International Journal of GEOMATE, Feb., 2023, Vol.24, Issue 102, pp.26-33
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.102.g12148
Geotechnique, Construction Materials and Environment

EXPERIMENTAL STUDY ON STATE BOUNDARY SURFACE OF COMPACTED SILTY SOIL

* Tufail Ahmad[1], Riko Kato[1] and Jiro Kuwano[1]

[1]Department of Civil & Environmental Engineering, Saitama University, Japan

*tufailafghan@yahoo.com, Received: 23 June 2022, Revised: 25 Dec. 2022, Accepted: 27 Jan. 2023

ABSTRACT: To understand the behavior of unsaturated soil, considerable research has already been done. However, there is limited research to model the behavior of unsaturated soil in a generalized state boundary surface (SBS). SBS is the surface outside which a soil stress state can never exist. It is an envelope surface of all the possible soil stress paths in the p'-q-e space. To investigate the SBS of unsaturated soils, a series of triaxial compression tests were performed in this study under constant water content conditions using a double-cell triaxial test apparatus. The samples were prepared with 80%, 83%, and 86% degrees of compaction and water contents of 20% (Optimum water content) and 25%. All the soil specimens were consolidated isotropically under 500kPa confining pressure before being sheared with a constant void ratio under monotonic loading. The results show that constant void ratio tests depict contour-like lines, which can help in defining the SBS of unsaturated soil.

Keywords: Unsaturated soil, State Boundary Surface (SBS), Constant water content, Constant void ratio, Contours

1. INTRODUCTION

The soil near the surface of the earth ground is usually unsaturated by nature. The processes of excavation, compaction, and soil reshaping used in various civil engineering structures such as highways, earth fill dams, embankments, and runways result in unsaturated soils. There are only two phases in saturated soil which are soil and water, while for unsaturated soil, there are three phases: namely, soil, air, and water [1].

A novel approach to soil mechanics was developed in the 1950s and 1960s based on the concepts of the critical state. It establishes a framework for relating a saturated soil's shear distortion during yielding to its stress and volume condition [2]-[3]. For saturated soils, the critical state theory is a three-dimensional (3D) approach that is defined by three state variables: effective mean stress (p'), deviatoric stress (q), and specific volume (v). When the soil is sheared, it eventually reaches a critical state condition, located on a unique line in the p', q, and v space. This surface contains both sets of stress paths. This is known as the Roscoe surface or state boundary surface. All drained and un-drained stress paths appear to lie on a 3D surface for normally consolidated soil, bordered at the top by the critical state line (CSL) and at the bottom by the normal consolidation line (NCL). Another state boundary surface that connects to the Roscoe surface at the CSL is the Hvorslev surface. The significance of this surface is that a sample's shear strength is a function of the specific volume and the mean net stress (p'). Marto [4] and Moradi [5] demonstrated the Roscoe and Hvorslev surfaces using compression and extension triaxial tests on soil samples. The Roscoe-Hvorslev model, based on elastic-perfectly plastic behavior, was presented by Houlsby et al. [6].

The critical state framework for saturated soils is built around the concepts of the yielding and critical state. Sasitharan et al. [7] found that very loose saturated sand is loaded slowly under drained conditions and can collapse undrained following a specific stress path. It was observed that for a particular void ratio and consolidation stress, the post-peak component of an undrained stress path specifies the state boundary above which a stress state cannot exist. Several researchers have attempted to extend the critical state concept to unsaturated soils [8]-[14]. The mechanical behavior of unsaturated compacted soil has already been thoroughly researched [8], [15]-[20]. However, due to the complexity and time-consuming nature of testing unsaturated soils, there is a limited experimental study to determine the state boundary surface for unsaturated soils.

Estabragh and Javadi [21] performed controlled suction triaxial tests with constant confining pressure under drained conditions on samples of unsaturated compacted silty soil to investigate the existence and features of Roscoe and Hvorslev boundary surfaces for unsaturated soil. The findings reveal that the Roscoe and Hvorslev surfaces exist for unsaturated silty soil as well. With the increase and decrease of suction, the Roscoe surface expands and shrinks, while the Hvorslev surfaces are almost parallel for different suction values.

2. RESEARCH SIGNIFICANCE

This study presents experimental data from triaxial compression tests performed on samples of unsaturated compacted silty soil under constant volume and constant water content conditions. The findings are being utilized to investigate the existence, shape, and features of the state boundary surface (SBS) of unsaturated soil. To better understand the behavior of unsaturated soil, SBS can offer a qualitative framework. It can also serve as a guide for selecting the strength parameters to be utilized in traditional stability calculations [8].

