6ICEGE
6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch. New Zealand

Cyclic Triaxial Behavior of an Unsaturated Silty Soil Subjected to Suction Changes

T. Nishimura[1]

ABSTRACT

Recently, implement or performance to unsaturated soil mechanism including concept of cyclic phenomena is necessary to prevent, decrease earthquake-induced great damages. The experimental practice and theory for unsaturated soil mechanism is significant effective to interpret liquefaction behavior of unsaturated soil. This study aims to interpret liquefaction phenomena for unsaturated soil subjected to drying-wetting process in suction. Each physical testing such as SWCC test and hydraulic conductivity test contributed further to describe the change of void structure in soil particle together. Three testing was performed in this study which were SWCC test, conductivity test and cyclic triaxial test. All testing had advanced measurement technique for controlling low matric suction. Before cyclic loading, the soil structure in apparent saturated soil was developed due to suction changes as well as the influence lateral pressure. Even if the soil was not fully saturation condition, the unsaturated soil indicated distinct liquefaction phenomena.

Introduction

Typical geotechnical disaster such as liquefaction and landslides by earthquakes occur several times in Japan (for example; 2011 Tohoku Earthquake, 2004 Mid-Niigata Earthquake and 1995 Hyogoken-Nambu Earthquake). The report of investigation regard to disaster induced by these earthquakes which indicated many tragic damages for lifeline facilities, public facilities, buildings and houses. It was proved that earth-quake-induced liquefaction or landslide had strong seismic forces. Earth structures received severe damages which were regardless of saturation or unsaturation condition. Yasuda (2013) reported so many damages induced by liquefaction after 2011 Tohoku Earthquake with soil profile such as N-value distribution, position of water level and soil physical properties. Kokusho (2009) investigated liquefied many sites in Niigata due to Chuetsu earthquake (2004). Yasuda et al. (2012) reported liquefaction-induced many damages around Tokyo bay by 2011 Tohoku Earthquake.

Soil liquefaction induced by earth-quake is one of the most important phenomena in geotechnical engineering which is growing interest in public society. Interpretation of liquefaction mechanism has been investigated since the 1960s, particular, clean sand was focus as first target soil material.

Recently, to understand unsaturated soil mechanism including concept of cyclic phenomena is necessary to prevent earthquake-induced great damages. The experimental studies for

[1] Professor, Department of Civil Engineering, Ashikaga Institute of Technology, Tochigi, Japan, tomo@ashitech.ac.jp

unsaturated mechanism is significant effective to interpret liquefaction behavior of unsaturated soil, but those results were not enough for establish theoretical framework of unsaturated cyclic mechanism. At least, accordingly testing procedure with controlling of matric suction should be modify first in possible. Monkut and Yamamuro (2011) focused on the previous literature regard into three major aspect following; i) influence of fines content; ii) influence of confining stress; iii) influence of specimen preparation method. Monkut and Yamamuro (2011) summarized previous literature including both three major aspects. The summary (Monkut and Yamamuro, 2011) indicated important considering the influence of fines contents (FC) on liquefaction potential of sands and silty sands Ishihara (1993) mentioned that silt in low plasticity range (less than < 10) does not change the cyclic liquefaction resistance of sandy soils, but the cyclic liquefaction resistance increase for the greater plasticity ranges. The summary suggested by Monkut and Yamamuro (2011) based on above mentioned three impact factors were suitable for generally saturated sand. Establishing of unsaturated cycle testing process need the more technical items.

Purpose of This Study

Apparent saturation soils having highly degree saturation encourage several times at geotechnical constructions that describe quiet difference behavior with fully saturated soils. More unsaturated soil mechanical parameters such as water retention, unsaturated hydraulic conductivity and drying-wetting hysteresis on suction are useful to interpretation of cyclic behavior for unsaturated soils. First all, a present unsaturated soil liquefaction testing procedures in literature are not adequate to control low matric suction. The mentioned test results have been not supported the inspection dynamic properties of unsaturated soils. The test results based on accurate suction control performance can explain the behavior unsaturated soil having air-water mixture component using pore-pressure data sets. This study appeared that drying – wetting process in suction directly influenced to soil structure, and it induced the change of water retention activity and hydration conductivity. Also, lateral pressure influenced to void structure, which it was related to hysteresis of SWCC and hydraulic conductivity. Even if unsaturated soils subjected to change the soil particle together, liquefaction phenomena was measured in not fully saturated condition.

