Geomechanics and Engineering, *Vol. 22, No. 3 (2020) 237-244*
DOI: https://doi.org/10.12989/gae.2020.22.3.237

Hydro-mechanical behavior of compacted silt over a wide suction range

Bo Chen[1], Xiuheng Ding[2], You Gao[*3], De'an Sun[1] and Haihao Yu[**4]

[1]College of Civil Engineering and Architecture, Quzhou University, 78 Jiuhua Road, Quzhou 324000, China
[2]Shanghai Civil Engineering Co. LTD of CREC, 237 Yangjiangsan Road, Shanghai 200436, China
[3]School of Civil and Environmental Engineering, Ningbo University, 818 Fenghua Road, Ningbo 315211, China
[4]Laboratory of Geomechnics and Geotechnical Engineering, Guilin University of Technology, 12 Jian Gan Road, Guilin, 541004, China

(Received October 13, 2019, Revised June 19, 2020, Accepted July 5, 2020)

Abstract. To achieve a wide suction range, the low suction was imposed on compacted silt specimens by the axis translation technique and the high suction was imposed by the vapor equilibrium technique with saturated salt solutions. Firstly, the results of soil water retention tests on compacted silt show that the soil water retention curves in terms of gravimetric water content versus suction relation are independent of the dry density or void ratio in a high suction range. Therefore, triaxial tests on compacted silt with constant water content at high suctions can be considered as that with constant suction. Secondly, the results of triaxial shear tests on unsaturated compacted silt with the initial void ratio of about 0.75 show a strain-hardening behavior with a slightly shear contraction and then strain-softening behavior with an obviously dilation. As the imposed suction increases, the shear strength increases up to a peak value and then decreases when the suction is beyond a special value corresponding to the peak shear strength. The residual strength increases to fair value and those at high suctions are almost independent of imposed suctions. In addition, the contribution of suction to the strength of compacted silt would not diminish even in a high suction range.

Keywords: unsaturated soil; soil water retention behavior; triaxial test; high suction

1. Introduction

In arid and semi-arid regions, unsaturated soils over a wide suction range or at high suctions are more commonly found in nature. Many geotechnical engineering structures, such as earth dams, subgrades, and covers etc., were closely related to unsaturated soils with high suctions in those regions. Therefore, unsaturated soils over a wide suction range or at high suctions are encountered in various geotechnical engineering projects.

In the past decades, many significant advances in understanding unsaturated soil behavior have been seen both in laboratory tests and constitutive models (e.g., Alonso *et al.* 1990, Uchaipichat *et al.* 2010, Estabragh and Javadi 2012, Al-Mahbashi *et al.* 2015, Zhou *et al.* 2016, Kim *et al.* 2019, Wang *et al.* 2020). The constitutive models for unsaturated soils have been widely verified by test data in a low suction range. The main reason is that a large number of laboratory tests have been conducted to study the hydro-mechanical behavior of unsaturated soils in a low suction range by using the axis translation technique, in which the maximum suction applied in conventional mechanical test apparatus to soils is 1.5 MPa. In general, the suction of 1.5 MPa is used as a boundary between the low and high suction ranges. However, the mechanical tests on unsaturated soils are rarely conducted in the high suction range (i.e., 1.5 to about 1000 MPa), where the pore-water is tightly held in the soil particles and moisture movement occurs mainly as the vapor flow.

The mechanical behavior of unsaturated soils is related to its soil water retention behavior, which is highly dependent on the soil types (e.g., the suction range is about 0-100 kPa for coarse sands and about 0-1000 MPa for clays; when the suction is greater than the up limit, water content is almost zero). Recently years, some researchers investigated the hydro-mechanical behavior of unsaturated soils over a wide suction range (i.e., the suction range covers the boundary, transition and residual zones) or at high suctions. Alsherif and Mccartney (2016) investigated the effects of temperature on the shear strength of unsaturated silty clay at high suctions and the suction was controlled using the vapor flow technique. Patil *et al.* (2017) obtained experimental evidence of shear strength behavior of compacted silty clay at a critical state over a wide suction range by using the vapor flow technique. Gao *et al.* (2019) and Zhang *et al.* (2020a) performed a series of triaxial tests on compacted silty clay and expansive soil over a wide suction range respectively by using the axis-translation technique and the vapor equilibrium technique with a saturated salt solution. Yu *et al.* (2019) studied the strength and microstructure of cemented soil at high suctions and the soil suction was controlled by using the vapor equilibrium technique with saturated salt solution. The above experimental studies mentioned mainly focused on fine-grained soils (e.g., silty clays, clays and expansive soils). But the test results about the mechanical behavior of sandy silts or silts over a wide suction range or at high

*Corresponding author, Lecturer, Ph.D.
E-mail: gaoyou@nbu.edu.cn
**Corresponding author, Lecturer, Ph.D.
E-mail: 2018094@glut.edu.cn

http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

suctions are still very limited in the literature.

In this study, the soil-water retention tests and suction-controlled triaxial tests were conducted on compacted silt over a wide suction range. To achieve a wide suction range, the low suction was imposed on silt specimens by the axis translation technique (ATT) and the high suction was imposed by the vapor equilibrium technique (VET) with different saturated salt solutions. Based on the results of above tests, a systematical study to investigate the effects of void ratio on the soil water retention curves and the hydro-mechanical behavior of compacted silt was made over a wide suction range.

