Comparison of Soil Water Characteristic Curves under Different Stress Conditions

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ABSTRACT: Understanding unsaturated soils behaviour is key to design of foundations and embankment structures. Geotechnical engineers have applied net normal stress and matric suction to these engineering problems. Water retention activity in soils is used to predict seepage problems and stability of slope failures. Soil Water Characteristic Curve (SWCC) tests contribute largely to matric suction interpretation. Conventionally, SWCCs are determined in the laboratory using a pressure plate apparatus in which vertical or confining stress cannot be applied. Mathematical models are commonly accepted in geotechnical engineering practices. However, these models are not adequate to apply fitting methods in consideration of effort of stress conditions such as the difference between one-dimensional condition and isotropic confining conditions. This study conducted SWCC tests using the pressure membrane, pressure plate and vapour pressure techniques and focused on the influences of one-dimensional and isotropic stress conditions to SWCCs data sets. A net normal and confining stress of 100 kPa was applied to the soil specimens under both stress conditions. The study suggests that the current SWCC models require further development to take good fittings with experimental data sets. Further, the soil stress state has a substantial influence on SWCC of unsaturated soil.

1 INTRODUCTION

Soils near the ground surface are usually under unsaturated conditions. The mechanical behaviour of these unsaturated soils is closely connected to the stability of the geotechnical systems such as shallow foundations, slopes, road embankment, river dike and waste disposal. Prediction of the mechanical behaviour of the unsaturated soils is essential for design of new geotechnical systems and health assessment of new ones. Geotechnical engineers have applied two stress state variables (i.e. net normal stress and matric suction) to the above-mentioned engineering problems (Fredlund and Rahardjo 1993). One of the key features in unsaturated soil mechanics is water retention activity in soils which is used to predict the stability or seepage problems in the ground. The Soil Water Characteristic Curve (SWCC) reflects the behaviour of unsaturated soils with regard to its hydraulic conductivity, shear strength, and volume change behaviour (Leong and Rahardjo 1997). Several researchers have reported on SWCC or suction controlling techniques to expand the mathematical simulation models (Alonso et al. 1990, 1999, 2010, 2013; Blatz and Graham 2003; Gens and Alonso 1992). The SWCC remains as a key parameter for establishing of mathematical models and basic physical parameters of soils (Sillers and Fredlund 2001; Sillers et al. 2001). Due to the limitations of time and of accurately measuring suction, a wide range of suction tests have not been performed and the influence of stress conditions such as the difference between one-dimensional condition and isotropic confining condition have not received great attention (Li and Chen 2016; Tavakoli et al. 2014). The difference of the stress condition applied has a significant influence on the soil deformation, and the related water retention activity in engineering practice.

This study focuses on the influence of different stress conditions on SWCCs. The paper compares SWCCs obtained through experimental testing performed in one-dimensional condition and isotropic confining conditions and draws some useful conclusions for engineering practice. The microporous membrane (Nishimura et al. 2012) with an air entry value of 250 kPa was used for controlling relatively low matric suction which is one of the latest testing methods in SWCC tests. The membrane technology has the advantage of improving the time required to reach matric suction equalization in SWCC tests. For matric suctions beyond 20 kPa, the pressure plate and vapour pressure techniques where employed for SWCC tests.

A soil normally experiences stress due to its depositional history in the field. It is therefore theoretically, recognized that the stress state of a soil has some influence on the SWCC (Fredlund and Rahardjo 1993b). Vanapalli et al. (1996, 1998, 1999) and Ng and Pang (2000) conducted experimental tests to study the influence of stress state on the SWCC. Their studies concluded that the stress state and the drying-wetting history have a substantial influence on the soil water characteristics curves of unsaturated soils.

Despite all these investigations and researches, the influence of stress state to SWCCs data sets in one-dimensional and isotropic compression conditions has not received great attention. This paper is motivated by the lack of experimental evidence of this type.

2 EXPERIMENTAL STUDY

2.1 *Soil material and specimens*

The soil material used in this testing is a silt soil known as DL-clay in Japan with a relatively uniform grain size distribution. Compacted specimens were prepared using a compaction steel mould designed especially for static compaction. The results of the standard proctor compaction test indicated a maximum dry density of 1.535 g/cm^3 at an optimum water content of 17%. The purpose of using static compaction as opposed to dynamic compaction was to obtain a more homogeneous specimen in terms of density and shear strength throughout the volume of the specimen.

