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TECHNICAL NOTE

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Expedited Soil–Water Characteristic Curve Tests Using Combined Centrifuge and Chilled Mirror Techniques

Reference

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ABSTRACT

A soil–water characteristic curve (SWCC) shows soil's ability to provide water availability and the rate that this water can be transmitted and replenished. However, the current commonly used method to determine the SWCCs of soils (the axis-translation method) is time consuming. This study combines two relatively new but established methods (centrifuge and chilled mirror psychrometer) to find a rapid and reliable way to obtain the SWCC for a large range of suctions. For comparison, the SWCC was also independently measured using the axis-translation method (Tempe cell and pressure plate). The comparisons show that the SWCC parameters (air-entry values, residual suctions, and slope of SWCC) determined using the combined centrifuge and chilled mirror psychrometer methods agree well with the same SWCC parameters determined using the Tempe cell and pressure plate methods (axis-translation method). At the same time, the time taken was cut down from a few months for the axis-translation method to about two days for the combined centrifuge and chilled mirror psychrometer.

Keywords

unsaturated soil, soil–water characteristic curve, centrifuge, suction, axis-translation method, chilled mirror

Nomenclature

a, n, m = fitting parameters
BFC = best fitting curve
C_r = parameter related to residual suction
g = acceleration due to gravity
r_1 = radial distance to the midpoint of the soil specimen
r_2 = radial distance to the free water surface
s = slope of transition zone
SWCC = soil–water characteristic curve
θ = volumetric water content

θ_s = saturated volumetric water content
θ_r = residual volumetric water content
ρ = density of the pore fluid
Ψ = suction in the soil specimen
Ψ_a = air-entry value
Ψ_r = residual suction
ω = angular velocity

Introduction

Soil's physical (hydraulic and mechanical) properties are very sensitive to changes in water content. These changes mainly come from environmental factors such as climate, vegetation, and groundwater regimes. The soil–water characteristic curve (SWCC) is a fundamental relationship that can be used to describe the physical behavior of unsaturated soils (Fredlund and Rahardjo 1993). There are several methods (ASTM D6836-02, *Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge*) that can be used to obtain the SWCC of soils in different suction ranges. The most common method is the axis-translation method, in which suction is applied to the soil specimen via gauge air pressure across a water continuum in a pressure plate or Tempe cell to determine the equilibrium water content of the soil. This technique takes a long time (in the range of weeks to months), and the highest suction that can be applied is usually only around 1,500 kPa (ASTM D6836-02). Therefore, performing these tests can be quite costly.

Briggs and McLane (1907) were among the first to use a centrifuge to measure SWCC. They determined the water content of a soil specimen after exposure to a 10,000-*g* gravitational field for 40 min. via centrifugation, which induced a water potential or suction. By measuring the water contents of soil specimens at the suctions induced by the various centrifugal forces, the SWCC of the soil was produced. Russell and Richards (1938) explained this observed phenomenon of decreasing water contents with increasing gravitational field mathematically, in terms of velocity head. Croney, Coleman, and Bridge (1952) discovered that, using the centrifuge method, the induced suctions at the equilibrium condition could be increased by using a solid ceramic cylinder. However, due to low rotational speeds available in the older-generation centrifuges, the centrifuge method was abandoned in favor of pressure plates and Tempe cells. Recently, the centrifuge method for obtaining the SWCC was revisited due to improvements in centrifuge technology. Due to the ability of modern centrifuges to apply and sustain higher gravitational fields, higher suctions now can be applied, and the required equilibrium period has been reduced significantly. Khanzode (2002) used the centrifuge method while varying the thickness of ceramic cylinders to apply different suctions to the specimens and then compared the obtained SWCCs with the SWCCs obtained using the Tempe cell. Caputo and Nimmo (2005) used a quasi-steady centrifuge (QSC) method to study the hydraulic properties of unsaturated soils. Reatto et al. (2008) compared the centrifuge and pressure-plate methods with appropriate run durations using tropical soils.

It was concluded from those tests that the SWCCs determined using the centrifuge method compared well with the SWCCs determined using the axis-translation method. The centrifuge method could be used to obtain the SWCCs of soil specimens.

Although useful suctions can be induced using the centrifuge method, the rotational speeds required for generating the required gravitational fields for higher suctions are often beyond the capabilities of even the most modern commercially available centrifuges. For measuring suctions beyond the capabilities of the centrifuge, a chilled mirror psychrometer could be used (Leong, Tripathy, and Rahardjo 2003).