3. EXPERIMENTAL PROGRAMME

The physical properties of soil, sample preparation, experimental setup, and procedure will be discussed in this part.

3.1 Soil Properties

The commercial term for the soil utilized in this study is DL Clay; it is fine soil with negligible plasticity. Freshly and freely deposited DL clay has a yellowish-brown color. According to the Japanese Geotechnical Society (JGS), it has Medium-Low compressibility (ML) and is made of 10% clay and 90% silt, indicating that the grain size is larger than ordinary clay. The grain size distribution of this soil is relatively uniform, with a mean grain size D50 of about 0.03 mm [22]. The physical properties of DL Clay are shown in Table 1.

Table 1 Physical Properties of DL Clay

Properties	Unit	Value
Density of soil particle, ρ_s	g/cm^3	2.635
Maximum dry density, ρ_{dmax}	g/cm^3	1.55
Optimum water content	%	20
Consistency	-	Non-Plastic

3.2 Sample Preparation

A static compaction machine with a hydraulic jack was used to prepare homogenous specimens by compacting the soil in 5 layers in a cylindrical mold having a diameter of 5cm, each layer being 2 cm thick [23]. The low energy of static compaction can provide a homogeneous density in the specimen, preventing the formation of a weaker zone [16]. Water was mixed with dry DL clay prior to compaction to make specimens at water contents of 20% and 25%, i.e., to the wet side of optimum water content. Specimens were compacted to degrees of compaction of 80%, 83%, and 86%. Specimens prepared with an 80% degree of compaction represent the loose state of soil with a void ratio of 1.13, an 83% degree of compaction represents the medium dense state of soil with a void ratio of 1.05, and an 86% degree of compaction represents the dense state of soil with a void ratio of 0.98.

Table 2 Specimen Properties

Properties	Value					
D_c (%)	80	80	83	83	86	86
ρ_d (g/cm^3)	1.24	1.24	1.29	1.29	1.33	1.33
w (%)	20	25	20	25	20	25
S_r (%)	46.2	57.8	49.5	62.6	53.6	67.5
e	1.13	1.13	1.05	1.05	0.98	0.98
Comp. Pressure (kPa) ≈	200	100	300	210	850	375

For specimens prepared with 80% and 83% degrees of compaction, the pressure exerted on the soil during sample preparation was less than the confining pressure during the test phase. Hence the samples are known to be normally consolidated. Similarly, for a sample compacted with 86% degree of compaction and 20% water content, the pressure exerted during sample preparation is higher than the applied stress during the test phase, so the sample is deemed slightly over-consolidated (OCR ≈ 2). All prepared specimens were 10 cm in height and 5 cm in diameter. The features of the specimens used in this study are shown in Table 2.

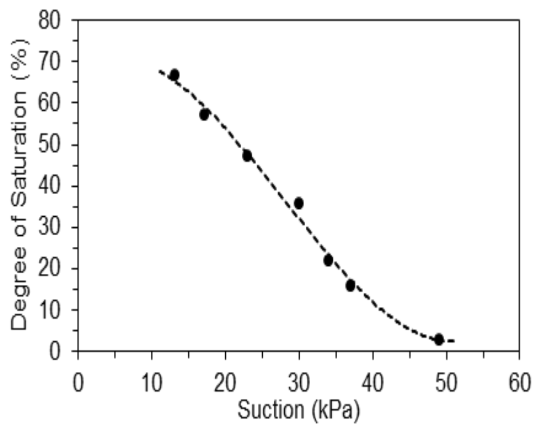


Fig. 1 SWCC for the studied soil [19]

Initial matric suction of soil samples prepared with 20% and 25% water content and degrees of compaction of 80%, 83%, and 86% were around 20kPa and 15kPa, respectively. This is consistent with the findings of Yang et al. [24], who found that compaction energy has a lower impact on soil suction in soils having a lower clay content. The soil-water characteristic curve (SWCC) represents the relationship between matric suction and water content. For determining the SWCC of DL-clay, the initial suction was measured for several specimens prepared with variable water content (or initial degree of saturation) after placing them on top of a saturated pedestal with a thin membrane filter. The results are shown in Fig. 1, indicating that the suction falls when the saturation ratio rises [23].

