Shear strength of unsaturated silty soil under water infiltration conditions

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ABSTRACT

The stress path that simulates the field condition of soil slope when it is failed under water infiltration condition and wetting process after a rainy period is modeled in this laboratory testing. The results indicate that soil change its behavior from dilatant to compression with the decrease in matric suction and a decrease in shear strength is directly related to change in water content.

Keywords: water infiltration, shear stress, suction

1 INTRODUCTION

Rainfall-induced slope failures are considered as one of the most destructive natural hazards. The reduction in shear strength due to water infiltration is considered as the primary cause of slope failure by a number of previous researchers. The failure mechanism in soils due to water infiltration should simulate the stress path in the field conditions (Meilani, 2005). However, the stress path that leads to the failure cannot be modeled using a routine triaxial test in which the specimen is sheared by increasing deviator stress. Brand (1981) suggested that the field stress path should be modeled using a triaxial test conducted under a constant total stress and increasing pore-water pressure. The same procedure was also adopted by Brenner et al. (1985), Anderson & Sitar (1995), Anderson & Riemer (1995) and Melinda (1998). However, the stress path followed by the soil specimens that simulate field condition of soil slope when it is failed under water infiltration condition and after a rainy period when the soil above the water table experienced a wetting process is seldom modeled in laboratory testing.

2 MATERIAL, TEST SETUP & PROCEDURES

Detailed experimental procedure is described in the following subsections.

2.1 Material and test setup

In this study triaxial tests on unsaturated soil specimens considering the above field conditions were performed with aim to study shear stress, pore pressure and deformation behavior under water infiltration conditions. The silty soil known as “DL clay” in Japan was used. It is a fine material without plasticity and homogenous and easy to obtain. It is larger in grain size than average clay and is composed of 90% silt and 10% clay. The soil’s index properties are WL=NP, IP=NP and Gs=2.635g/cm^3. The soil specimens were statically compacted in the steel mold with water content of 20%. The compacted soil specimens had a dry density of 1.3 g/cm^3, a degree of saturation 47.5%, a void ratio 1.10 and a degree of compaction 80%. In order to get the uniform density, the specimens were compacted in 5 layers, each 2cm thick (Rasool et al. 2015). The test apparatus used in this study consists of a double-walled triaxial cell, an axial loading device, pore-air, pore water and cell pressure transducers. The salient feature of this triaxial apparatus is that both pore air and water pressures can be measured separately. Water in an unsaturated soil specimen was infiltrated from the bottom pedestal which was connected to a beaker and the pore water pressure transducer through the water line. The beaker was placed on an external load cell to measure the amount of drained water and encased in a pressure chamber to control pore water pressure as shown in Figure 1. The rate of infiltration was controlled by pressure applied on top of the water surface in the beaker.

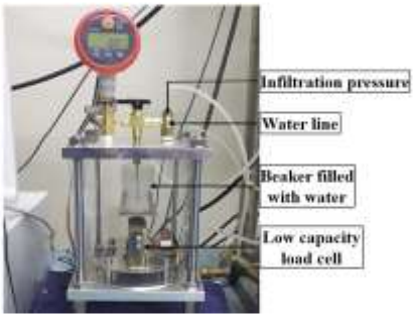

Fig. 1. External load cell to measure amount of drained water.

2.2 Experimental procedure

To investigate the failure mechanism of soil slopes and to obtain the associated shear resistance change due to water infiltration, two series of drained triaxial shearing infiltration tests are carried out on unsaturated soil specimens. The tests in the first series are named as shear-infiltration tests and second as a pre-infiltration shear test. Figure 2 shows the stress paths adopted in two test series. The shear-infiltration test is conducted in order to observe the shear behavior of soil in a slope when it is failed under water infiltration conditions.

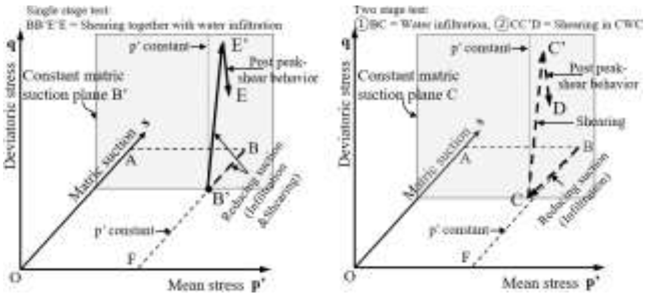

Fig. 2. Stress paths adopted in (a) Shear-infiltration;
(b) Pre-infiltration shear test series.

