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Research Article

Experimental Measurement of Creep Deformations of an Unsaturated Silty Soil with Matric Suction

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Abstract

Geotechnical engineers often encourage geological disaster in ground related to saturated soil and unsaturated soil. Landslide, settlement and slope failure related to creep phenomena are typical problems in geotechnical practices. Creep behavior of saturated soils can explain including time-dependent on effective stress of saturated soil by Terzaghi effective stress theory. Some papers already published to apply the practice problems related soft ground settlements. Landslide in unsaturated conditions was induced by changing of matric suction as one stress of unsaturated soil stress variables, and some experimental researchers have reported interesting test results and effectively models for unsaturated soil creeping deformations. This study conducted out unsaturated soil creep test, which suction controlling has a low range with two lateral confining pressures using revised unsaturated triaxial compression apparatus. Solving the practical problems regard to unsaturated soils consider the properties of unsaturated soil that are subjected to creep before occurrence instability of natural slope. Excess pore-water pressures were measured and evaluated matric suction in unsaturated creep test using pressure membrane technique that creep stress increased step by step till unsaturated soil was failure. Comparison failure condition obtained from conventional triaxial compression test under undrained condition and mean effective principal stresses against creep stress. It was found out mean effective principal stress reached to failure line. In addition, soil-water characteristic curve was investigated in order to interpret hydro-mechanical properties and relationship between unconfined compressive strength and matric suction was obviously useful that shear resistance of unsaturated soil depend on matric suction.

Keywords: *Creep Test; SWCC Test; Unconfined Compressive Strength; Suction; Unsaturated Soils; Pore-Water Pressure; Stress Path*

Introduction

Geotechnical engineers often encourage geological disaster in ground related to saturated soil and unsaturated soil. Landslide, settlement and slope failure are typical problems in geotechnical practices [1-4]. Landslide and deformation of embankment are majority geological disaster which are induced by rainfall events [5] emphases that the triggering phase of slope failure phenomena is often related to rainfall events which significantly increment of soil moisture in the shallower soil layers. It can seemed that increment of soil moisture leads reduction of matric suction because matric suction contributes to maintain shear strength resistance on contact plane soil particle together. Matric suction attribute formulated meniscus due to water tension force (Graton and Fraser, 1935, put reference). Graton and Fraser, (1935) reported that geometry of the inter sphere voids revised lar attention as affecting fluid flow through void structure; and described plentiful graphs of the surprisingly complex void sections. Gvirtzman and Roberts (1991) evaluated capillary model using a matric suction associated meniscus curvature in several size soil particles.

Few studies have been presented in unsaturated soil creep behavior for experimental researches and establishing prediction mathematical models in limitation previous works as follow. Lai., *et al*. (2014) [6] considered the long-term deformation of landslides with the influence of water content variation, a series of unsaturated triaxial creep tests with suction control was conducted on clay specimens taken from one large-scale landslide in the Three Gorges Reservoir area in China. For theoretical analysis, Lai., *et al*. (2014) [6] indicated that, in the double-logarithmic coordinates, the axial strain increases linearly and the axial strain rate decreased linearly with the elapsed time. In addition, the axial strain and strain rate increase with increasing deviator stress level and decreasing matric suction. Then, suction effects were developed in a revised model, a power function was adopted for the description of the strain–time relationship with a hyperbolic function. Miaojun., *et al*. (2016) [7] conducted out that a series of triaxial drained creep tests used specimens on the slip band soil from a creep landslide, making a description that the creep properties of slip zone soil were critical to deformation prediction and slope stability analysis. Liangchao., *et al*. (2013) [8] developed based on conventional triaxial creep apparatus and unsaturated triaxial apparatus. A revised Burgers creep model for unsaturated soils in triaixial state was constructed for analyze between parameters of the model and matric suction in unsaturated soils. Used apparatus consisted of loading system and air pressure controlling system that was capable of applying constant shear stress and constant air pressure. Controlling suction had a range from 50 kPa to 250 kPa with lateral confining pressure of 100 kPa, and ratio of identified deviator stress to deviator stress at failure was 0.55 in constant. Liangchao., *et al*. (2013) [8] exhibited under some matrix suctions that simulated results were in good agreement with the experimental results.

The shear strength behavior of unsaturated soil subjected to creep stress is considered to reflect two stress variables, such as net normal stress and matric suction. Bishop's equation [9] for the effective stress of unsaturated soil, which has been accepted in the research field of geotechnical mechanics and uses two stress variables a component [10]. Matric suction can be described as scalar, which is useful to be explanation, establishments of safety factors and development of mathematical simulations. Experimental tests for unsaturated soil commonly remained matric suction. Matric suction was then defined as the difference between pore-air pressure and pore-water pressure, and it is a component of a significant stress variable for the interpretation of unsaturated soil properties in geotechnical problems associated to the evaluation of stability of unsaturated ground.

Many effective mathematical simulation models contributed the prediction of hydro-mechanics properties for unsaturated soils. Rainfall event is correct that one of hydro-mechanical properties recognized to refer prevent slope failure. Soil-water characteristic curves are addressed as significant properties on presenting unsaturated soil mechanics which is defined relationship between suction and parameters such as water content, degree of saturation and volumetric water content. The abbreviated notation of SWCC related to geotechnical engineering research fields, and it was necessitated by the consideration of the properties of unsaturated-saturated coupling. Incidentally, it is representative of unsaturated stress-strain properties that SWCC was effort in simulating effective stresses for unsaturated soil as two stress state variables such as matric suction and net normal stress.

Essentially, soil creep [11] caused by intense rainfall or changing of water level in ground results in a reduction of matric suction by increasing excess pore-water pressure. This creep behavior should be measured with pore-water pressure through experimental tests, as it is possible to evaluate the change in matric suction using a pressure plate technique. Though the influence of excess pore-water pressures in fully saturated soils have been investigated on experimental works for decades. Other hand, it is significant in practice for shear strength and deformation of unsaturated soil comparison with saturated soil strength-deformation properties. The shear strength properties of unsaturated soils subjected creep stress are related to some factors such as matric suction, degree of saturation, void ratio and deterioration. Because deterioration of soil causes degrade of continue reduction of matric suction that these factors are of significant concern. On experimental works, unsaturated soil creep behavior leading large deformation was in equilibrium to defined external loading with a long time, and unsaturated soil conventional triaxial apparatus have been revised, and conducted out in order to establish mathematical model parameters regards to time-dependent. It is often required that definition of critical failure line [12,13] realized to interpret creep behavior of unsaturated soils on yield surface coordinate comparison with saturated critical yield surface. It is importance to develop constitutive models of unsaturated soils creep behavior involved time-dependent. The situation requires that many experimental test results should be report in unsaturated creep properties.