The chilled mirror psychrometer measures the temperature of a chilled mirror where the water vapor from the soil specimen in a sealed container starts to condense on the mirror surface to infer total suction under isothermal conditions. The chilled mirror psychrometer used for the experiments described in this paper is a product of Decagon Devices, Inc. and is known as the WP4 Dew Point Potentiometer (www.decagon.com). Measurement of suction with the WP4 is based on equilibrating the liquid phase of the water in a soil specimen with the vapor phase of the water in the air space above the specimen in a sealed chamber. A Peltier cooling device is used to cool the mirror until dew forms and then to heat the mirror to eliminate the dew. The temperature of the specimen is measured with an infrared thermometer. An optical sensor is also employed to detect the start of dew formation on the mirror. A sensitive thermocouple that is attached to the chilled mirror measures the dew point temperature. To accelerate vapor equilibrium, a small fan is employed to circulate the air in the sensing chamber. Both the dew point and soil specimen temperature are then used to determine the relative humidity above the soil specimen within the closed chamber. The chilled mirror technique offers a fundamental characterization of humidity in terms of the temperature at which water vapor condenses. Bulut, Hineidi, and Bailey (2002) compared the accuracy of the chilled mirror psychrometer with the filter paper method for total suction measurements of undisturbed soil specimens. Bulut, Hineidi, and Bailey (2002) found that the degree of error associated with the WP4 psychrometer is higher than that with the filter paper method at low suction levels, but there is very good correlation between the two methods at high total suction levels. Leong, Tripathy, and Rahardjo (2003) evaluated the accuracy of a chilled mirror dew point device for total suction using compacted soil specimens by comparing it with independent measurements of matric and osmotic suctions. Leong, Tripathy, and Rahardjo (2003) found that the total suction measured by the chilled mirror dew point device was higher than the sum of matric and osmotic suctions.

The objective of this study was to verify the viability of combining the centrifuge and chilled mirror psychrometer methods to determine SWCC over a large range of suction. Centrifuge tests were carried out to obtain the SWCCs of three soil types: clean sand, clayey sand, and clay (obtained from residual soils in Singapore) for suctions up to 250 kPa. For the higher suction range (>250 kPa), the WP4c Dewpoint Potentiometer was used to continue the SWCCs in the higher suction range.

SUCTION DETERMINATION BY THE CENTRIFUGE METHOD

Using the centrifuge method, an initially saturated soil specimen is subjected to increasing gravitational fields for a sufficient time that causes the induced excess pore-water pressures to drain pore-water from the soil specimen into the water reservoir at atmospheric pressure. The equilibrium water content for each increase in a gravitational field is measured.

Inside the soil specimen, the water content profile after attaining equilibrium is dependent on sample thickness and the distance from the center of rotation. The larger the distance, the higher the centrifugal force that acts on the free water in the soil. Based on the equation by Gardner (1937), the average induced suction using the centrifuge can be calculated as follows,

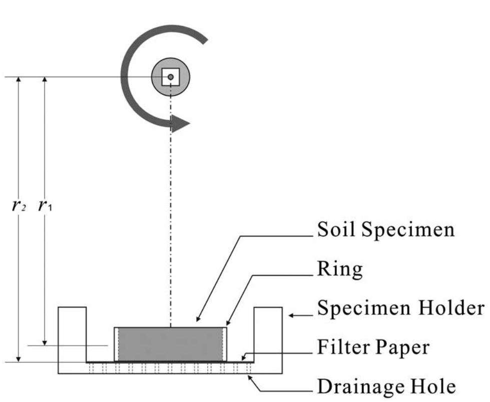
$$\Psi = \frac{\rho\omega^2}{2g}\left(r_1^2 - r_2^2\right) \tag{1}$$

where:

Ψ = suction in the soil specimen,
ρ = density of the pore fluid,
ω = angular velocity,
g = acceleration due to gravity,
r_1 = radial distance to the midpoint of the soil specimen, and
r_2 = radial distance to the free water surface.

In this study, the density, ρ, and centrifugal radii, r_1 and r_2, were held constant. The soil suction, Ψ, becomes a function of the angular velocity, ω. Eq 1 shows a nonlinear relationship between soil suction and angular velocity. A higher angular velocity can induce a higher suction. **Fig. 1** demonstrates the principle used in the centrifuge method for measuring soil suction.

FIG. 1 Soil suction measurement principle of the centrifuge.



BEST FITTING CURVE DETERMINATION

The Fredlund and Xing (1994) equation was adopted to establish the best fitting curve of the SWCC data. The equation with a correction factor $C(\psi)$ is shown below:

$$\theta = C(\psi) * \frac{\theta_s}{\{\ln[e + (\frac{\psi}{a})^n]\}^m} = \left[1 - \frac{\ln(1 + \frac{\psi}{\psi_r})}{\ln(1 + \frac{10^6}{\psi_r})}\right] * \frac{\theta_s}{\{\ln[e + (\frac{\psi}{a})^n]\}^m} \tag{2}$$

where:

ψ_r = parameter related to residual suction,
θ_s = saturated volumetric water content, and
a, n, m = fitting parameters.

