Comparison of Soil-Water Characteristic Curves from Conventional Testing and Combination of Small-Scale Centrifuge and Dew Point Methods

Harianto Rahardjo[1], Alfrendo Satyanaga[2], Haneena Mohamed[3], Sabrina Ip Chui Yee[4], Rishi Suryakant Shah[5]

[1]School of Civil and Environmental Engineering, Nanyang Technological University, Block N1, #1B-36, 50 Nanyang Avenue, Singapore 639798, Singapore. (corresponding author). E-mail: chrahardjo@ntu.edu.sg

[2]School of Civil and Environmental Engineering, Nanyang Technological University, Block N1, B1a-01a, 50 Nanyang Avenue, Singapore 639798. E-mail: alfrendo@ntu.edu.sg

[3]School of Civil and Environmental Engineering, Nanyang Technological University, Block N1, B1a-01a, 50 Nanyang Avenue, Singapore 639798. E-mail: haneena@ntu.edu.sg

[4]School of Civil and Environmental Engineering, Nanyang Technological University, Block N1-01a-29, 50 Nanyang Avenue, Singapore 639798, E-mail: C150118@ntu.edu.sg

[5]Department of Civil Engineering, IIT Bombay, Powai, Mumbai, India 400076. E-mail: rishi_s@iitb.ac.in

Abstract

Soil-water characteristic curve (SWCC) is an important unsaturated soil property relating the water content of a soil to soil suction and it is conventionally measured using Tempe cell, pressure plate and salt solution methods. However, these tests are tedious and time consuming. The SWCC measurements using fast and efficient methods are required for engineering designs such as excavation, slope protection, retaining wall and landfill cover designs. This paper describes the testing procedures and apparatuses associated with rapid measurements of a complete SWCC of a residual soil as obtained from combined measurements using a small-scale centrifuge and dew point methods. The SWCC test results obtained using these alternative methods were compared with the SWCC data from Tempe cell, pressure plate and salt solution methods. Shrinkage tests were carried out in this study to incorporate the volume change of soil into SWCC. The experimental data from all SWCC tests were evaluated using first order analysis with 95 % confidence interval for determination of upper and lower bounds of SWCC. The analysis results showed that the SWCC data obtained from tests using small-scale centrifuge and dew point methods were in good agreement with those obtained from Tempe cell, pressure plate and salt solution methods. This indicates that the combination of small-scale centrifuge and dew point methods can be used to generate a complete curve of SWCC for the residual soil. In addition, the time required to perform SWCC tests using the alternative methods is shorter than the SWCC tests using the conventional methods.

KEYWORDS: Dew-point, small scale centrifuge, soil-water characteristic curve, shrinkage test

Introduction

Residual soil slopes can be found in many tropical countries. A significant portion of residual soil slope is commonly unsaturated due the presence of deep groundwater table. Two third of Singapore consists of residual soils derived from two major formations, Bukit Timah Granite and Jurong Formation (PWD, 1976). Bukit Timah Granite underlies the Bukit Timah nature reserve and the central catchment area in the centre of the island. Sedimentary rocks of the Jurong

Formation which contain variations of conglomerate, shale and sandstone are located in southern, southwestern and western part of Singapore. Therefore, it is important to incorporate the unsaturated soil properties in the slope stability analyses and design of slope preventive measures.

The engineering behaviour of unsaturated soil is significantly controlled by soil-water characteristic curve (SWCC) (Fredlund and Rahardjo, 1993). The soil-water characteristic curve determines the relationship between the gravimetric water content (w) or volumetric water content (θ_w) or degree of saturation (S) with soil suction. It was suggested that SWCC be used to represent the relationship between volumetric water content, θ_w, and matric suction, (u_a-u_w) (Fredlund, 2006). Tempe cell, pressure plate and salt solution methods are commonly used for measurement of SWCC (Fredlund et al., 2012). Tempe Cell (supported with 1 bar ceramic disc) is used for SWCC tests at suction range up to 100 kPa. Pressure plate (supported with 15 bar ceramic disc) is used for SWCC tests at suction range between 100 and 1500 kPa, whereas salt solution method shall be used for suction range above 1500 kPa. Establishing SWCC for fine-grained soils using the Tempe cell, pressure plate and salt solution method requires a longer duration as compared to that for coarse-grained soils. For clayey soils, the time taken to obtain data points for soil-water characteristic curve varies from 6 to 8 weeks for 10 data points (Fredlund et al. 2012). Such long laboratory test duration will affect practical engineering designs, as engineering industry is driven by rigorous timelines. Therefore, fast and effective methods for soil-water characteristic curve generation should be explored and adopted.

Khanzode et al. (2000) conducted SWCC tests on fine-grained soils using a small scale centrifuge. Zornberg and McCartney (2010) developed a new centrifuge permeameter for measurement of SWCC and the unsaturated permeability of soil. The results of their experimental works indicated that centrifuge can be used to accelerate the water flow processes. Previous research works indicated that centrifuge can be used for SWCC measurement. However, the measurement of SWCC using this method was limited for suctions less than 250 kPa. Leong et al. (2003) performed SWCC tests on residual soil using the chilled-mirror dew-point technique. However, the measurement of SWCC using this method was limited for suctions higher than 500 kPa. Therefore, there is a need to combine SWCC tests using centrifuge and chilled-mirror dew-point methods for determination of complete SWCC. Limited studies have been made to measure the SWCC of undisturbed soil using combination of small-scale centrifuge and chilled-mirror dew-point methods.

In this study the measurements of SWCC on a residual soil using the combination of small scale centrifuge and dew point methods were carried out as well as using the combination of Tempe cell, pressure plate and salt solution methods. The results are then discussed and compared in this paper.

Different Methods for Measurement of SWCC in Laboratory

There are various testing techniques and models to establish SWCC. A lot of research works have been carried out to establish SWCC data using reliable, but tedious and time consuming, methods such as Tempe cell, pressure plate and salt solution methods (Agus et al., 2001; Xiaoli et al., 2011; Fredlund et al., 2012; Leong and Wijaya, 2015). Agus and Schanz (2007) compared four methods (noncontact filter paper method, psychrometer technique, relative humidity (RH) sensor, and chilled-mirror hygrometer technique) in determining the suction of a bentonite–sand mixture. Patrick et al. (2007) compared chilled-mirror and filter paper measurements of total soil suction. Nam et al. (2009) compared six different testing methods, i.e. filter paper, dewpoint potentiameter, vapor equilibrium, pressure plate, Tempe cell and osmotic methods to establish the SWCC for riverbank soils. The filter paper test is the only test that could provide both matric and total suction at the same time. It is simple and low cost testing method, and does not require special equipment. However, it is sensitive to small differences in weight, and there are still controversies related to the calibration method and the length of the required equilibrium period. The dewpoint potentiameter provides a wide range of suction measurement, but it generates larger variation for low suction values. Vapor pressure and osmotic techniques are relatively easier and safer to use for high suctions, but they require long equilibrium periods. Axis translation technique is one of the most common methods and the procedure is simple. However, it requires a long equilibrium period and is applicable only to a narrow range of suction values. Fredlund et al. (2012) also explained the different types of apparatus for SWCC measurements including the usage of tensiometers within soil specimen. Tensiometers only can measure suction up to 100 kPa since the cavitation of the water inside tensiometers will occur at suction higher than 100 kPa.