Purpose of the Study

This study focused on the shear strength of unsaturated soil subjected to creep stress leading to large deformation (i.e. leading large reduction of matric suction). Solving the practical problems mentioned above requires considering the properties of unsaturated soil that are subjection to creep progress before occurrence instability of earth structure such as natural slope, embankment, excavation slope, dike. At present some experimental researchers have reported creep deformation properties or model as playing a significant role in prediction of landslide stability [14-19]. The sliding zone are basically in unsaturated state having some matric suction at relatively shallow depth from ground surface. Natural fluctuations such as rainfall and infiltration often applied mechanical damages in unsaturated soils. In addition, deformation processes usually take a long period of time, describing that time-dependent properties occupied variations effective stress due to be capable of fluid pressures.

Hydro-mechanical properties such as stress and strain behavior has obviously included creep behavior, evolutions of creep model are developed based on creep test data sets. Few appropriate data sets obtained from unsaturated creep test realize good reflection between experimental works and consideration of mathematical creep model. Moreover, to investigate creep behavior of unsaturated soils subjected to lateral confining pressure contributes for interpret practice problems such as settlement and slope failure of unsaturated soil ground is necessary to revise conventional triaxial compression test apparatus, establishing that measurement of suction produce under some creep stresses.

This study conducted out mainly unsaturated soil creep test, which suction controlling has a low range with two lateral confining pressures using unsaturated triaxial compression apparatus. Measured deformations were of both total volume and axial strain inner cell. Micro-porous membrane was used on pressure membrane method as one of pressure techniques under standard suction controlling methods. It was avoided time consuming associated with soil moisture movement due to low matric suction controlling process. Previously, soil-water retention test results verified soil-water characteristic curve through drying process and wetting process that hydro-mechanical properties of unsaturated soil are refereed sufficiently. Change of degree of saturation with increment and decrement in matric suction was measured. Then, it is accepted that shear resistance of unsaturated soil belongs to suction, and suction was measured during unconfined compression test for two different water content at same dry density. This testing program consisted of a creep test and a static triaxial compression test under undrained condition for measurement of changing of matric suction. A silty soil was used that a soil-water characteristic curve (SWCC) [20] was appeared prior to the creep tests using a pressure membrane technique. To interpret the relationship between matric suction and the degree of saturation is useful to understand experimental results from creep test. Particularly, a low suction range of soil structure contribute relatively into hydro-mechanical phenomena, indicating reduction shear resistances, large deformations and reduction of strength parameters in defined failure envelope criteria such as Mohr- column failure. Creep force was applied under various lateral confining pressures, and measurement of suction indicated a gradual growth of excess pore-water pressure. Moreover, this study performed a triaxial compression test under the undrained condition for apparent saturated soil. Also, shear strength of unsaturated soil subjected to creep stress was interpreted with both deformation behavior and changing of suction.

Materials and Methods

Soil material

This test program used silty soil with a relatively uniform grain size distribution, which maximum soil particle size was 2.0 mm. The silty soil notated as DL-clay had a fine content (particles smaller than 0.075 mm in diameter) of 99.0% by absolutely dry weight. Liquid limit is close to plastic limit in consistency properties that it was evaluated as non-plastic. DL-clay described a relatively high coefficient of permeability similar to clean sands. The soil material had an optimum water content of 17.0% and maximum dry density of 1.530 g/cm^3 as obtained from the Proctor compaction test following in JIS A 1210 code by Japanese geotechnical Society. Compaction process performed in five layers with 25 dumplings for each layer. The material used in this study has also been investigated often to unsaturated soil hydro-mechanical properties researches such as shear strength, measurement of SWCCs, volume change properties, seepage properties and establishing factors to constitutive model [21,22].

This testing program consist of unsaturated creep test, soil water characteristic curve test (SWCC test) and unconfined compression test with measuring matric suction, using DL-clay with different specimen sizes. Static compaction was performed in steal mold in order to making specimen which lateral surface of steal mold was covered by special coat assessing elimination of friction forces between steal surface and soil particles. All of specimens had at compaction condition which water content was 10.0%, dry density was 1.387 g/cm^3, void ratio was 0.911 and degree of saturation was 29.0% as physical properties. Size of specimen was a height of 100 mm and a diameter of 50 mm for creep test and unconfined compression test. Each a height of 20 mm and a diameter of 60 mm was limitation in only soil-water characteristic curve test.

Testing apparatus used in this study

This unsaturated creep test used a modified unsaturated soil triaxial compression apparatus which had double cell for both creep test. Many unsaturated soil mechanics researchers already referred the unsaturated soil triaxial compression apparatus established by some researcher [23-29], and some apparatus had been revised for considering influence of suction on unsaturated soil shear strength properties and finding parameters in constitutive yield surface [30]. Particularly, it is most importance points that measuring or controlling of suction is possible to unsaturated soils during triaxial test. Measured suction is evaluated based on either pressure plate technique or pressure membrane technique [29,31], and high air entry disc [32] or micro porous membrane are installed into a pedestal in triaxial basement. Corresponding to apply high suction (i.e. more than suction of 1.0 MPa), vapor pressure technique [33] is accurate due to salt solutions which verified relationship between suction and relative humidity.

Suction mean sum of osmotic suction and chemical suction is called as total suction. It was quite difference between pressure technique and vapor pressure technique regard to define measured suction. Pressure technique using either high air entry disc or micro porous membrane available in correct to a range including transition zone and transition zone in whole soil-water characteristic curve. Beyond residual suction as one component of verifying soil-water characteristic curve, vapor pressure technique often has been performed to indicate change of degree of saturation with considering soil moisture changes.

As above mentioned, the micro-porous membrane often useful to measure pore-water pressure of unsaturated soil specimen similar to taking high air-entry disc, and preparing of micro porous membrane was installed into pedestal. On measurement of negative pore-water pressure of unsaturated soil, ceramic disk (i.e. high air entry disc) was generally employed in conventional. Micro porous membrane having some air entry values was installed into pedestal in the apparatus instead of the ceramic disk. Nishimura*., et al*. (2012) [29] developed a pedestal for pressure membrane method and mentioned advantage of micro porous membrane on SWCC data sets. The micro porous membrane contributed to measure low matric suction (i.e. less than 20 kPa) and many experimental reports referred the role and effort in unsaturated soil experimental testing. The microporous membrane was used in this study was manufactured by Pall Corporation that material was made in Polyether sulfone [34]. Summaries of basic physical properties were as following; thickness of 140 mm, air entry value of 250 kPa and pore diameter of 0.0145 mm. The membrane had a role of measurement of positive and negative pore-water for all series of testing programs required in this study.

Volume change of unsaturated soils in creep testing was measured indirectly using a difference voltage sensor under loaded cell pressure. Previous, relationship between voltage data measured by sensor and mount of volume of water in inner cell was established as calibration working with correctly. Coefficient of calibration was determined at linear relationship.

Testing programs in this study

This testing programs was mainly divided into three stages, which are as follows. Unsaturated creep test is that lateral confining pressure was applied. The soil water characteristic curve test using pressure plate technique is of drying process and wetting process. Unconfined compression test is that matric suction is measured while compression process.

