Suction stress via thermo-servo/constant-water content ring shear testing

Ujwalkumar D. Patil i), Laureano R. Hoyos ii), Jairo E. Yepes iii), Anand J. Puppala iv), and Surya S. C. Congress v)

i) Assistant Professor, School of Engineering, University of Guam, UOG Station, Mangilao-96923, Guam.
ii) Professor, Civil Engineering Department, The University of Texas at Arlington, Arlington 76019, USA.
iii) Post-Doctoral Fellow, Department of Civil Engineering, Texas A & M University, College Station 913-2015, USA.
iv) Professor, Civil Engineering Department, The University of Texas at Arlington, Arlington 76019, USA.
v) Post-Doctoral Fellow, Civil Engineering Department, The University of Texas at Arlington, Arlington 76019, USA.

ABSTRACT

Limited experimental data is available to verify the variation of suction stress that is typically experienced by partially saturated soils under large deformations. The purpose of this study is to present soil suction characteristic curve (SSCC) for compacted high plasticity clay in light of the recent experimental data obtained from temperature controlled/constant water content ring shear testing over a matric suction range varying between 0-200 kPa. Failure envelopes are used to indirectly calculate the experimental values of suction stress corresponding to each level of matric suction. The experimental suction stress was found to increase non-linearly with increasing matric suction at constant temperature. Also, suction stress increased with increasing temperature when compared to constant matric suction. Furthermore, the soil water characteristic curve (SWCC) parameters were obtained on test soil and used to estimate the SSCC using the predictive model proposed by Lu et al. (2010). However, the suction stress values were mostly overpredicted using this model. On the other hand, a simple polynomial (two-parameter function) model was found to best predict the suction stress over the matric suction range of 0-200 kPa for clay of high plasticity.

Keywords: suction stress characteristic curves, ring shear testing, unsaturated soils, thermal effects

1 INTRODUCTION

Numerous researchers have conducted different types of suction-controlled shear strength tests including direct shear tests (i.e., Gan et al., 1988; Likos et al., 2010); triaxial tests (i.e., Fredlund and Morgenstern, 1977; Houston et al., 2008; Patil et al., 2016a and b); true triaxial tests (i.e., Hoyos, 1999; Hoyos et al., 2012); and ring shear tests (i.e., Hoyos et al., 2014; Yepes, 2016) to study the stress-strain response of various soils. Lu and Likos (2004 and 2006) introduced the concept of suction stress that could be indirectly obtained via analyses of data from suction-controlled shear strength tests. Suction stress was expressed as a function of water content, degree of saturation, or matric suction and the concept of suction stress characteristic curves (SSCC) for partially saturated soils was validated. Suction stress was obtained by summing up the inter-particle level forces including van der Waals forces, electrical double-layer forces, cementation forces, surface tension forces, and forces arising from negative pore water pressure into a macroscopic stress called suction stress ($\sigma_s$). The suction stress together with the net normal stress was used to completely define the effective stress for unsaturated soils and was expressed as below:

$$\sigma^e = (\sigma_n - u_n) - \sigma_s$$

where, ($\sigma_n-u_n$), is the net normal stress applied on the specimen. Thus, the increase in shear strength of partially saturated soil is then calculated by incorporating the additional suction stress due to matric suction minus the suction stress under saturated condition as shown below:

$$\tau_s = (-\sigma_s)\tan\phi'$$

where, $\tau_s$ is the additional shear strength due to imposed soil suction.

Lu and Likos (2006) proposed a simple method to determine the experimental suction stress. The Mohr-Coulomb failure envelope plotted at different suction levels in shear stress, $\tau$ against net normal stress, ($\sigma_n - u_n$) space were extended back to provide the intercept $c''$ which was then used to indirectly obtain value of suction stress, i.e. $\sigma_s = c''/\tan\phi'$. Existence of SSCC was experimentally verified using past data from numerous researchers on variety of soils (Lu and Likos, 2004).