From a practical perspective, methods for establishing the SWCC should be simple, easy to perform, inexpensive, fast and reliable. Hence, it is important to explore alternative methods for practical engineering design. Some of the newer equipments for determination of SWCC comprise Hyprop, small-scale centrifuge and dew-point chilled mirror. Each technique has its own limitation in terms of the suction. The suction range for different equipments is shown in Figure 1 (respective user manuals are given as in the Reference section), i.e. small-scale centrifuge - Operating Manual: Centrifuge 5804/5804 R/5810/5810 R, Hyprop - User Manual Hyprop, Chilled mirror dew point - WP4C Dew Point PotentiaMeter Operator's Manual.

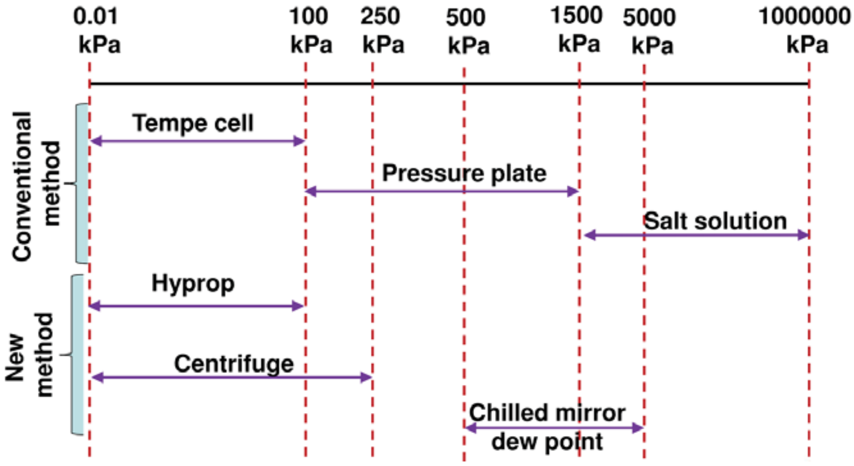


Figure 1. Suction range of different methods for SWCC measurements (Agus et al., 2001; Xiaoli et al., 2011; Fredlund et al., 2012; Leong and Wijaya, 2015)

Measurements of SWCC using Tempe Cell, Pressure Plate and Salt Solution Methods

SWCC is a very important soil property in unsaturated soil mechanics. It relates water content to the matric suction (u_a-u_w) of the soil. The SWCC tests were carried out following ASTM D6838-02 (2008). Conventional SWCC tests consist of three different methods, i.e Tempe cell, pressure plate and salt solution methods. A Tempe cell with a 1 bar capacity ceramic disc was used for the measurement of water content for suctions less than 100 kPa. A pressure plate with a 15 bar capacity ceramic disc was utilised for SWCC tests with suction range between 100 kPa and 1500 kPa. Salt solution method using vacuum desiccators was adopted for suctions greater than 1500 kPa.

The main part of the Tempe cell and pressure plate is the porous ceramic plate. Prior to the test, the ceramic plate was saturated in a desiccator with de-aired distilled water. The soil specimen was then set into the Tempe cell. Figure 2 shows the schematic diagram of Tempe cell. The specimen was saturated by applying de-aired distilled water from the top of the Tempe cell. The saturation process was ceased when the water content of the soil specimen reached its saturated value of at least 95%, which is the typical value adopted in practice for saturation of soil samples (ASTM D6838-02, 2008). After the saturation stage, the weight of the saturated specimen and the Tempe cell was recorded. The air pressure system was connected from the top of the Tempe cell. Air pressure was then applied to the specified value to create respective matric suction in the soil specimen. Air would not flow through the porous ceramic plate when higher air pressure was introduced into the cell, as long as the air pressure did not exceed the air-entry value of the ceramic plate and the ceramic plate was kept saturated. For this reason, the bottom of the Tempe cell was connected to a container filled with water to maintain the degree of saturation of the ceramic plate (Figure 3). Weighing of the specimen at regular intervals was necessary to obtain sufficient data for the plot of the water volume change in the specimen at various matric suctions.