The challenge for experimental is how to verify the creep behavior of unsaturated soil in changing of suction and different lateral confining pressures. Two lateral confining pressures were applied into cell, which are 10 kPa and 400 kPa. First, creep test under lateral confining pressure of 10 kPa was conducted out that an unsaturated soil specimen was placed on the pedestal installed saturated micro-porous membrane. Beyond whole triaxial apparatus was set up, applications of creep stress and lateral confining pressure of 10 kPa performed accomplishing with measurement of negative pore-water pressure and volume change. Increment of creep stress remained step by step till axial strain was over 16%. It can be observed changing of suction in a long time period.

Creep test with lateral confining pressure of 400 kPa was produced as below. Before applying matric suction of 20kPa an unsaturated soil specimen was swelled due to injection of distilled water from pedestal, which can be define a deletion of initial matric suction of unsaturated soil specimen. Identified matric suction of 20 kPa was applied using pressure membrane technique after further water seepage throughout was supplied. Injection of air pressure from upper portion of specimen was remained till the equilibrium was recorded, the meaning that changing of either adsorption or drains can be negligible. Therefore, a matric suction of 20 kPa was applied before increment of creep stress to obtained excess pore-water pressure under undrained conditions. To study the effect of creep stress on suction and deformation including whole volume deformation, measurement of excess pore-water pressure and volume change were measured a period of long time.

The soil water characteristic curve test was conducted out using SWCC test apparatus. SWCC apparatus was used which was revised conventional oedometer apparatus. The micro-porous membrane was installed into basement of SWCC apparatus was installed which had an air entry value of 200 kPa. Double glass burette was connected to water compartment system that changing of soil moisture is able to measure through absorption and draining from soil specimen. A difference voltage sensor was installed at bottom of the double glass burette, and variations of soil moisture induced by suction effort was made sure with elapsed time in voltage value. Compacted soil specimen had a dimeter of 60 mm and a thickness of 20 mm, which was swelled due to supplying distilled water under constant volume (i.e. maintaining initial volume) in order to deliration of initial matric suction. Physical properties such as compaction water content, dry density and degree of saturation are same with that of specimen prepared for creep test.

The first step is a drying process experiment for swelled specimen that low air pressure was applied into cell. Soil moisture moved out throughout micro-porous membrane corresponding to air pressure. When the equilibrium was confirmed (i.e. changing of draining water was negligible), increment of air pressure processed. 20 kPa was nearly maximum applying air pressure in drying process test. After drying process controlling suction was decreased for adsorption performance, and decreasing of water in double glass burette was measured. Negligible obviously was recognized to changing water that evaluated as equilibrium. The end of test was, when suction was close to zero.

Unconfined compression test conducted out using the creep triaxial test, which was able to measure matric suction while pore-air pressure was equilibrium with atmospheric condition. It was that negative ore-water pressures were only measured throughout micro porous membrane. All specimens for unconfined compression test had a dry density of 1.387 g/cm^3 and void ratio of 0.911 with two different compaction water contents (i.e. 10% and 17%). Unconfined compression test was that deviator stress was applied without lateral pressure. Particularly, negative pore-water pressure was measured for determination of matric suction at compression process. Two different specimens were prepared with different water contents at constant dry density. Used all of soil specimens had a diameter of 50.0 mm and a height of 100.0 mm. Compression forces were applied till either finding maximum deviator stress or reached to axial strain of 8.0% over under compression speed was 1.0%.

Results and Discussion

Soil-water characteristic curve

Figure 1 shows a soil-water characteristic curve, which consists of changes of soil moisture in soil specimen with zero suction at initial condition against the application of suction. A rage of controlling matric suction was from zero kPa to 18 kPa that was relative low suction rages. Determined soil-water characteristic curve involved a drying process and a wetting process due to increasing and decreasing in matric suction until suction reached 18 kPa which was measured under vertical stress of 100 kPa using a revised oedometer type apparatus. Pressure membrane method in axial translation technique was used that changing of degree of saturation was verified in the drying and wetting process. Specimen was less than 100% in degree of saturation at beginning of SWCC test that initial matric suction was possible to assume zero kPa because enough swelled process was treated in SWCC apparatus. Increment of suction gradually applied that it was due to increment of air pressure at remaining atmospheric in pore water. Degree of saturation decrease due to increment of suction that drainage of soil moisture significant effort in shrinkage of void structure associated to close soil particle together [35]. Then, it was obviously to occurre large reduction of degree of saturation over suction was 4.0 kPa, beyond suction of 7.0 kPa degree of saturation was steady, indicating around 73% at constant till suction of 18 kPa. Within wetting process (i.e., allowing adsorption of water), degree of saturation was similar with degree of saturation at suction of 18 kPa down to 7 kPa. While suction was less than 7.0 kPa, adsorption of water slightly increased according to reduce suction. It was however to not reach to initial degree of saturation of specimen that was less than 89.3%. Thus, it can be observed that all data sets regard to degree of saturation for drying process was indicated upper portion compare to wetting process data sets in relationship between suction and degree of saturation coordinate space. In fact, defined two soil water characteristic curves under both suction increment and decrement d, finding that the hysteresis was presented in typically hydro-mechanical properties related to unsaturated soil mechanics [36]. It can be explained that the behavior of material used in

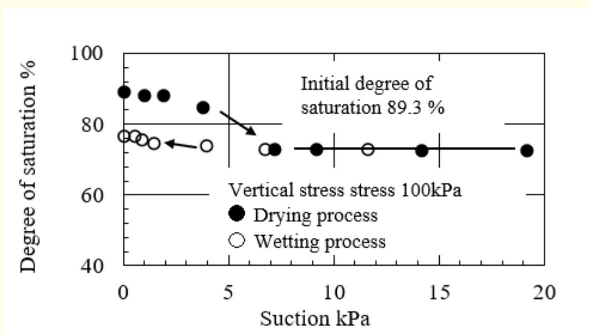

Figure 1: Soil-water characteristic curve.

this creep test associated to suction effort.