2. Experimental techniques and testing program

2.1 Experimental techniques

The soil used in this study is non-expansive silt called DL-clay, which has a liquid limit of 28.4% and a plastic limit of 21.7%, and a specific gravity of 2.68. Fig. 1 shows the grading curve of DL-clay. It can be seen that the soil is composed of about 88% silt and 9% clay. Soil samples were prepared by mixing dry powders of DL-clay with distilled water to the target water content. The blended sample was then sealed in airtight storage bags for 24 hours and was allowed to equilibrate. All of the specimens were compacted with the initial water content of about 20%.

For the soil-water retention tests, compacted specimens were prepared with the initial void ratios of about 0.75 and 1.0. In order to shorten the suction equilibrium time, specimen sizes were 20 mm in height and 50 mm in diameter. The low suction was imposed on specimens by using the ATT and the high suction was imposed by using the VET, which was commonly employed to control high suctions for unsaturated soil tests (Delage *et al.* 1998). Different saturated salt solutions were used in the VET to generate constant total suction conditions in sealed desiccators, as shown in Fig. 2. The potential of saturated salt solutions forces the water potential in the closed space and that in the soil sample to reach the equilibrium. Table 1 lists the relative humidities of saturated salt solutions used in this study and their corresponding suctions, which are from Greenspan (1977). After the suction equilibrium, the size and weight of specimens were measured by vernier calipers and electronic balance before triaxial tests, respectively. The testing procedure that was adopted for testing the soil-water retention curves was described in detail by Sun *et al.* (2016).

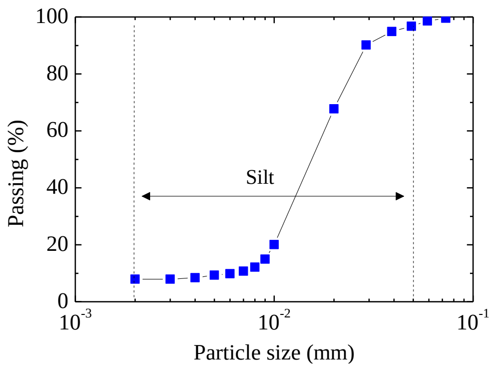


Fig. 1 The grading curve

Fig. 2 A desiccator with a saturated NaCl solution

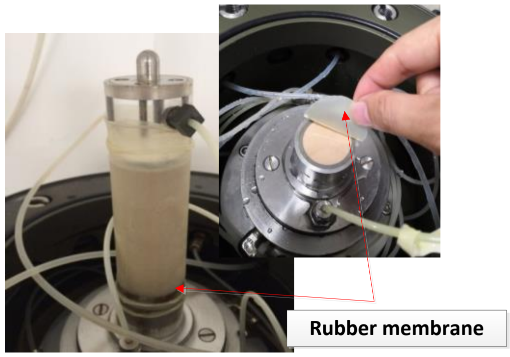


Fig. 3 GDS unsaturated triaxial testing apparatus

Table 1 Saturated salt solution and corresponding suction

Saturated salt solution	*RH*(%)	Total suction (MPa)
$MgCl_2$	33.1	149.5
NaCl	75.5	38.0
KCl	85.1	21.8
KNO_3	94.6	7.48
K_2SO_4	97.6	3.29

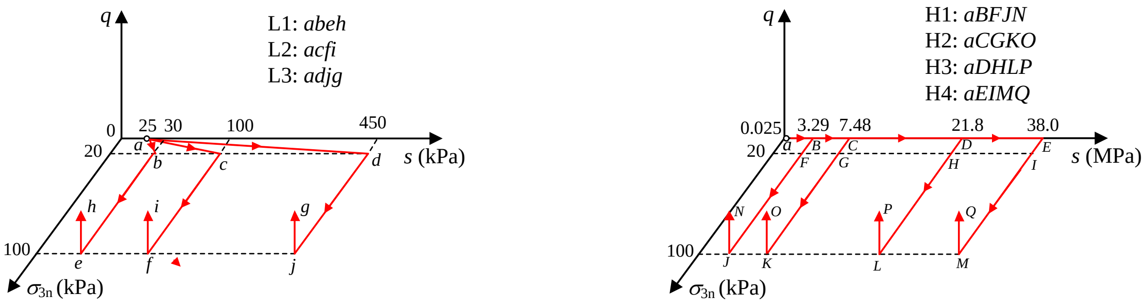
For the triaxial shear tests, the specimens were statically compacted to a target void ratio in five layers with a diameter of 38 mm and a height of 76 mm at a mould. The prepared void ratio of compacted triaxial specimens is about 0.75. All the triaxial shear tests were performed using a GDS triaxial apparatus for testing unsaturated soils, which was manufactured by the GDS Company (Hampshire, UK), as shown in Fig. 3. The specimen volume change is measured by a double cell system with a bottle-shaped inner cell, the principle of which was described in detail by Ng *et al.* (2002). The water volume change of specimens was measured by a standard pressure controller. The average initial suction of triaxial specimens was about 25 kPa, which was obtained by measuring the negative pore-water pressure value and setting the pore air pressure value to zero in the triaxial apparatus. The shear rate (i.e., axial displacement rate) was set to 0.00192 mm/min. The shear rate was selected by no excess pore-water pressure occurred in the specimens during testing.