3.3 Experimental Setup

Figure 2 shows a schematic of the double-cell triaxial apparatus utilized in current research, which includes a pore water pressure transducer, pore air pressure transducer, cell pressure transducer, and loading system for exerting axial load. The device could measure both pore air and pore water pressures at the same time. The pore air pressure transducer is installed in the top cap and connected to an air regulator for continuous air supply to the specimen. A Low-Capacity Differential Pressure Transducer (LCDPT) measured the volume change in the soil sample as a function of the fluctuation in water level in the inner cell. In contrast, an external Linear Variable Displacement Transducer (LVDT) measured the vertical deformation of the specimens.

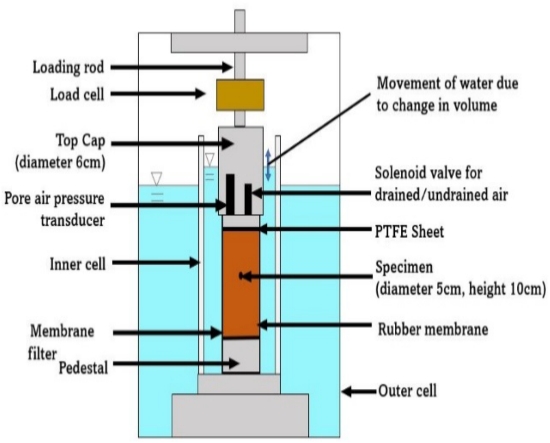


Fig. 2 Schematic of Double Cell Triaxial

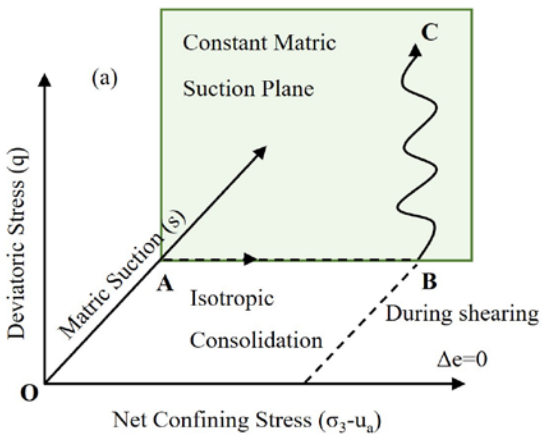
For effective control and measurement of pore water and pore air, a thin membrane "Supor 450" and a Polytetrafluoroethylene (PTFE) sheet were utilized. The thin membrane having a pore size of 0.45 µm, thickness of 140 µm, and air entry value of 250 kPa, was mounted on the bottom pedestal to allow water to flow while blocking the air passage [25]. The PTFE sheet was pasted to the bottom of the top cap to oppose the flow of water. A solenoid-controlled exhaust air valve was also fitted inside the top cap to reduce the volume of air in the pore air drainage line. A balance with an external load cell is also connected to the triaxial apparatus to measure the amount of water drained or infiltrated into the specimen.

3.4 Test Procedure

Before the start of each experiment, the bottom pedestal is fully saturated so that no air bubble remains inside the porous stone of the pedestal. During the testing, de-aired water was utilized to reduce inaccuracies caused by air entrapment in the soil. The water in the external upper and lower tanks was de-aired for at least 24 hours by applying vacuum pressure using the suction pump.

After the specimen preparation, the sample was wrapped in a rubber membrane using a membrane holder and placed over the pedestal with a thin membrane to note the value of the initial suction. The Axis translation technique (ATT) was carried out after measuring the initial suction and setting all necessary connections. The primary purpose of ATT was to prevent the formation of cavities or voids inside the pedestal, which would ultimately influence the reading of pore-water pressure. To make the pore water pressure zero, the confining pressure and pore air pressure increased simultaneously, leaving the specimen volume unaltered [26]. During ATT, volumetric strain should theoretically be zero.

Following ATT, the specimen was isotropically consolidated by applying the required net confining pressure of 500kPa, to get the sample to the desired state before the start of shearing. To dissipate the excess pore water pressure, the drain valve was opened throughout the consolidation. The axial stress was automatically controlled by the load control system to keep deviatoric stress (q) equal to zero. The test phases and stress path followed during the current research are illustrated in Fig. 3.