Unconfined compressive strength with matric suction

It is one important factor to interpret mechanical properties of unsaturated soils [37,38] that unconfined compressive strength was obtained in this study. As above mentioned (Section 3.2), negative pore-water pressures were measured using pressure membrane technique through compression process. Assuming was that the pore-air pressure was atmospheric, changing of suction can be obtained in conventional. In this case, during compression process deviator forces were measured without lateral confining pressure for two compaction water contents (i.e. 10% and 17%). Figure 2 and 3 showed stress strain curves and suction variations compression durations. As far as, two stress strain curves, the influence of compaction water content on initial suction (i.e. suction before loading compression) was obviously that suction at water content of 10% was larger than that of 17%. It was agreement that suction of compacted soil described high suction according to decrement compaction of water content [39]. Initial suction of water content of 10% was 21.5 kPa (Figure 2), and suction slowly increased with commencement of compression. When maximum deviator stress was described as 55.4 kPa, the suction was 24.5 kPa. It was slightly increment compare to initial suction. Beyond maximum deviator compression stress slight suction increment maintained up to end of test, and maximum suction was 31.8 kPa that increment of suc-

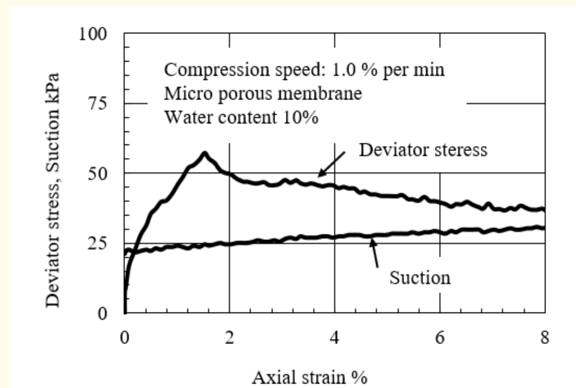

Figure 2: Stress-strain curve and suction variation on unconfined compression test for water content of 10%.

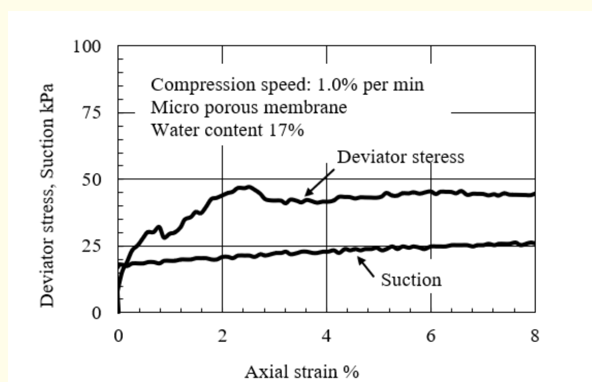

Figure 3: Stress-strain curve and suction variation on unconfined compression test for water content of 17%.

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tion due to compression was nearly 10 kPa.

Other hands, initial suction of 17.6 kPa was measured in case of water content of 17% (Figure 3) that initial suction depend on compaction water content with comparison to that of water content of 10%. Deviator stress was increased gradually with axial strain, and maximum deviator stress was indicated as 46.7 kPa at axial strain of 2.6%. Observing was that suction increased with a growing of deviator stress. After failure, further reduction was seen that constant deviator stress was remained beyond axial strain was 4.0% (i.e. under residual condition). Determined suction at end of test was 26.4 kPa. Thus, it was recognized in two test result limitations that suction increased unconfined compression duration regardless of compaction water content.

Test results

Creep properties of an unsaturated soils under lateral confining pressure of 10 kPa

Unsaturated creep test was conducted out that lateral confining pressure of 10 kPa was applied to specimen with compaction water content of 10%. In a series of lateral confining pressure of 10 kPa, seepage performance did not in order to delete initial suction as above mentioned in Section 3.2. All data sets obtained from creep test were described in relationship between axial strain and creep stress as shown in figure 4, and entirely axial strain due to applying of creep stress approached to 16.0%. Occurred axial strain remained less than 0.36%, it was small deformation, when creep strain was 41.7 kPa. Continually, few increments of creep stress were loaded step by step, and large increasing in axial strain was measured which was produced till 8.3%. Evaluated creep stress was 51.2 kPa that the mount of difference stresses to previous creep stress was 9.5 kPa. Small increment even occurred further deformation in unsaturated soil. As next creep stress, small increment was applied from 51.2 kPa that shrinkage deformation produced suddenly and was over 11.0% in axial strain. Creep test took the end according to achievement for axial strain of 16.0%.

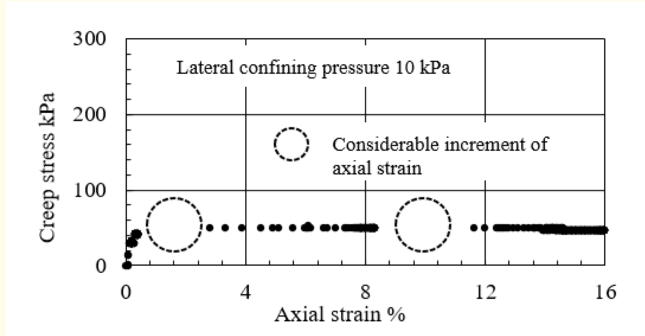

Figure 4: Increment of axial strain with creep stress.

Volume strain was described, and specimen indicated further shrinkage as comprehensive behavior in figure 5. It was clarified that rapidly shrinkage deformation was produced at small axial strain (i.e. less than 0.36% in axial strain). Obtained volume strain mounted up to minus 3.7%. Volume strain decreased to minus 15.0% smoothly at end of test that it was seemed to be failure. To concern with effective stress of unsaturated soil subjected to creep stress is exceeding importance to understand general mechanism involving time-dependent at remaining creep stress. Accumulated axial strain had adequate effort to changing of excess pore-water pressures that excess pore-water pressure variations were described at small axial strain as shown in figure 6. Negative value in pore-water pressure occurred at first. Excess pore-water pressure grew into positive ranges at contrary that a large increment was observed at slightly axial strain increment interval. Excess pore-water pressure was over 20 kPa at axial strain of 0.38%. Figure 7 showed all of excess pore water pressure changing within axial strain range was from zero to 16.0%. Excess pore-water pressure maintained roughly same value (i.e. 23.0 kPa) beyond axial strain of 0.38%. Suction was calculated using measured excess pore-water pressure data sets. Suction value approached to zero rapidly in-

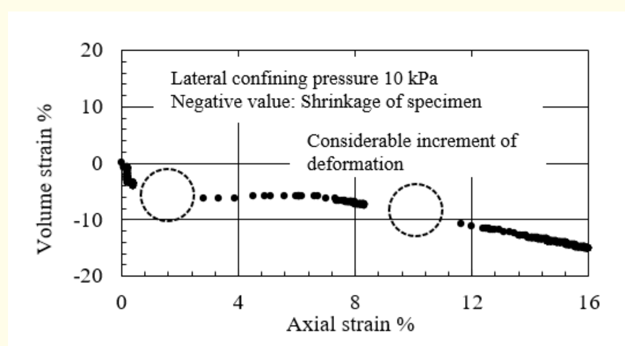

Figure 5: Volume dilation due to creep stress.

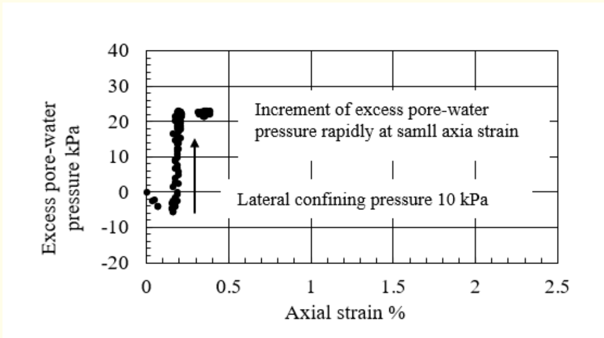

Figure 6: Occurrence of excess pore-water pressure due to creep stress till axial strain of 0.5%.