The stress path of the shear-infiltration test is shown in Figure 2a. All the shear-infiltration tests performed in this study were single stage tests. The soil specimens prepared with static compaction were placed on the saturated pedestal having a membrane filter and initial matric suction was measured (B). The desired infiltration pressure was applied to chamber shown in Figure 1 by keeping the drainage valve for the pore water pressure closed. Once the infiltration pressure was applied to the chamber and kept constant so as to keep suction constant throughout the shear process, the shearing process was started simultaneously by opening the drainage valve for the pore water pressure. Path *BB'* shows the reduction in matric suction which occurred with water infiltration along with shearing. *B'E'* is the increase in deviator stress during water infiltration within the constant matric suction plane B' with the change of p'. Finally, *EE'* is the movement of stress path rightwards within the constant suction plane B' after the failure of soil specimen. During the shear-infiltration test, the drainage valve for pore-air remained open (i.e. under drained conditions). The pre-infiltration shear test is conducted to simulate the condition of a soil slope during or after a rainy period when the soil above the groundwater table experienced a wetting process that caused the pore-water pressure to become negative as a result reduction in shear strength occurred. The stress path of the pre-infiltration shear test is shown in Figure 2b. There are two main stages in the pre-infiltration shear tests performed in this study. The first stage of the test is to infiltrate water from the base of the saturated pedestal through high air entry membrane filter into the soil specimen while maintaining the zero axial strain on the specimen (B→C). The second stage of the test is to shear the soil specimen under constant water content conditions without allowing drainage water. The method of measuring matric suction for pre-infiltration tests is essentially similar to shear-infiltration tests. However, in this test series after applying the desired infiltration pressure to the chamber, the drainage valve for the pore water pressure was opened while maintaining the zero axial strain on the specimen. Path *BC* shows the reduction in matric suction which results in wetting of soil specimen. The water infiltration was carried out until no further water was infiltrated into the specimen. Once the water infiltration completed, the soil specimen was sheared in constant water content conditions by closing drainage valve for the pore water pressure. Path *CC*' shows the increase in deviator stress of soil specimen when the shearing was carried out in constant water conditions within constant suction plane C. During the shearing, it was observed that the matric suction increased slightly, therefore, the stress path *CC'D* moved towards the back of constant matric suction plane C. During the pre-infiltration shear test the drainage valve for pore-air remained open. The stress state of specimens for this study is shown in Table 1. The shear infiltration and pre-infiltration tests were carried out in unconfined conditions i.e. at a net normal stress of 0kPa and matric suction was decreased to 15, 10, 5, 0kPa and 20, 15, 10, 5, 0kPa.

Table 1. Stress state of specimens

$\sigma_n = (\sigma_a - U_a)$	Test series	Ua	Uw	s = (Ua-Uw)
0	Shear-infiltration (SI)	20	0	20
		20	5	15
		20	10	10
		20	15	5
0	Pre-infiltration (PI)	20	0	20
		20	5	15
		20	10	10
		20	15	5
		20	20	0

*All values in kPa

3 EXPERIMENATL RESULTS

In this part, the experimental results from two test series are presented and discussed. For both test series, after measurement of initial matric suction, pore air and cell pressures were increased using axis translation technique to keep pore-water pressure above atmospheric. Figure 3 shows a typical response of a decrease in matric suction due to increase in pore-water pressure. The axial strain on the abscissa is for shear-infiltration test series in which the matric suction was kept constant during the shear process with water infiltration. The time is for pre-infiltration shear test series in which the water infiltration was made before the shearing process by keeping matric suction constant. Then, the shearing was carried out in constant water content conditions.

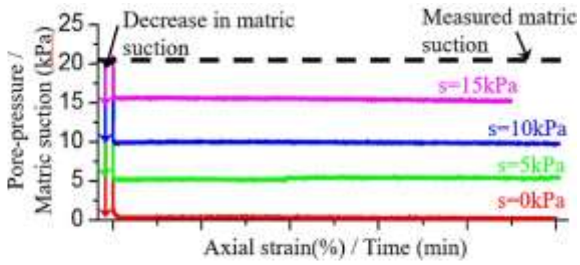

Fig. 3. Decrease in matirc suction for test series.