Test Procedure

Soil material and apparatus

This test program used Silt which has a relatively uniform distribution. DL-clay had a fine content of 99.0 % (particles smaller than 0.075 mm in diameter) by dry weight. Some properties such as soil particle density, maximum void ratio, minimum void ratio, mean grain diameter of sand (D_{50}) and mean grain diameter of silt (d_{50}) are given in Table 1. The soil specimens were statically compacted in the steel mold at the as compacted water content of 10 %. The compacted soil specimen had a dry density of 1.39 g/cm^3, a degree of saturation of 29.2 % and void ratio of 0.91. The size of specimen was a diameter of 50 mm and a height of 100 mm. Maximum and minimum void ratios against fines content (FC) for DL-clay had good agreement with limiting void ratios of silty sands for different fines contents mentioned by Monkut and Yamamuro (2011).

Table 1. Summary of physical properties of silt.

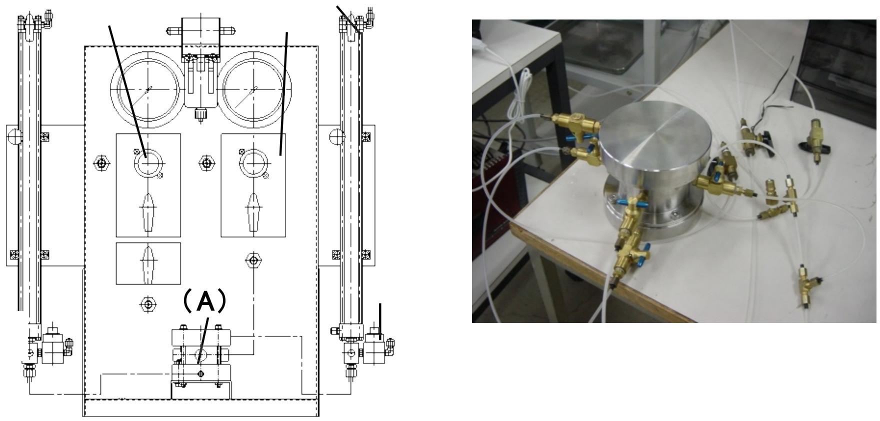
Specific gravity	2.65
Percentage of sand fraction %	1
Percentage of silt fraction %	87
Percentage of clay fraction %	12
Fine component %	99
Mean grain diameter D50 mm	0.0196
Mean grain diameter of silt d50 mm	0.0193
Maximum void ratio	1.46
Minimum void ratio	0.85
Liquid limit %	24.7
Plastic limit %	22.8
Plasticity index	1.9
United Soil Classification System	ML
Maximum dry density g/cm3	1.53
Optimum water content %	17

This study conducted out cyclic triaxial test using a modified cyclic triaxial apparatus for controlling of suction. The apparatus consist of vibrator, control equipment, triaxial cell, supply system for cell pressure, pore-water pressure and pore-air pressure. The cell pressure, pore-water-pressure and pore-air pressure can be controlled independently. Inner cell was used for measuring volume change of the soil specimen. Volume change of soil specimen was measured using gap sensor installed into the inner cell. The gap sensor measured voltage changes which can be translated to volume changes. In addition, a solenoid controlled valve is installed near specimen cap which connected pressure sensor. A double glass burette installed with a difference pressure sensor was connected into the triaxial cell. The difference pressure sensor measured the either drainage or absorption water from the soil specimen induced suction.

The axis translation technique was used applying matric suction to soil specimen under constant net normal stress. The micro porous membrane which had an air entry value of 250 kPa was installed into the modified pedestal.

The SWCC test was conducted used the modified SWCC apparatus. The soil specimen was compacted in the steel mold, and installed into the apparatus. The micro porous membrane was installed into the pedestal that pressure membrane technique was applied for control suction. Before applying of suction, the initial suction of specimens was deleted due to submerge in water.

The modified mold was prepared for hydraulic conductively test that was shown in Figure 1. The apparatus consist of the modified mold, air pressure regulator and water supply system. The micro porous membrane at both upper and under portion were installed, and was possible to control the suction.