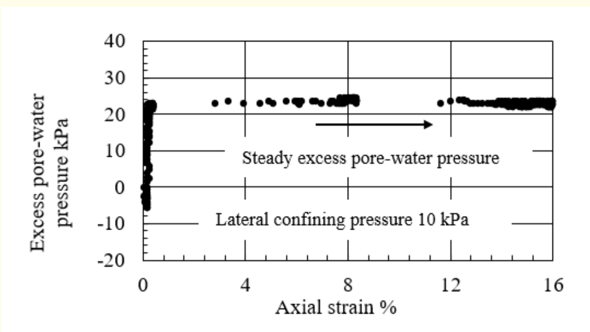

Figure 7: Excess pore-water pressure against axial strain due to creep stress.

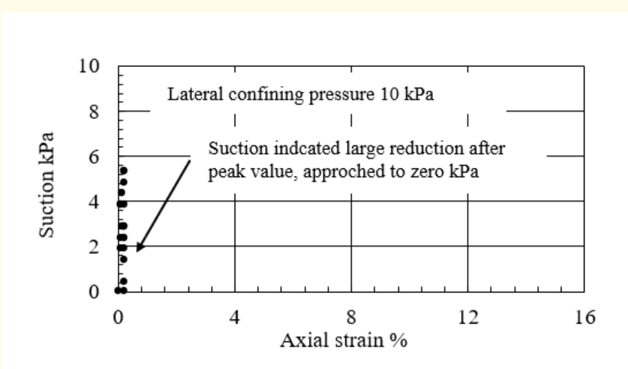

Figure 8: Variation of suction due to creep stress.

duced by large increment of excess pore water pressure while axial strain was considerable small ranges as shown in figure 8.

Both axial strain and suction associated with increment of creep stress were indicated in figure 9 and 10. It can be not seen that obviously occurrence of axial strain was quite small till creep stress was over 41.7 kPa at least. Subsequently, it was shown that highlighted increment regard to axial strain was identified. Processing of failure or destruction with collapsing in void structure was assumed rightly. Growing of creep stress in gradually afforted on suction, and severe suction reduction was inducted at limited creep

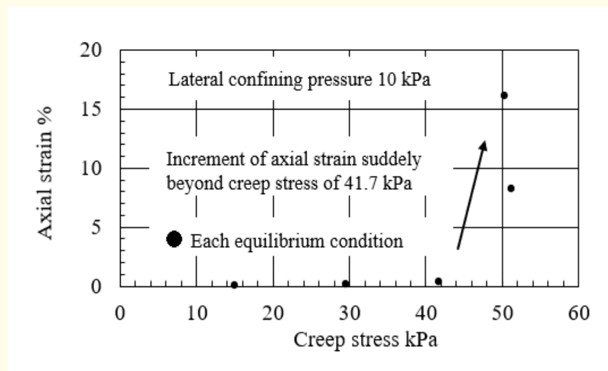

Figure 9: Variation of axial strain at each equilibrium condition.

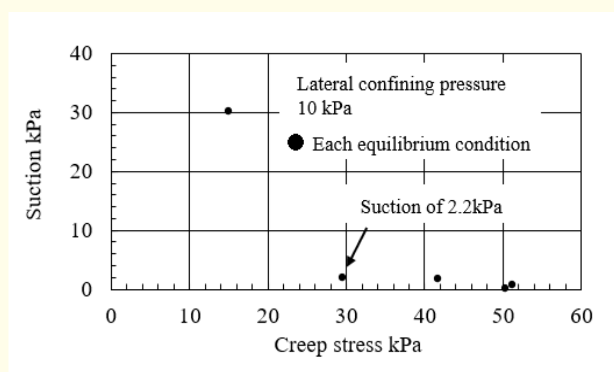

Figure 10: Reduction of suction at each equilibrium condition.

stress range (i.e. from 14.9 kPa to 29.5 kPa), which was 28.1 kPa in dropping. Consequently, suction reached to zero, delete with great ratio associated to deformations within creep stress increments.

Creep properties of an unsaturated soils under lateral confining pressure of 400 kPa

As other cases, an unsaturated creep test was conducted out with lateral confining pressure of 400 kPa that distilled water seepage was passes through specimen in order to delete initial suction. Pressure membrane technique was imposed for suction of 20 kPa. Subsequently, suction of 20 kPa was equilibrium, creep stresses were loaded step by step under undrained conditions. It was similar process with a series of lateral confining pressure of 10 kPa. Relationship between axial strain and creep stress were described as shown in figure 11 that whole accumulated axial strains were provided with creep stress. Creep stress approached to 142 kPa in early portion (i.e. less than 1.0% in axial strain), and commencement of creep stress reduction was observed. Decreasing of creep stress identified with deviator stress in a triaxial compression test

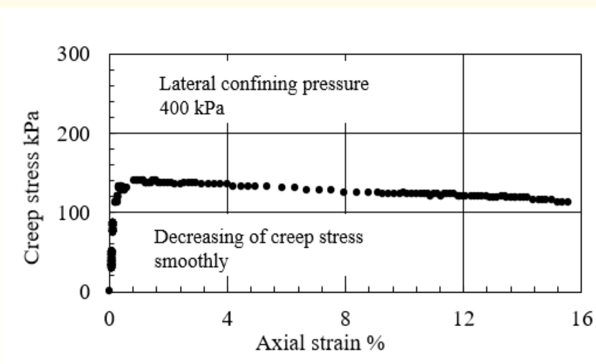

Figure 11: Increment of axial strain due to creep stress.

caused, inducing the volume change to estimate deviator stress. The described plotted data was seemed a like of smoothly stress strain curve that plotted all data sets included with/without complete equilibrium condition to applied creep stress.

When axial strain was a range of 15%, measurement of excess pore-water pressure, volume change and axial deformation took a successful, achieved to end of creep test. Volume changes was presented as shown in figure 12, which negative value appeared shrinkage of specimen under creep stress loading. The dilation in

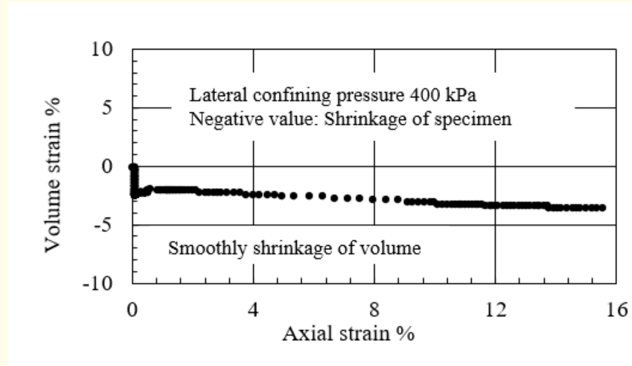

Figure 12: Volume dilation due to creep stress.

shrinkage phenomena occurred suddenly around few axial strains, which was less than axial strain of 0.2%. Shrinkage was dominant over all creep behavior that slowly reductions was rest through creep test was competition. Finally, evaluated volume change was close to minus 4.0%.

