

INFLUENCE OF MATRIC SUCTION ON INSTABILITY OF UNSATURATED SILTY SOIL IN UNCONFINED CONDITIONS

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ABSTRACT: Rainfall has been recognized as one of the main causes of natural or manmade slope failure in many tropical areas of the world. In order to reduce and mitigate rainfall-induced slope failures, there is a need to develop an understanding of reduction in shear strength of soil due to water infiltration. This research aimed at understanding the influence of matric suction on water infiltration and transformation of shear strength in unsaturated soil in unconfined condition. In the present study, two types of test series have been performed using modern triaxial test apparatus: (1) shear-infiltration test, and (2) pre-wetting shear test. From test results, it was concluded that water infiltration causes the excessive deformations and softening which decreases the cohesion and hence reduces the shear strength of the soil. The more decrease in shear strength was witnessed in case of pre-wetting shear tests and maximum reduction observed was 85% against 36cm³ of infiltrated water.

Keywords: Slope failure, Water infiltration, Suction, Shear strength, Unconfined

1. INTRODUCTION

A number of shallow depth slope failures have taken place during or just after heavy rainfall. Most of these slope failures are characterized by the fact that they take place in silty and sandy soils. Some of them seem to be caused not only by an increase of pore water pressure in soils resulting from a rise in the groundwater table, but also by the degradation of the strength of soil forming the slopes. In view of these conditions, Yoshida et al. estimated that the cause of the rain-induced slope failure is largely due to a reduction in strength of the slope-forming soil materials caused by the infiltration of water [11]. The amount of rainwater that infiltrates the slope is an important factor. Infiltration of rainwater into a soil slope may impair slope stability by changing the pore water pressure in the soil which in turn controls the water content of the soil. It is important to understand the pore-water pressure changes due to water infiltration in order to calculate the extent of reduction of shear strength under certain rainfall condition. It has implicated that during rainfall, the increased water content in the soil decreases the soil suction above the ground water table and, thus, the shear strength of the soil [7].

The stress state in natural slope or the surface layer of an embankment is under very low confining pressure conditions. A triaxial test performed in unconfined conditions can simulate this type of situations. From a practical standpoint, the test performed in unconfined conditions can also play an important role to get a thorough understanding of the mechanical behavior of unsaturated soils and to

predict the stability and deformation of the surface layer in natural slopes or embankments. Since no confining pressure is applied to soil specimen in unconfined conditions, it is primarily the matric suction that controls the measured shear strength. There have been very few studies on unsaturated soils performed in triaxial test apparatus in unconfined conditions. Kato et al. (2002), Pineda et al. (2005), Chae et al. (2010), Kwon et al. (2011) have examined the behavior of unsaturated soil in unconfined conditions and tried to interpret the effects of matric suction and suction stress on the shear strength of the soil.

The detailed and fundamental studies on the instability of unsaturated soils due to matric suction have seldom been performed in a laboratory using element test. In the present study, a series of shear infiltration and the pre-wetting shear test has been conducted with the main objective of investigating the mechanical behavior and failure mechanism of silty soil gradually infiltrated by water. The effects of decrease in matric suction on water absorption, volume deformation and shear strength are discussed, and finally, the results of two series are compared.

2. TESTING PROGRAMME

In this part physical properties of soil, specimen properties, test program and main parts of triaxial test apparatus will be discussed.

2.1 Physical properties of soil

DL Clay is the commercial name of the soil used

in this study, it is a fine material without plasticity. The appearance of freshly and freely deposited DL clay looks yellowish brown. Dried and powdered DL clay consists of Kaolinite and silica. Kaolinite and silica stones are used as agricultural chemicals. According to the Japanese Geotechnical Society (JGS), it is classified as having Medium-Low compressibility (ML) and is composed of 90% silt and 10% clay which show that it is larger in grain size than average clay. Table 1 shows the physical properties of this soil.

Table 1 Physical properties of DL clay

Properties	Unit	Value
Density of soil particle, ρ_s	g/cm ³	2.654
Consistency	-	NP
Maximum dry density, ρ_{dmax}	g/cm ³	1.538
Optimum water content	%	20

2.2 Specimen properties

The specimens used in the present study were prepared using the static compaction method. Prior to performing the compaction, dry DL clay, with a soil particle density of 2.654g/cm³, was mixed well with water to make up 20% of the water content. Then, the mixed wet DL clay was compacted statically in a cylindrical mold, 5cm in diameter, to obtain a uniform density throughout the length of the specimens. The specimens were compacted in 5 layers, each 2cm thick [10]. The low energy from the static compaction can produce a uniform density that prevents the development of a weaker region in the specimen [8]. The pre-consolidation pressure on a specimen during preparation was approximately 300kPa. The void ratio of the specimens was around 1.1 and the initial degree of saturation was 47.5%. The measured initial matric suction was 19~20kPa for all specimens, which means that the preparation procedure was always followed carefully in order to maintain a suction state of approximately 20kPa. All the specimens had a dry density of 1.3g/cm³ and a degree of compaction 80%.