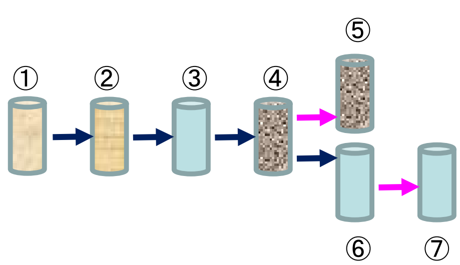


A) Developed mold, (B)(C) Regulator, (D)(F) Air supply, (E)(G) Difference voltage sensor

Figure 1: A hydraulic conductivity apparatus for unsaturated soil.

Test program

This test program consists of cyclic triaxial test under undrained condition, SWCC test and hydraulic conductivity test. The suction was controlled using pressure membrane technique through all tests. Figure 2 shows the all testing program flow and seven difference test steps. After isotropic consolidation, seepage was applied to specimens for deleting initial matric suction. De-air water was percolated through specimen from bottom, and volume shrinkage was measured due to collapsing phenomena. All specimens approached to apparent saturation condition (i.e. a degree of saturation was less than 100 %). Its reason was no apply the flushing with CO_2 (Carbon dioxide). Measurement of collapse is important for assessing the influence of density on liquefaction potential. Subsequently, suction of 20 kPa. The net normal stress of 100 kPa was remained with controlling suction. After the equilibrium with the suction of 20 kPa, at once all specimens were percolated that was meant wetting process. Its procedure was similar with above mentioned process, and the suction of 20 kPa reduced to zero value. Seepage and applying of matric suction had volume change as collapsing.



①	Initial soil sample
②	Apply net normal stress
③	Apply back pressure of 100 kPa
④	Apply suction using pressure membrane technique
⑤	Monotonic triaxial compression test
⑥	Seepage
⑦	Cyclic triaxial test

Figure 2: Flow of this testing program.

The cyclic triaxial test was conducted with controlling of principal stress deviations. All testing conditions were as following; difference initial cyclic stress ratios were 0.141 and 0.241, the applied loading frequency was 0.5 Hz and undrained condition. Sensor interface used in testing was PCD 30A (KYOWA Co. Ltd.).

A hydraulic conductivity was measured using the apparatus shown in Fig. 1. The mount of seepage through sample was measured with an initial water head of 35 cm and initial hydraulic gradient of 3.5. The hydraulic conductivity of unsaturated soil specimen was measured when the suctions was 2.1 and 3.5 kPa. Also, the hydraulic conductivity for the apparent saturated specimen was determined according to Darcy's law.

The soil-water characteristic curve was measured using pressure membrane technique in the range. The seepage performance was applied to delete the initial suction of all specimens, and the suction increased to maximum 20 kPa at drying process. Subsequently, wet process was performed. The two different stresses were conducted that were one-dimensional condition and isotropic compression condition. Net normal stress of 100 kPa were applied to the specimen. In case of one-dimensional condition, dry process and wet process was repeated in four times.

Test Results

Hydration properties for silty soil

The relationship between suction and three different parameters such as water content, void ratio and degree of saturation were described as soil-water characteristic curves in Figures 3 to 5. Also, the influence of stress condition (i.e. one-dimensional and isotropic compression) was appeared into SWCC curves. The water content under isotropic compression condition was lower than that of specimen under one-dimensional condition. The isotropic compression condition had strong hysteresis between drying process and wetting process compare with one-dimensional condition. Change of void ratio was extremely slight at a range from zero to 20 kPa of suction. It was possible to negligible that deformation induced by increment and decrement of suction. The repetition of dry process and wet process induced the degree of saturation gradually. Particularly, the distinct decrement of degree of saturation was indicated under isotropic compression condition.