3.1 Shear-infiltration (SI) test

Four tests were conducted under the stress states as shown in Table 1. Figure 4b shows the results of the deviator stress versus the axial strain. For each soil specimen, the deviator stress increased almost linearly with axial strain and decreased with a decrease in matric suction. The axial strain corresponding to the peak strength for all unsaturated soil specimens ranged between 1.20% to 2.10%. Due to water infiltration during the shearing process, the stress-strain curves showed strain softening at a higher axial strain of above 6%. Following Japanese Geotechnical Society Standard "JGS 0527-1998 Method for Triaxial Compression Test on Unsaturated Soils" the shearing was continued to 15% axial strain. At the end of each test, it was observed that all the soil specimens showed the failure by bulging. As the soil was compacted at degree of compaction of 80% during the preparation stage, the impact of over-consolidation stress history can be clearly seen. First, a peak failure followed by the post-peak softening type of stress-strain response, secondly in the form of dilation type of volume change response during the shearing stage (Figure 6). Figure 4a shows the water volumetric strain throughout the shear-infiltration test. Water volumetric strain is defined as the percentage of infiltrated water volume change relative to the initial total volume of the specimen. It increased during shearing with an increase in axial strain due to water infiltration. It shows a direct relationship between the volume of water infiltrated into the soil specimen and deformation. The volume of water infiltrated into soil specimens corresponding to decrease in matric suction of 15, 10, 5 and 0kPa was 4, 12, 28 and 35cm^3. It can also be seen that most of the water was infiltrated up to peak deviator stress (represented as x), after which water infiltration became gradually constant till the end of the shear process. Figure 4c shows increase in saturation ratio due to increase in water content. When the matric suction was about 0kPa the maximum saturation ratio achieved was ≈86%. That means the specimens could not be fully saturated even at zero suction. The incomplete full saturation at zero suction may be attributed to the trapped air in the pores of soil specimens or in the testing system. The specimen SI-s15 initially showed an increase in saturation ratio up to peak deviator stress after which it decreased. As the small amount of water was infiltrated up to peak deviator stress which contributes to increasing saturation ratio and then became constant, the further decrease in saturation ratio is due to the dilative behavior of specimen. Lastly, the shear-infiltration tests showed that maximum amount of water infiltrated into the soil specimen was 35cm^3 at 0kPa matric suction which reduced shear stress to 55%.

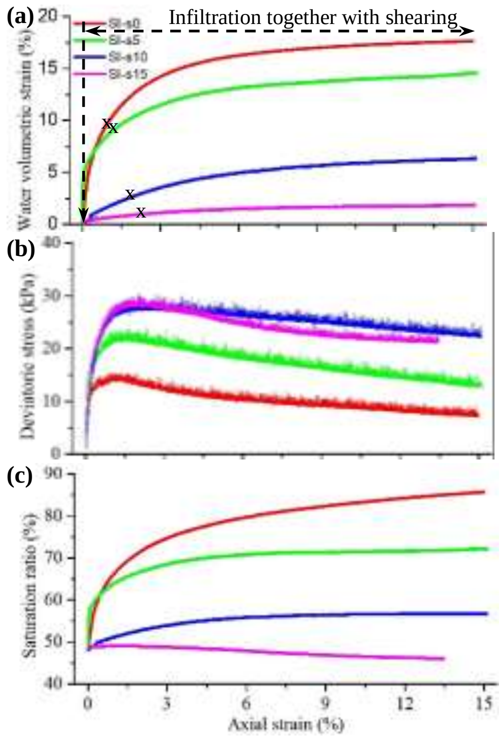

Fig. 4. Results of shear-infiltration tests: (a) water volumetric strain; (b) deviator stress; (c) saturation ratio.

3.2 Pre-infiltration (PI) shear test

Five tests were conducted under the stress state as shown in Table 1. In this series, water was infiltrated into soil specimens before the shearing process which is shown in Figure 5a. No water was infiltrated into the specimen at 20kPa matric suction. However, the amount of water infiltrated into soil specimens increased with decrease in matric suction and the maximum amount of water infiltrated was ≈36cm^3 at 0kPa matric suction which reduced shear stress to 85%. Due to a large amount of infiltrated water, the saturation ratio of specimen increased from 47.5% to 82.2%, as a result the specimen became slurry and showed very low deviator stress of 4kPa. Due to less amount of water infiltration, specimen PI-s10, s15, s20 showed decrease in saturation ratio due to the dilative behavior of specimen. The deviator stress versus axial strain behavior of other specimens is shown in Figure 5b. The maximum deviator stress was obtained by specimen sheared at 20kPa matric suction, it decreased with decrease in matric suction as water infiltration increased. Change in matric suction during water infiltration and shearing process is shown in Figure 5c. The specimens were sheared in constant water constant