2.2 Testing program

For the triaxial shear tests, firstly, the prepared triaxial

Table 2 Gravimetric water content and void ratio of triaxial specimens at the initial state and before shearing

Test No.	Suction (MPa)	Suction control method	Initial state		Before shearing	
			w_0 (%)	e_0	w_c (%)	e_c
L1	0.03	ATT	20.11	0.751	18.48	0.724
L2	0.10	ATT	20.04	0.752	12.80	0.745
L3	0.45	ATT	19.98	0.753	5.71	0.727
H1	3.29	VET	20.03	0.746	2.14	0.726
H2	7.48	VET	20.12	0.745	1.63	0.717
H3	21.8	VET	20.08	0.746	1.41	0.690
H4	38.0	VET	20.21	0.748	1.15	0.688



(a) At low suction (b) At high suction

Fig. 4 Stress paths for all specimens

specimens were put into different sealed desiccators above saturated salt solutions, as shown in Fig. 2. The suction equilibrium was achieved after two up three months under a constant room temperature under zero total stress. The size and weight of specimens were measured by vernier calipers and electronic balance after the suction equilibrium (i.e., before triaxial tests), respectively. Finally, the specimen was installed on the bottom pedestal of triaxial testing apparatus. For the low suction range, after the target suction sheared under a constant suction based on the ATT under drained condition. For the high suction range, the specimen was equilibrated, the specimen was consolidated and was consolidated and sheared under constant water content. Here the triaxial shear tests under constant water content can be considered to be constant suction shear tests at high suctions. The reason will be presented in the following section (i.e., "Soil water retention behavior"). In order to keep water content constant in triaxial tests, a sheet of thin rubber membrane with about 0.3 mm in thickness was inserted between the specimen bottom and the ceramic disk surface, as shown in Fig. 3.

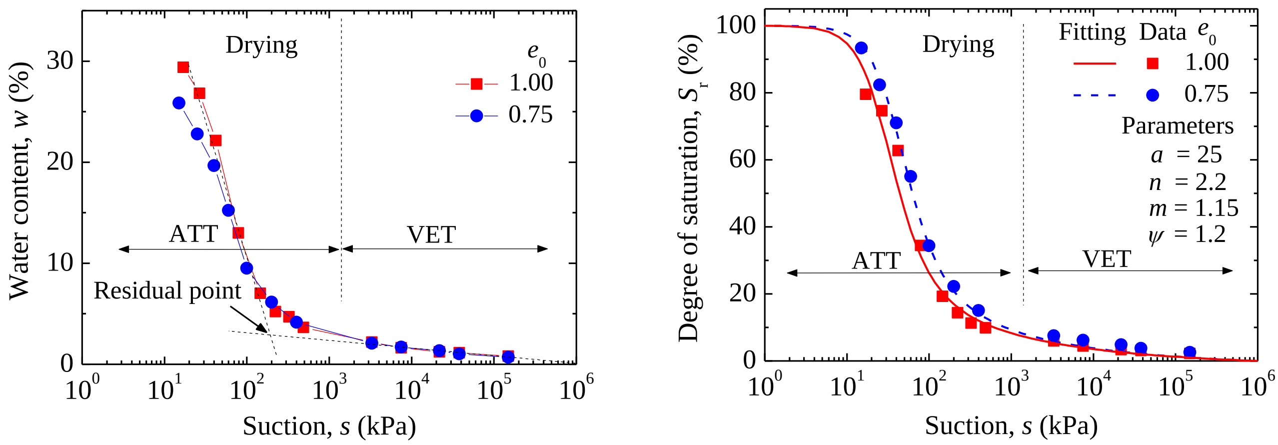
To investigate the effects of suction level on hydro-mechanical behavior of unsaturated soil, a series of triaxial shear tests with constant suctions on compacted DL-clay was conducted using the GDS triaxial testing apparatus. The initial void ratio of compacted DL-clay specimens for triaxial shear tests is about 0.75. A summary of the gravimetric water content and void ratio of triaxial specimens at the initial state and before shearing in detail are shown in Table 2. Here, the initial state means a specimen state just after the specimen preparation or before triaxial tests.

Fig. 4 shows the stress paths for all triaxial tests. q is the deviator stress, s is the suction, σ_{3n} is net confining stress. In Fig. 4(a), the specimens L1, L2 and L3 were isotropically compressed at net stress of 20 kPa with suctions of 30, 100 and 450 kPa being applied respectively (i.e., the stress paths *ab*, *ac* and *ad*). Then isotropic net stress of 100 kPa was applied on the specimens corresponding to the stress paths of *be*, *cf* and *dj*. Finally, the specimens L1, L2 and L3 were triaxially sheared under constant net confining stress of 100 kPa and constant suctions (s=30, 100 and 450 kPa) by the ATT. The corresponding stress paths above are *eh*, *fi* and *jg*. In Fig. 4(b), the specimens H1, H2, H3 and H4 were first dried to different suctions of 3.29, 7.48, 21.8 and 38.0 MPa using the VET under zero net stress, respectively (the stress paths *aB*, *aC*, *aD*, and *aE* in Fig. 4(b)). After the suction equilibrium, the size and weight of triaxial specimens were measured by vernier calipers and electronic balance, and then the specimens were installed on the triaxial apparatus. Next, the specimens H1, H2, H3 and H4 were isotropically compressed successively at isotropic net stresses of 20 and then 100 kPa (i.e., the stress paths *BFJ*, *CGK*, *DHL* and *EIM*) under constant water contents. Finally, the specimens were triaxially sheared under constant net confining stress of 100 kPa and different constant suctions (s=3.29, 7.48, 21.8 and 38.0 MPa). The corresponding stress paths above are *JN*, *KO*, *PL* and *MQ*.