Soil specimens with different dimensions were prepared for SWCC tests. For one-dimensional condition, a diameter of 60 mm and height of 65 mm specimen was prepared. Furthermore, a diameter of 50 mm and height of 100 mm was prepared for the isotropic condition testing. Two additional specimens of diameter 6 cm and height 2 cm were also prepared and placed in the glass desiccator for SWCC test using the Vapour Pressure Technique (VPT).

2.2 *Apparatus*

In this study, new SWCC apparatus as shown in figure 1 were utilised.

For one-dimensional condition testing, a modified steel mould was placed in the triaxial cell. The modified unsaturated triaxial apparatus was used for isotropic conditions which had an inner and outer cell. The modified SWCC apparatus consisted mainly of a pedestal, a steel mould, a triaxial chamber, and a double glass burette connected to a differential pressure transducer. The steel mould had an inside diameter of 60 mm and a height of 65 mm. The pedestal attached to the triaxial base plate had a porous stone and an O-ring on the upper surface that was fastened to the base of the triaxial apparatus.

In both testing setups, the cell pressure, pore-water-pressure and pore-air pressure were essentially controlled independently. Soil water was allowed to flow into the glass burettes by means of a water compartment connected to the porous stone. A differential pressure transducer which was attached to the lower portion of the double glass burette was also calibrated to directly give a relationship between the voltage and the volume of water in the glass burettes.

A pressure plate apparatus with a ceramic disk was used to conduct SWCC test beyond the air entry value of the microporous membrane.

The high air entry ceramic disk was installed into the pedestal in place of the microporous membrane. Epoxy was used to fasten the ceramic disk into the pedestal. The ceramic disk had a thickness of 7 mm, a pore size of 0.5μm and an air entry value of 500 kPa.

To obtain the suction versus water content relationship beyond 500 kPa (i.e. 500 to 296000 kPa), the vapour equilibrium or relative humidity technique was used which essentially uses the vacuum glass desiccator apparatus. This apparatus was used for equilibrating silt specimens in a constant relative humidity environment above a controlled salt solution. In this test setup, seven different salt solutions were utilized to conduct SWCC tests of the silt soil specimen.

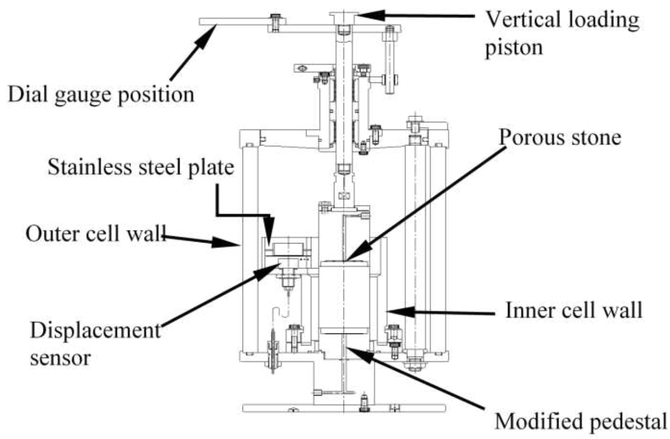

Figure 1. Schematic diagram of modified triaxial apparatus

3 TEST METHODOLOGY

The testing methods adopted for this study involved establishing SWCC in both low and high matric suction ranges following procedures outlined by Fredlund and Rahardjo (1993).

