctions using the basic volume–mass relationships.

Disagreements between the water content of soil specimens calculated from the water outflow measurements during drying tests and that measured from the oven-drying tests have been reported in several studies (Chen, Fredlund, and Gan 1999; Perez-Garcia et al. 2008; Likos et al. 2010). The duration of tests, response of the measuring system, and experimental challenges associated with the tests, such as water phase continuity, air diffusion through ceramic disk, condensation in the measuring system, leakage in the measuring system, and soil water evaporation through the compressed air line, are some of the factors that have been identified to potentially impact the test results (Klute 1986; Bocking and Fredlund 1980; Leong, Tripathy, and Rahardjo 2004; Perez-Garcia et al. 2008; Tripathy, Elgabu, and Thomas 2012).

The SWCCs established from drying tests and for both single and multiple soil specimens have been reported by several researchers in the past; however, there are no studies available yet that have compared the relevant test results from both test types undertaken contemporaneously on the same soil and for the wetting process using a suction control oedometer. The objective of the current study is to explore the impact of single and multiple soil specimen suction control oedometer testing on the measurement of the SWCC.

Soil Used and Testing Details

The soil used in this study was prepared by thoroughly mixing M400 silt (40 %), Speswhite kaolin (20 %), and Leighton Buzzard sand (40 %). The silt was procured from Sibleco UK Ltd. (www.sibelco.com), whereas Speswhite kaolin and Leighton Buzzard sand were procured from Aggregate Industries UK (www.aggregate.com). The composition of the prepared soil is comparable to that of many naturally occurring aeolian deposits (Al-Khyat 2018). The properties of the soil used are shown in **Table 1**. Based on the grain-size distribution and plasticity properties, the soil was classified as sandy lean clay, CL, according to the ASTM version of the Unified Soil Classification System, or sandy clay with low plasticity, CLS, according to the British Soil Classification System.

Several compaction conditions of the soil were chosen during the initial phase of this investigation. The chosen compaction dry unit weights were based on the compaction conditions reported in the literature for various collapsible soils. Laboratory single and double oedometer tests (ASTM D4546-14e1, *Standard Test Methods for One-Dimensional Swell or Collapse of Soils*; Jennings and Knight 1957) on compacted specimens of the soil showed a variation of the collapse strain. Typical test results from double and single oedometer tests for a compaction dry unit weight of 15.5 kN/m^3 and water content of 12.9 % are shown in **figure 1*A*** and **1*B***, respectively. The applied static compaction pressure during preparation of the specimens was 365 kPa. The collapse strain (ϵ) for single oedometer tests was calculated based on the void ratio before flooding with

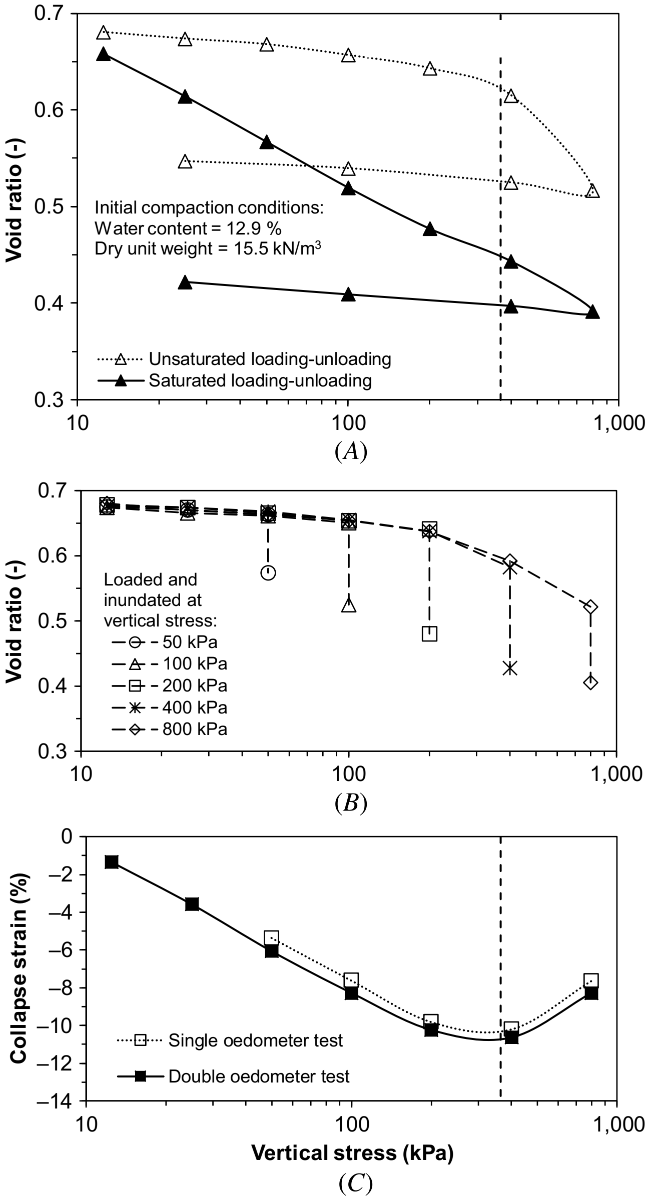
TABLE 1

Properties of the soil used

Soil Property	
Specific gravity	2.65
Liquid limit (%)	24
Plastic limit (%)	16
Compaction characteristics	
Maximum dry unit weight (kN/m^3)	18.5
Optimum water content (%)	13.3
Mineralogy	quartz, kaolinite

FIG. 1

Collapse strain measurements by (*A*) double oedometer test method, (*B*) single oedometer test method, and (*C*) collapse strains at various applied vertical stresses.



water (e_0) and the void ratio after flooding with water (e_f) from equation (1). The collapse strain for double oedometer tests was also calculated from equation (1). In this case, e_0 and e_f are the void ratios of unsaturated-loaded and saturated-loaded soil specimens, respectively (Jennings and Knight 1957).

$$\epsilon = \frac{e_0 - e_f}{1 + e_0} \times 100 \tag{1}$$

The shearing resistance offered at the interparticle level by collapsible soils in their unsaturated state is due to matric suction, bonding between coarse particles created by clay and silt-sized fractions, and cementing agents (iron oxide, calcium carbonate) (Jennings and Knight 1957; Barden, McGown, and Collins 1973; Houston et al. 2001; Jefferson and Ahmad 2007). The magnitude of the collapse strain depends upon the compaction conditions and the applied stress during saturation (Lawton, Fragaszy, and Hetherington 1992). The maximum collapse strain occurred at about 365 kPa (**fig. 1C**). The collapse strains from the single oedometer tests were slightly lower (about 0.6 %) than those of the double oedometer test results (**fig. 1C**). Similar observations have been reported by Booth (1977).