3. Results and discussion

3.1 Soil water retention behavior

Fig. 5 shows the gravimetric water content or degree of



(a) Water content (b) Degree of saturation

Fig. 5 Main drying SWRCs over a wide suction range

saturation versus suction relationships in the drying tests on compacted DL-clay with the initial void ratios of about 1.0 and 0.75 over a wide suction range using two suction control methods (i.e., ATT and VET). The specimens were firstly saturated at zero suction, and the water contents of specimens increased to about 27 and 30% due to saturation. In Fig. 5(a), the SWRCs in terms of gravimetric water content are independent of the initial void ratio when the suction is larger than about 100 kPa. While the SWRCs in terms of the degree of saturation, as shown in Fig. 5(b), the influence of initial void ratio or dry density on the SWRCs is highlighted. Birle *et al.* (2008) and Salager *et al.* (2013) made a similar observation for compacted soils. The residual suction is about 200 kPa determined by the graphical method (see Fig. 5), which is independent of the initial void ratio or density. For the same type of soil, the residual suction depends mainly upon the specific surface area of soil particles (Lloret *et al.* 2015). For the high suction range, the pore-water is tightly held in the soil particles and moisture movement occurs mainly as the vapour flow, where the water retention capacity is mainly controlled by the specific surface and mineral of the soil particles, not by soil fabric (Wang *et al.* 2020).

In Fig. 5(b), the soil-water retention curve (SWRC) of compacted DL-clay in terms of the degree of saturation versus suction relation shifts slightly up with decreasing the initial void ratio. Based on Fredlund and Xing's equation, Gao *et al.* (2018) proposed an initial dry density-dependent equation, which can be expressed as

$$S_r(s,e_0) = C(s)\frac{1}{\{\ln(2.71828+[(e_0)^{\psi}s/a]^{n})\}^{m}} \quad (1)$$

where, n, m and ψ are the fitting parameters, e_0 is an initial void ratio, $C(s)$ is a correction function, which is equal to 1-[ln(1+s/ψ_{re})/ln(1+$10^6/\psi_{re}$)] (where ψ_{re} is a fitting parameter). In most cases, Eq. (1) gives a satisfactory approximation when ψ_{re} takes a value ranging from 1.5 to 3 MPa (Fredlund and Xing 1994). For simplicity, here, ψ_{re} is assumed to be 1.5 MPa. In fact, ψ_{re} is not an actual residual suction value in Eq. (1) and it is just a fitting parameter.

In Fig. 5(b), the fitting parameters (a, n, m and ψ) of Eq.

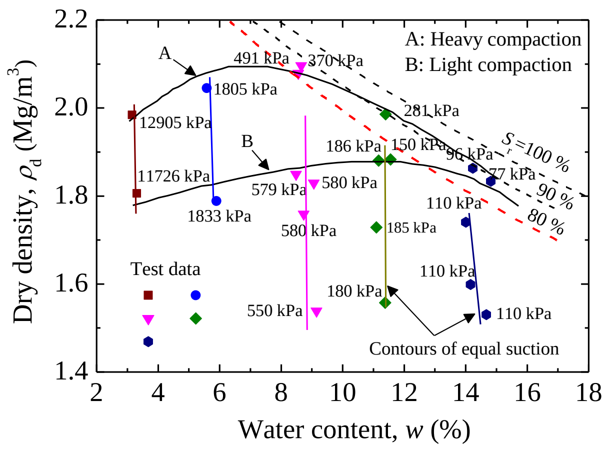
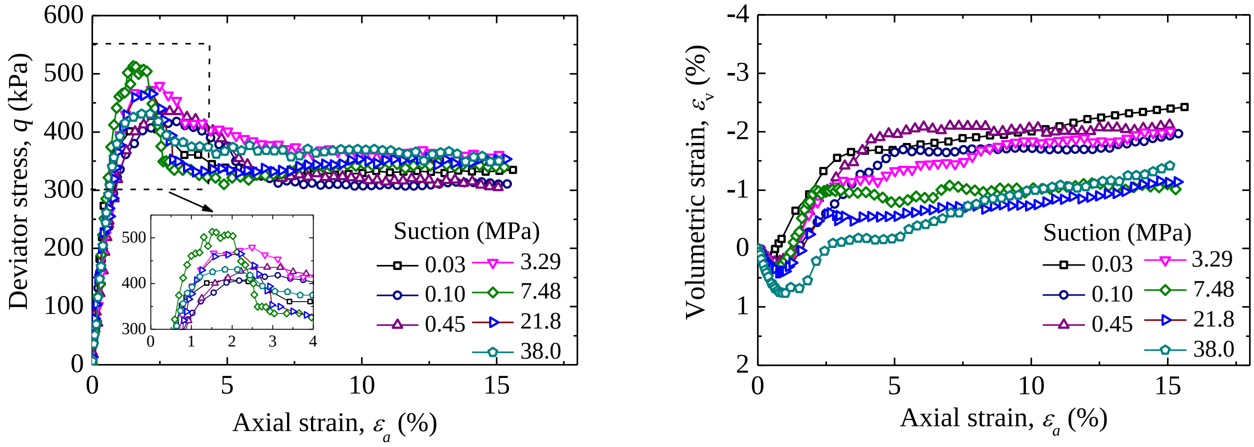