Experimental Apparatus

In the research program, the Eppendorf model 5804R centrifuge (**Fig. 2**) was used to determine the water contents of soil specimens up to the suction of 250 kPa. The value of 250 kPa was the maximum suction calculated from Eq 1. The rotor assembly of the centrifuge consisted of four buckets. Inside each bucket, there was a lightweight aluminum soil specimen holder. Four specimens could be tested in one test run. The bucket in the centrifuge could be subjected to angular velocities varying from 200 to 3,900 r/min. When the rotor was spinning, the swinging buckets of the centrifuge turned to a horizontal position. The soil specimens were tested from the minimum angular velocity of 200 r/min to the maximum angular velocity of 3,900 r/min. The water contents of the specimens were measured after attaining the equilibrium state.

The chilled mirror technique (Decagon's WP4c Dew Point Water Potential Meter, **Fig. 3**) was utilized to continue the determination of water content of the soil specimen at higher suctions (>250 kPa). The higher suctions were realized by natural drying. The range of suction that can be detected by WP4c is from

FIG. 2 Centrifuge used to study the soil-water characteristic curve.

FIG. 3 Water potential meter used to study the soil-water characteristic curve.

0 to 300 MPa. The accuracy for the range from 0 to 5 MPa is ±0.05 MPa and, for the range from 5 to 300 *MPa*, is 1 %. The instrument was checked with a one-point calibration using a salt solution with a known osmotic potential (*Dew Point PotentiaMeter Operator's Manual*, 2014). When the temperature readings had stabilized, the instrument determined the relative humidity of the enclosed space above the soil specimen and displayed the total suction of the specimen. Temperature control was found to be important. The measured temperature difference between dew point and specimen had to be kept small. The WP4c chilled mirror psychrometer was found to be a very robust instrument that is suitable for rapid total suction measurements, usually less than 20 min.

The axis-translation method was used to evaluate the SWCC at suctions from 0 to 500 kPa as a comparison. **Fig. 4** shows the pressure chambers that incorporate the axis-translation method.

Tested Soils

Three soil types (clean sand, clayey sand, and clay) were used for this study. Clean sand (**Fig. 5**) was collected from the ground surface to 0.3 m depth at the Old Alluvium formation found in the eastern part of Singapore. Sand cone tests were conducted to measure the average in situ densities of the clean sand within that depth. Clayey sand (**Fig. 6**, left) and clay (**Fig. 6**, right) were obtained from the sedimentary residual soil of the Jurong Formation found in western Singapore. The clayey sand was sampled from the ground surface to 0.3 m depth, and the clay was taken below the 0.3 m depth. Clayey sand and clay samples were collected using the Shelby Tube Sampler with an inner diameter of 70 mm.

Basic soil properties were measured for the soils. Atterberg Limit tests were performed using ASTM D4318-95, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. Wet sieving and hydrometer tests were performed based on ASTM D1140-92, *Standard Test Methods for Determining the Amount of Material Finer than 75-μm (No. 200) Sieve in Soils by Washing*, and ASTM D422-63, *Standard Test Method for Particle-Size Analysis of Soils*, respectively. Specific gravity was measured based on ASTM D854-92, *Standard Test Method for Specific Gravity of Soils*. Basic soil properties of the soils are listed in **Table 1**, and their grain size distributions are shown in **Fig. 7**.

Test Procedure

The dimension of the centrifuge specimens was 70 mm in diameter and 20 mm in length. The specimens were placed in a 70-mm inner diameter retaining ring. During the tests, the specimens were spun at predetermined angular velocities in the centrifuge. The angular velocities and the corresponding suctions for the centrifuge are shown in **Table 2**.

FIG. 4 Pressure chambers using the axis-translation method. (a) Tempe cell; (b) pressure plate.

(a) (b)

FIG. 5 Sampling of clean sand at Old Alluvium formation, Singapore.

FIG. 6 Residual soil specimens from Jurong Formation, Singapore. Left: clayey sand; Right: clay.

At each applied suction, the masses of the specimens were periodically recorded until the mass came to an equilibrium value. This centrifugation method was carried out for the various suction values below 250 kPa. In the equilibrium condition for each of the various suctions, the volumes of the specimens were also measured to calculate the volumetric water contents. Upon reaching the maximum suction applicable by centrifugation using the tabletop centrifuge, most of the soil specimens were oven-dried to determine the gravimetric water contents at 250 kPa suction. The rest of the samples were prepared for continuing the drying process using the chilled mirror method (WP4c). The drying process for the chilled mirror tests was carried out using air-drying under the ambient room temperature of 24°C. As required by the WP4c, the soil specimens were cut into small chips. The chips were placed in a stainless-steel cup for the WP4c tests. Enough soil chips had to be used to cover the bottom of the cup completely. The mass of each specimen was also measured periodically to find the water content for each suction.

TABLE 1 Detail of soils.