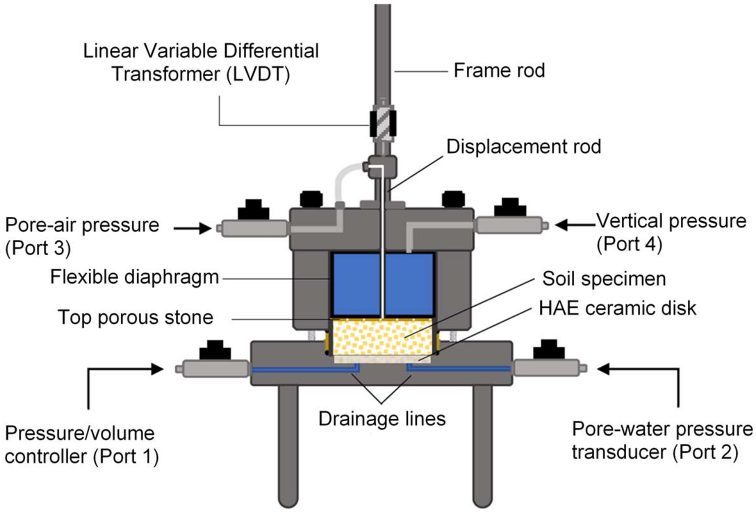
SUCTION CONTROL OEDOMETER

A schematic of the suction control oedometer used in this study is shown in **figure 2**. A 500-kPa high air-entry (HAE) ceramic disk is sealed to the circumference of a grooved water compartment, which facilitates separating the fluid pressures on either side of the disk. The net stress on the soil specimen is applied by pressurizing the water in the flexible diaphragm via controlled compressed air supply through port 4. The pore-air pressure is applied via compressed air supply through port 3. The pressurized air flows through the central channel of the displacement rod on to the top porous stone and the soil specimen. The magnitude of pore-air pressure is monitored via an air pressure transducer connected to port 3. The pore-water pressure in the soil specimen is controlled by a pressure/volume controller connected to the water compartment below the ceramic disk via port 1. The pressure/volume controller monitors the inflow/outflow volume of water during a test. A pore-water pressure transducer is connected to port 2 for measuring the pore-water pressure if the initial suction of the soil specimen is measured prior to the SWCC tests by the null-type axis translation technique. The pressure/volume controller is not used during the initial suction measurement.

In this study, only wetting tests were carried out. Soil specimens of 100-mm diameter and height of 25 mm were tested. A pressure/volume controller (volume resolution = 1 mm^3, pressure resolution = 0.1 kPa, volumetric accuracy = 0.25 %) was connected to the water reservoir via port 1. A data acquisition system was used to monitor

FIG. 2

Suction control oedometer used in this study.



the applied pore-air pressure, water pressure below the ceramic disk, vertical deformation (via the attached linear variable differential transformer [LVDT]), and water volume changes. The tests were carried out in a temperature-controlled laboratory.

Experimental Program

Soil specimens were prepared by the static compaction method at dry of standard Proctor optimum conditions. The dry unit weight and water content of compacted specimens were 15.5 kN/m^3 and 12.9 %, respectively. A trial study showed that an applied static compaction pressure of 365 kPa was required to achieve the targeted dry unit weight, with an error in the dry unit of less than ± 0.1 kN/m^3. The initial suction of the specimen was measured by the null-type axis translation technique in the suction control oedometer and was found to be about 95 kPa.

Three series of tests were carried out under a predetermined vertical net stress of 365 kPa. The chosen value of net stress was the same as the applied static compaction pressure during preparation of the specimens. **Table 2** shows the compaction conditions of the soil specimens. **Figure 3** shows the test program adopted in this study. In test series I, a single specimen (specimen 1, **Table 2**) was taken through a stepwise wetting process by reducing suction. The water contents of the specimen at all applied suctions were calculated based on initial and final measured water contents and the water volume measurements during the test. In test series II (specimens 2*a* to 2*e*), each specimen was taken through a stepwise wetting process to the targeted suction and water content was measured by the oven-drying method. In test series III, multiple specimens were also tested (specimens 3*a* to 3*e*); however, the specimens were directly wetted to target suctions without going through a stepwise suction reduction process, and water content was measured by the oven-drying method at the end of each applied suction step. The stepwise wetting to suction of 0 kPa was not included in test series II because the water content at the end of test series I was measured in the case of specimen 1. Similarly, the applied suction of 70 kPa was not considered in test series III because this was covered in test series II for specimen 2*a*.