2.3 Soil water characteristic curve (SWCC)

The relationship between matric suction and water content is generally termed as the soil-water characteristic curve (SWCC). Such curves are usually measured in the laboratory through pressure plate tests or pF tests, though the current experimental setup was used to establish the SWCC relation. Several soil specimens with varying water content were prepared and placed on top of a membrane filter and values of initial suction were measured, the same technique to draw SWCC was also used by Farooq et al. (2004). Fig. 1 shows the expected results i.e. the suction decreases as the saturation ratio increases.

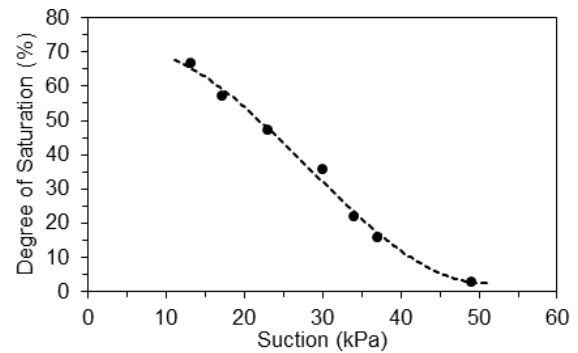


Fig. 1 Variation of suction with degree of saturation

2.4 Test series

Two series of experiments with twelve shearing tests on unsaturated soil specimens were conducted under stress states as shown in Table 2 to observe the shear strength of soil due to the decrease of matric suction. The first series involved the infiltration of water during the shearing process in drainage conditions, whereas, in the second series, wetting of specimens was performed before the shearing process.

Table 2 Stress state of specimens

Net normal stress ($\sigma_a - u_a$) kPa	Matric suction ($u_a - u_w$) kPa				
	0	5	10	15	20
Shear infiltration (SI) test					
0	✓	✓	✓	✓	-
Pre-wetting (PW) test					
0	✓	✓	✓	✓	✓
20	✓	✓	-	-	-
30	-	-	✓	-	-

2.5 Experimental setup

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 as shown in Fig. 1(a). The salient feature of this triaxial apparatus is that both pore air and water pressures can be measured separately. The Pore air pressure transducer is installed in the top cap and is connected to the air regulator in order to give a continuous supply of air throughout the test. The change in volume of the specimen during the triaxial tests was measured as the change in the water level in the inner cell through a Low Capacity Differential Pressure Transducer (LCDPT). In order to separate the routes for measurement and control of the pore air pressure and the pore water pressure, a membrane and a PTFE sheet were used. The PTFE sheet was placed in the top cap (Fig. 2(c)) to cut off the flow of water, and the membrane filter was installed in the lower pedestal (Fig. 2(d)) to cut off the flow of air. The thin membrane filter with pores of 0.45mm has an air entry value of 420kPa. In

addition, a solenoid controlled valve to control the exhaust air was also installed in the air drainage line inside the top cap to minimize the air volume (in the air drainage line).

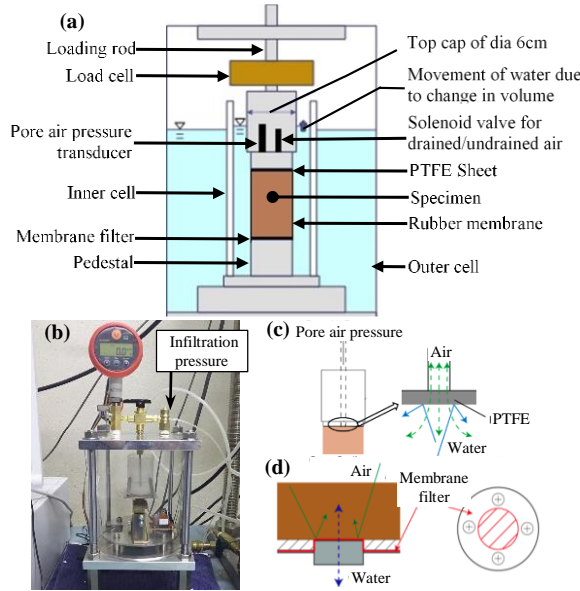


Fig. 2 (a) Schematic figure of the triaxial cell; (b) external load cell; (c) top cap; (d) bottom pedestal

Since this study focuses more on shallow slope failure, it was assumed that the pore air pressure remained atmospheric throughout the test and water infiltration increased only the pore water pressure [2]. Water in an unsaturated soil specimen was injected 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 and encased in a pressure chamber as shown in Fig. 2(b). The rate of infiltration was controlled by regulating the pressure applied on top of the water surface in the beaker [2], [8].