3.1 *Microporous Membrane Technique*

To obtain the SWCC in the low matric suction range, the microporous membrane technique was utilised. The pedestal of the modified SWCC apparatus was mounted with a saturated microporous membrane with an air entry value of 250 kPa. The testing program essentially allowed performing the test under a maximum matric suction of 20 kPa. A net normal and confining stress of 100 kPa was applied to the soil specimens under both stress conditions. Prior to commencement of the SWCC test, the soil specimens were first saturated through seepage from the bottom and this essentially released the initial matric suction of the specimens to zero. To obtain the drying path of the SWCC, matric suctions were progressively increased from zero to 20 kPa and air pressure in the chamber was decreased following the path of wetting of the SWCC. During the testing process, soil water moved in response to the externally applied suction and this accumulated in the double burette with elapsed time. The registered changes in the voltage on the differential pressure transducer of the modified triaxial apparatus were eventually translated into changes in the amount of water in the soil specimen. When the wetting process of the SWCC test was completed, the water content of the soil specimen was measured by oven-drying. This water content together with soil specimen changes in the amount of water recorded by the differential pressure transducer were used to back-calculate the water content corresponding to each applied suction value during drying and wetting process of the SWCC test.

3.2 *Pressure Plate Technique*

The steps used to establish SWCCs using the membrane technique above were also utilized to conduct the test using the pressure plate technique except that the high air entry ceramic disk was installed into the pedestal in place of the microporous membrane. The matric suction was progressively increased to about 500 kPa. After the application of the maximum matric suction, the air pressure in the chamber was decreased following the path of decreasing matric suction. The adsorption of water allowed the measurement of the wetting SWCC.

3.3 *Vapour pressure technique*

The SWCC in the high suction range (2.8 MPa to 296 MPa) was measured using the Vapour Pressure Technique (VPT). High suction values can be achieved by controlling relative humidity (RH) using several different salt solutions in desiccators to achieve different suction values (Oteo-Mazo et al. 1995, Delage et al. 1998, Vanapalli et al. 1999).

Two soil specimens prepared in both dry and wet conditions were suspended above a specific salt solution inside a totally closed desiccator. Seven different saturated chemical solutions (i.e. K_2SO4, KNO_3, $NH_4H_2PO_4$, NaCl, $Mg(NO_3)_2.6H_2O$, $MgCl_2.6H2O$, LiCl) recommended by JGS0151-2000: Japanese test standard of Japanese Geotechnical Society) were prepared to control relative humidity (VPT) and eventually for the determination of total suctions. The mass, height and diameter of the specimens were measured every three weeks with the assumption that equilibrium of the specimens was achieved with respect to suction values. For the wetting process, specimens were first stored in the chamber with the lowest relative humidity salt solution (i.e. Lithium Chloride with RH 11% which corresponds to a suction value of 296 MPa). After equilibrium of the specimens were achieved, salt solutions were progressively changed until the wetting process was complete. After testing for both dry and wet process was complete, soil samples were taken out of the glass desiccator and oven-dried to determine the water content at equilibrium condition.

4 TRIAXIAL COMPRESSION TEST

Triaxial compression tests under undrained conditions were performed on the soil specimen at a strain rate of 0.013% per minute with varying confining pressure. The obtained stress-strain curves and effective mean stress paths of the specimen are as shown in Figures 2 and 3, respectively.

From the stress-strain curves obtained, it can be seen that the deviator stresses increased with strain at each confining pressure. Each specimen reached residual conditions at which the deviator stresses became constant. It was further observed that as confining pressure was increased, the soil stiffness, peak strength and brittleness also increased. Therefore, a considerable increase in confinement pressure inhibited a large amount of shear-induced dilation.

All the seven specimens failed by bulging, without any distinct shear planes. The angle of internal friction was evaluated from the tangent of failure envelope of the silt soil. The calculated angle of internal friction is 33.4 degrees and cohesion is zero. In geotechnical engineering practice, effective stress strength parameters (c’ and Φ′) are critical to stability related problems.