EXPERIMENTAL PROCEDURE

The ceramic disk of the oedometer was saturated prior to the tests. The permeability of the saturated ceramic disk was found to be 3.53×10^{-10} m/s, which agreed well with the reported values for 5-bar (500 kPa) ceramic disks (Leong, Tripathy, and Rahardjo 2004; Tripathy, Elgabu, and Thomas 2012). The initial suctions of specimens in all test series were measured in the suction control oedometer by the null-type axis translation technique to explore the impact of a small variation of water content on the suction of the specimens. The suction

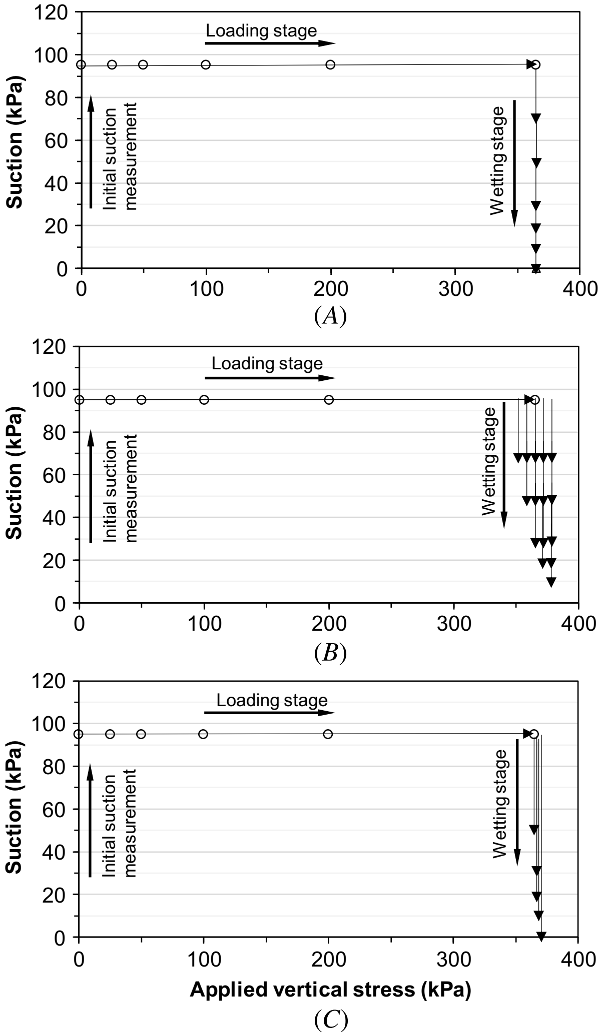
TABLE 2

Compaction conditions of the specimens and experimental program

Specimen (1)	Compaction Conditions (2) Water Content, % (2a)	Compaction Conditions (2) Dry Unit Weight, kN/m^3 (2b)	Initial Suction, kPa (3)	Wetting Steps at Suction, kPa (4)	Test Series (5)
1	12.9	15.5	94.3	70, 50, 30, 20, 10, 0	I
2*a*	13.0	15.5	93.2	70	II
2*b*	12.9	15.5	95.4	70, 50	
2*c*	12.7	15.4	96.1	70, 50, 30	
2*d*	12.9	15.5	93.9	70, 50, 30, 20	
2*e*	12.8	15.5	95.2	70, 50, 30, 20, 10	
3*a*	12.8	15.4	96.6	50	III
3*b*	12.9	15.4	92.4	30	
3*c*	12.9	15.5	94.4	20	
3*d*	12.9	15.5	95.3	10	
3*e*	12.9	15.5	94.5	0	

FIG. 3

Test program showing stress paths for (*A*) test series I, involving a single soil specimen taken through a stepwise suction reduction, (*B*) test series II, involving multiple soil specimen taken through a stepwise suction reduction, and (*C*) test series III, involving multiple soil specimen wetted directly at the targeted suction.



measurements were carried out prior to applying the net stress in each case. A compacted specimen was placed on the saturated ceramic disk (fig. 2). To ensure a good hydraulic contact between the specimen and the ceramic disk, a vertical pressure of 1.25 kPa on the soil specimen was applied (Olson and Langfelder 1965). Port 1 of the device was kept closed, whereas the pore-water pressure was monitored via port 2. Once the pore-water pressure transducer recorded a negative value, this value was countered by manually increasing the pore-air pressure (port 3). The water pressure below the ceramic disk was maintained at zero throughout the test. At equilibrium, the matric suction is equal to the applied air pressure because the pore-water pressure was zero.

Following the initial suction measurements, specimens were incrementally loaded to a net vertical stress of 365 kPa. Under this constant net stress, the wetting process was accomplished by decreasing the pore-air pressure to a targeted value of suction while the pore-water pressure was kept at zero. Simultaneously, in order to maintain a constant vertical net stress, the vertical stress was reduced by an amount equal to the reduction in pore-air pressure. Under each applied suction, the water volume change was monitored by the pressure/volume controller. Water equalization was assumed to be attained when the change in the water volume was less than 0.04 % per day (Sivakumar 1993). Flushing of the water reservoir below the ceramic disk was made using ports 1 and 2 after each suction equalization step in test series I and II. This enabled isolating the error associated with dissolved air diffusion through the ceramic disk to each applied suction step, and hence the cumulative error on the measured water volume change was avoided.

Test Results and Discussion

INITIAL SUCTION OF COMPACTED SPECIMENS

Figure 4 shows the elapsed time versus measured suctions of all the specimens tested in this study (**Table 2**). The measured equilibrium suctions of the specimens are shown in **Table 2**. The suction equilibrium time was found to vary between one and two hours. The suction equilibrium time depends upon the water phase continuity between the water in the specimens, the water in the saturated ceramic disk, and the water in the water compartment below the ceramic disk (Bocking and Fredlund 1980; Tripathy, Elgabu, and Thomas 2012). The results indicate that variability in compaction conditions, experimental errors associated with handling and setting up the specimens in the device, and any delay in the commencement of suction measurements slightly affected the measured suction of the specimens, which remained between 92.4 and 96.6 kPa (mean = 94.7 kPa and standard deviation = 1.2 kPa).

WATER VOLUME CHANGE DURING THE WETTING PROCESS

Figure 5*A* shows the water volume change measurements for specimens in test series I and III. Measured water volume changes in test series II were found to be similar to those of test series I and hence are not presented. Test series III results were calculated based on the initial water content, the mass of soil solids, and the measured water content at each applied suction. The time versus vertical deformation for the specimens are shown in **figure 5*B***. The cumulative vertical deformation are presented for the specimen in test series I, whereas for the specimens in test series III, the measurements are at various applied suctions.