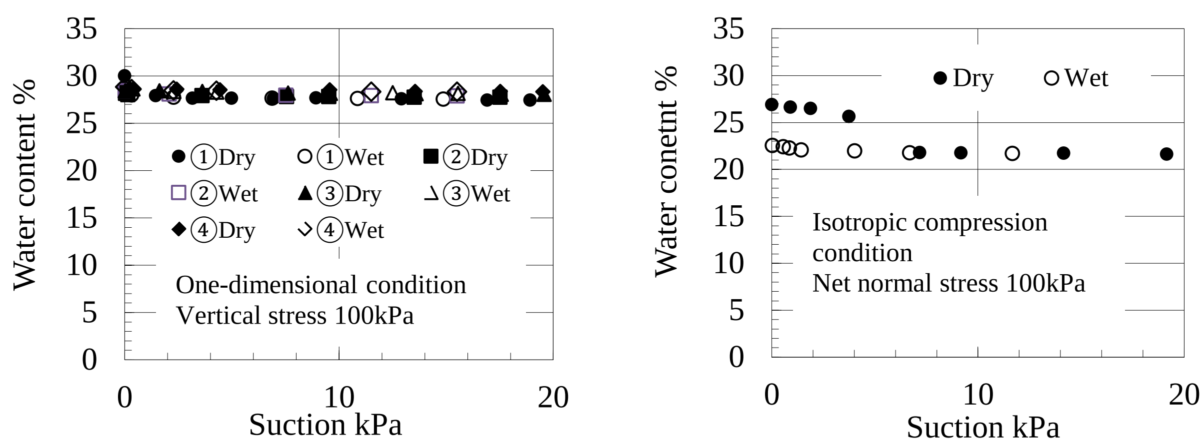


Figure 3. Relationship between water content and suction

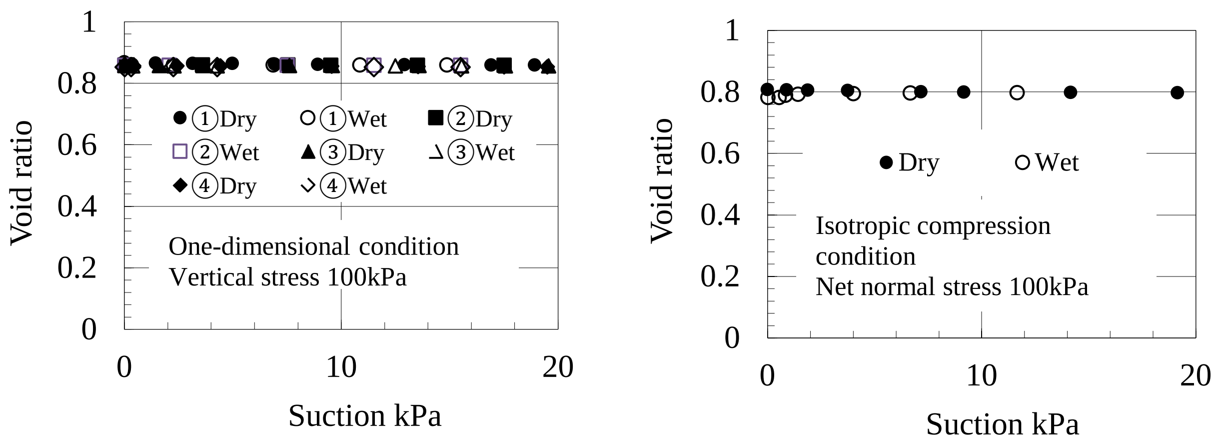


Figure 4. Relationship between void ratio and suction

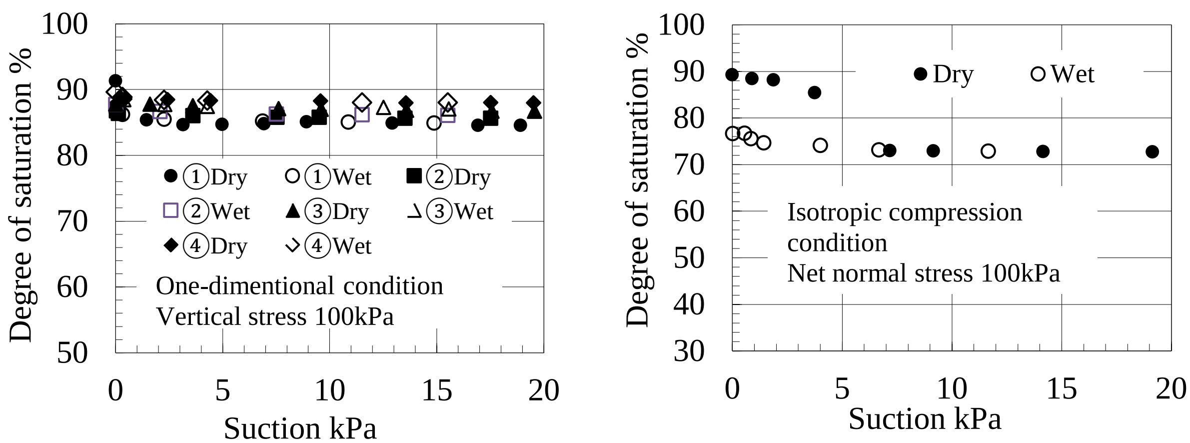


Figure 5: Relationship between degree of saturation and suction.