Fig. 6 Water content versus dry density relation of compacted bentonite-enriched sand with measured suction (data from Dineen *et al.* 1999)

(1) for compacted DL-clay are 25, 2.2, 1.15 and 1.2, respectively. It can be seen that the fitting results are in good agreement with test data. In addition, the air entry values of compacted DL-clay with the initial void ratios of 1.0 and 0.75 are determined to be about 10 and 18 kPa from Fig. 5(b), respectively.

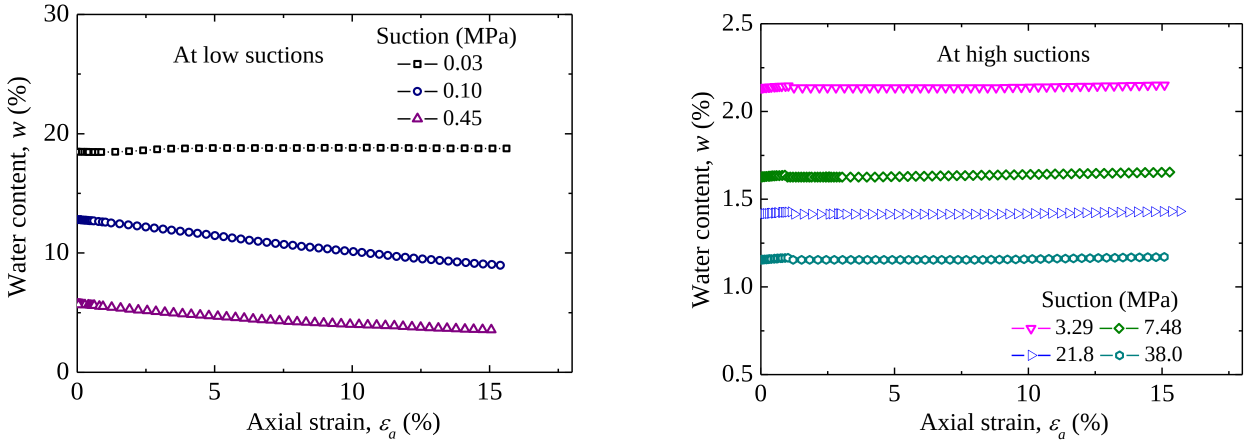
Fig. 6 shows water content versus dry density relation of compacted bentonite-enriched sand with 10% bentonite and 90% sand, together with measured suctions (data from Dineen *et al.* 1999). The suctions were obtained via the filter paper and the suction probe methods. Suction contours and two compaction curves are drawn. In Fig. 6, the contours of suction become nonlinear at the high water content (i.e., the high degree of saturation). The vertical contours of suction are observed when the degree of saturation is less than 80% (i.e., below the red dash line in Fig. 6). This implies that the void ratio or dry density has no significant effect on the suction of specimens as long as the water content is kept constant over a high suction range. Birle *et al.* (2008), Salager *et al.* (2013) and Romero *et al.* (1999) made a similar observation for compacted clay, silty sand, and Boom clay, respectively.

Based on the discussion above, the void ratio or dry



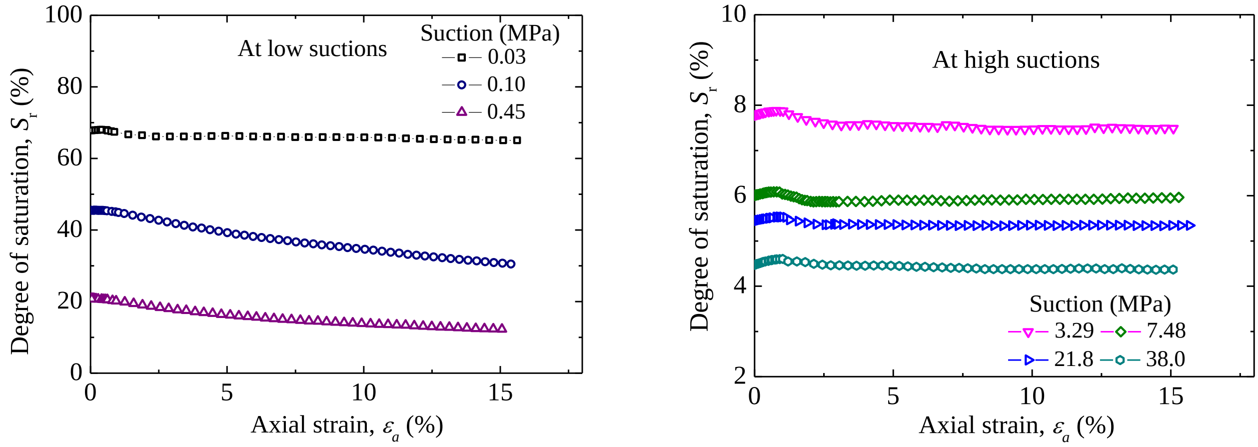
(a) Stress versus strain relation (b)Volumetric strain versus axial strain relation

Fig. 7 Triaxial shear test results of compacted silt at constant suctions



(a) At low suction (b) At high suction

Fig. 8 Variation in water content over a wide suction range



(a) At low suction (b) At high suction

Fig. 9 Variation in degree of saturation over a wide suction range

density does not have an effect on the soil-water retention curves in a high suction range. The specimens with constant water content can be considered as almost constant suction over a high suction range. Therefore, the triaxial tests under constant water content can be considered to be a constant suction test at high suctions, even though the void ratio changes during compressing or shearing.