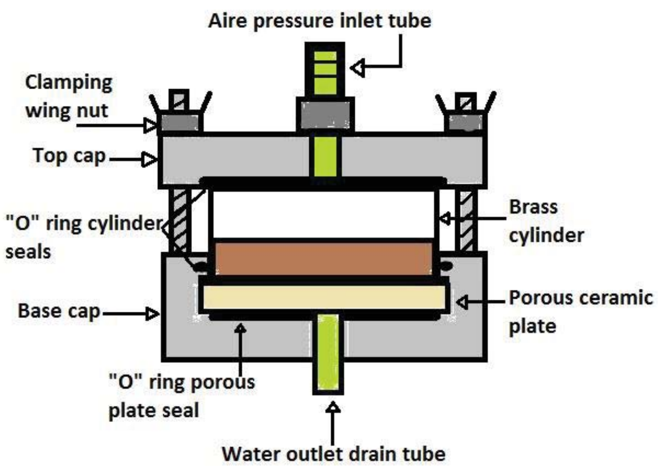


Figure 2: Schematic diagram of Tempe cell

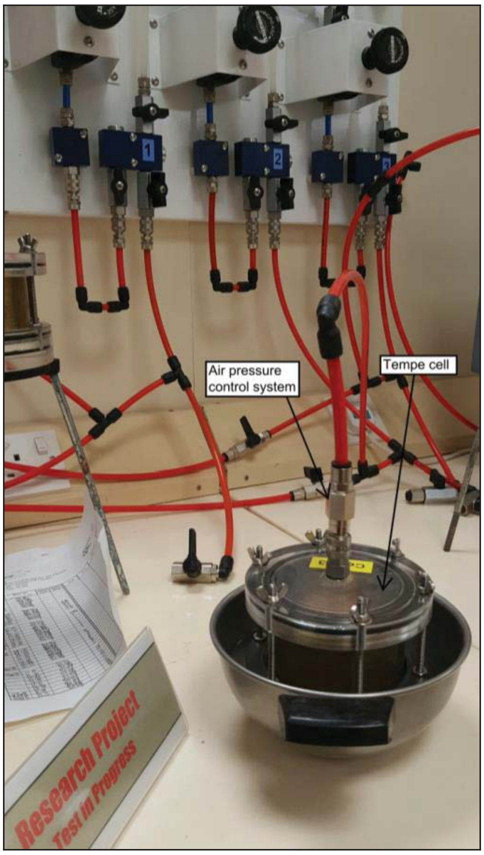


Figure 3: SWCC process using Tempe cell test

Pressure plate consists of a pressure chamber that contains a saturated ceramic plate (Figure 4). The pressure plate was connected to a burette for measurement of water volume change and maintenance of degree of saturation of the ceramic plate (Figure 5). There must be a good contact between the soil specimen and the ceramic plate to ensure the water flow between the specimen and the plate is continuous. As with the Tempe cell test, the specimen was weighed at regular intervals. When equilibrium was reached, a higher pore-air pressure was then applied.

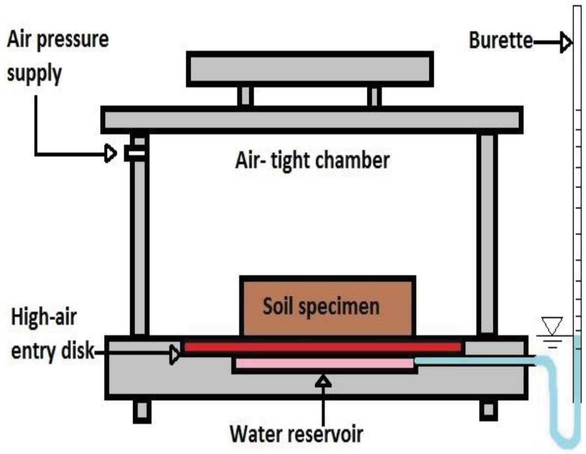


Figure 4: Schematic diagram of pressure plate

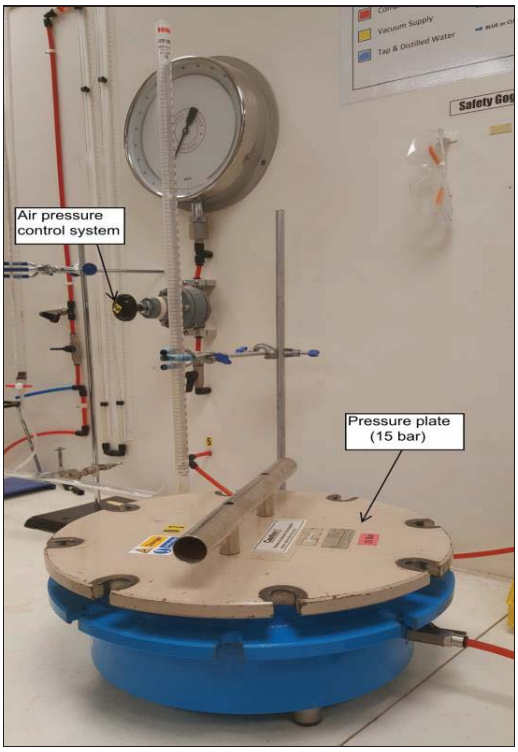


Figure 5: SWCC process using pressure plate test

Salt solution method was carried out using an air-tight desiccator (Figure 6). This method was carried out based on the theoretical standpoint that a water potential (i.e. suction) is related to a particular relative vapour pressure of the water in the soil-water system (Agus et al., 2001). The relative vapour pressure of water in equilibrium with the system is characterised by its relative humidity. Therefore, suction can be established by creating the relative humidity, which is related to the concentration of a salt solution placed in the desiccator.

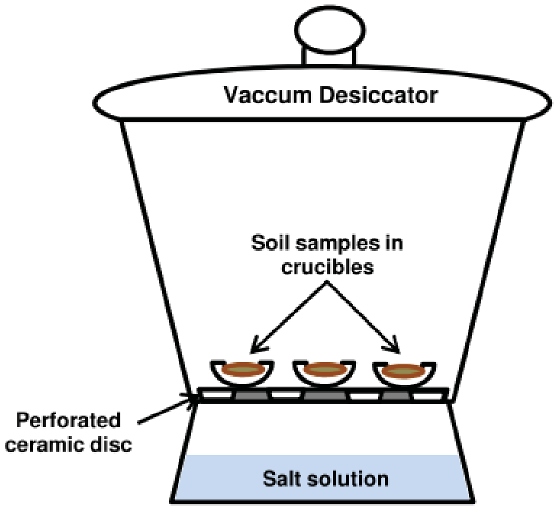


Figure 6: Schematic diagram of vaccum desiccator

Salt solution was prepared using Sodium chloride. Equation proposed by Marinho (1994) was used to relate suction and molarity.

$$\psi = 4598.95 \text{ x } 1.00122 \text{ m} \qquad \text{(Equation 1)}$$

where: ψ is the suction, m is the molarity of the salt solution

Range of suctions versus salt concentrations are given in the Table 1

Table 1. Relationship between suction and molarity of the salt solution

Suction (kPa)	Molarity
2000	0.4353
3000	0.6527
4000	0.8699
5000	1.0871

Sodium chloride solution with a specific concentration corresponding to a particular suction was prepared and poured in a vacuum desiccator to generate a vapour pressure in the desiccator. The soil specimens were taken in crucibles and kept in the desiccators (Figure 7). The weight of soil specimen with crucible was measured periodically until there was negligible change in mass of the soil specimen.

Figure 7: SWCC process by salt solution method

Measurement of SWCC using Small-Scale Centrifuge and Chilled Mirror Dew Point Method

The small-scale centrifuge was used for low to medium suction range (0.6kPa ~ 250kPa) whereas the chilled-mirror hygrometer was used for higher suction range (500kPa ~ 5000kPa).

Small-scale Centrifuge

Centrifuge method is described as Method E for the measurement of soil-water characteristic curve (SWCC) (ASTM D 6836-02, 2008). This method yields SWCC in terms of matric suction. The specimen was kept in a chamber in a centrifuge that is subjected to a centrifugal force. Different matric suctions were applied by varying the angular velocity of the centrifuge. Water displaced from the soil at a given angular velocity was measured by weighing the specimens. SWCC was determined by subjecting the soil specimen to a series of angular velocities (each corresponding to one matric suction) and measuring the amount of water displaced from the soil at each velocity.