Hydraulic conductivity for both unsaturated soil and apparent saturation soil was described in Figure 6 that it was a range from zero to 3.5 kPa of suction. The existent or increment of suction that the hydration conductivity decrease distinctly. Symbol (●) lay on symbol (○), that the difference in two conductivity seems to be negligible. Symbol (▲) under isotropic compression condition was plotted in Fig. 6 which contained the influence of stress condition. Its conductivity was low compare to one-dimensional condition. Lateral pressure on isotropic compression condition is probably larger than that on one-dimensional condition that is main factor induced reduction of hydration conductivity. Isotropic compression caused the dense in void structure, and consequently soil moisture flow movement decreased.

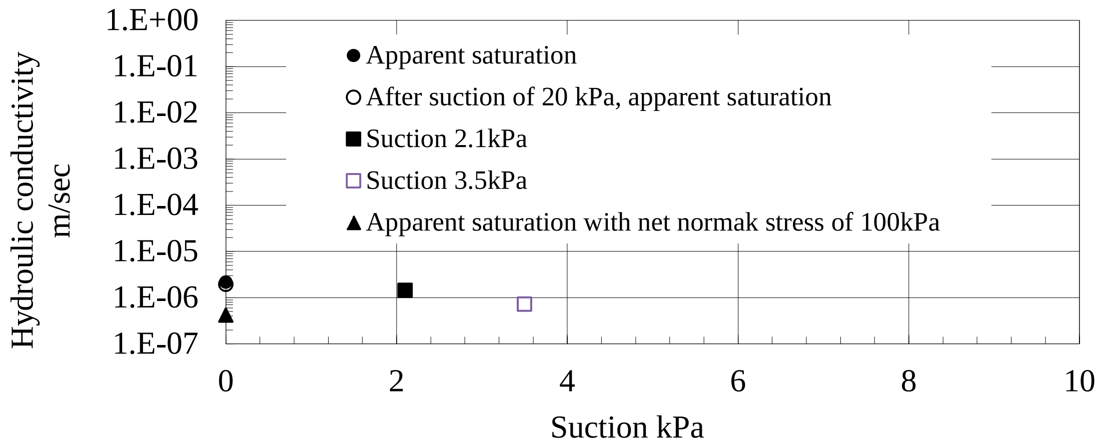


Figure 6: Hydraulic conductivity for unsaturated soil.

Liquefaction properties of apparent saturated silty soil

The excess pore-water pressure ratios were measured, and were described in Fig. 7. The excess pore-water pressures rapidly increased, were approached to the ratio of 1.0 when number of cyclic was less than five. Before excess pore-water pressure approach to 1.0, slight axial deformation was maintained as shown in Figure 8 that soil structure resisted the disturbance induced by external loading. Subsequently development of compression deformation was superiority, and the specimen at end of cyclic test was completely stayed in compression mode. When number of cyclic was less than five, cyclic stress ratio slightly decrease with cyclic loading as shown in Fig. 9. At cyclic loading number was over five, the significant reduction of resistance in soil particle together was measured, and the resistance maintained quite slight. Thus cyclic behavior of apparent saturation subjected to drying-wetting in suction process was similar to full saturation soils that liquefaction for unsaturated soil was verified certainly.