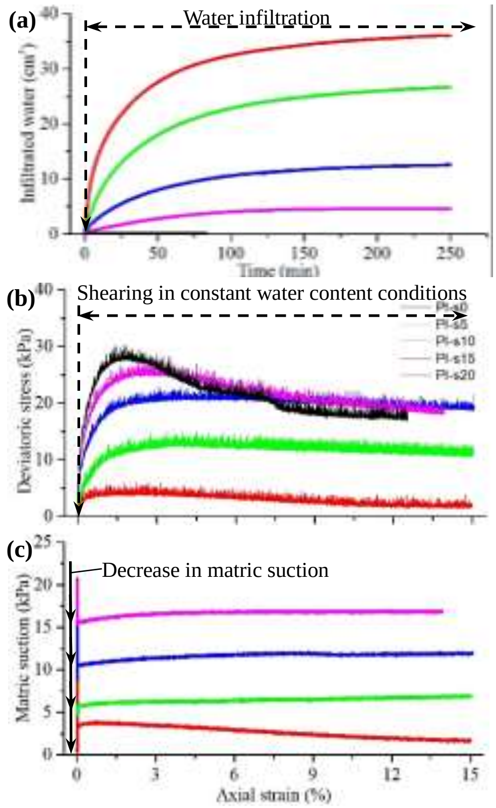

Fig. 5. Results of pre-infiltration shear tests: (a) infiltrated water; (b) deviator stress; (c) matric suction.

conditions, as a result, a small decrease in pore water pressure was observed in specimens PI-s5, s10, s15, s20 and relatively large decrease in specimen PI-s0, due to which matric suction increased during the shearing process. Due to increase in matric suction during shearing process the stress path moved away from constant suction plane shown in Figure 2b.

3.3 Discussion

The deformation behavior of SI test series is shown in Figure 6. Due to high past pressure the specimens in both test series initially showed dilative behavior, however, dilatancy decreased with the increase in water infiltration. The specimen SI-s0 initially showed dilation followed by compression with an increase in axial strain due to water infiltration. The change in soil behavior from dilatant to compression is also termed as "softening of the soil". The figure also shows that the peak deviator stress occurs within small volumetric strain range and it is difficult to get any direct relation between deviator stress and volume deformation. A more direct relation is drawn in Figure 7. The figure shows that initial water content of soil specimens was 20%, the specimen prepared at this water content give maximum deviator stress and for each specimen the deviator stress decreased linearly with increase in water content. In both series, at 15kPa matric suction almost the same amount of water was infiltrated, the specimens showed the same volume deformation and the difference in shear stress was not that much. However, at 0kPa matric suction although more deformation was

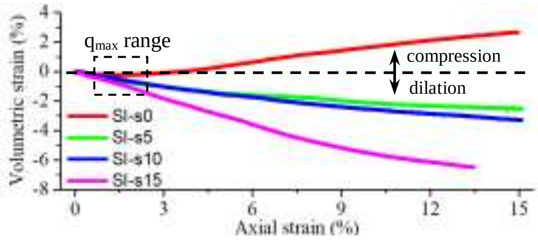

Fig. 6. Deformation behavior of shear- infiltration test.

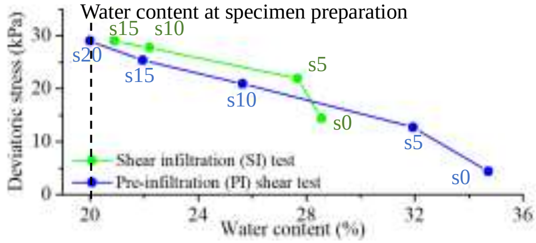

Fig. 7. Relationship between q_{peak} and water content.

showed by the specimen tested in shear-infiltration conditions but more reduction in shear stress was showed by specimen tested in pre-infiltration conditions as more amount of water was infiltrated in this condition. This shows that soil slopes subjected to rainfalls are more vulnerable to failure than other factors. It also shows that decrease in shear stress of the unsaturated soil is not directly related to volume deformations but related to amount of water infiltrated or increase in water content of soil slopes.

4 CONCLUSIONS

The test results showed that the soil subjected to shear-infiltration conditions failed at higher shear strength than pre-infiltration conditions. The maximum reduction in shear strength was 55% and 85% respectively. It was also observed that the decrease in shear strength of the unsaturated soil is directly related to the increase in water content. This indicates that a better approach for the early warning system to predict the occurrence of slope failure is one that incorporated the monitoring of water content instead of just depending on the monitoring the slope deformations.

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