A 5810 R small-scale centrifuge with an A-4-62 rotor with an operable radius of 155 mm was used in this study. The centrifuge consists of four swinging type buckets. The buckets in the centrifuge are able to rotate at angular velocities varying from 200 to 3900 rpm. During the spinning of the centrifuge, the swinging type buckets of the small-scale centrifuge are assumed in horizontal position. All four buckets can be used simultaneously with four specimen holders for SWCC testing. The mass in all the specimen holders should be maintained the same to avoid rotary imbalance.

Soil specimen was trimmed and placed in a specially designed steel ring. This steel ring was placed on a customized mould with perforations at the base. During saturation of soil specimen, the mould containing the ring and the specimen was placed in a tray filled with water for about 24 hours. During the first 12 hours of saturation process, weight of the soil sample was measured on hourly basis. After the next 12 hours of saturation process, weight of the sample was measured again and it was observed to have insignificant change of mass from the penultimate weight.

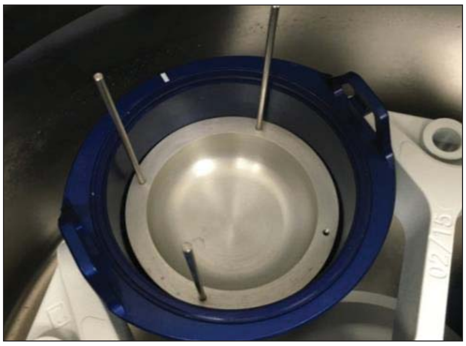
Upon completion of the saturation process of the specimen, the weight of the soil specimen was recorded. The soil specimen with the mould was placed inside the closed chamber of the centrifuge. Then, the chamber was sealed tightly. The angular velocity of the centrifuge was set to the corresponding values, for about 5 minutes. In every phase, once the rotation was completed, the cover of the centrifuge was opened and the specimen with the mould was taken out carefully and its weight was recorded. The water contents of the specimens that were measured in every phase have reached equilibrium state. The procedure was repeated at incrementally higher angular velocities to define the SWCC. Figures of small-scale centrifuge are presented in Figures 8.

The matric suction is calculated using Equation 2, as proposed by Gardner (1937).

$$\Psi = (r_1^2 - r_2^2)*(\rho\omega^2)/2 \qquad \text{(Equation 2)}$$

ψ is the suction in the soil specimen (kPa), r_1 is the radial distance to the midpoint of the soil specimen (m), r_2 is the radial distance to the free water surface (m), ω is the angular velocity (rpm), ρ is the density of the pore fluid (kg/m^3).

(a)



(b) (c)

Figure 8. (a) Small-scale centrifuge (b) Specimen holder

(c) Specimen placed in centrifuge for testing

Chilled Mirror Dew Point Method

ASTM D 6836-02 (2008) describes five methods (methods A – E) for measurement of soil-water characteristic curve (SWCC). Chilled mirror hygrometer method is classified as Method D which is generally used to determine the SWCC corresponding to high suctions and low water contents. The chilled mirror hygrometer uses the dew point technique to measure the water potential of a soil specimen. The specimen is equilibrated with the headspace of a sealed chamber, containing a mirror. At equilibrium, the water potential of the air in the chamber and the water potential of the specimen becomes the same. The mirror temperature is controlled by a thermoelectric (Peltier) cooler. A photoelectric cell detects the exact point at which condensation occurs on the mirror. The device directs a beam of light onto the mirror reflecting into a photodetector, which senses the change in reflectance when condensation occurs on the mirror. A thermocouple, attached to the mirror, records the temperature at which condensation occurs. Values start to be displayed and this indicates that initial measurements are being recorded. A green LED is flashed with beeping sound when it reaches the final value. The final water potential and temperature of the specimen is displayed on the screen of the device. The device uses an internal fan that circulates the air within the specimen chamber to reduce equilibrating time.

Figure 9. Device for dew-point chilled mirror

The chilled mirror hygrometer measures the total suction (sum of the osmotic and matric suctions) in the soil specimen. Soils bind water mainly through matric forces, and therefore dominate the matric component, especially at low water content. The chilled mirror hygrometer used for the studies presented in this paper is Water Potential 4C (WP4C), as shown in Figure 9. An illustrative diagram indicating the inside view of the device is given in Figure 10. Soil specimens were trimmed using the cutter customized specifically for the chilled mirror hygrometer. The specimen cutter is shown in Figure 11.

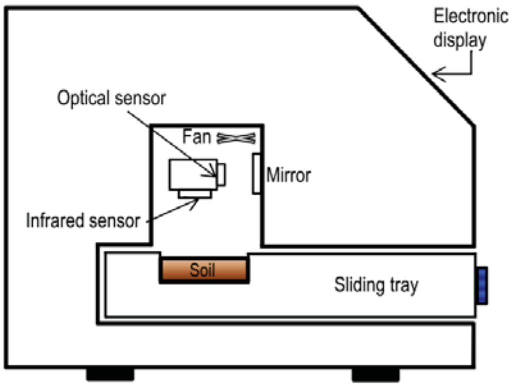


Figure 10. Schematic diagram of dew-point chilled mirror

Figure 11. Specimen trimmer and pusher to prepare specimen for dew-point chilled mirror device

The specimen drawer knob is turned to open position and the drawer is pulled open. The specimen prepared is placed in the drawer. The specimen drawer knob is turned to read position to seal the specimen cup within the chamber. Once, the specimen is ready with the result, a green light flashes with a beep, to indicate the reading cycle has been started. Within about 40s, the measurement is displayed. The weight of the specimen is recorded to estimate the water content. The total suction is calculated using Kelvin equation (Equation 2) and the total suction value is displayed on the screen of the device.

$$\Psi_{ti} = (RT/M)*\ln(a_w) \quad \text{(Equation 2)}$$

where a_w is the water activity, R is the gas constant, T is the laboratory temperature (°K), and M is the molecular mass of water. The value of R/M is 461 kPa/°K. Temperature in °K is obtained by adding 273° to the temperature in °C.

Different Designations to Indicate Amount of Water in Soils

There are three primary ways to describe the amount of water in the soil; namely, gravimetric water content, volumetric water content and degree of saturation. Each designation has a role to play in understanding the physical behaviour of unsaturated soils (Fredlund and Houston, 2013). The measurement of water content in the laboratory is generally first measured in terms of gravimetric water content, w, because the mass of water is the easiest variable to measure. Other designations are then computed based on the volume-mass relations.