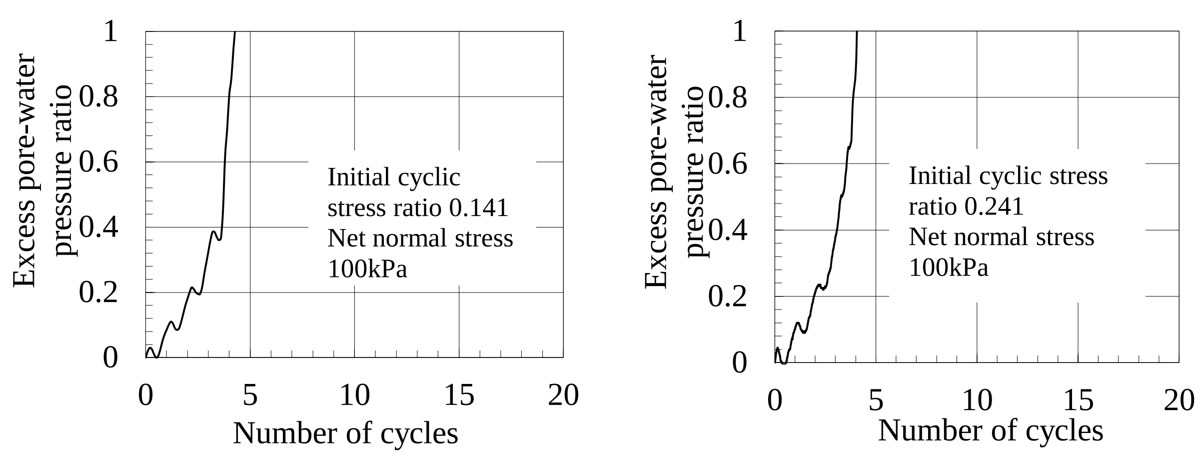


Figure 7: Excess pore-water pressure ratio.

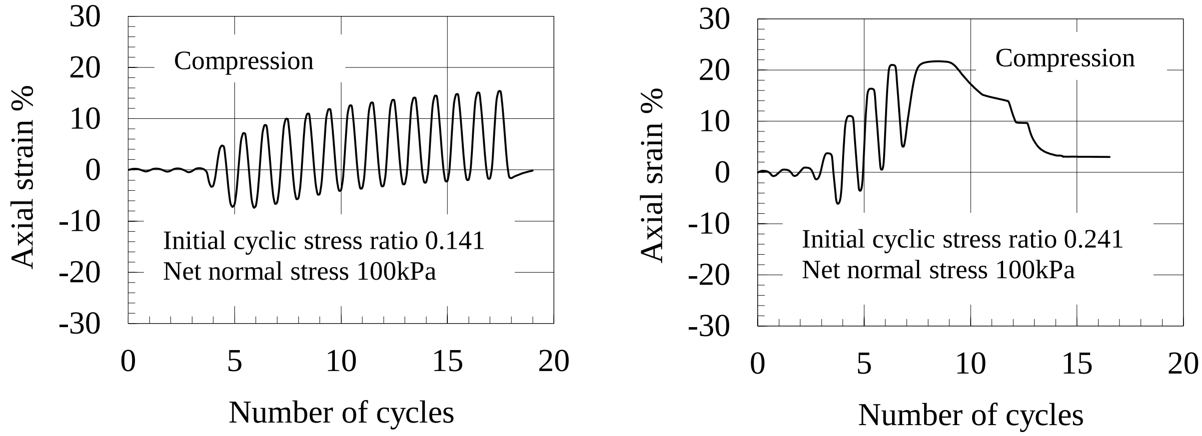


Figure 8: Axial deformation of apparent saturated soil due to cyclic loading.

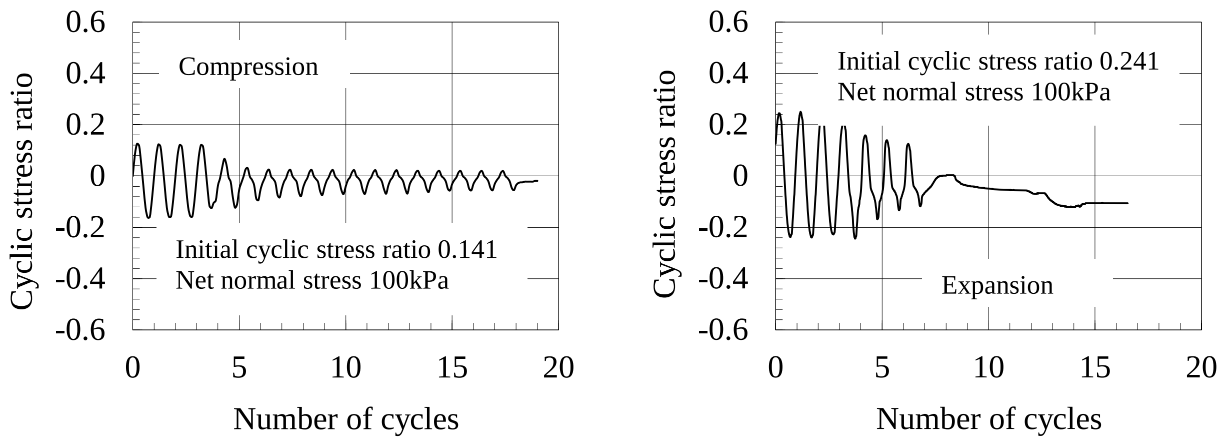


Figure 9: Decreasing of cyclic stress ratio.