Very few temperature-controlled studies have been carried in past to understand the thermo-mechanical response of partially saturated soils which has practical
applications in analyses and design of geothermal systems including nuclear waste containment systems and heat-dissipation embankments (McCartney, 2013; Alsherif and McCartney, 2015). Recently, Alsherif and McCartney (2015) developed a new Triaxial cell to conduct a series of drained Triaxial compression tests on partially saturated silt at elevated temperatures and high suction values. They characterize the suction stress using the approach by Khalili & Khabbaz (1998) and it provided a good fit to the suction stress for the specimens sheared at ambient temperature and for specimens that were heated first and followed by suction equilibrium, prior to shearing. On the other hand, Grant and Salehzadeh (1996) model was found suitable to predict the increase in suction stress for specimens that were first equilibrated for suction and then heated prior to shearing.

Analyses of earth structures such as slopes, embankments, and bearing capacity of soil requires knowledge of stress-strain response under large deformations. This requires experimental response of soil varying from peak until residual failures. Triaxial and direct shear tests have testing restrictions and it is almost impossible to shear the soil specimen to large strains that would reveal its residual strength.

Recently, researchers at University of Texas at Arlington have developed a new ring shear device (RS-device) and modified it to accommodate axis-translation technique and temperature control assembly to induce matric suction and temperature changes, respectively within the soil specimen (Velosa, 2011; Hoyos et al., 2014; Yepes, 2016). The newly developed thermo-servo/suction-controlled ring shear device can shear the soil specimens to large deformations and obtain the fully softened residual shear strength of soils. Such soil response is required for detailed analyses of slopes.

Yepes (2016) conducted a suite of single-stage-constant water content ring shear tests on high plasticity clay (CH) specimens under three different test variables i.e., net normal stress, matric suction, and temperature. In this paper, the suction stress values at three different soil suction values are calculated from the ring shear test data to plot the suction stress characteristic curves for the high plasticity clay. Furthermore, the effect of temperature on the experimental suction stress of partially saturated CH is also studied.

2 TEST MATERIALS AND TESTING METHOD

The test soil used in this paper was a high plasticity clay (CH) obtained from a depth of approximately 3 meters and was located from a failed slope in Texas, USA. The liquid limit and the plastic limit of soil were 67 and 29, respectively. The in-situ density and moisture content of the test soil were 14.18 kN/m³ and 33%, respectively. Single-stage and multi-stage ring shear tests were conducted to demonstrate the repeatability of the test equipment. More details on sample preparation, matric suction application, temperature controller connections, consolidation and shearing procedure can be obtained from Yepes (2016). Fig.1a shows the entire thermo-servo/suction-controlled ring shear device and Fig. 1b shows the picture of the attached thermal unit.

![Panoramic view of the thermo-servo/suction-controlled ring shear apparatus (Yepes, 2016)](image1)

![Temperature controller connections inside the main cell (Yepes, 2016)](image2)

Soil water characteristic curve (SWCC) was obtained for the test soil and the water content corresponding to three matric suction values used for shear strength testing was estimated, i.e., $\psi = 25$ kPa (33%), $\psi = 100$ kPa (28%), and $\psi = 200$ kPa (21%). Constant water content tests were conducted in the ring shear device keeping the temperature constant throughout the shearing stage until residual failure was reached at large strains.

In the first series of experiments, CH was tested at a normal temperature of $T = 20^\circ C$ to study the influence of three values of matric suction on the suction stress. Another suite of tests was conducted at relatively elevated temperature, i.e., $T = 30^\circ C$, three net normal stress, $(\sigma_{n,u}) = 25, 100, \text{ and } 200$ kPa and at a matric suction value of $\psi = 25$ kPa to study the effect of increasing temperature on suction stress obtain via
3 EXPERIMENTAL SS CC FROM THERMO-SERVO/CONSTANT WATER CONTENT TESTING

Residual shear stress obtained from thermo-servo/constant water-content tests were analyzed to plot Mohr-Coulomb failure envelopes at a constant temperature of $T = 20^\circ C$ and matric suction values of 25, 100, and 300 kPa at three different net confining pressures of 25, 100, and 200 kPa in shear stress versus net normal stress plane (Figs. 2-4).