Shrinkage Test

The water content for different suctions as obtained from SWCC tests using Tempe cell, pressure plate, salt solution method, small-scale centrifuge and dew point method was measured in terms of gravimetric water content. It is important to determine SWCC in terms of volumetric water content and degree of saturation for design analyses, especially, when the results from numerical analyses are to be compared with instrumentation results. Instrumentation outputs commonly indicate the varying water content in terms of volume. SWCC in terms of degree of saturation is ideal for determining parameters such as air entry value, inflection point, residual suction and residual water content (Fredlund et al., 2002; Leong and Wijaya, 2015). Therefore, shrinkage tests were carried out in this study to measure total volume of the soil specimens.

The shrinkage test involved the evaporation process of the soil specimen which was allowed to air dry slowly under controlled room temperature of 25ºC (Greene-Kelly, 1974). The specimen was weighed at regular time intervals until reaching its equilibrium condition. Also, direct measurements of the total volume of the soil specimens are taken at regular intervals (two times everyday) using a Vernier Caliper. The diameters and heights of the samples at 4 places were recorded and average of the values was considered to estimate the volume change. Then, the void ratios for different water contents can be calculated. A plot between void ratio and gravimetric water content (e verses w plot) is generated. The shrinkage curve can be best-fit using the hyperbolic curve proposed by Fredlund et al., (1996, 2002). The equation has parameters with physical meaning as follows:

$$e(w) = a_{sh}[w^{c_{sh}}/b_{sh}^{c_{sh}} + 1]^{(1/c_{sh})} \quad \text{(Equation 3)}$$

where: a_{sh} is the minimum void ratio (emin), b_{sh} is slope of the tangent line, c_{sh} is curvature of the shrinkage curve, and w is gravimetric water content.

Volumetric water content (θ_w) is estimated based on the Equation 4 (Fredlund et al., 2012):

$$\theta_w = Vs\ (1 + e) \quad \text{(Equation 4)}$$

where θ_w is the volumetric water content, V_s is the volume of solids in the soil specimen and e denotes the void ratio, obtained from e verses w plot.

The results from shrinkage test were combined with the results from dew-point method and small-scale centrifuge tests to establish SWCC with respect to volumetric water content.

The experimental data of SWCC was best fitted using Satyanaga et al. (2013) equation (Equation 5) since the parameters in this equation can be used to represent variables of SWCC.

$$\theta_w = \left(1 - \frac{\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left(1+\frac{10^6}{\psi_r}\right)}\right)\left[\theta_r + \left\{(\theta_s - \theta_r)\left(1-(\beta)erfc\left(\frac{\ln\left(\frac{\psi_a-\psi}{\psi_a-\psi_m}\right)}{s}\right)\right)\right\}\right] \qquad \text{(Equation 5)}$$

where:

β = 0 when $\psi \le \psi_a$; β = 1 when $\psi > \psi_a$

θ_w = calculated volumetric water content

θ_s = saturated volumetric water content

ψ = matric suction under consideration (kPa)

ψ_a = parameter represents the air-entry value of soil (kPa)

ψ_m = parameter represents the matric suction at the inflection point of SWCC (kPa)

s = parameter represents the geometric standard deviation of SWCC

S_r = parameter represents the residual degree of saturation

ψ_r = parameter represents the matric suction corresponding to residual water content (kPa)

Equation 5 consists of six unknown parameters which require a numerical solution to obtain their values for best fitting the laboratory data of SWCC. Therefore, it is necessary to provide a suitable initial value for each parameter to minimize the complexity of Equation 3. The initial values of θ_s, ψ_a, ψ_m, s, S_r, ψ_r are 0.5, 1, 10, 1, 1, 1000, respectively. An iterative non-linear regression procedure that is provided in the Microsoft Excel software (Dodge and Stinson, 2007) can be used to adjust all parameters to best fit the equation to the laboratory data of SWCC.

Evaluation Criteria of SWCC data

The goodness of fit of the best fitting equation and the experimental data of SWCC was quantified with the R-squared (R^2) (Equation 6). The value of R^2 equal to 1 indicates a good fitting between the data from the experimental tests and the proposed model.

The calculation of R-squared is as follows:

$$R^2 = 1 - SSE \quad \text{(Equation 6)}$$

where:

$$SSE = \sum_{i=1}^{n} \left(y_{li} - y_{mi} \right)^2 \quad \text{(Equation 7)}$$

SSE = Sum of Square Error

Y_{li} = Data from laboratory tests

Y_{mi} = Data from the best fitting equation

n = number of the investigated data

Upper and lower bounds of SWCC for Specimens 1 and 2 were generated following procedures proposed by Zhai and Rahardjo (2013). The first order analyses with 95 % confidence limits were used to evaluate the quality of SWCC data obtained from small scale centrifuge and WP4C. In order to establish the upper confidence interval, the maximum value of ψ_a, ψ_m, s and ψ_r. must be used as parameters in Equation 5. On the other hand, the lower confidence interval must be generated using the minimum value of ψ_a, ψ_m, s and ψ_r as parameters in Equation 5.

Soil Properties

The soil specimens of residual soil from Bukit Timah Granite were used in this study. Undisturbed residual soil specimens from Bukit Timah Granite were obtained from different depths using a Mazier sampler. Specimens were retrieved from the depths of 2 m and 9 m and are designated as Specimen 1 and Specimen 2 in this paper, respectively. Laboratory tests were carried out to determine the particle size distribution and index properties of the soil specimens. Index properties and grain-size distribution of soil specimens from both depths are presented in Table 2 and Figure 12, respectively.

Results and Discussions

Comparisons were made between the measured SWCCs, obtained using the small-scale centrifuge and chilled mirror dew-point device with the results from the conventional methods, to substantiate the viability of adopting faster and easier methods for SWCC generation for practical engineering design. Time taken for the SWCC tests carried out in this study are summarised in Table 3. The experimental works of SWCC indicated that 75 days were required to complete the SWCC test using conventional methods, whereas only about 16 days were needed to attain the SWCC data using the alternative methods.