3. EXPERIMENTAL RESULTS

In this parts, experimental results from two test series will be presented and discussed.

3.1 Shear Infiltration (SI) test

A shear infiltration test simulates the condition and failure mechanisms of slop failures induced by water infiltration. The schematic representation of the test procedure is shown in Fig. 3. After measurement of the initial matric suction, pore air and cell pressures were increased using axis translation technique to keep pore water pressure above atmospheric [4]. Four soil specimens were tested in this series, and before the start of the shearing process each specimen was brought to a

matric suction value of 0kPa, 5kPa, 10kPa, and 15kPa by applying an infiltration pressure of 20kPa, 15kPa, 10kPa, and 5kPa. The pore air was drained and controlled throughout the test process, whereas, drainage valve for pore water was kept open during the shear process in order to continuously supply water to the specimen during the shear process.

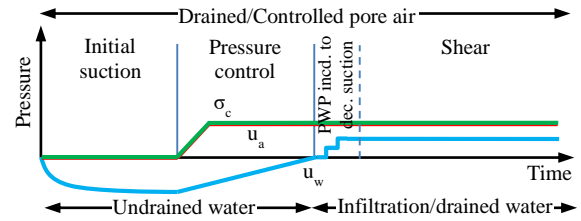


Fig. 3 Schematic illustration of shear infiltration test

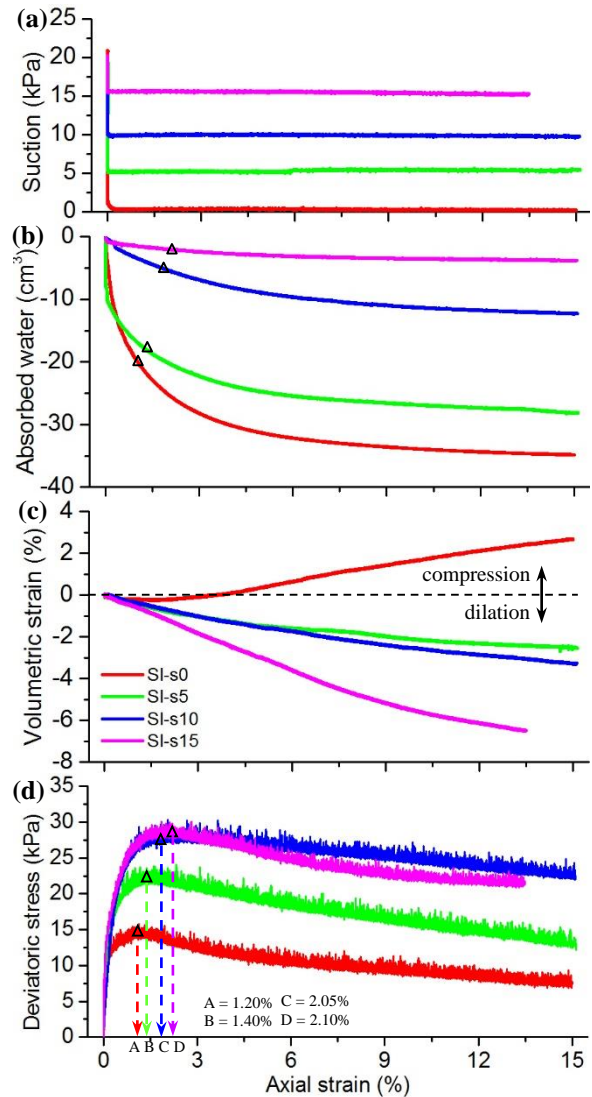


Fig. 4 Shear infiltration test results: (a) matric suction; (b) water flow; (c) volume change; (d) deviator stress

Fig. 4 shows the results of the shear infiltration

test conducted on unsaturated soil specimens in unconfined conditions. Before the start of the shearing process, an infiltration pressure to individual specimens was applied and the drainage valve for pore water was opened at the start of the shearing process to decrease soil suction as shown in Fig. 4(a). The value of the infiltration pressure was kept the same therefore no further change in suction was observed during the shearing process. Rainfall-induced slope failures are directly related to rainfall intensity in a specific area. Some part of rain water penetrates and some flows as surface runoff. A better parameter to analyze would be the volume of rainwater infiltrating the soil profile as shown in Fig. 4(b), it shows a more direct relation between water content and deformation. It can be seen that the water infiltration continued until the end of the shearing process and the amount of water flow into specimen increases while matric suction decreases. In addition to this, it was observed that most of the water was infiltrated up to peak deviatoric stress (represented as Δ), after which water absorption becomes gradually constant. The bond between the soil particles broke after attaining peak strength, which affects the water infiltration process, it decreases and gradually becomes constant towards the end of shearing.