Loading of creep stresses caused that excess pore air/water pressures occurred clearly under complete undrained/unexhausted conditions, and changing of excess pore-water pressure was described as shown in figure 13. Excess pore-water pressure increased strongly associated to axial strain induced by creep stress loading. Excess pore water pressure indicated 350 kPa suddenly until axial stress was 0.5%. The difference between lateral confining pressure of 400 kPa and excess pore-water pressure decreased further, it can be expected to the reduction of effective stress. It was similar to static liquefied failure condition [40-42] that effective stress approach to zero due to be equal to zero between lateral confining pressure and excess pore-water pressure. Simultaneously, the excess pore-air pressure behavior was entirely same to that of pore-water pressure as shown in figure 14. It was found out that excess pore-air pressure approached to 400 kPa, indicating nothing at all. Thus, extremely large increment of both pore-air pressure and pore-water pressure were observed at occurrences of axial strain.

Shear strength consists of net normal stress and suction such as two stress variables [43]. Net normal stress was defined as between confining pressure a pore- air pressure, suction has been defined as between pore-air pressure and pore-water pressure. Calculated suction was provided as shown in figure 15 that remarkable variations was measured at small axial strain ranges (i.e. less than 0.2%). Beyond axial strain was 1.0% calculated suction verified stabilization around 18 kPa. Its value remained till end of creep test.

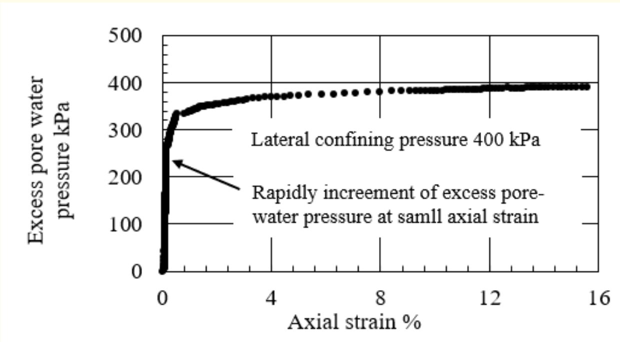

Figure 13: Excess pore-water pressure.

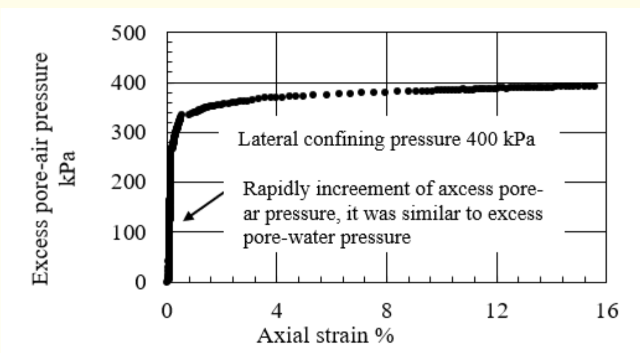

Figure 14: Excess pore-air pressure.

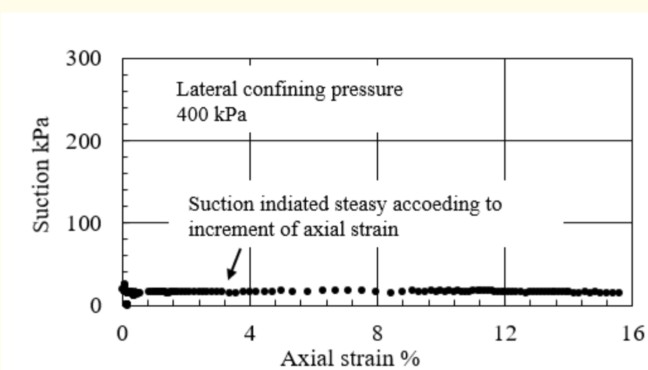

Figure 15: Suction.

Regard to axial strain, suction and creep stress were leaded from above mentioned in figure 16 and 17 which axial strain increase slightly according to loading of creep stress as shown in Figure 16.

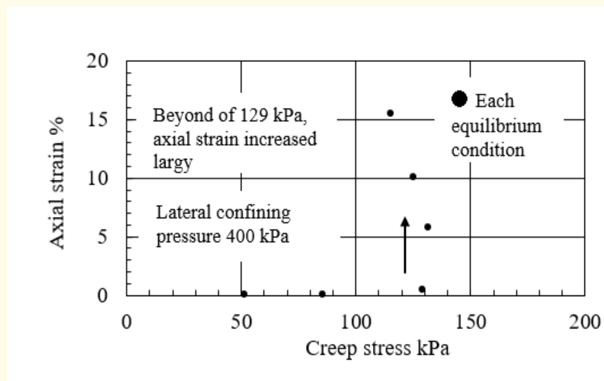

Figure 16: Variation of axial strain at equilibrium condition.

While creep stress was of 130 kPa, produced axial strain was less than 0.5%. It was however found that significant increment of axial strain was indicated beyond creep stress was over 130 kPa, and axial strain approached to 16% with including quite sever acceleration. Occurrence of axal strain 15.6% probably attributed complete failure condition in unsaturated soil sample.

Other hands, suction during creep test almost stabilization as shown in figure 17, variations remained from 15 kPa to 20 kPa. Even if suction change was small in unsaturated soil subjected to creep stress, it was determined that excess pore-air/water pressures grew much like to approach lateral confining pressure. It was consequently that considerable large fluid pressures caused the reduction of effective stress at process creep stresses.

Description of relationship between mean effective principal stress and creep stress

This creep test contained both creep test under lateral confining pressure of 10 kPa and 400 kPa. Simultaneously, excess pore-air/

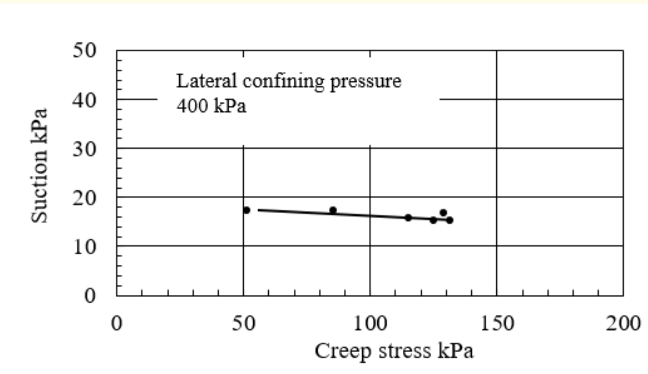

Figure 17: Steady suction with creep stress.