Differences in the measured water volume change were noted between the specimens tested under test series I and III at all applied suctions (**fig. 5*A***). Similarly, at any of the applied suctions, differences in the vertical deformation were also observed for the specimens tested under test series I and III (**fig. 5*B***). Testing of a soil specimen in suction control oedometer involves several stages, such as determination of the initial water content of soil, preparation of a soil–water mixture, curing of the soil–water mixture for moisture equilibration, determination of the water content of the prepared soil–water mixture prior to compaction process, the compaction

FIG. 4

Initial suction measurements of compacted specimens using the null-type axis translation technique.

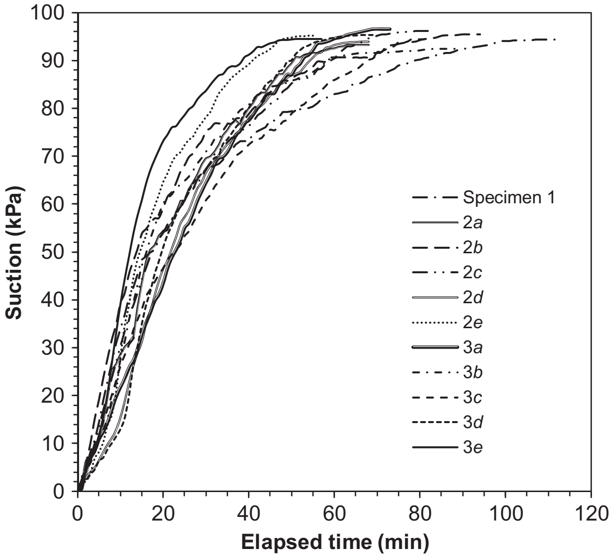
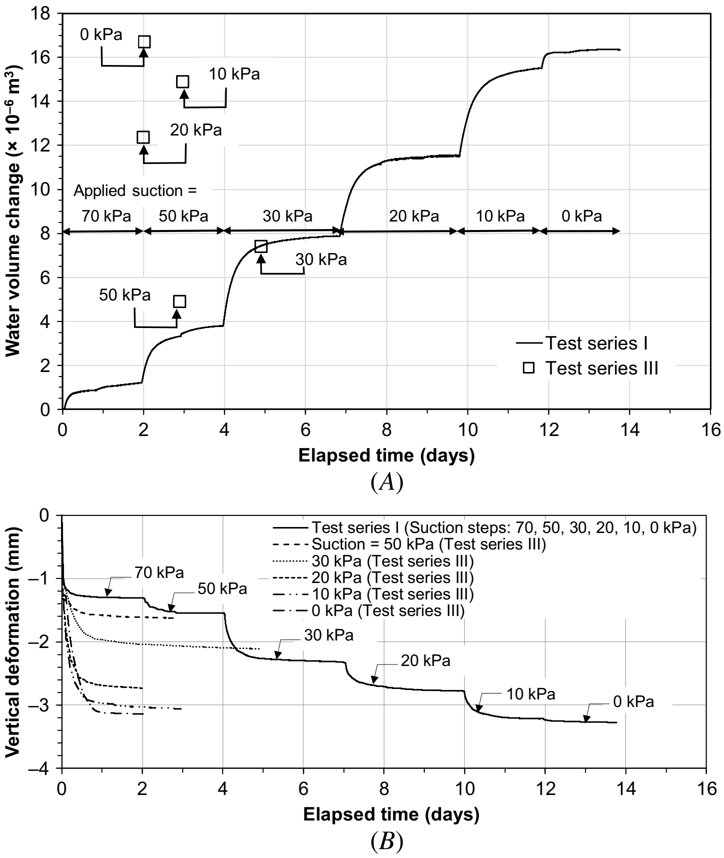


FIG. 5

(*A*) Water volume change and (*B*) vertical deformation in test series I and III.



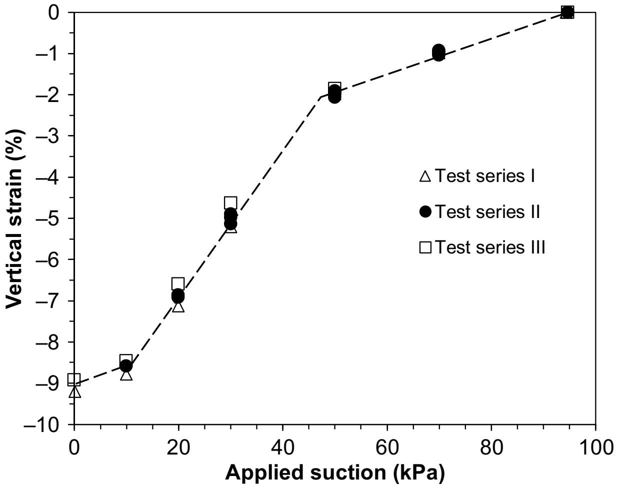
process, measurement of initial suction (optional), suction equilibration at applied suctions (about three days at each suction), and determination of final water content of the soil specimen. In total, about three weeks was required to obtain the SWCC data for the single soil specimen tested in test series I. Considering that an additional four specimens were used in test series II and III, in each case the time spent for preparing the duplicate soil specimens was about two weeks, which in turn extended the time required for establishing SWCCs in test series II to about nine weeks and to about five weeks in test series III. These estimates are only true if one suction control oedometer is available for testing.

The vertical strains of the specimens are presented in figure 6. The collapse strain gradient with respect to a change in suction is distinct for different ranges of applied suctions. The collapse strain was greater due to changes in suction between 50 and 10 kPa, in which case more than 70 % of the collapse strain occurred. The difference in the collapse strains at any applied suction was less than 0.6 % between various test series, which may be considered insignificant. The differences in the test results between test series I and III in terms of the measured water volume change and the vertical strain can be attributed to the differences in the initial compaction conditions of the specimens and the errors introduced by diffused air during the tests.