Table 2. Index properties of the investigated residual soils from Bukit Timah Granite

Properties	Specimen 1	Specimen 2
Liquid Limit, LL (%)	63	41
Plastic Limit, PL (%)	31	23
Plasticity Index, PI (%)	32	18
Sand (%)	27	45
Silt (%)	34	16
Clay (%)	39	39
Total density, ρ (kN/m^3)	18	18
Water content, w (%)	39	31
USCS	MH	CL

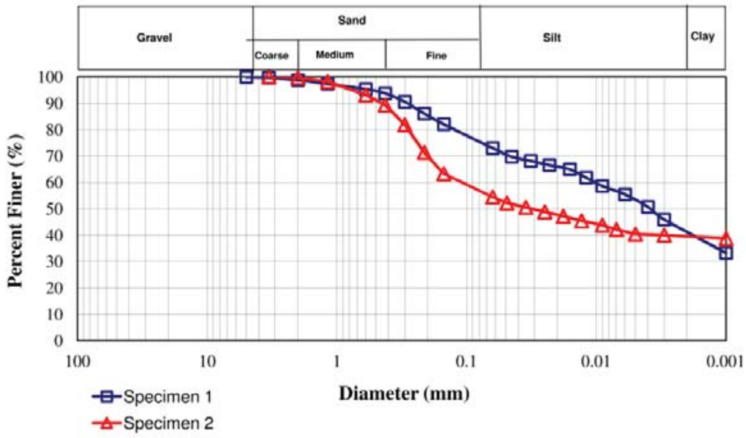


Figure 12. Grain-size distribution curve

Table 3. Times required to perform SWCC tests in this study

SWCC Test Methods		No. of equipments used	Samples tested at the same time	Suction Range	Duration
Conventional test method	Tempe cell	2 units	Specimen 1 Specimen 2	0.1kPa ~ 100kPa	49 days
	Pressure plate (5bar)	1 unit	Specimen 1 Specimen 2	100kPa ~ 500kPa	13 days
	Pressure plate (15 bar)	1 unit	Specimen 1 Specimen 2	500kPa ~ 1500kPa	13 days
	Salt Solution	1 unit	Specimen 1 Specimen 2	1500kPa ~ 5000kPa	63 days
New test method	Small scale centrifuge	1 unit	Specimen 1 Specimen 2	0.1kPa ~ 250kPa	0.5 day
	Dew-point chilled mirror	1 unit	Test on Specimen 1 completed and followed with test on Specimen 2	500kPa ~ 5000kPa	15 days

The SWCC data in this study were best fitted using Satyanaga et al. (2013) equation (Equation 5). The fitting parameters of the SWCCs for Specimen 1 and Specimen 2 are summarized in Table 4. An iterative non-linear regression procedure that is provided in the Microsoft Excel software (Dodge and Stinson, 2007) was used to adjust all parameters to best fit the equation to the laboratory data of SWCC.

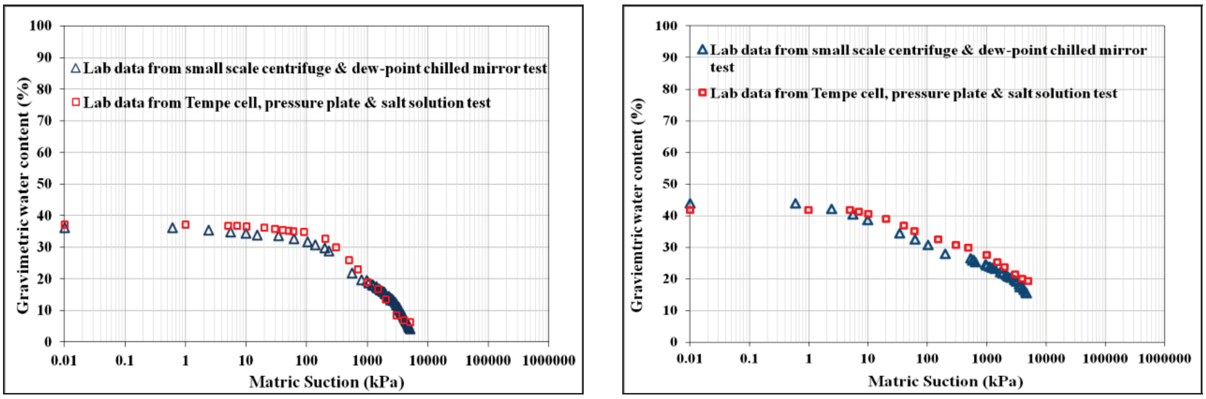
Table 4(a). Fitting parameters of SWCC for Specimen 1

Fitting Parameters	SWCC in terms of Degree of Saturation			
	Centrifuge & WP4C	Tempe cell	Pressure plate	Salt solution (>1500kPa)
ψ_a (kPa)	100	100	150	200
ψ_m (kPa)	20000	10000	20000	30000
s	3.00	2.50	2.75	3.00
ψ_r (kPa)	5000	5000	5000	5000
S_r	0.00	0.00	0.00	0.00

Table 4(b). Fitting parameters of SWCC for Specimen 2

Fitting Parameters	SWCC in terms of Degree of Saturation			
	Centrifuge & WP4C	Tempe cell	Pressure plate (≤ 500kPa)	Salt solution (>1500kPa)
ψ_a (kPa)	10	10	20	30
ψ_m (kPa)	55000	25000	50000	75000
s	4.00	3.75	3.80	3.90
ψ_r (kPa)	100000	100000	100000	100000
S_r	0.00	0.00	0.00	0.00

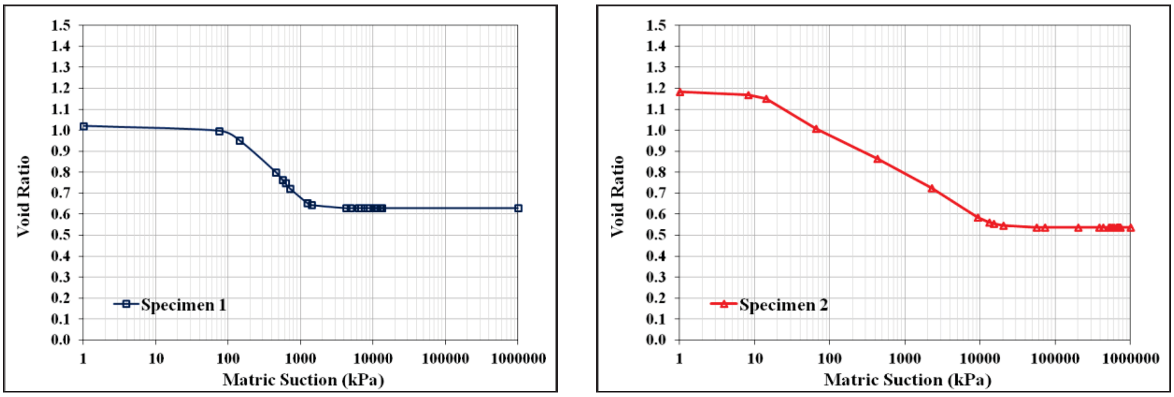
SWCCs in terms of gravimetric water content were plotted based on the laboratory data obtained from the conventional and alternative methods. Shrinkage curves were used to produce SWCCs in terms of volumetric water content. SWCCs based on degree of saturation were also generated for the two different soil specimens. The results of the experimental data of SWCC are compared and presented in Figures 13 to 16.