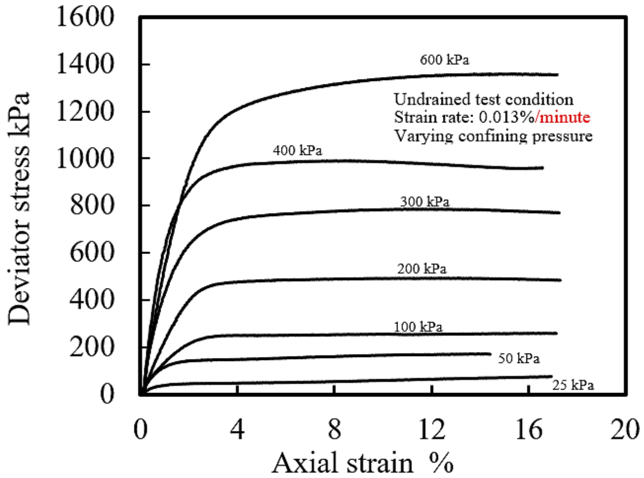

Figure 2. Stress-strain curves at different confining pressures

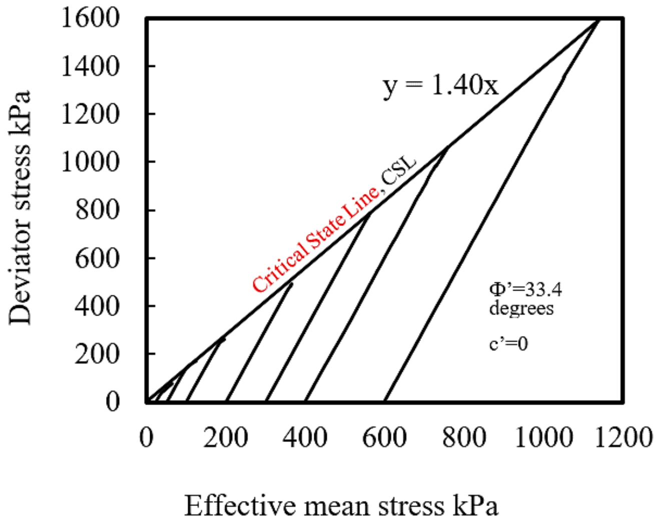

Figure 3. Effective mean stress path curves

In addition, the effective stress paths measured during the triaxial compression tests were also conducted under undrained conditions. During the tests, pore pressure was being generated according to the amount of confinement pressure applied.

5 RESULTS AND DISCUSSION

From the experimental data, relationships among suction, water content, degree of saturation and void ratio where obtained to describe the SWCCs under one-dimensional and isotropic stress conditions. The SWCCs obtained under different stress conditions are presented in Figures 4, 5 and 6 respectively.

It is clear from the results obtained that the influence of stress conditions seems to affect the shape of SWCC. The results show that the water content obtained for the specimen under one-dimensional compression condition was higher than that under isotropic compression condition.