Soil Type Based on USCS			Clean Sand	Clayey Sand	Clay
Symbol			SW	SC	CL
Natural Moisture Content		%	5.1	20.7	22.2
Density	Bulk Density	Mg/m^3	1.52	1.99	2.08
	Dry Density	Mg/m^3	1.44	1.65	1.70
Organic Content		%	2.38	4.9	1.62
Atterberg	Liquid Limit	%	\	33	29
Limits	Plastic Limit	%	\	23	17
	Plasticity Index	%	\	10	12
Particle	Gravel	%	0	0.4	0
Size	Sand	%	95	60.0	48.4
Analysis	Fine	%	5	39.6	51.6
Specific Gravity			2.600	2.631	2.621

USCS, Unified Soil Classification System.

For pressure chamber tests, the dimension of specimens was 70 mm in diameter and 20 mm in height. The specimens were maintained by a 70-mm inner diameter retaining ring and placed on a saturated ceramic disc. The theoretical air-entry values of the ceramic disc for the Tempe cell and pressure plate were 100 kPa and 500 kPa, respectively. In the pressure chamber, the suctions of 2, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, and 400 kPa were applied. The specimens were tested in Tempe cells for suctions from 0 to 100 kPa and then shifted to the pressure plate for the application of higher suctions from 100 to 400 kPa. The masses of specimens were periodically measured until equilibration was attained. After equilibration, a higher suction was applied by adjusting the air pressure regulator. This procedure was repeated at the subsequent suctions to define the SWCC.

Results and Discussion

For the centrifuge tests, as two specimens were tested at the same time, two series of data were obtained. These series of data were compared with the results from pressure chamber tests using the axis-translation technique. Fig. 8 indicates the identification of the different zones on the SWCC.

Fig. 9 shows the comparisons of results from the centrifuge and axis-translation methods for the clean sand. The average initial volumetric water content of specimens tested in the centrifuge was 0.38, and the average initial dry density was 1.44 Mg/m^3. The initial volumetric water content of the specimen tested by the axis-translation method was 0.40, and the initial dry density was 1.44 Mg/m^3. The total testing period of the centrifuge and WP4c combination was 1.5 days, and the total testing period using the axis-translation method was 24 days. The testing times

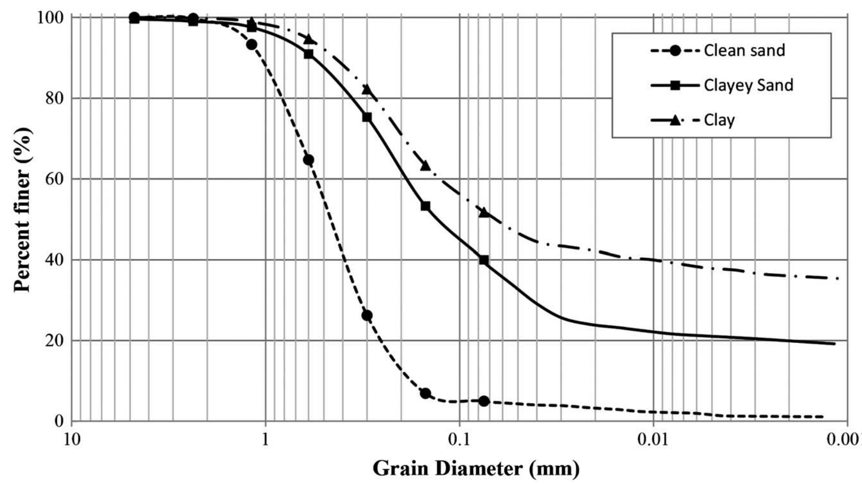


FIG. 7 Grain size distribution. The classifications of soils are based on ASTM D2487-93, *Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System)*.

TABLE 2 Centrifuge test speed and the calculated suction in this study.

Test Speed (r/min)	Suction at the Midpoint of the Specimen (kPa)	Test Speed (r/min)	Suction at the Midpoint of the Specimen (kPa)
200	0.66	1,000	16.45
250	1.03	1,500	37.01
300	1.48	2,000	65.80
350	2.02	2,500	102.81
400	2.63	3,000	148.04
500	4.11	3,500	201.50
600	5.92	3,900	250.19
800	10.53		

required to obtain the SWCC from different equipment are listed in **Table 3**. After the centrifuge tests, there was between 2-mm and 3-mm axial shrinkage for the clean sand specimen (at the suction of 250 kPa); however, no significant shrinkage was observed for the specimens from the axis-translation methods. This 2-mm to 3-mm axial shrinkage was due to the increase in the gravitational field, and this may cause the results to be different from the results from the axis-translation tests.

The comparisons of centrifuge and axis-translation test results for the clayey sand are shown in **Fig. 10**. The average initial volumetric water content of the specimen tested in the centrifuge was 0.41, and the average initial dry density was 1.65 Mg/m^3. The volumetric water content of the specimen tested using the axis-translation method was 0.42, and the dry density was 1.65 Mg/m^3.