(a) (b)

Figure 13. SWCC with respect to Gravimetric Water Content

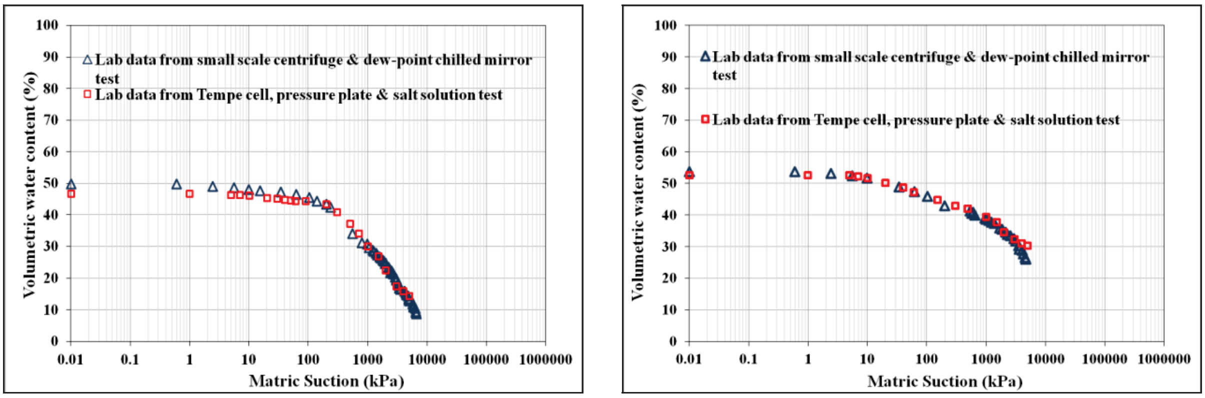
(a) Specimen 1, (b) Specimen 2



(a) (b)

Figure 14. Shrinkage curve

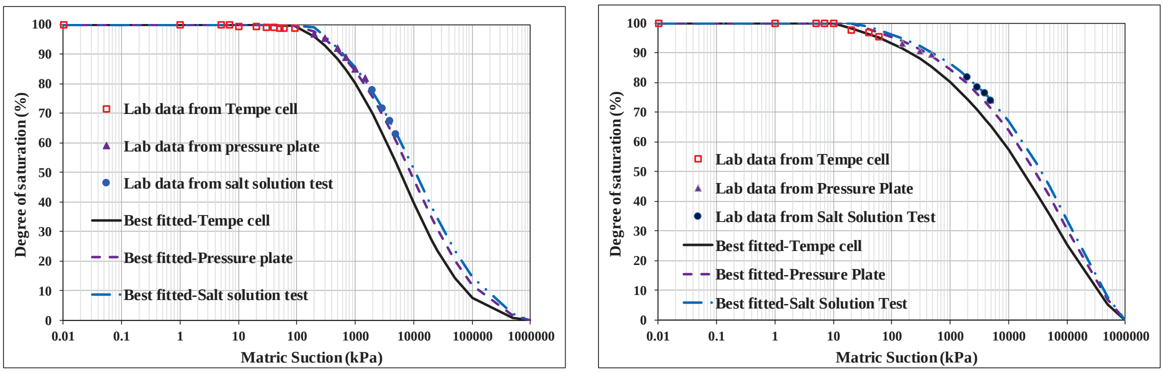
(a) Specimen 1, (b) Specimen 2



(a) (b)

Figure 15. SWCC with respect to Volumetric Water Content

(a) Specimen 1, (b) Specimen 2



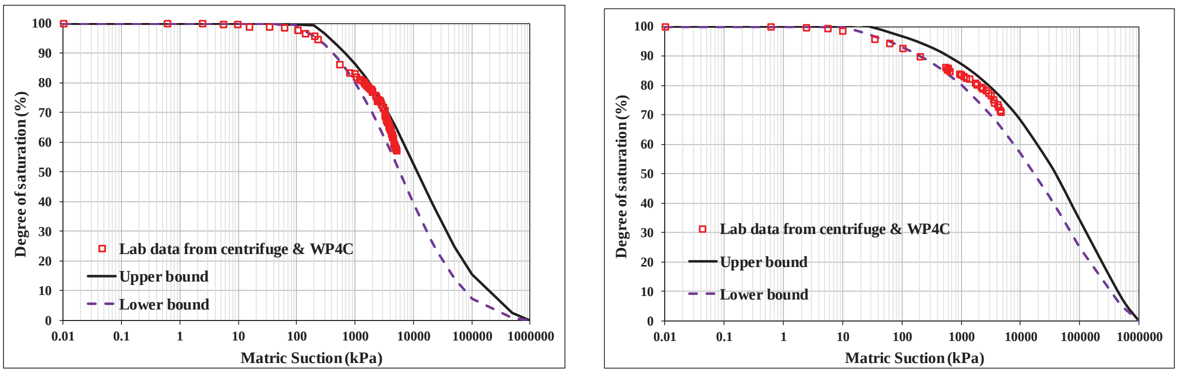
(a) (b)

Figure 16. SWCC with respect to Degree of Saturation

(a) Specimen 1, (b) Specimen 2

Figures 13 to 16 present the SWCC from the conventional and alternative methods in term gravimetric water content, volumetric water content and degree of saturation. Figure 16 shows the similarity of air-entry values for Specimen 1 and Specimen 2 as obtained from the conventional and alternative methods. Air-entry value of Specimen 1 obtained from the alternative methods was 100 kPa (within the range of air-entry value of Specimen 1 obtained from the conventional method, 100 to 200 kPa). Air-entry value of Specimen 2 obtained from the alternative method was 10 kPa (within the range of air-entry value of Specimen 2 as obtained from the conventional method, 10 to 20 kPa). Figure 16 indicates that the air-entry value of Specimen 1 was higher than that of Specimen 2. This could be attributed to the smaller pore sizes within Specimen 1 as compared to Specimen 2 due to the higher percentages of fine contents within Specimen 1 than Specimen2. As a result, it is more difficult for water to flow within Specimen 1 as compared to that within Specimen 2.