The residual frictional angle was assessed to be approximately $25.5^\circ$ at $\psi = 25$ kPa, $10^\circ$ at $\psi = 100$ kPa, and $11.5^\circ$ at $\psi = 200$ kPa (Figs. 2-4). Thus, an increase in matric suction between $\psi = 25$-100 kPa caused the residual frictional angle to decrease between $\psi = 25$-100 kPa and then remain pretty much constant between $\psi = 100$-200 kPa (Figs. 2-4).

The residual failure envelope at $T = 30^\circ C$ and $\psi = 25$ kPa is plotted in Fig. 5. The residual frictional angle was assessed to be approximately $10.5^\circ$. Comparison of Figs. 2 and 5 indicates that the residual friction angle decreased from $25.5^\circ$ to $10.5^\circ$ with increase in temperature from $T = 20^\circ C$ to $30^\circ C$. Also, the apparent cohesion slightly reduced by 1 kPa with temperature increasing from 20-30°C.

The apparent cohesion value ($c''$) obtained as the intercept of Mohr-Coulomb failure envelope was used
to estimate the value of suction stress as $\sigma_s = c''/\tan \phi'$ (Figs. 2-5) as per the method proposed by Lu and Likos (2006). Fig. 6 illustrates the variation of suction stress with matric suction (i.e., $\sigma_s = f(u_a-u_w)$) at $T = 20^\circ C$. A non-linear relationship was found to exist between suction stress and matric suction (Fig. 6). The residual suction stress increased with increasing suction between $\psi = 25$-100 kPa and thereafter remained pretty much constant between $\psi = 100$-200 kPa.

$\sigma^\theta = A \psi^2 + B \psi$

\[ \Theta_e = \left\{ \frac{1}{1 + \left[ \sigma (u_a-u_w) \right]^n} \right\}^{1-n} \]  

(4)

Where, $\alpha$ and $n$ are the van Genutchen (1980) parameters obtained from its best fit to experimental points on SWCC. $\Theta_e$ is the effective saturation expressed by Eq. 4. The parameter $\alpha$ depends on air entry suction and $n$ depends on pore size distribution. These parameters were obtained from the SWCC of the test soil (CH) and further used in Eq. 3 to predict the values of suction stress for the complete soil suction range (i.e., 0-1000 MPa). Fig. 6 shows the predictive suction stress response from Eq. 3 alongside with the experimental data points.

Clearly, the suction stress was overpredicted from using the Lu and Likos (2010) model (Fig 6). On the other hand, a simple polynomial (two-parameter function) model fitted well ($R^2 = 0.94$) with the experimental values (Fig. 6).

4 CONCLUSIONS

Thermo-servo/constant water-content ring shear test results were analyzed to obtain the experimental suction stress using method proposed by Lu & Likos (2006) over a matric suction between 25-200 kPa on some high plasticity clay specimens. Residual failure envelopes were plotted in the net normal stress versus shear stress plane and extended back to intersect the negative net normal stress axis thereby yielding the experimental values of the suction stress corresponding to each value of soil suction applied in this experimental program. Closed form equation proposed by Lu et al. (2010) overpredicted the suction stress over the soil suction range of 0-200 kPa.

On the other hand, a simple polynomial equation (two-parameter function) gave good predictions ($R^2 = 0.94$) when compared with the experimental values of suction stress. Finally, an increase in temperature from 20°C to 30°C showed sharp increase in suction stress at a matric suction value, $\psi = 25$ kPa.

ACKNOWLEDGEMENTS

The core system of the RS apparatus used in this experimental program was developed under the research effort sponsored by the U.S. National Science Foundation (NSF award # CMS-0626090) and this support is gratefully acknowledged. Any findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

1) Alsherif, N. A. and McCartney, J. S. (2015): Thermal behaviour of unsaturated silt at high suction magnitudes, Géotechnique, http://dx.doi.org/10.1680/geot.14.P.049, 65(9), 703–716
2) Fredlund, D. G. and Morgenstern, N. R. (1977): Stress state variables for unsaturated soils, *ASCE J. Geotech. Eng. Div.*, Am. Soc. Civ. Eng., 609 103(5), 447–466.