WATER CONTENT AND DEGREE OF SATURATION SWCCs

Calculated water contents in test series I and the measured water contents in test series II and III at various suctions are plotted in figure 7*A*. The water contents of the specimen in test series I at various applied suctions were calculated based on two different considerations: (1) the initial water content of the specimen and the volume of water in the specimens at various applied suctions (i.e., forward calculations) and (2) the final measured

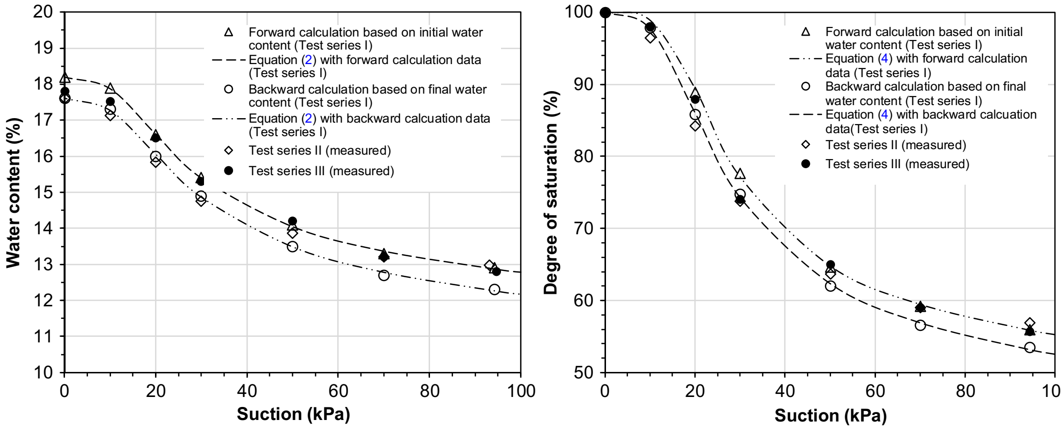
FIG. 6 Influence of suction decrease on vertical strain of the soil tested.



water content by the oven-drying method and the volume of water in the specimens at various applied suctions (i.e., backward calculations). In the former, the volume of water absorbed by the specimen at any suction was added to the initial volume of water in the specimen to obtain the water content at that suction, whereas for the latter the volume of water absorbed by the specimen was deducted from the volume of water in the specimen at 0 kPa suction to obtain the water content at the required suctions. The vertical strain and water content at all suctions were used to calculate the degree of saturation based on the basic volume–mass relationships. **Figure 7*B*** shows the suction-degree of saturation SWCCs from various test series.

As can be seen in **figure 7*A***, up to applied suctions of 50 kPa or greater of the measured water contents in test series II and III are similar to the calculated water contents based on the initial water content in test series I, whereas at smaller suctions (≤30 kPa), the measured water content is similar to the calculated water content based on the final water content in test series I. In general, the water contents of specimens in test series III (multiple specimens with specimens directly wetted at predetermined suctions) are found to be greater than those of the

FIG. 7 SWCCs in terms of water content based on single and multiple soil specimen testing: (*A*) in terms of water content and (*B*) in terms of degree of saturation.



(*A*) (*B*)

specimens in test series II (multiple specimens taken through stepwise suction decrease). The measured water contents at 0 kPa suction in test series II and III were smaller than the calculated water content from forward calculations in test series I. Similarly, the water content calculated from backward calculations was found to be lower than the initial water content of the specimens (12.9 %). A maximum difference (absolute) in water content of 0.7 % was noted between measured and calculated water contents for the suction range considered in this study. This value is greater than the variations in the initial water content of the compacted specimens (i.e., 0.1 %).

The differences in the water content and vertical strain at all suction levels affected the degree of saturation of the soil specimens in various test series (fig. 7*B*). The degree of saturation of the specimen based on forward calculations (i.e., calculated based on the initial water content and the cumulative water volume change) exceeded 100 %, indicating errors associated with the volume of water measured by the pressure/volume controller. Similarly, differences were noted between the calculated degree of saturation from backward calculations (i.e., based on the final measured water content and the cumulative water volume change) and the initial degree of saturation of the soil specimens. The degree of saturation of soil specimens in test series III was found to be greater than that of specimens in test series II. The agreement between the calculated degree of saturation from forward calculations with the degree of saturation of the specimens in test series II and III was better at higher suctions (>50 kPa), whereas the calculated degree of saturation from backward calculations was closer to the measured values at smaller applied suctions.

Figure 8*A* and 8*B* show the relative errors associated with water content and degree of saturation based on forward and backward calculations. The percentage errors were calculated by considering the measured values as

FIG. 8

Percent errors in single and multiple soil specimens testing: (*A*) errors in water content and (*B*) errors in degree of saturation.

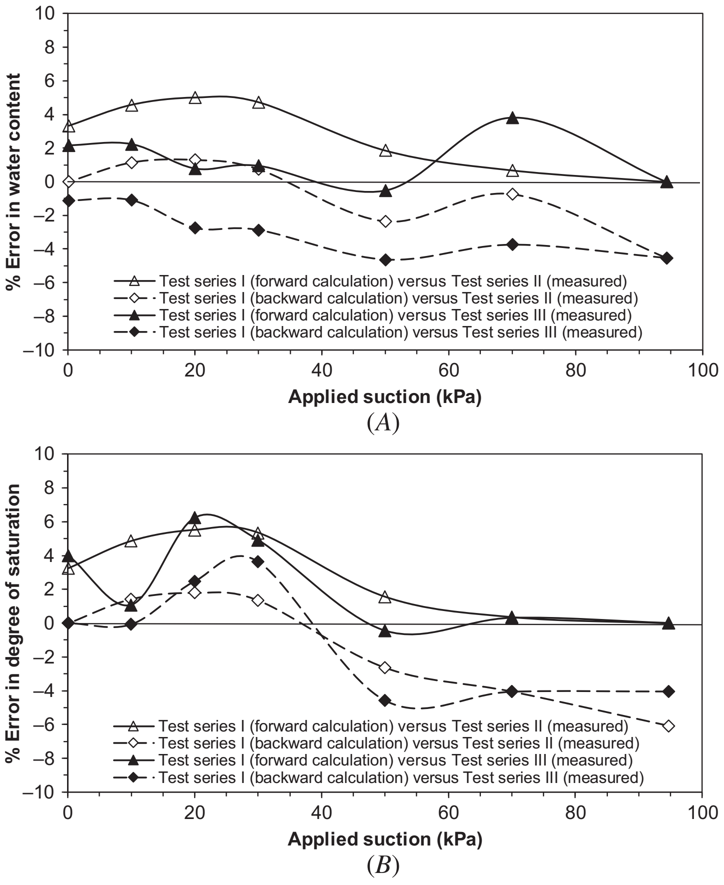


TABLE 3

Statistical analyses results for water content and degree of saturation in various series of tests