3.2 Hydro-mechanical behavior

Fig. 7 shows the deviator stress and volumetric strain versus axial strain relationships obtained from triaxial shear tests on compacted silt with the initial void ratio of 0.75 under the net confining pressure of 100 kPa. The low suctions of 0.03, 0.10 and 0.45 MPa were imposed on specimens by the ATT, and the high suctions of 3.29, 7.48, 21.8 and 38.0 MPa were imposed by the VET with saturated salt solutions. All the specimens in Fig. 7 show a strain-hardening-softening behavior with an obviously shear contraction and dilation with increasing the axial strain. When the axial strain is smaller than roughly 2%, the specimens showed a response of strain-hardening with a slightly shear contraction; when the axial strain is larger than roughly 2%, the specimens showed a response of strain-softening with an obviously shear dilation. The axial strain where the maximum volume contraction occurred is about 1%, and it increases slightly with increasing the suction. Besides, the peak shear strength first increases with the imposed suction and then obviously decreases with increasing the suction in a high suction range, as shown in Fig. 7(a). The axial strains corresponding to the peaks decrease with increasing the suction. The residual strengths are almost independent of imposed suction in a high suction range.

Fig. 8 shows the gravimetric water content versus axial strain relationship obtained from triaxial shear tests on compacted DL-clay over a wide suction range. For the low suction range (see Fig. 8(a)), the gravimetric water content of specimen with the imposed suction of 0.03 MPa increases slightly with increasing the axial strain; while the gravimetric water content of other two specimens with the imposed suction of 0.10 and 0.45 MPa obviously decreases with increasing the axial strain under constant suctions and net confining pressure. For the high suction range (see Fig. 8(b)), the gravimetric water content of all specimens remained unchanged during shearing. This is because the specimens in the high suction range were triaxially sheared with constant water content.

Fig. 9 shows the degree of saturation versus axial strain relationship obtained from triaxial shear tests on compacted DL-clay over a wide suction range. In the low suction range (see Fig. 9(a)), the degree of saturation of specimens with the imposed suction of 0.03 MPa almost keep a constant with increasing the axial strain; while the degree of saturation of specimens with the imposed suction of 0.10 and 0.45 MPa decreases with increasing the axial strain. In the high suction range (see Fig. 9(b)), the degree of saturation of all the specimens increased slightly with the volume contraction during shearing at the axial strain of roughly between 1 and 2%, and then decrease slightly to a fairly constant value. This is because the shear contraction occurred in the axial strain roughly between 1 and 2 %.

Fig. 10 shows the deviator stresses at failure and residual over a wide suction range for compacted DL-clay. q_f is the deviator stress at failure and q_r is the deviator stress at residual. In this paper, the failure point was determined as follows: if the stress-strain curve has a peak, the peak was chosen as the failure point; if the stress-strain curve has no peak, the point at the axial strain of 15% was chosen as the failure point according to the ASTM D4767-11.

In Fig. 10, the shear strength increases to a peak value as the soil suction increases and then decreases when the suction was beyond a special value corresponding to the peak shear strength. This is mainly because the contribution of water meniscus on shear strength decreases with increasing the suction in the high suction range. The residual strengths increases to a fairly constant value and those are almost independent of imposed suctions at high suctions. In addition, the failure strength and residual strength of unsaturated silt at high suctions are slightly larger than that of the specimen at very low suctions. This indicated that the contribution of suction to the strength of compacted silt would not diminish after the residual suction.