Upper and lower bounds of SWCC for residual soil Specimens 1 and 2 from Bukit Timah Granite were generated following the procedure proposed by Zhai and Rahardjo (2013) to establish confidence limits of SWCC. The confidence limits were developed using SWCC data from Tempe cell, pressure plates and salt solution technique. Figure 17 indicates that SWCCs for both soil specimens obtained from alternative methods fell within the band of confidence limits throughout the entire suction range. Therefore, it is concluded that SWCC tests using alternative methods could be accepted to complement SWCC tests using the conventional method. In other words, experimental data up to a suction of 5000kPa can be obtained accurately using the relatively new and faster methods of SWCC generation using a combination of small scale centrifuge (up to 250kPa suction) and dew-point chilled mirror (up to 5000kPa).



(a) (b)

Figure 17. Confidence Limits of SWCC

(a) Specimen 1, (b) Specimen 2

Conclusions

The SWCCs of residual soils from Bukit Timah granite were established using alternative and fast methods of SWCC tests from small scale centrifuge and dew-point chilled mirror apparatuses. The SWCC obtained from the alternative methods were compared with those obtained from the conventional equipment such as Tempe cell, pressure plate and vaccum desiccator with salt solution using the confidence limit interval established from equations proposed by Zhai and Rahardjo (2013). The results indicate that SWCCs for both soil specimens of residual soils which were obtained using alternative and conventional methods of SWCC tests fall within the upper and lower band of confidence limits throughout the entire suction range. In the other words, the alternative and conventional measuring techniques used in the study provide comparable results. Also, the time duration by the alternative methods is only one fifth of the time associated with the conventional techniques, to achieve the complete set of data presented in this paper. Therefore, the alternative methods of SWCC tests using small scale centrifuge and dew-point chilled mirror could be adopted for fast, reliable and practical testing method.

Acknowledgements

The authors would like to acknowledge the assistance provided for this study by Geotechnics Laboratory staff, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.

References

S.S. Agus and T. Schanz (2007). "Errors in total suction measurements". Experimental Unsaturated Soil Mechanics, pp. 59–70.

S. S. Agus, E. C. Leong and H. Rahardjo (2001). "Soil-water characteristic curves of Singapore residual soils". Geotechnical and Geological Engineering, Vol. 9, pp. 285-309.

ASTM D6838-02. 2008. "Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge". *Annual Book of ASTM Standards*.

M. Dodge, C. Stinson. Microsoft office excel 2007 inside out. Washington (USA): Microsoft Press; 2007. 1088 pp.

E.C. Leong and M. Wijaya (2015). "Universal soil shrinkage curve equation". Geoderma, January, Vol. 237–238, pp. 78-87.

E.C. Leong, S. Tripathy, and H. Rahardjo (2003). "Total suction measurement of unsaturated soils with a device using the chilled-mirror dew-point technique". Géotechnique, March, Vol. 53, pp. 173-182.

D.G. Fredlund and H. Rahardjo (1993). "Soil Mechanics for Unsaturated Soils", John Wiley and Sons Inc., New York.

D.G. Fredlund, A. Xing, M.D. Fredlund and S.L. Barbour (1996). “The relationship of the unsaturated soil shear strength to the soil-water characteristic curve”. Canadian Geotechnical Journal, Vol. 33, pp. 440–448.

M.D. Fredlund, G.W. Wilson and D.G. Fredlund (2002). “Representation and estimation of the shrinkage curve”. UNSAT 2002, Proceedings of the Third International Conference on Unsaturated Soils, Recife, Brazil, March 10–13, pp. 145–149.

D.G. Fredlund (2006). “Unsaturated Soil Mechanics in Engineering Practice”. Journal of Geotechnical & Geoenvironmental Engineering, 132(3), 286-321.

D.G. Fredlund, H. Rahardjo and M.D. Fredlund (2012). “Unsaturated Soil Mechanics in Engineering Practice”, John Wiley & Sons, Inc., Hoboken, New Jersey.

D.G. Fredlund and S.L. Houston (2013). “Interpretation of soil-water characteristic curves when volume change occurs as soil suction is changed”. Advances in Unsaturated Soils – Caicedo et al. (eds), Taylor & Francis Group, London, ISBN 978-0-415-62095-6.

R.A. Gardner (1937). “The method of measuring the capillary tension of soil moisture over a wide moisture range”. Soil Science, Vol. 43, pp. 277–283.

R. Greene-Kelly (1974). “Shrinkage of clay soils: A statistical correlation with other soil properties”. Geoderma, July, Vol. 11, Issue 4, pp. 243-257.

R.M. Khanzode, S.K. Vanapalli, and D.G. Fredlund (2002). “Measurement of soil-water characteristics curves for fine-grained soils using a small-scale centrifuge.” Can. Geotech. J., 39:1209–1217.

S. Nam, M. Gutierrez, P. Diplas, J. Petrie, A. Wayllace, N. Lu and J.J. Munoz (2009). “Comparison of testing techniques and models for establishing the SWCC of riverbank soils.” Eng. Geology, 110:1-10.

Operating Manual: Centrifuge 5804/5804 R/5810/5810 R. Hamburg: Eppendorf AG.

P.W.D., 1976. “The Geology of the Republic of Singapore”, Public Works Department, Singapore.

P. Patrick, H. Olsen and J. Higgins (2007). “Comparison of chilled-mirror measurements and filter paper estimates of total soil suction”. Geotechnical Testing Journal, 30 (5), 1–8.

A. Satyanaga, H. Rahardjo, E.C. Leong and J.Y. Wang (2013). “Water Characteristic Curve of Soil with Bimodal Grain-size Distribution”. Computer and Geotechnics, January, Vol. 48, pp. 51-61.

User Manual Hyprop. Munich: UMS GmbH (2012).

WP4C Dew Point PotentiaMeter Operator’s Manual. Washington: Decagon Devices, Inc. (2015).

Xiaoli Fu, Mingan Shao, Dianqing Lu, Huimin Wang (2011). “Soil water characteristic curve measurement without bulk density changes and its implications in the estimation of soil hydraulic properties”. Geoderma, November, Vol. 167–168, pp. 1-8.

Q. Zhai, and H. Rahardjo (2013). “Quantification of uncertainties in soil-water characteristic curves in association with fitting parameters” Engineering Geology. Vol. 163, pp. 144–152.