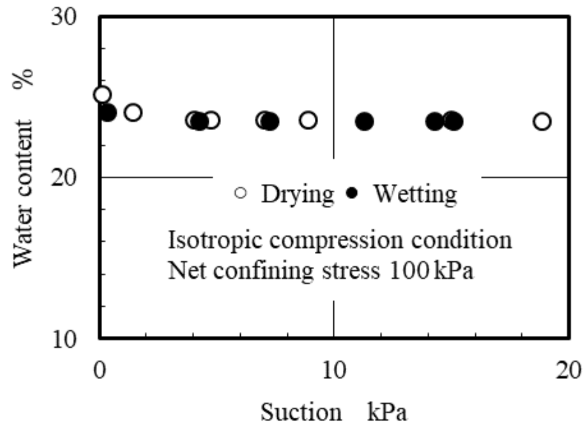

Figure 4. Suction vs water content in isotropic condition

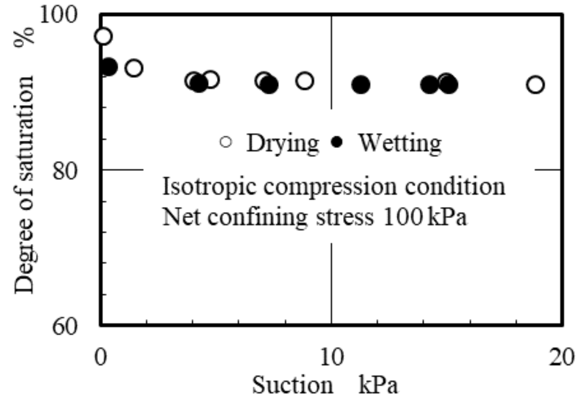

Figure 5. Suction vs degree of saturation in isotropic condition

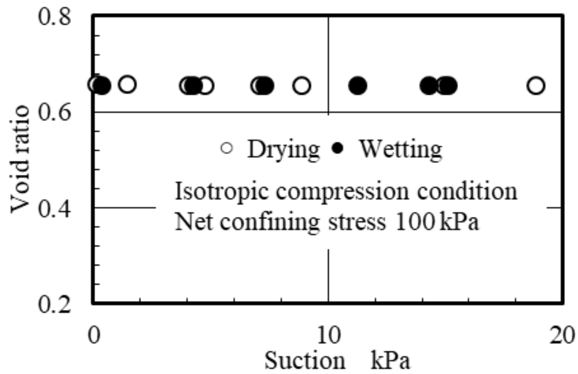

Figure 6. Suction vs void ratio in isotropic condition

The drying and wetting branches of SWCC showed less hysteresis in both one-dimensional compression and isotropic compression conditions for these results.

A comparison of the degree of saturation versus matric suction of the specimen is also presented. It was observed that the degree of saturation for the specimen tested in one-dimensional compression condition was lower than that obtained for the isotropic compression condition. The increase in the degree of saturation recorded for isotropic conditions seem to have been induced by lateral pressure. This is as one result of confining the specimen under isotropic conditions thereby causing high retention activities in the soil specimen.

Isotropic compression caused the specimen to become dense in void structure and thereby decreasing soil moisture flow movement. It was further worth noting that void ratio versus matric suction took a form similar to that of a SWCC. There was no significant change in void ratio in both one-dimensional and isotropic compression conditions for the matric suction range from zero to 20 kPa. Therefore, void ratio seems to have no effect on the shape of the SWCC in both stress conditions. Additionally, since statically compacted specimens are relatively stiff and resistant to shrinkage, the change in void ratio is not considered to have a significant effect on the SWCCs (Vanapalli et al. 1996). However, a little decrease in the void ratio of the soil specimen may imply a relative increase in the air-entry value of the soil. In other terms, a higher amount of suction which is necessary for the soil to experience a transition from the saturated regime to the unsaturated regime. Therefore, the influence of different stress state has a considerable effect on the SWCCs.

Data sets obtained using the pressure plate and vapour pressure techniques were joined together with the membrane technique data sets to complete the entire SWCC for a maximum matric suction of 296 MPa. Thereafter, the Soil Water Characteristic Curves were best-fit over the entire range of matric suction using the prediction model suggested by van Genuchten (1980).

The best-fit curve of the SWCC for the entire range of matric suction is as shown in Figure 7. Additionally, Figures 8, 9 and 10 contain SWCC in isotropic compression condition conducted at a net confining stress of 300 kPa. The results appear to show negligible hysteresis between drying process and wetting process in both isotropic compression condition and one-dimensional conditions. Lateral pressure had an influence on the void structure of the specimen which also directly caused reduction in soil moisture flow movement in the specimen.

Essentially, the key parameters of the SWCC are the air-entry value, the residual water content and the slope of the straight-line portion of the drying branch. Following the changing laws described by van Genuchten model, the parameters a, n and m where derived as shown in Figure 7. It was clearly observed that the parameter ‘a’ did not seem to affect the shape of the SWCC but shifts the curve towards the higher or lower suction regions depending on the value. Another factor of interest is the unevenness of the curve. A smaller value of ‘m’ corresponded to a smooth slope in low suction range and a steeper slope in high suction range.