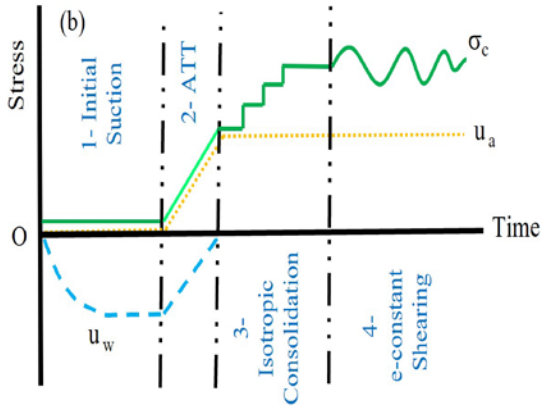


Fig. 3 (a) Stress path followed in constant void ratio test: (b) Test phases involved.

The soil specimens were sheared with a constant void ratio (constant volume) at a strain rate of 0.05 mm/min under constant water content conditions by keeping the drainage valve for pore water pressure closed. In contrast, the pore air pressure was constantly drained and controlled. The constant water content test simulates the state of compacted soil in an embankment or slope. The sample volume was maintained constant by varying the confining pressure in response to the specimen's volume change (i.e., reading of the LCDPT value). According to the standards of the Japan Geotechnical Society, the shearing phase was automatically stopped when the axial strain reached 15% [27].

4. TEST RESULTS

The initial matric suction significantly impacts the mechanical behavior of unsaturated soils. It can be seen from Fig. 4 that the specimen prepared with 20% and 25% water contents have different values of initial matric suction.

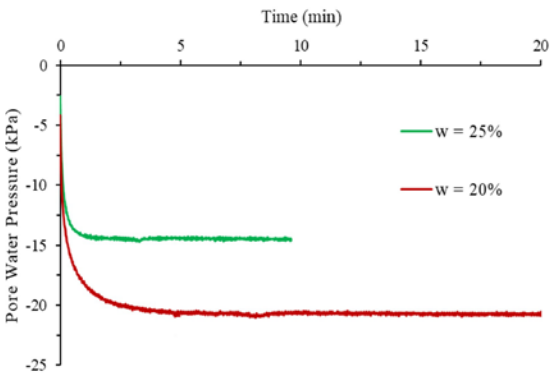


Fig. 4 Variation in initial matric suction over time.

The matric suction is high for samples with lower water content, and it takes more time to stabilize the matric suction than for samples with high water content. The sample was sheared at a rate of 0.05% per minute up to an axial strain of 15%. The shearing was performed under constant water conditions, i.e., the water drain valve was closed while the air drain valve was open. As the samples were to be sheared with a constant void ratio or zero volumetric strain, the cell pressure increased or decreased correspondingly to the LCDPT value to keep the sample void ratio constant.

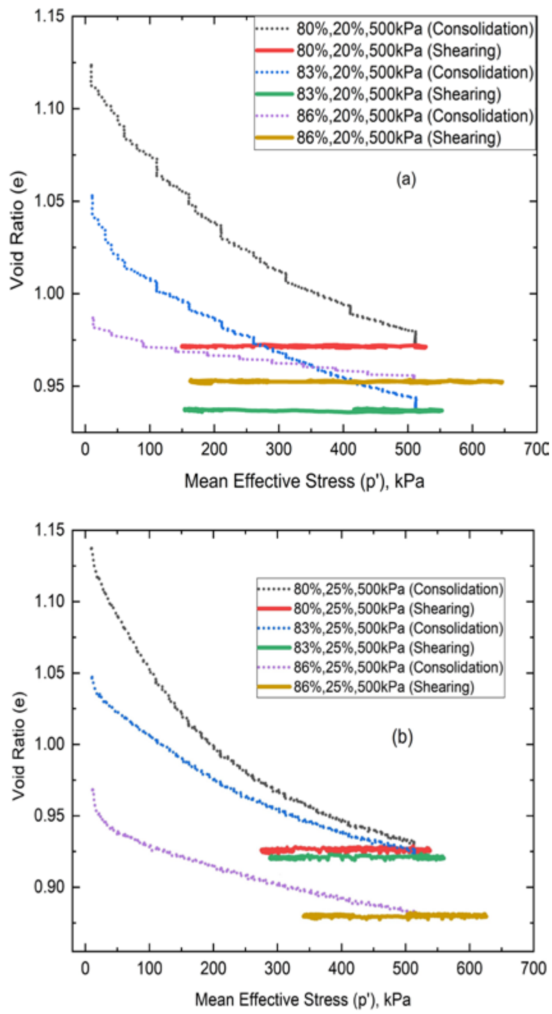


Fig. 5 Void ratio Vs. Mean effective stress for samples prepared with (a) 20% water content (b) 25% water content.