The relationship between mean effective principal stress and deviator stress were describe as effective stress path in Fig. 10. In addition, the failure envelope confirmed liquefied stress condition on cyclic loading, which were obtained from the monotonic undrained triaxial compression test. At beginning of cyclic loading, the effective stress was deceased due to develop the excess pore water pressure, and mean effective principal stress rapidly decreased, and approach to the origin point in coordinate space. The specimen reached the failure envelope of expansion side, and destroyed or flowed. It was similar behavior regardless of initial cyclic stress ratio.

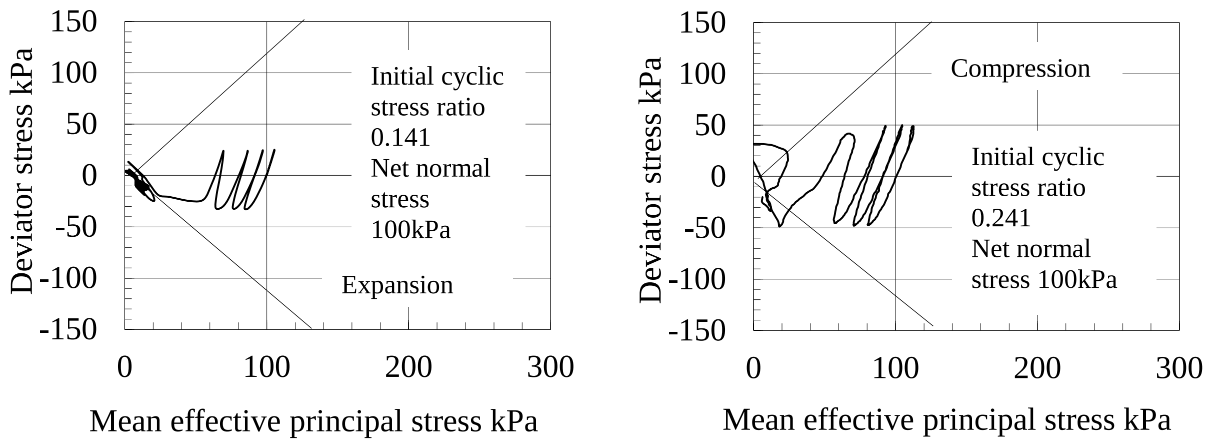


Figure 10: Effective stress paths with failure envelope.

Conclusions

1. To obtain the properties such as water retention and hydraulic conductivity related to interpret the unsaturated soil cyclic behavior indirectly. The soil-water characteristic curve described strong hysteresis on isotropic compression, at same the soil structure was developed during drying-wetting process in suction. Thus developed soil structure clearly appeared the reduction of water flow conductivity on isotropic compression.
2. Even if the apparent saturated soil obviously indicated liquefaction phenomena as well as fully saturated soil which was subjected to drying-wetting process in suction. The liquefied deformation progressed further into the expansion mode that the stress path first approached to failure envelope at expansion.

References

Ishihara, K. Liquefaction and flow failure during earth-quakes. *Geotechnique***.** 1993; **43**(3): **351-451**.

Kokusho, T. *Earthquake Geotechnical Case Histories for Performance-based Design*, CRC Press. Taylor & Francis Group. 449pp. 2009.

Monkul, M. M. and Yamamuro, J. A. Influence of silt size and content on liquefaction behavior of sands. *Canadian Geotechnical Journal*. 2011; **48**: 931-942.

Yasuda, S., Harada, K., Ishikawa, K. and Kanemaru, Y. Characteristics of the liquefaction in Tokyo bay area by the 2011 Great East Japan earthquake. *Soils and Foundations*. 2012; **52**(5). 793-810.

Yasuda, S. 2013. Damage to lifeline facilities by the 2011 Great East Japan Earthquake. *Proceedings of International Geotechnical Symposium on Geotechnical Engineering for Disaster Prevention & Reduction. Enviromentable Development*. Incheon. Republic of Korea. IGS-Incheon Vol.1. 320-326. 2013.