Compared Data Set	Statistical Parameters for			
	Water Content		Degree of Saturation	
	(2)		(3)	
(1)	t (2a)	p (2b)	t (3a)	p (3b)
Test series I (forward calculations) versus I (backward calculations)	0.51	0.62	0.29	0.78
Test series II versus I (forward calculations)	0.40	0.69	0.25	0.8
Test series II versus I (backward calculations)	0.14	0.89	0.05	0.96
Test series II versus III	0.27	0.79	0.08	0.94
Test series III versus I (forward calculations)	0.14	0.89	0.17	0.88
Test series III versus I (backward calculations)	0.39	0.71	0.13	0.90

Note: Mean values of the water content in test series I (forward/backward), II, III = 15.5/14.9, 15.05, 15.33, respectively, and variance = 4.64/4.63, 3.44, 4.08; mean values of the degree of saturation in test series I (forward/backward), II, III = 78.84/75.80, 76.31, 77.10, respectively, and variance = 392.16/371.9, 312.1, 336.1; degree of freedom = 12.

the reference. The results presented in **figure 8*A*** and **8*B*** suggest that there was no specific trend (i.e., an increase or a decrease) in terms of the variations of the errors. The percent errors in terms of both water content and degree of saturation from testing single and multiple soil specimens remained less than about ±5 %. Similar magnitudes of error have been reported in the literature for drying tests on various soils (Chen, Fredlund, and Gan 1999; Perez-Garcia et al. 2008; Likos et al. 2010).

A statistical analysis was performed on both water content and degree of saturation data obtained from the three series of tests. The two-tailed t-test for unequal variances was considered for determining the statistical differences in the SWCC results. In a t-test, the t-value measures the size of the difference relative to the variation in the sample data. The calculated difference between two sets of data is represented in units of standard error. The p-value corresponds to the probability of obtaining a t-value. A high t-value or a low p-value would indicate that the statistical difference between any two data sets is significant. Six combinations of the data sets were compared, including (1) test series I (forward calculations) versus test series I (backward calculations), (2) test series II versus test series I (forward calculations), (3) test series II versus test series I (backward calculations), (4) test series II versus test series III, (5) test series III versus test series I (forward calculations), and (6) test series III versus test series I (backward calculations). The analysis was carried out using the Analysis ToolPak of Microsoft Excel. The value of α (i.e., the significance level) was assumed to be 0.05 for testing the null hypothesis.

Table 3 shows the data sets that were compared and the corresponding values of t and p for water content and degree of saturation. It can be seen that the null hypothesis is satisfied, with the p-value being greater than α in all cases, indicating that the statistical difference in the results from any two series of tests is not significant. Between the compared data sets, poorer agreements can be found between the data from backward and forward calculations in test series I, in which cases the values of t were higher and p lower than those for the other compared data sets. The agreements between SWCCs from test series II and test series I (backward calculations) were found to be superior.

EVALUATION OF SWCC PARAMETERS

The impacts of testing a single or multiple soil specimens on the suction-water content and suction-degree of saturation SWCC parameters were evaluated based on Fredlund and Xing (1994) equations (equations (2) and (4)).

$$w(\psi) = C(\psi)\frac{w_s}{\{\ln[e + (\psi/a)^n]\}^m} \tag{2}$$

where $w(\psi)$ is the water content at any soil suction (ψ); w_s is the saturated water content; and a, n, and m are fitting parameters associated with the suction-water content SWCC. The variable e is the base of the natural logarithm. The correction factor, $C(\psi)$, is written as follows:

$$C(\psi) = 1 - \frac{\ln(1 + \psi/\psi_r)}{\ln[1 + (1{,}000{,}000/\psi_r)]} \tag{3}$$

where ψ is any soil suction value and ψ_r is soil suction at residual conditions.

Fredlund (2017) presented the Fredlund and Xing (1994) SWCC equation in terms of the degree of saturation (equation (4)). The correction factor directing the SWCC toward a suction of 10^6 kPa at zero water content is included in equation (4).

$$S(\psi) = \frac{S_f(1 - \ln(1 + \psi/\psi_r)/\ln(1 + 10^6/\psi_r))}{(\ln(\exp(1) + (\psi/a_{fs})^{n_{fs}}))^{m_{fs}}} \tag{4}$$

where $S(\psi)$ is the degree of saturation at any soil suction; S_f is the final degree of saturation; and a_{fs}, n_{fs}, and m_{fs} are the fitting parameter related to the suction-degree of the saturation SWCC.

Leong and Rahardjo (1997) stated that curve fitting parameters should be obtained from experimental data that should include points beyond the residual conditions. They noted that consideration of fewer data points may yield higher values of the parameters a and m and a lower value of n as compared to the parameters that are derived based on a higher number of data points. Fredlund and Xing (1994) stated that for many soils, the magnitude of ψ_r will generally be in the range 1,500–3,000 kPa. The textural soil classification system suggested that the soil dealt with in the study falls in the category of a loam. Vanapalli, Sillers, and Fredlund (1998) reported ψ_r for various loams to remain within a range of about 20 to 50 kPa. Calculations were performed in this study to explore the impact of a variation of ψ_r from 50 to 1,500 kPa on various SWCC parameters. It was noted that a decrease in ψ_r affected the initial portion of the SWCC (Leong and Rahardjo 1997) and the values of a and a_{fs} were found to increase only slightly, whereas n and n_{fs} increased significantly and m and m_{fs} decreased. For the current study, with the wetting test results for a suction range of about 95 to 0 kPa, a comparative study was only possible for the SWCC parameters in different series of tests both in terms of water content and degree of saturation. The magnitude of ψ_r was taken as 1,500 kPa for the sake of comparing the SWCC parameters.