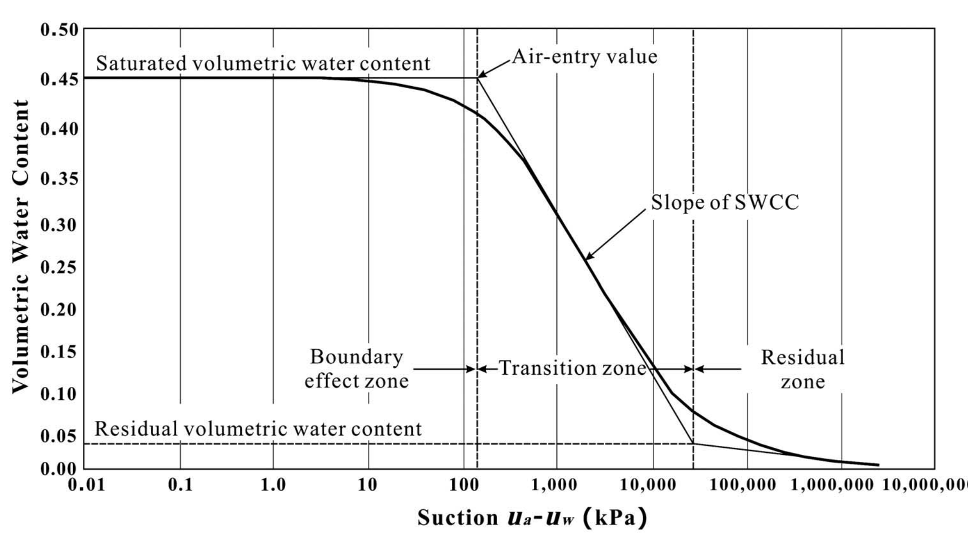


FIG. 8 Identification of the zones on the soil–water characteristic curve.

FIG. 9
The soil-water characteristic curves of clean sand measured from centrifuge and Tempe cell.

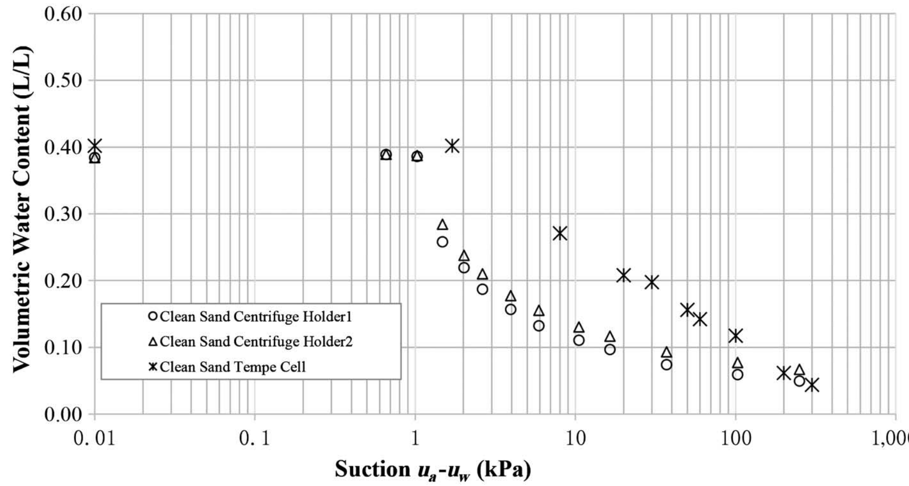
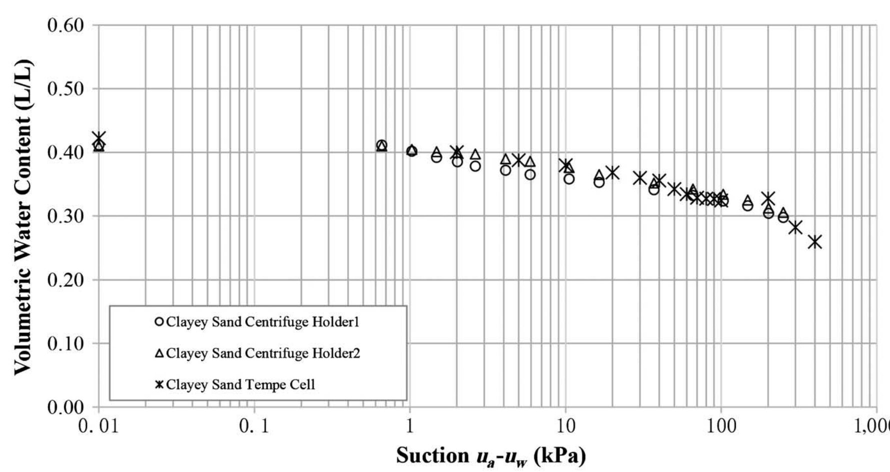


TABLE 3 Time periods to obtain the soil-water characteristic curve.