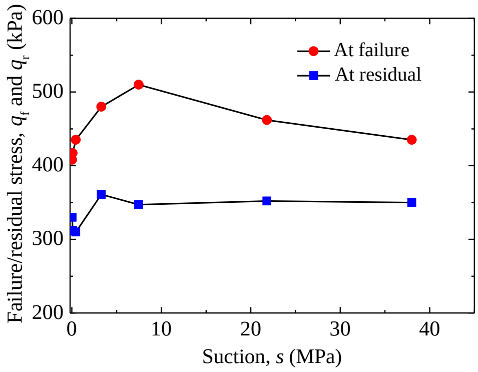


Fig. 10 Failure and residual strength over a wide suction range

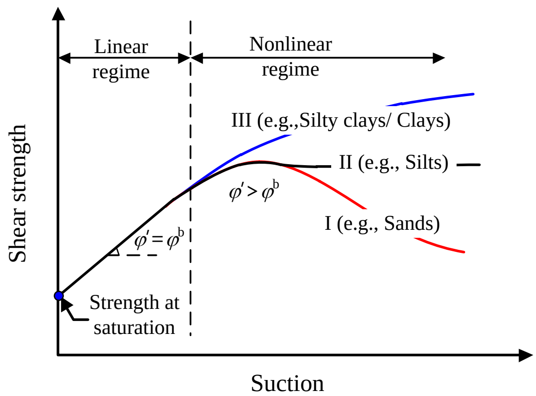


Fig. 11 Failure strength of unsaturated soils for different types

The failure strength of unsaturated soils is dependent on several factors, such as soil type, particle distribution, density, and stress state (Vanapalli 2010, Gao *et al.* 2020, Zhang *et al.* 2020b). For sands, the failure strengths usually increase with soil suction to a marked peak value and then decrease sharply to a fairly constant value. Donald (1957) reported the failure strength of five different types of sand increased to a peak value as the soil suction was increased and then decreased sharply. For silt or silty clay, as the soil suction increases, the measured failure strength increases to a fairly constant value or a maximum value and then slightly decreases in the high suction range. Ng *et al.* (2017) and Gao *et al.* (2019) reported the measured shear strength for their compacted loess and silty clay kept increasing until it reached to a fairly constant value over a wide suction range. For some silty clays or clays, an increase in the soil suction always leads to an increase in the shear strength. Zhang *et al.* (2020) and Patil *et al.* (2017) reported the peak strength at failure kept increasing and never decreased for expansive soil and clay over a wide suction range. Therefore, the failure strength of different soil types over a wide suction range can be broadly classified into three groups, as shown in Fig. 11(the figure was modified from Vanapalli 2010). In Fig. 11, φ' is the angle of effective friction; φ^b is the angle of friction related to the matric suction. In the linear regime, φ' is the same as φ^b. Once the soil starts to be desaturated, there is a nonlinear increase in the shear strength, and φ^b is less than φ'.

4. Conclusions

This paper investigated the soil-water retention and mechanical behavior of compacted silt over a wide suction range. The following conclusions can be drawn from this study.

• Results of soil-water retention tests show that the SWRCs in terms of the suction and water content relationship is independent of the void ratio or dry density over a high suction range. Based on the above results of soil-water retention tests, triaxial shear tests under constant water contents can be regarded as those under constant suctions in a high suction range.

• Results of triaxial shear tests show a strain-hardening behavior with a slightly shear contraction and then strain-softening behavior with an obvious dilation for compacted silt with the initial void ratio of 0.75. Over a wide suction range, the shear strength increases up to a peak value with increasing the suction, and then decreases when the suction is beyond a special value corresponding to the peak strength. The residual strength increases to a reasonably constant value, and those at high suctions are almost independent of imposed suctions.

• The failure strength and residual strength of unsaturated compacted silt at high suction are slightly larger than that of the specimen at very low suction. This indicated that the contribution of suction to the strength of compacted silt would not diminish.

Acknowledgments

The authors express their gratitude for the grants provided by the National Natural Science Foundation of China (Nos. 41902279), the Public Welfare Technology Research Projects of Zhejiang Province (No. LGG19E080002), the Natural Science Foundation of Zhejiang Province (Nos. LQ19E080006), Natural Science Foundation of Ningbo (2018A610430).

References

Al-Mahbashi, A.M., Elkady, T.Y. and Alrefeai, T.O. (2015), "Soil water characteristic curve and improvement in lime treated expansive soil", *Geomech. Eng.*, **8**(5), 687-696. https://doi.org/10.12989/gae.2015.8.5.687.

Alonso, E.E., Gens, A. and Josa, A. (1990), "A constitutive model for partially saturated soils", *Geotechnique*, **40**(3), 405-430. https://doi.org/10.1680/geot.1990.40.3.405.

Alsherif, N.A. and Mccartney, J.S. (2016), "Yielding of silt at high temperature and suction magnitudes", *Geotech. Geol. Eng.*, **34**(2), 501-514. https://doi.org/10.1007/s10706-015-9961-x.

ASTM Standard D4767-11 (2011), *Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Birle, E., Heyer, D. and Vogt, N. (2008), "Influence of the initial water content and dry density on the soil-water retention curve and the shrinkage behavior of a compacted clay", *Acta Geotechnica*, **3**(3), 191-200. https://doi.org/10.1007/s11440-008-0059-y.

Delage, P., Howat, M. and Cui, Y.J. (1998), "The relationship between suction and swelling properties in a heavily compacted unsaturated clay", *Eng. Geol.*, **50**(1-2), 31-48. https://doi.org/10.1016/S0013-7952(97)00083-5.

Dineen, K., Colmenares, J.E., Ridley. A.M. and Burland, J.B. (1999), "Suction and volume changes of a bentonite-enriched sand", *Proc. Inst. Civ. Eng. Geotech. Eng.*, **137**(4), 197-201. https://doi.org/10.1680/gt.1999.370405.

Donald, I.B. (1957), "Effective stresses in unsaturated non-cohesive soils with controlled negative pore pressure", M.Sc. Thesis, University of Melbourne, Melbourne, Australia.

Estabragh, A.R. and Javadi, A.A. (2012), "Effect of suction on volume change and shear behaviour of an overconsolidated unsaturated silty soil", *Geomech. Eng.*, **4**(1), 55-65. https://doi.org/10.12989/gae.2012.4.1.055.

Fredlund, D.G. and Xing, A. (1994), "Equations for soil-water characteristic curve", *Can. Geotech. J.*, **31**(4), 521-532. https://doi.org/ 10.1139/t94-061.