Equations (2)–(4) were used to obtain the SWCC parameters (a, n, m,a_{fs}, n_{fs}, and m_{fs}) for both forward and backward calculations in test series I (columns 2a and 2b of **Tables 4** and **5**). To obtain a closer fit to the experimental data (**fig. 7*A*** and ***7B***), the fitting parameters were determined using a least squares method. In all cases, the R^2 value was close to 1.0. The value of w_s used for forward calculations was the value based on the initial water content of the specimen and the total volume of water absorbed by the specimen when suction was reduced to 0 kPa in a stepwise manner (**fig. 7*A***, **Table 4**). The value of S_f used for forward calculations was set equal to 100 % because the calculated S_f was greater than 100 % at 0 kPa suction (**fig. 7*B***, **Table 5**). The values of w_s and S_f

TABLE 4

Suction-water content SWCC parameters in various test series in this study

	Value Corresponding to SWCC Based on (2)				
SWCC Parameters (1)	Forward Calculations (Test Series I) (2*a*)	Backward Calculations (Test Series I) (2*b*)	Corrected (Test Series I) (2*c*)	Measured (Test Series II) (2*d*)	Measured (Test Series III) (2*e*)
w_s (%)	18.2	17.6	17.6	17.6	17.8
a (kPa)	16.2	15.8	15.8	12.7	17.3
n	3.05	2.88	3.45	3.06	2.74
m	0.22	0.20	0.17	0.17	0.21

TABLE 5

Suction-degree of saturation SWCC parameters in various test series in this study

SWCC Parameters (1)	Value Corresponding to SWCC Based on (2)				
	Forward Calculations (Test Series I) (2*a*)	Backward Calculations (Test Series I) (2*b*)	Corrected (Test Series I) (2*c*)	Measured (Test Series II) (2*d*)	Measured (Test Series III) (2*e*)
S_f (%)	100	100	100	100	100
a_{fs} (kPa)	18.2	16.7	16.4	14.3	16.6
n_{fs}	4.02	3.36	3.53	3.28	4.16
m_{fs}	0.30	0.35	0.32	0.31	0.29

for backward calculations were the measured water content and the degree of saturation calculated based on the volume of specimen at 0 kPa applied suction (**fig. 7**).

It can be seen in **Tables 4** and **5** that the fitting parameters near the inflection point on SWCCs (a and a_{fs}) and the fitting parameters related to the maximum rate of water content and degree of saturation changes (n and n_{fs}) are higher in forward calculations than that in backward calculations, whereas the fitting parameters related to the curvature near residual conditions (m and m_{fs}) are lower in forward calculations than those in backward calculations. The fitting parameters obtained for the SWCCs based on forward and backward calculations in test series I do not represent the actual values because the forward calculations of water content and degree of saturation overestimated the SWCC at smaller suctions and underestimated it at higher suctions in the case of backward calculations.

CORRECTED SWCCs FOR A SINGLE SOIL SPECIMEN TESTING

Perez-Garcia et al. (2008) suggested corrections to water content and degree of saturation can be made when differences are noted in these values from direct measurement and water volume measurement at the end of an SWCC test. The correction in terms of water content (equation (5)) is applicable when a single specimen is taken through a stepwise wetting process.

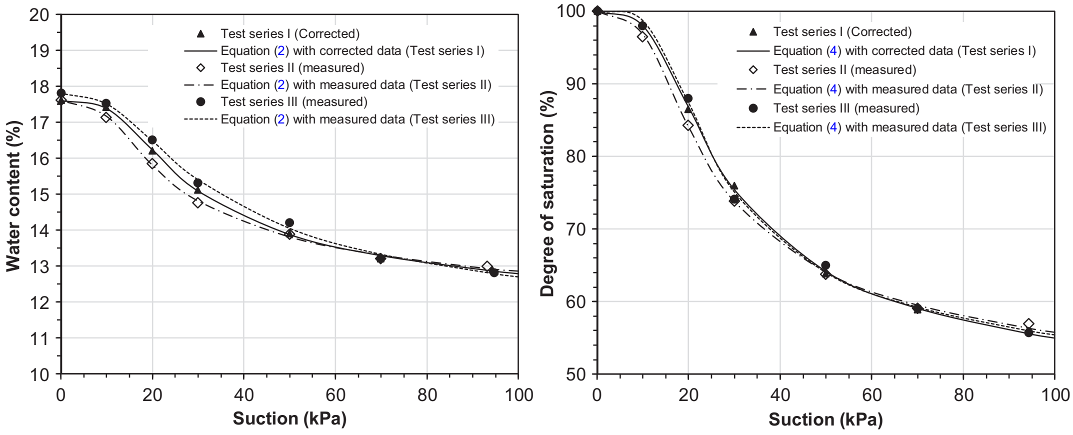
$$\Delta w_c = (w_{fm} - w_{fcal})\frac{t(\psi)}{t} \tag{5}$$

where Δw_c is the water content correction, w_{fm} is the final measured water content, w_{fcal} is the final calculated water content based on the initial water content and water volume measurements at the end of the test, $t(\psi)$ is the time of the test at any applied soil suction, and t is the total testing time, which is the sum of elapsed times at all applied suctions.

Figure 9*A* and **9*B*** shows the corrected water content and degree of saturation of the soil specimen in test series I at various applied suctions based on equation (5) and the measured water contents and degrees of saturation of the specimens in test series II and III. It can be seen that applying corrections to the results from test series I improved the agreements with the results from test series II and III, particularly at suctions greater than 50 kPa.