Figure 5 shows the void ratio against mean effective stress during consolidation and shearing for samples prepared with 20% and 25% water content. It can be observed from Fig. 5 that as the degree of compaction increases from 80% to 86%, the decrease in void ratio becomes less during the consolidation for both 20% and 25% water content samples. Similarly, for samples with the same degree of compaction (e.g., 80%, 83%, or 86%), the decrease in void ratio during consolidation is slightly smaller for samples with 20% water content than the samples with 25% water content. The void ratio is kept constant throughout the shearing.

It can be seen from Fig. 6 that the peak deviatoric stress was slightly more toward the optimum moisture content than the wet side of the optimum moisture content. This is because of matric suction in unsaturated soil. When the water content in a specimen increases, the deviatoric stress decrease accordingly. When there is less water content, water will not be sufficient to act as a lubricant between soil particles so they can slide and reorient when stress is increased. Hence, the internal friction between soil particles increases, increasing the deviatoric stress. Also, the deviatoric stress is more for samples prepared with a high degree of compaction.

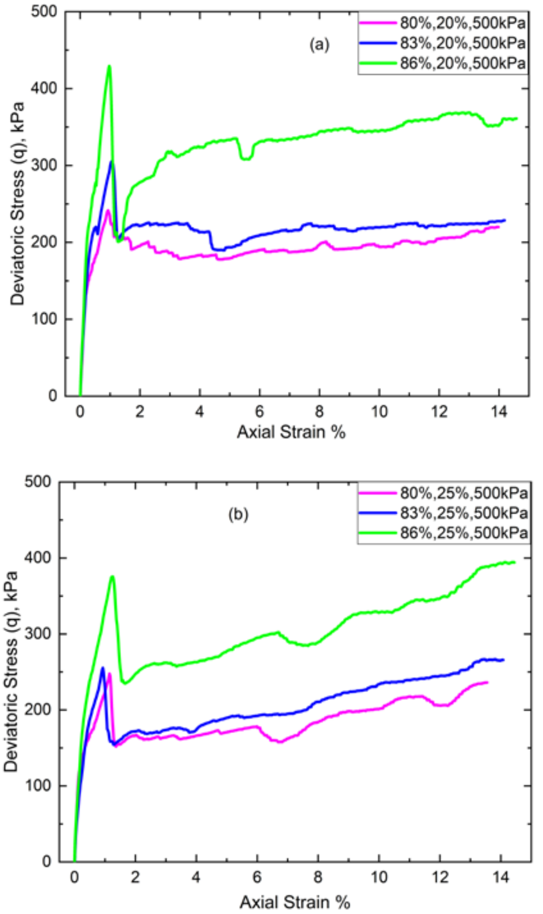


Fig. 6 Deviatoric stress during shearing for samples prepared with (a) 20% water content (b) 25% water content

The effective stress plotted against the axial strain is shown in Fig. 7. The effective stress value is more for dense samples than the semi-dense and loose samples. It can be noted from Fig. 7 that there is some unusual behavior for the axial strain range of 0-2%. The effective stress initially increases slightly, followed by a sudden decrease, then increases and decreases continuously until the specimen reaches the critical state.

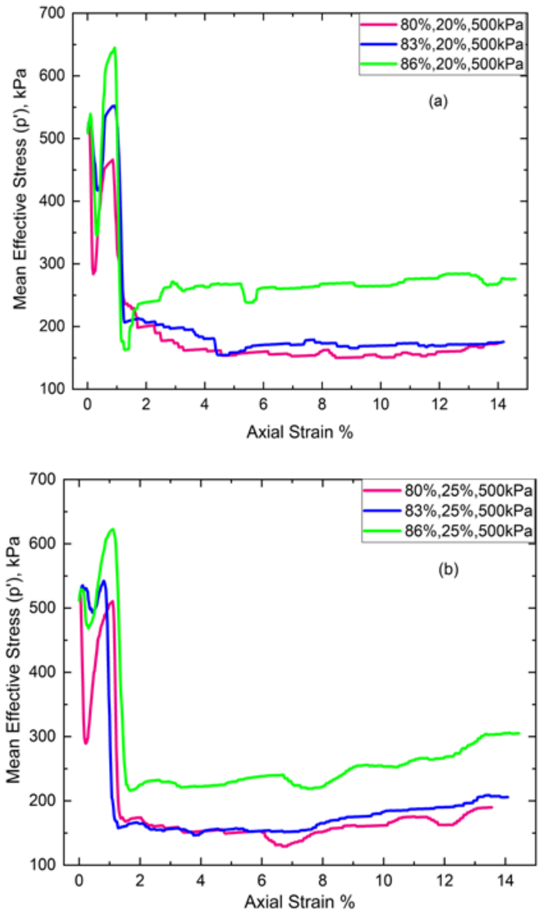
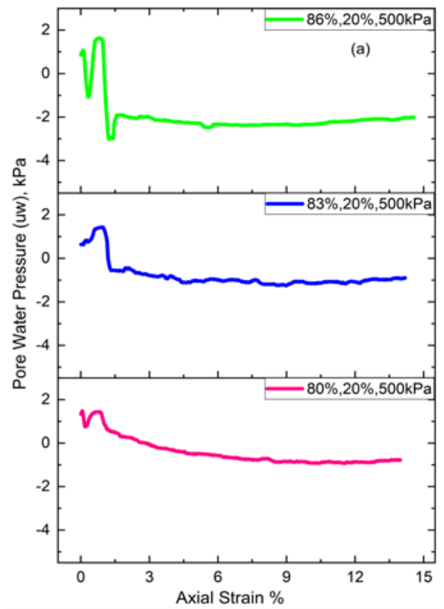