3) Gan, J. K. M., Fredlund, D. G. and Rahardjo, H. (1988): Determination of the shear strength parameters of an unsaturated soil, *Canadian Geotechnical Journal*, 25, 500-510.

4) Houston, S., Perez-Garcia, N. and Houston, W. (2008): Shear strength and shear-induced volume change behavior of unsaturated soils from a Triaxial test program, *J. Geotech. Geoenviron. Eng.*, 134(11), 1619-1632. 10.1061/(ASCE)1090-0241(2008)134:11(1619), 1619–1632.

5) Hoyos, L., Perez-Ruiz, D. and Puppala, A. (2012): Modeling unsaturated soil response under suction-controlled true triaxial stress paths. *Int. J. Geomech.*, 10.1061/(ASCE)GM.1943-5622.0000159, 292–308.

6) Hoyos, L. R. (1998): Experimental and computational modeling of unsaturated soil behavior under true triaxial stress states, Doctoral dissertation, Georgia Institute of Technology, Atlanta.

7) Likos, W. J., Wayllace, A., Godt, J. and Lu, N. (2005): Modified Direct Shear Apparatus for Unsaturated Sands at Low Suction and Stress, *Geotechnical Testing Journal*, 33(4), 286-298. https://doi.org/10.1520/GTJ102927. ISSN 0149-6115

8) Lu, N. and Likos W. J. (2006): Suction stress characteristic curve for unsaturated soil, *Journal of Geotechnical and Geoenvironmental Engineering*, 132(2), 131–142.

9) Lu, N. and Likos W. J. (2004): Unsaturated soil mechanics, John Wiley & Sons Inc., New York.

10) Lu, N., Godt, J. W. and Wu, D.T. (2010): A closed-form equation for effective stress in unsaturated soil, *Water Resources Research*, https://doi.org/10.1029/2009WR008646, 46 (5), W05515.

11) McCartney, J. S. (2012): Issues involved in using temperature to improve the mechanical behavior of unsaturated soils. In Unsaturated soils: theory and practice 2011, *Proceedings of the 5th Asia-Pacific unsaturated soils conference* (eds A. Jotisankasa, A. Sawangsuriya, S. Soralump and W. Mairaing), 509–514, Thailand: Kasetsart University.

12) Patil, U. D., Hoyos, L. R. and Puppala, A. J. (2016a): Modeling essential elasto-plastic features of compacted silty sand via suction-controlled triaxial testing, *International Journal of Geomechanics*, Available online, 1-22. DOI:10.1061/(ASCE)GM.1943-5622.0000726.

13) Patil, U. D., Hoyos, L. R. and Puppala, A. J. (2016b): Characterization of compacted silty sand using a double-walled triaxial cell with fully automated relative-humidity control, *Geotechnical Testing Journal*, 39(5), 742-756. http://dx.doi.org/10.1520/GTJ20150156.

14) Vanapalli, S. K., Fredlund, D. G., Pufahl, D. E. and Clifton, A. W. (1996): Model for the prediction of shear strength with respect to soil suction, *Canadian Geotechnical Journal*, 33, 379-392.

15) van Genuchten, M. T. (1980): A closed-form equation for predicting the hydraulic conductivity unsaturated soils. *Soil Science Society of American Journal*, 44, 892-898.

16) Velosa, C.L. (2011): Unsaturated soil behavior under large deformations using a fully servo/suction-controlled ring shear apparatus. (Ph.D. dissertation) University of Texas at Arlington, Texas (192 pp.).

17) Vilar, O. M. (2006): A simplified procedure to estimate the shear strength envelope of unsaturated soil, *Canadian Geotechnical Journal*, 43, 1088-1095.

18) Yepes, J. E. (2016): Thermo-hydro-mechanical behavior of unsaturated clayey soils via thermo/suction-controlled ring shear testing. (Ph.D. dissertation) University of Texas at Arlington, Texas (221 pp.).