Equations (2)–(4) were used to establish the best-fit SWCCs for the data presented in **figure 9*A*** and **9*B*** for test series I (corrected), II, and III. The fitting parameters for suction-water content SWCCs and suction-degree of saturation SWCCs are shown in **Tables 4** and **5** (see columns 2*c* to 2*e*), respectively. The fitting parameters corresponding to the corrected SWCCs in test series I (column 2*c* in **Tables 4** and **5**) can be compared with their counterparts obtained from the SWCCs based on the measured water contents and degrees of saturation (columns 2*d* and 2*e* in **Tables 4** and **5**). The results from test series II (i.e., multiple soil specimen taken through a stepwise suction decrease and the water content measured at all applied suctions) formed the reference for

FIG. 9 SWCCs (*A*) in terms of water content and (*B*) in terms of degree of saturation.



(*A*) (*B*)

comparisons. The values of a and a_{fs} are found to be the lowest in test series II and the highest in test series III. Between test series I (corrected), II, and III, the values of a and a_{fs} differed by about 2 to 5 kPa. As compared to test series II, test series I overestimated, whereas test series III underestimated, the value of n. Similarly, both test series I and III overestimated n_{fs}. Minor variations of m and m_{fs} were noted in all test series.

A statistical analysis was once again performed on the corrected water content and degree of saturation results for test series I, which in turn were compared with the results from test series II and III. Table 6 presents the t- and p-values obtained from the two-tailed t-test for unequal variances. It can be seen that applying corrections to the water content results improved the agreements for water content data slightly, whereas the improvement in results for degree of saturation were better; that is, the t-value decreased and the p-value increased, indicating that the overall the agreements between the SWCC results from all the test series improved.

The results from the current study suggested that testing multiple soil specimens, taking each specimen through a stepwise wetting process and dismantling at the end of suction equalization to determine the water content by oven-drying method, does not rely upon the water volume change measurements during the tests, and hence errors introduced by diffused air do not impact on the water content results. However, the method suffers from the following limitations: (1) a significantly longer testing time is required for testing multiple soil specimens, (2) the need for rigorous quality control of the initial compaction conditions of the duplicate soil

TABLE 6
Statistical analyses results for corrected water content and degree of saturation in test series I versus test series II and III

Compared Data Set	Statistical Parameters for			
	Water Content		Degree of Saturation	
	(2)		(3)	
(1)	t (2*a*)	p (2*b*)	t (3*a*)	p (3*b*)
Test series I (corrected) versus II	0.13	0.90	0.07	0.94
Test series I (corrected) versus III	0.14	0.89	0.006	0.99

Note: Mean value for corrected water content in test series I = 15.2 and variance = 3.76; mean value for corrected degree of saturation in test series I = 77.03 and variance = 336.24; degree of freedom = 12.

specimens, and (3) the cumbersome process of frequent flushing of the water reservoir below the ceramic disk to remove entrapped air, which in turn requires frequent user intervention. The testing time may be reduced by considering an alternative approach in which multiple soil specimens are wetted directly at the targeted suctions. However, the method again requires preparing multiple soil specimens with appropriate quality control of the initial compaction conditions and flushing of the water reservoir during the tests. Testing of a single soil specimen taken through a stepwise wetting process to establish the SWCC is the most attractive approach. The method requires the least effort in terms of soil specimen preparation, a much shorter testing time, and the lowest user intervention time among all the approaches. However, the water content test results in this case must be corrected based on the initial and final water contents and the suction equalization time. The method also requires frequent flushing of the water reservoir. The errors in the water volume change measurements and flushing of the water reservoir may be overcome by using a diffuse air volume indicator for water inflow/outflow measurements (Fredlund 1975); however, this would tend to increase the costs toward testing and establishing SWCCs.

The statistical analyses undertaken in this study (**Table 3**) showed that the agreements between the SWCCs established from single and multiple soil specimens testing (stepwise suction decrease) are superior among all the comparisons made, provided that the water content and degree of saturation in single soil specimen testing are calculated based on the final measured water content and water volume change measurements (i.e., backward calculations). The best-fit SWCC parameters in these two cases were also found to be in good agreement with each other (**Tables 4** and **5**). The statistical agreements between the SWCCs and the values of the best-fit SWCC parameters further improved marginally (**Tables 3**–**6**) upon correcting the water content results of single soil specimen testing, as shown by a decrease in the t-value and an increase in the p-value.

Conclusions

The SWCCs in terms of water content and degree of saturation were established by carrying out laboratory suction control oedometer tests involving single and multiple soil specimens. The following conclusions were drawn from the study.

1. Differences were noted between the calculated water contents (based on the initial or final water content and the measured water volume changes during the tests) and the measured water contents of soil specimens by the oven-drying method at all applied suctions considered. Evaluation of the SWCC fitting parameters both in terms of water content and degree of saturation showed differences depending upon two specific conditions, such as (i) whether the SWCCs are established based on the calculated or measured water content and (ii) whether the specimens are taken through stepwise suction decrease or wetted directly at targeted suctions. Statistical analysis suggested that the differences in the results of single and multiple soil specimen testing are insignificant.
2. Testing multiple soil specimens, with the specimens taken through a stepwise wetting process and water content determined by oven-drying method at the end of suction equalization, is considered to provide a reasonable estimation of SWCCs. In this case, the errors associated with air diffusion do not impact the SWCCs because the water volume measurements are not required. However, the testing approach suffers from several limitations (a much longer testing time, necessary quality control to produce duplicate soil specimens, and frequent user intervention). The method is best suited when multiple devices are available in the laboratory. Establishing the SWCC by testing a single soil specimen taken through a stepwise wetting process and calculating water content based on the water volume measurements and final water content is more attractive (a shorter testing time, less effort required for specimen preparation, and the lowest user intervention time). However, the calculated water content in this case must be corrected to achieve reasonable results. Corrections applied to the water volume change measurements in the SWCC tests involving a single soil specimen improve the agreements between calculated and measured water content and degree of saturation, which in turn minimizes the errors in various SWCC fitting parameters.

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