Fig. 7 Mean effective stress during shearing for samples prepared with (a) 20% water content (b) 25% water content.



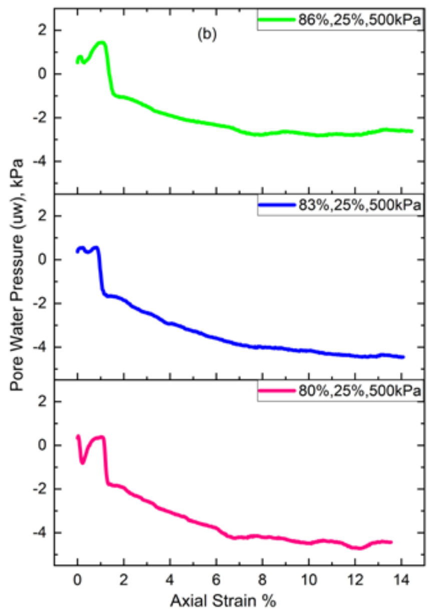


Fig. 8 Pore water pressure during shearing for samples prepared with (a) 20% water content (b) 25% water content

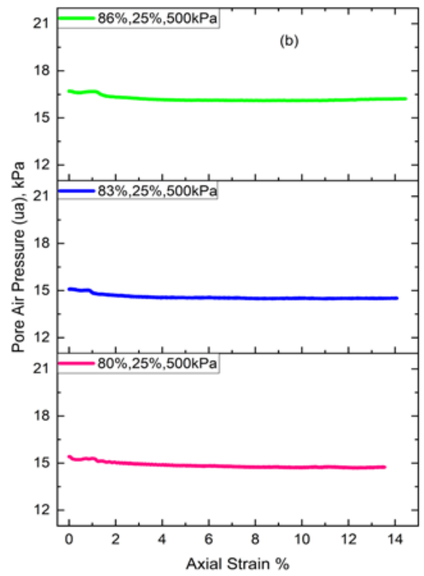
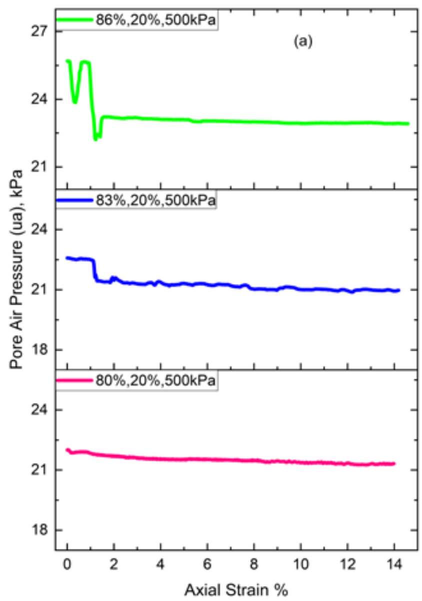


Fig. 9 Pore air pressure during shearing for samples prepared with (a) 20% water content (b) 25% water content

This phenomenon may be due to the sudden loading impact under a high cell confining pressure of 500 kPa during shearing. This may cause the soil particles held together by suction to collapse suddenly to fill in the gaps and reorient. Both pore water and pore air pressure decreased throughout the shearing phase, as illustrated in Fig. 8 and Fig. 9, respectively. However, the decrease in pore water pressure was more than the pore air pressure. As a result, the matric suction also increased slightly. The degree of saturation of samples did not alter throughout shearing as the water drainage valve was closed, and the tests were performed with a constant void ratio.