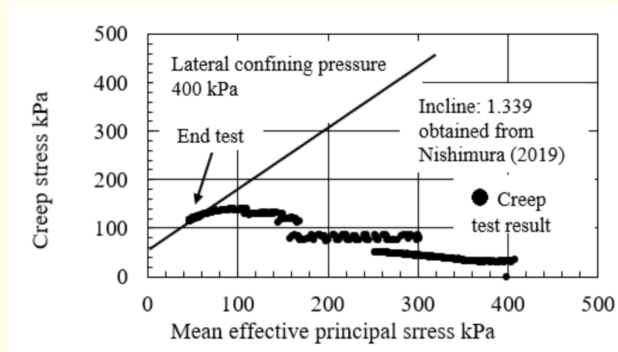

Figure 19: Effective stress path (400 kPa).

water pressures were measured in order to define effective stress path in mean effective principal stress and deviator stress coordinate space. Effective stress path often contributes to understand mechanical properties of soils, and determining two strength parameters such as effective angle of internal friction and effective cohesion from critical state line [44,45].

The obtained relationship between mean effective principal stress and deviator stress was shown in figure 18 and 19. Black circle symbol referred creep test results. Each black slender line accompanied in figure 18 and 19 had same incline of failure line, which was 1.339. Nishimura (2019) [46] conducted out monotonic triaxial compression test for saturated soil material under undrained condition that used material was same material used in this study. Identified lateral confining pressure had a range from 50 kPa to 400 kPa. Nishimura (2019) [46] reported that the failure line with incline of 1.339 passed though the origin of the mean effective principal stress and deviator stress coordinate axes. The determined effective angle of internal friction was 33.1 degrees from the incline of 1.339.

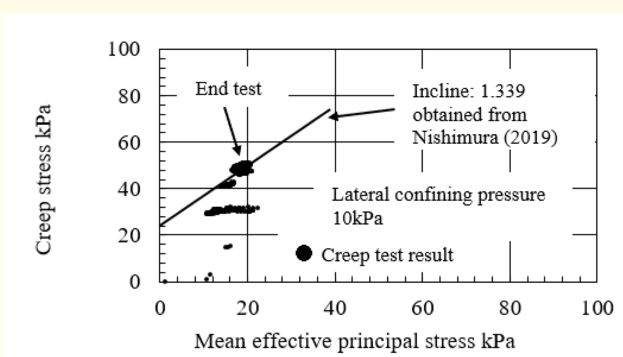

Figure 18: Effective stress path (10 kPa).

At beginning creep test for lateral confining pressure of 10 kPa, mean effective principal stress increased gradually with increment of creep stress till creep stress was 30 kPa. Subsequently, mean effective principal stress obviously decreased, even if, creep stress was around 30 kPa. Then, mean effective principal stress increased again, and maximum creep stress was indicated. It was assumption that effective angle of internal friction was constant. Identified stress condition connected to the failure line with incline of 1.339, which was a maximum creep stress. Effective cohesion was verified using determined both the incline of failure line and intercept on the creep stress axis which was 10.8 kPa. It is accepted commonly that failure line at critical state for saturated soil was established without apparent cohesion. Creep test specimen was unsaturated condition, and had not a little suction that two factors caused remaining cohesion as shown in figure 18.

Effective stress path in lateral confining pressure of 400 kPa was shown in figure 19. Firstly, mean effective principal stress decreased clearly at once, and mean effective principal stress described significant reduction duration almost constant creep stress was remained as distinguishing features. The failure line above mentioned was adjusted with data sets close to end of creep test. Effective cohesion was determined using both the incline of failure line and intercept on the creep stress axis which was 29.3 kPa. Comparison effective cohesion can be emphased that effective cohesion had the influence of lateral confining pressure.

Conclusion

This study conducted out mainly unsaturated soil creep test using revised unsaturated triaxial compression apparatus in order to understanding geotechnical problems such as slope failure settlement for embankment. Hydro-mechanical properties of unsaturated soils closely related to matric suction that controlling suction used pressure membrane technique contributed to verify creep behavior of unsaturated soil. In addition, soil-water characteristic curve and unconfined compressive strength were discussed to consider hydro-mechanical properties for unsaturated silty soil. The obtained test results are enough to apply relevance to geotechnical practices.

- Soil material used in this study was silty soil with a relatively uniform grain size distribution. Soil-water characteristic curve was determined using pressure membrane technique at a range from 0 to 18 kPa in matric suction. Evaluated degree of saturations were that it was found out hysteresis between drying process and wetting process. At end of wetting process (i.e. matric suction was zero), the degree of saturation was less than that of initial condition (i.e. at beginning of SWCC test).
- Matric suction occupied by compaction water content that compacted soil with low water content described high matric suction. It was good agreement with common tendency mentioned published many papers for previous works. Unconfined compressive strength having high matric suction developed high resistance.
- Two different lateral confining pressures were applied to unsaturated soil under creep test which were 10 kPa and 400 kPa. It was provide that axial strain and shrinkage volume strain were clearly developed according to increment of creep stress.
- Relationship between creep stress and axial strain at equilibrium condition was that axial strain rapidly increased with increment of creep stress. As excess pore-water pressure was measured under undrained condition that increments of pore-water pressures was larger than that of excess pore-air pressure. Consequently, determined matric suction evidenced obviously reduction, and simultaneously matric suction approached to zero value.
- Measured data sets in creep test was corresponded into relationship between mean effective principal stress and creep stress that was referred critical state theory accepted in saturated and unsaturated soil mechanics. It was assumed that failure line (i.e. critical state line) obtained from conventional triaxial compression test under undrained condition was possible to associate to creep behavior for unsaturated soil. Adjusting the failure line to limitation stress condition, which was of large axial strains.

Bibliography

1. Rodrıguez CE., *et al*. "Earthquake-induced landslides: 1980-1997". *Soil Dynamics and Earthquake Engineering* 18 (1999): 325-346.

2. Cui P., *et al*. "Formation and Risk Reduction of Landslide-Dammed Lakes Resulted by the Ms 8.0 Wenchuan Earthquake: A Brief Review and a Proposal". *Earthquake-Induced Landslides, Proceedings of the International Symposium on Earthquake-Induced Landslides* (2012): 3-10.

3. Oberender PW and Puzrin AM. "Observation-guided constitutive modelling for creeping landslides". *Géotechnique* 66.3 (2016): 232-247.

4. Hazarika H., *et al*. "The 2017 July Northern Kyushu Torrential Rainfall Disaster—Geotechnical and Geological Perspectives". *Geotechnics for Natural Disaster Mitigation and Management* (2019): 1-19.

5. Giuseppe S and Nicotera MV. "Unsaturated soil mechanics in rainfall-induced flow landslides". *Engineering Geology* 165 (2013): 105-132.

6. Lai XL., *et al*. "Experimental investigation on the creep behavior of an unsaturated clay". *Canadian Geotechnical Journal* 51.6 (2014): 621-628.