	Clean sand		Clayey Sand		Clay	
Test Method	Days	Total Days	Days	Total Days	Days	Total Days
Centrifuge	0.5	1.5	0.5	1.5	1	2
Water potential meter	1		1		1	
Tempe cell	14	24	32	46	48	59
Pressure plate	10		14		21	

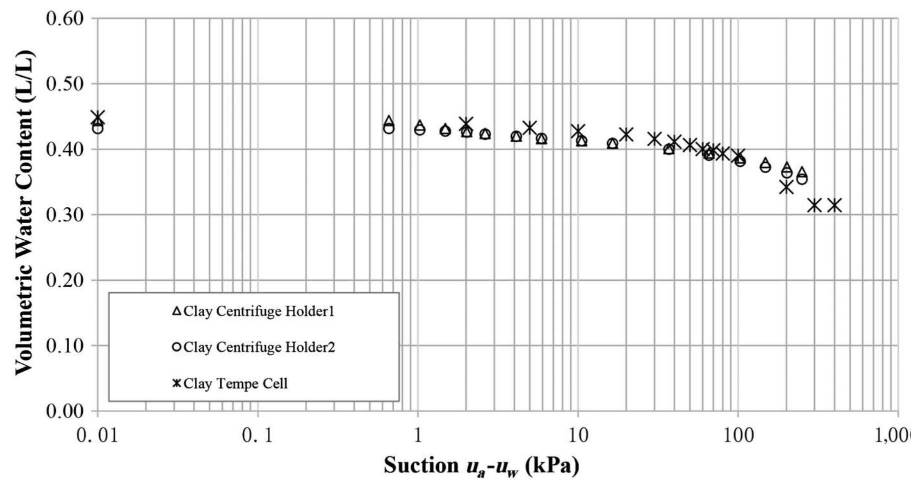
FIG. 10
The soil-water characteristic curves of clayey sand measured from centrifuge and Tempe cell.



The total testing period for the centrifuge and WP4c combination was 1.5 days, and the testing period using the axis-translation method was 46 days.

Fig. 11 shows the comparisons of centrifuge and axis-translation test results for the clay. The average initial volumetric water content of the specimen tested in the centrifuge was 0.44, and the average dry density was 1.76 Mg/m^3. The volumetric water content of the specimens tested using the axis-translation method was 0.45, and the dry density was 1.76 Mg/m^3. The total testing period using the centrifuge and WP4c combination was 2 days, and the total testing period using the axis-translation method was 59 days.

FIG. 11
The soil–water characteristic curves of clay measured from centrifuge and Tempe cell.



For the clayey sand (Fig. 10) and clay (Fig. 11), no significant shrinkage occurred during the centrifuge and axis-translation tests. The results agree very well with each other.

Besides the axial shrinkage issue, the evaporated and condensed water in the Tempe cell could affect the volumetric water content. For the Tempe cell method, during the equalization period for each increase in the air pressure, most of the excess pore-water drains through the ceramic disc. However, it was also observed that at room temperature, some of the water (from the soil and the ceramic disk) also evaporated into the cell. Some of this water also condensed on the Tempe cell walls. This condensed water can be significant and is still considered as pore water during the volumetric water content calculation. This may cause the volumetric water content of the specimens tested using the Tempe cells to be higher than in the centrifuge (Fig. 9). As the applied suctions increase, the reduction in the volumetric water contents in the soil specimens and higher water tension in the ceramic discs also reduces the amount of free surface water available for evaporation. Therefore, at higher applied suctions, the differences of measured volumetric water contents between the soil specimens from the Tempe cell and centrifuge also becomes smaller. For coarse-grained soil, most of the volumetric water content change occurs over a smaller and lower suction range when compared to fine-grained soils. Therefore, the water vapor and condensation issues were more significant for the coarse-grained soil specimens.

Figs. 12–14 show the series of data combined from the centrifuge and WP4c tests. Following Eq 2, the best-fitting curve for each series and the average value of SWCC were drawn in the figures. The average value is the average value of the measurements from holder 1 and holder 2. The key factors to determine the differences in SWCC are saturated volumetric water content,

FIG. 12
The testing results and the best-fitting curves (BFC) of clean sand.

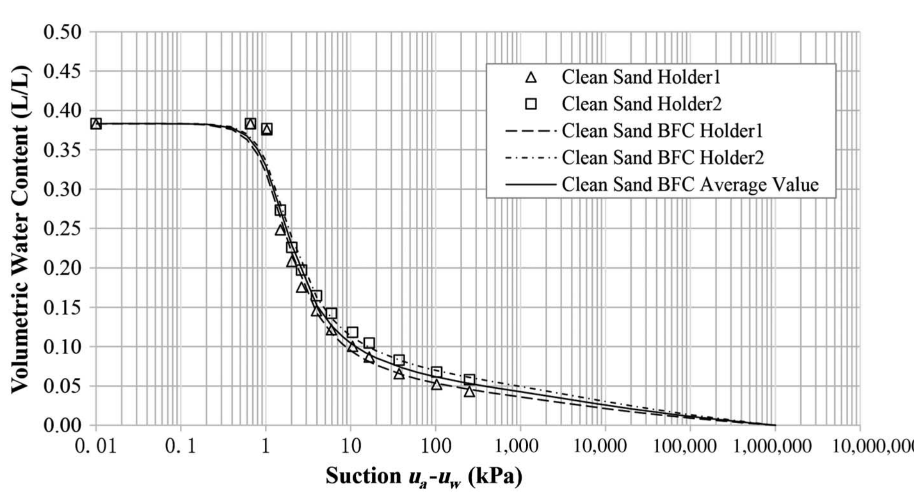


FIG. 13
The testing results and the best-fitting curves (BFC) of clayey sand.