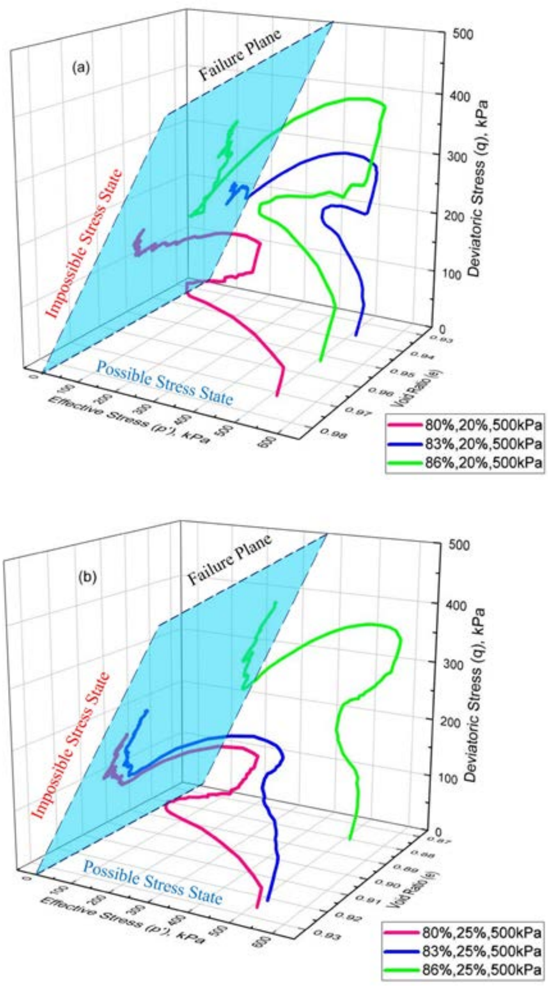


Fig. 10 State Boundary Surface for samples prepared with (a) 20% water content (b) 25% water content tested

The void ratio (e), net mean effective stress (p'), and deviator stress (q) are plotted in a 3D space, as shown in Fig. 10. All the stress paths lie on the same failure plane that shapes the state boundary surface. SBS separates the possible and impossible stress states. It can be observed that the constant void ratio test provides contour-like lines that help in identifying the shape of the state boundary surface. With an increase in matric suction, the SBS extends outwards.

5. CONCLUSIONS

A series of laboratory element tests were carried out to investigate the state boundary surface of unsaturated soil under a constant void ratio and constant water content conditions. It was found that for soil samples with higher water content, initial suction values stabilize in a shorter time interval, while lower water content soil samples take longer to stabilize. The soil samples prepared at optimum water content show higher shear strength than those prepared at the wet side of optimum water content. Also, the shear strength of soil increased with an increase in the degree of compaction. The effective stress increased and decreased multiple times within the axial strain range of 0-2%. The matric suction of samples slightly increased during shearing due to reduced pore water pressure. The SBS was set up by contour-like lines obtained with constant void ratio tests, which separate the possible and impossible stress states.

6. ACKNOWLEDGEMENTS

The Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) is gratefully acknowledged for research facilities and financial assistance.

7. REFERENCES

[1] Fredlund D. G., and Rahardjo H., Soil Mechanics for Unsaturated Soils. New York: John Wiley and Sons Inc., Soil Dynamics and Earthquake Engineering, Vol. 12, No. 7, 1993, pp. 449–450.

[2] Roscoe K. H., Schofield A. W., and Worth C. P., On the yielding of soils. Géotechnique, Vol. 8, No. 1, 1958, pp. 22-53.

[3] Schofield A. W., and Worth C. P., Critical State Soil Mechanics. Engineer, Vol. 16, No. 3-4, 1968, pp. 53-66.

[4] Marto A., Volumetric compression of a silt under periodic loading. Ph.D. thesis, Univ. of Bradford, Bradford, U.K, 1996.

[5] Moradi G., Symmetric and non-symmetrical cyclic triaxial loading of silt. Ph.D. thesis, Univ. of Bradford, Bradford, U.K, 1998.