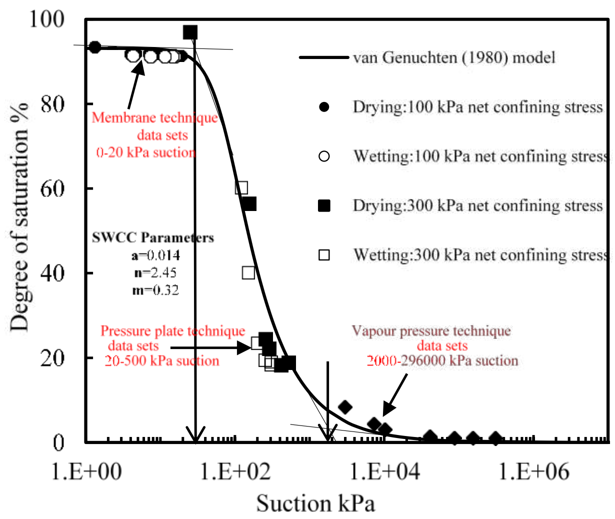

Figure 7. Curve fitting of SWCC data sets

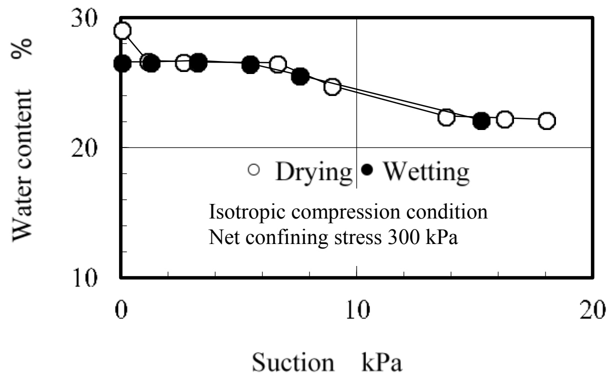

Figure 8. Suction vs water content in isotropic condition

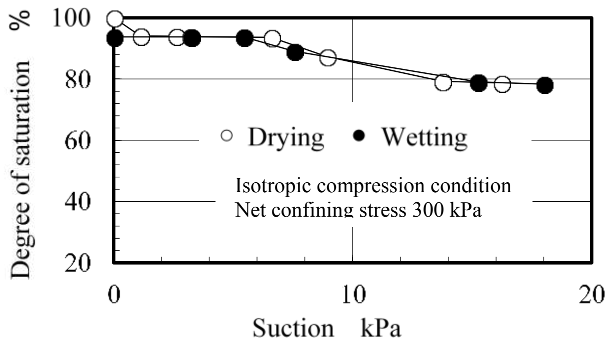

Figure 9. Suction vs degree of saturation in isotropic condition

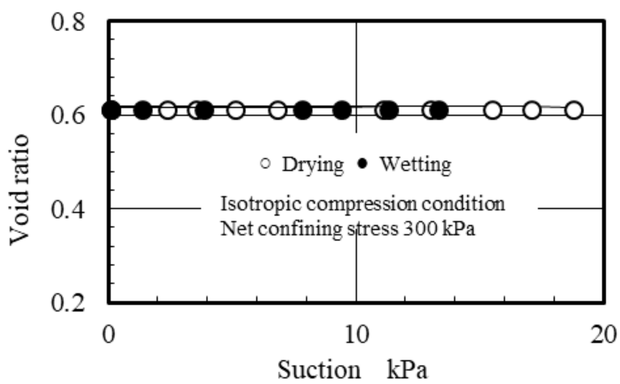

Figure 10. Suction vs void ratio in isotropic condition

On the other hand, the larger the value of 'n', the steeper the shape of the SWCC. It is worth mentioning that the SWCC model by van Genuchten required some modifications to take good fittings with these experimental data sets. To curve fit the data sets, the mathematical expression of the model was modified. Details of the modifications of the model are beyond the scope of this paper.

The last portion of the curve fit in Figure 7 shows data sets obtained using the vapour pressure technique. In as much as there was negligible hysteresis in the data sets obtained using the membrane and pressure plate techniques, there was considerable hysteresis in the vapour pressure data sets. The modified van Genuchten model clearly shows this behaviour of the data sets in Figure 7.

6 CONCLUSION

This study investigated the influence of one-dimensional and isotropic stress conditions to Soil Water Characteristic Curves. Laboratory measurements of SWCCs were conducted using the membrane technique on the new modified triaxial apparatus. In this investigation, a vertical and confining stress of 100 kPa was applied to the specimens in both stress conditions. Key issues drawn from this study include:

(1) The SWCC appears to be affected by the influence of stress conditions (i.e. one-dimensional and isotropic compression conditions). The effect is more evident in isotropic compression condition. This is probably attributed to lateral pressure and confinement of the soil specimen causing high retention activities in the soil. Isotropic compression caused the specimen's void structure to become dense and hence soil moisture flow movement also decreased.
(2) There was negligible hysteresis of the SWCCs obtained between void ratio and suction in both stress conditions. Therefore, void ratio seems to have no effect on the shape of the SWCC in both stress conditions.

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