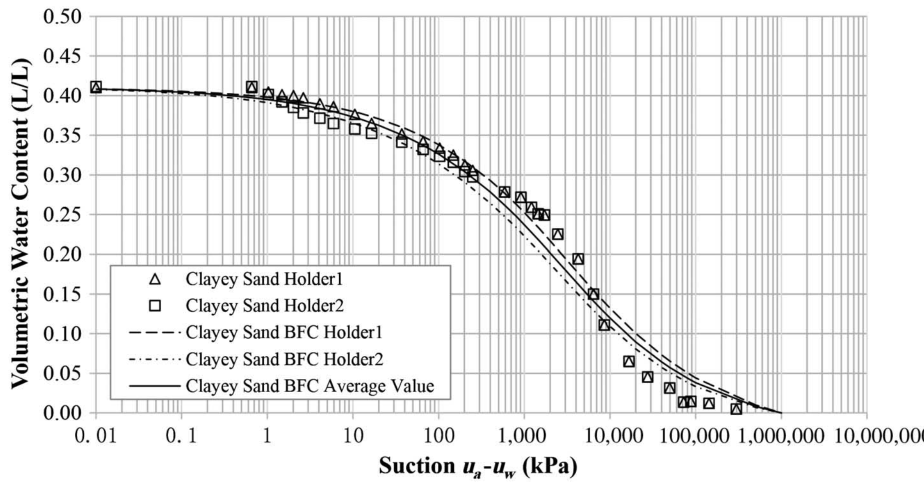


FIG. 14
The testing results and the best-fitting curves (BFC) of clay.

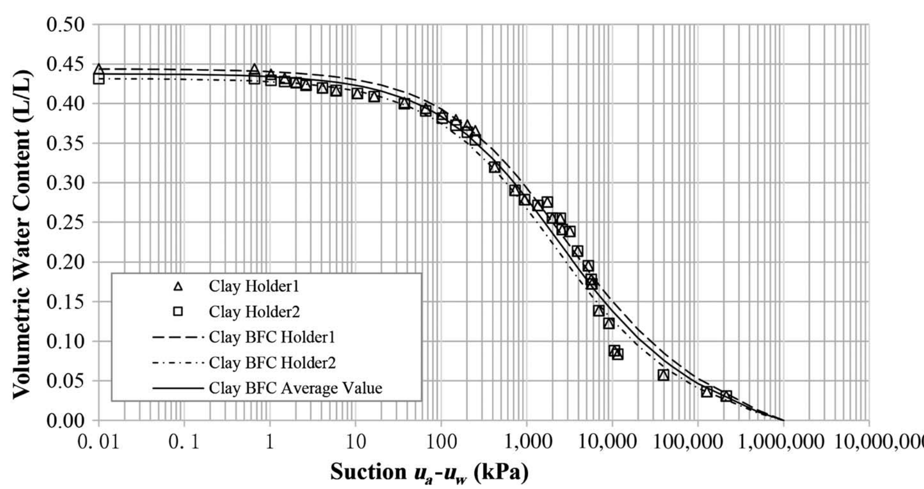


TABLE 4 Results of the soil-water characteristic curves, the Fredlund and Xing (1994) best-fit parameters.

			Clean Sand			Clayey Sand			Clay		
Description	Symbol	Unit	Holder 1	Holder 2	Average	Holder 1	Holder 2	Average	Holder 1	Holder 2	Average
Saturated volumetric water content	θ_s	1	0.38	0.38	0.38	0.41	0.41	0.41	0.44	0.43	0.44
Air-entry value	Ψ_a	kPa	1	1	1	35	20	27	54	51	52
Residual suction	ψ_r	kPa	6	7	6	66,362	22,592	33,932	120,202	44,884	86,070
Residual volumetric water content	θ_r	1	0.082	0.101	0.092	0.055	0.073	0.068	0.020	0.062	0.048
Slope	s		0.305	0.288	0.298	0.109	0.111	0.110	0.116	0.125	0.121
Best fitting parameters	a	kPa	1.1	1.2	1.1	850.8	925.6	887.7	497.3	527.1	511.9
	n		2.647	2.875	2.792	0.422	0.380	0.401	0.604	0.605	0.605
	m		0.790	0.664	0.719	1.406	1.906	1.656	0.905	1.105	1.005