[6] Houlsby G. T., Wroth C. P., and Wood D. M., Predictions of the results of laboratory test on a clay using a critical state model. Proc., Int. Workshop on Constitutive Behavior of Soil, Balkema, Rotterdam, Netherlands, 1982, pp. 99–121.

[7] Sasitharan S., Robertson P. K., Sego D., and Morgenstern N.R., Collapse behavior of sand. Canadian Geotechnical Journal. Vol. 30, No. 4, 1993, pp. 569-577.

[8] Wheeler S. J., and Sivakumar V., An Elasto-Plastic Critical State Framework for Unsaturated Soil. Geotechnique, Vol. 45, No. 1, 1995, pp. 35-53.

[9] Maâtouk A., Leroueil S., and La Rochelle P., Yielding and critical state of a collapsible unsaturated silty soil. Géotechnique, Vol. 45, No. 3, 1995, pp. 465-477.

[10] Loret B., and Khalili N., An effective stress elasto-plastic model for unsaturated porous media. Mech. Mater., Vol. 34, No. 2002, pp. 97-116.

[11] Toll D. G., and Ong B. H., Critical-State Parameters for an Unsaturated Residual Sandy Clay. Géotechnique, Vol. 53, No. 1, 2003, pp. 93-103.

[12] Tarantino A., A possible critical state framework for unsaturated compacted soils." Géotechnique, Vol. 57, No. 4, 2007, pp. 385-389.

[13] Estabragh A. R., and Javadi A. A., Critical State for Over-consolidated Unsaturated Silty Soil. Canadian Geotechnical Journal, Vol. 45, No. 3, 2008, pp. 408-420.

[14] Liu K., Yin J. H., Chen W. B., Feng W. Q., and Zhou C., The stress–strain behaviour and critical state parameters of an unsaturated granular fill material under different suctions. Acta Geotechnica, Vol. 15, No. 12, 2020, pp. 3383-3398.

[15] Cui Y. J., and Delage P., Yielding and plastic behaviour of an unsaturated compacted silt. Géotechnique, Vol. 46, No. 2, 1996, pp. 291-311.

[16] Jotisankasa A., Coop M., and Ridley A., The mechanical behavior of an unsaturated compacted silty clay. Géotechnique, Vol. 59, No. 5, 2009, pp. 415-428.

[17] Melinda F., Rahardjo H., Ha K. K., and Leong E. C., Shear strength of compacted soil under infiltration conditions, Journal of Geotechnical Eng. Div. ASCE, Vol. 130, No. 8, 2004, pp. 807–817.

[18] Pujiastuti H., Rifa A., Adi A. D., and Fathani T. F., The effect of matric suction on the shear strength of unsaturated sandy clay. International Journal of GEOMATE, Vol. 14, No. 42, 2018, pp.112-119.

[19] Rasool A.M., and Kuwano J., Effect of wetting stress paths on mechanical behavior and instability of unsaturated soil in stress state space. European Journal of Environmental and Civil Engineering, 2022, pp.1-20.
[20] Maleki M., and Bayat M., Experimental evaluation of mechanical behavior of unsaturated silty sand under constant water content condition. Engineering Geology, 2012, Vol. 141-142, pp. 45-56.
[21] Estabragh A. R., and Javadi A. A., Roscoe and Hvorslev Surfaces for Unsaturated Silty Soil. International Journal of Geomechanics, Vol. 14, No. 2, 2014, pp. 230-238.
[22] Chae J., Kim B., Park S. W., and Kato S., Effect of suction on unconfined compressive strength in partly saturated soils. KSCE Journal of Civil Engineering, Vol. 14, No. 3, 2010, pp. 281-290.
[23] Rasool A. M., and Kuwano J., Influence of matric suction on instability of unsaturated silty soil in unconfined conditions. International Journal of GEOMATE, Vol. 14, No. 42, 2018, pp. 1–7.
[24] Yang S. R., Lin H. D., and Huang W. H., Variation of initial soil suction with compaction conditions for clayey soils. Journal of Mechanics, Vol. 28, No. 3, 2012, pp. 431-437.
[25] Habasimbi P., Nishimura T., Soil water characteristic curve of an unsaturated soil under low matric suction ranges and different stress conditions. International Journal of Geosciences, Vol. 10, No. 1, 2019, pp. 39-56.
[26] Hilf J. W., “An investigation of pore water pressure in compacted cohesive soils” U.S. Department of Interior Bureau Reclamation Technical Memo. no. 654, 1956.
[27] Japanese Geotechnical Society, Method for triaxial compression test on unsaturated soils. JGS 0527–2020.