Gao, Y., Sun D.A., Zhou A.N. and Li, J. (2018), "Effect of stress state on soil–water retention and its application on the strength prediction", *Geotechnique Lett.*, **8**(4), 324-329. https://doi.org/10.1680/jgele.18.00159.

Gao, Y., Sun, D.A., Zhou, A.N. and Li, J. (2020), "Predicting shear strength of unsaturated soils over wide suction range", *Int. J. Geomech.*, **20**(2), 04019175. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001555.

Gao, Y., Sun, D.A., Zhu, Z.C. and Xu, Y.F. (2019), "Hydro-mechanical behavior of unsaturated soil with different initial densities over a wide suction range", *Acta Geotechnica*, **14**(2), 417-428. https://doi.org/10.1007/s11440-018-0662-5.

Greenspan, L. (1977), "Humidity fixed points of binary saturated aqueous solutions", *J. Res. National Bureau Standards*, **81**(1), 89-96.

Kim, B., Kato, S. and Park, S. (2019), "Experimental approach to estimate strength for compacted geomaterials at low confining pressure", *Geomech. Eng.*, **8**(5), 687-696. https://doi.org/10.12989/gae.2019.18.5.459.

Lloret, A., Villar, M.V., Nchez, M.S.A., Gens, A., Pintado, X. and Alonso, E.E., (2015) "Mechanical behaviour of heavily compacted bentonite under high suction change", *Geotechnique*, **53**(1), 27-40. https://doi.org/10.1680/geot.53.1.27.37258.

Ng, C.W.W., Sadeghi, H. and Jafarzadeh, F. (2017), "Compression and shear strength characteristics of compacted loess at high suctions", *Can. Geotech. J.*, **54**(5), 690-669. https://doi.org/ 10.1139/cgj-2016-0347.

Ng, C.W.W., Zhan, L.T. and Cui, Y.J. (2002), "A new simple system for measuring volume changes in unsaturated soils", *Can. Geotech. J.*, **39**(2), 757-764. https://doi.org/10.1139/t02-015.

Patil, U.D., Puppala, A.J., Hoyos, L.R. and Pedarla, A. (2017), "Modeling critical-state shear strength behavior of compacted silty sand via suction-controlled triaxial testing", *Eng. Geol.*,

231, 21-33. https://doi.org/10.1016/j.enggeo.2017.10.011.

Romero, E., Gens, A. and Lloret, A. (1999), "Water permeability, water retention and microstructure of unsaturated compacted Boom clay", *Eng. Geol.*, **54**(1-2), 117-127. https://doi.org/ 10.1016/S0013-7952(99)00067-8.

Salager, S., Alessio, M., Ferrari, A. and Laloui, L. (2013), "Investigation into water retention behavior of deformable soils", *Can. Geotech. J.*, **50**(2), 200-208. https://doi.org/10.1139/cgj-2011-0409.

Sun, D.A., Gao, Y., Zhou, A.N. and Sheng, D.C. (2016), "Soil-water retention curves and microstructures of undisturbed and compacted Guilin lateritic clay", *Bull. Eng. Geol. Environ.*, **75**(2), 781-791. https://doi.org/ 10.1007/s10064-015-0765-2.

Uchaipichat, A. (2010), "Effect of suction on volume change and shear behaviour of an overconsolidated unsaturated silty soil", *Geomech. Eng.*, **2**(3), 203-211. https://doi.org/10.12989/gae.2010.2.3.203.

Vanapalli, S.K. (2010), "Shear strength of unsaturated soils and its applications in geotechnical engineering practice", *Proceedings of the 4th Asia Pacific Conference on Unsaturated Soils*, New South Wales, New Castle, Australia, November.

Wang, H., Koseki, J. and Nishimura, T. (2020), "Water retention characteristics of iron ore fines", *Can. Geotech. J.*, In Press, https://doi.org/10.1139/cgj-2018-0840.

Wang, L., Zhou, A.N., Xu, Y.F. and Xia X.H. (2020), "Consolidation of unsaturated composite ground reinforced by permeable columns", *Comput. Geotech.*, **125**, 103706. https://doi.org/10.1016/j.compgeo.2020.103706.

Yu, C., Wang, H., Zhou, A.N., Cai, X. and Wu, Z. (2019), "Experimental study on strength and microstructure of cemented soil with different suctions", *J. Mater. Civ. Eng.*, **31**(6), 04019082. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002717.

Zhang, J.R., Niu, G., Li, X.C. and Sun, D.A. (2020a), "Hydro-mechanical behavior of expansive soils with different dry densities over a wide suction range", *Acta Geotechnica*, **15**(1), 265-278. https://doi.org/10.1007/s1144.0-019-00874-y.

Zhang, J.R., Sun, D.A., Yu, H.H., Jiang, J.H. and Xu, Y.F. (2020b), "Swelling of unsaturated GMZ07 bentonite at different temperatures", *Bull. Eng. Geol. Environ.*, **79**(2), 959-969. https://doi.org/10.1007/s10064-019-01595-y.

Zhou, A.N., Huang, R.Q. and Sheng, D.C. (2016), "Capillary water retention curve and shear strength of unsaturated soils", *Can. Geotech. J.*, **53**(6), 974-987. https://doi.org/10.1139/cgj-2016-0489.

CC