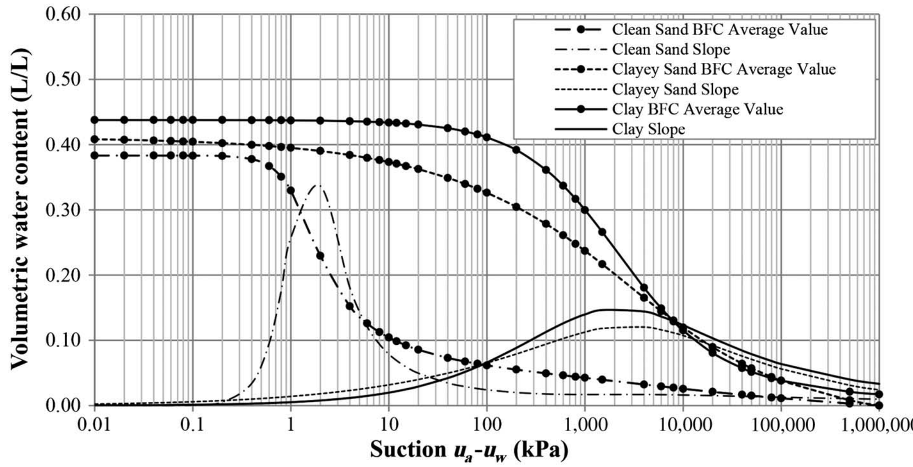


FIG. 15
Best-fitting curves (BFC) from average value and slopes of soil–water characteristic curve.

θ_s, air-entry value, Ψ_a, residual water content, θ_r, and residual suction, Ψ_r. These parameters can be obtained from the best-fitting curves. The calculations of the parameters were introduced by Zhai and Rahardjo (2012). The fitting parameters are shown in Table 4. For the clean sand, the average value of θ_s is 0.38, and Ψ_a is 1 kPa; for the clayey sand, the average value of θ_s is 0.41, and Ψ_a is 27 kPa; for the clay, the average value of θ_s is 0.44, and Ψ_a is 52 kPa.

The best-fitting curves of average value of SWCC and the slopes of the transition zone are shown in Fig. 15. The slopes of SWCCs can be obtained by the following formula (Zhai and Rahardjo 2012):

$$s = \frac{\theta_s - \theta_r}{\log \psi_r - \log \psi_a} \tag{3}$$

where:

θ_s = saturated volumetric water content,
θ_r= residual volumetric water content,
Ψ_r= residual suction, and
Ψ_a= air-entry value.

The results agree with the observations made by Fredlund and Xing (1994), who discussed the relationships between Ψ_a and a, Ψ_r and m, and s and n. The parameter m is a factor showing the residual suction (Ψ_r). A smaller m is associated with a higher Ψ_r. Parameter n is the factor that affects the slope of SWCC in the transition zone. A smaller n can lead to a gentler slope of SWCC. As the clay has finer content than the clayey sand, the residual suction (Ψ_r) of the clay is greater than that of the clean sand and clayey sand.

Conclusions

The SWCCs obtained using the centrifuge and WP4c have a good agreement with the results obtained from the axis-translation method, especially for clayey sand and clay. The combination of the centrifuge and WP4c technique allowed us to determine the SWCC within a short period. The different suctions can be obtained by running the centrifuge at different angular velocities, ω. In this study, the centrifuge used can generate suctions up to 250 kPa. For higher suctions, the chilled mirror method is a fast and ideal method. The total testing period of centrifuge and chilled mirror tests is 1.5 to 2 days, which is much shorter than 46 to 59 days when using the axis-translation method.

During the centrifuge tests, there were also some observed issues. The first was the balance of the centrifuge. As the specimens were in situ, the balance was difficult to maintain even though, on the weighing scale, the mass was almost the same to less than 1 g. This was because the flat specimens might not be of uniform density, and this could cause fluttering of the centrifuge at high revolutions per minute. Heavy vibrations occurred in some cases, and these led to auto cut-off by the machine. The second issue was evaporation. The evaporation can affect the equilibrium of the mass of a soil specimen, especially under the higher applied angular velocities. To reduce this influence, a plastic film was placed on the top of each specimen. The third issue was that the soil matrix could be changed due to the increase of applied gravity fields, especially for the coarse-grained soils like clean sands. As an example, the volume of the clean sand was reduced by 10 % to 15 % at the suction of 250 kPa. This volume change may introduce some errors in the results for fine-grained soils (e.g., clay in this study). Finally, the evaporated and condensed water in the Tempe cell could affect the volumetric water content.

For the coarse-grained soils, combining the axis-translation methods and chilled mirror technique is appropriate for the determination of SWCC. For clayey sand and clay, combining the centrifuge and chilled mirror technique is appropriate for quick and reliable SWCC determination.

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