7. Miaojun S., *et al*. "Creep behavior of slip zone soil of the Majiagou landslide in the Three Gorges area". *Environmental Earth Sciences* 75 1199 (2016).

8. Liangchao Z., *et al*. "Creep model for unsaturated soils in sliding zone of Qianjiangping landslide". *Journal of Rock Mechanics and Geotechnical Engineering* 5 (2013): 162-167.

9. Bishop AW and Blight GE. "Some aspects of effective stress in saturated and partly saturated soils". *Geotechnique* 13.3 (1963): 177-197.

10. Fredlund DG and Rahardjo H. "Chapter 4, Measurement of Soil Suction". Soil Mechanics for Unsaturated Soils, A Wiley-Interscience Publication, JOHN WILEY and SONS, INC (1993): 64-106.

11. Bishop AW. "Creep characteristics of two undisturbed clays". *Proceedings of the 7th International Conference on Soil mechanics. Mexico* 1 (1969): 29-37.

12. Wheeler SJ and Sivakumar V. "An elasto-plastic critical state framework for unsaturated soil". *Geotechnique* 45.1 (1995): 35-53.

13. Blatz JA and Graham J. "Elastic-plastic modelling of unsaturated soil using results from a new triaxial test with controlled suction". *Geotechnique* 53.1 (2003): 113-122.

14. Skempton AW. "Long-term stability of clay slopes". *Géotechnique* 14.2 (1964): 77-102.

15. Skempton AW and LaRochelle P. "Bradwell slip - a short-term failure in London Clay". *Géotechnique* 15.3 (1965): 221-242.

16. Bjerrum L. "Progressive failure in slopes of over consolidated plastic clay and clay shales". *Journal of the Soil Mechanics and Foundations Division* 93.5 (1967): 1-49.

17. Puzrin AM and Sterba I. "Inverse long-term stability analysis of a constrained landslide". *Géotechnique* 56.7 (2006)): 483-489.

18. Glastonbury J and Fell R. "Geotechnical characteristics of large slow, very slow, and extremely slow landslides". *Canadian Geotechnical Journal* 45.7 (2008): 984-1005.

19. Puzrin AM., *et al*. "The in-situ stiffness of the sliding layer in a creeping landslide". *Proceedings of 4th international symposium on deformation characteristics of geomaterials* 1 (2008): 407-412.

20. Sillers WS., *et al*. "Mathematical attributes of some soil-water characteristic curve models". *Geotechnical and Geological Engineering* 19 (2001): 243-283.

21. Wang H., *et al*. "SWCC measurement of two types of iron ores". Proc. 6th Int. Conf. on unsaturated soils Unsat 2014 (2014): 973-979.

22. Wang H., *et al*. "A system to measure volume change of unsaturated soils in undrained cyclic triaxial tests". *Geotechnical Testing Journal* 39.4 (2016): 532-542.

23. Bishop AW. "The use of pore pressure coefficients in practice". *Geotechnique* 4.4 (1954): 148-152.

24. Bishop AW. "The measurement of pore pressure in the triaxial test". Proceedings of Conference on Pore Pressure and Suction in Soils. London (1961): 38-46.

25. Cole DM. "A technique for measuring radial deformation during repeated load triaxial testing". *Canadian Geotechnical Journal* 15 (1978): 426-429.

26. Drumright E. "Shear strength for unsaturated soils". PhD Thesis, University of Colorado, Fort Collins, CO (1987).

27. Wheeler SJ and Sivakumar V. "Critical state concepts for unsaturated soil". Proceedings of the Seventh International Conference on Expansive Soils. Dallas TX (1992): 167-172.

28. Juca JFT and Frydman S. "Experimental techniques". *International Conference on Unsaturated Soils* (1996): 1257-1292.

29. Nishimura T., *et al*. "Microporous membrane technology for measurement of soil-water characteristic curve". *Geotechnical Testing Journal* 35 (2012): 201-208.

30. Chiu CF and Ng CWW. "A state-dependent elasto-plastic model for saturated and unsaturated soils". *Géotechnique* 53.9 (2003): 809-829.

31. Nishimura T. "Evaluation of Effective Stress of an Unsaturated Soil Under Cyclic Loading". *Earthquake-Induced Landslides, Proceedings of the International Symposium on Earthquake-Induced Landslides* (2012): 537-546.

32. François B and Laloui L. “An Oedometer for Studying Combined Effects of Temperature and Suction on Soils”. *Geotechnical Testing Journal* 33.2 (2010): 112-122.

33. Blatz JA *et al*. “Vapour Equilibrium and Osmotic Technique for Suction Control”. *Geotechnical and Geological Engineering* (2008).

34. Alenazi N. *et al*. “Modified polyether-sulfone membrane: a mini review”. *Journal Designed Monomers and Polymers* 20.1 (2017): 532-546.

35. Lu N and Likos WL. “Suction Stress Characteristic Curve for Unsaturated Soil”. *Journal of Geotechnical and Geoenvironmental Engineering* 132.2 (2006).

36. Lu NF and Dong Y. “Correlation between Soil-Shrinkage Curve and Water-Retention Characteristics”. *Journal of Geotechnical and Geoenvironmental Engineering* 143.9 (2017).

37. Atkinson J and Nocilla A. “Suction and strength in heavily compressed carbonate sand”. *Géotechnique* 53.9 (2003): 831-832.

38. Zhou WH., *et al*. “Measurement of unsaturated shear strength parameters of silty sand and its correlation with unconfined compressive strength”. *Measurement* 93 (2016): 351-358.

39. Gan JKM., *et al*. “Determination of the shear strength parameters of an unsaturated soil using the direct shear test”. *Canadian Geotechnical Journal* 25.3 (1988): 500-510.

40. Yamamuro JA and Lade PV. “Static liquefaction of very loose sands2”. *Canadian Geotechnical Journal* 34 6 (1997): 905-917.

41. Picornell M and Nazarian S. “Effect of soil suction on the low-strength shear modulus of soils”. *Proceedings of the Second International Conference on Unsaturated* Soils 1 (1998): 102-107.

42. Yamamuro JA and Lade PV. “Static Liquefaction and “Reverse” Behavior of Silty Sand”. GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering (2012): 829-838.

43. Fredlund DG and Morgenstern NR. “Stress state variables for unsaturated soils”. *Journal of Geotechnical Engineering, Division, ASCE* 103 GT5 (1977): 447-466.

44. Schofield A and Wroth P. “Chapter 6 Cam-clay and the Critical State Concept, Critical State”. *Soil Mechanics* (1968): 228.

45. Cristhian M., *et al*. “Critical state model for structured soil”. *Journal of Rock Mechanics and Geotechnical Engineering* 12.3 (2020): 630-641.

46. Nishimura T. ”Shear strength of an unsaturated silty soil subjected to creep deformation”. Geotechnics for Sustainable Infrastructure Development, The International Conference GEOTEC HANOI (2019): 977-985.