The volumetric strain response during shearing is important to assess or predict the likely field deformations. Hence the monitoring of volume changes during shearing becomes crucial. The volume changes due to water absorption during shearing process are shown in Fig. 4(c). All the test specimens showed dilatative behavior, however, dilatancy decreased with the increase in water absorption. The specimen SI-s0 showed first an initial dilation followed by compression with an increase in axial strain due to water absorption. As expected, stress-strain curves in Fig. 4(d) show that deviatoric stress decreases with a decrease in matric suction. The axial strain corresponding to the peak strength for all unsaturated 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% of axial strain. At the end of each test, it was observed that all the specimens showed failure by bulging. All the specimens had an over consolidation stress history of approximately 300kPa. The impact of over consolidated stress history and imposed suction is clearly seen in the form of first, a peak failure followed by the post-peak softening type of stress-strain response and second, in the form of dilation type of volume change response during the shearing stage.

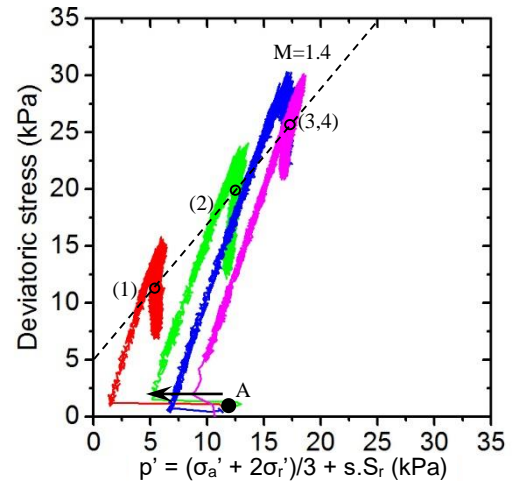


Fig. 5 Stress paths for shear infiltration tests

The stress paths followed by the soil specimens during the shear infiltration test are plotted in p' - q plot as shown in Fig. 5. Since the pore air pressure was exhausted in this series, the stress paths thus sloped at a gradient of 1:3 on the p' - q plot. Initially, the stress path moved towards the left from point “A” due to a decrease in matric suction. The soil used in this study was over-consolidated soil, for such soils, the stress path first crosses the critical state line (CSL) but eventually reverses its direction and fails on a critical state line corresponding to critical state strength (1,2,3,4) and ultimately dropped to residual strength. The gradient M of CSL was 1.4 and intercept q -axis was 5kPa.

3.2 Pre-wetting (PW) shear test

A pre-wetting shear test simulates the condition and failure mechanism of a soil slope after a rainy period where the soil above the water table experienced a wetting process. Such kind of situation has seldom been tested in the laboratory using unsaturated triaxial test apparatus. Initial suction was measured and matric suction was applied using the axis-translation technique [4]. The initial phase of each test consisted of a wetting stage in which five soil specimens were brought to matric suction values of 0kPa, 5kPa, 10kPa, 15kPa and 20kPa respectively. This was achieved by applying an infiltration pressure of 20kPa, 15kPa, 10kPa, 5kPa and 0kPa. The wetting stage of each test was finished when no further change in the flow of water into the specimen was observed. After the wetting stage, the drainage valve for pore water was closed and each specimen was subjected to shear under undrained conditions with measurement of pore water pressure. The pore air was drained and controlled throughout the test process. Fig. 6 shows the schematic diagram of the test procedure. In this series, three more tests were carried out by applying low confining stress to make a comparison.

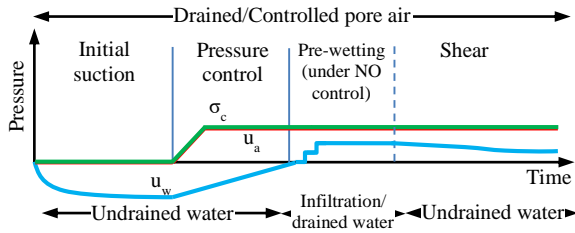


Fig. 6 Schematic figure of pre-wetting shear test

Fig. 7 shows the flow of water into the specimen due to a decrease in matric suction during the wetting process as a function of time. The volume of water infiltrating the specimen varied from 0cm³ to 36cm³ for specimens which were brought to a suction of 20kPa to 0kPa. At matric suction value of 20kPa no flow of water occurred which shows that a decrease in suction was required to start the infiltration process, the amount of water flow increases with a decrease in suction. However, by just applying a small net confining stress of 20 or 30kPa, the amount of water flowing into the specimen decreases. This is because of a decrease in void ratio due to the confining stress.

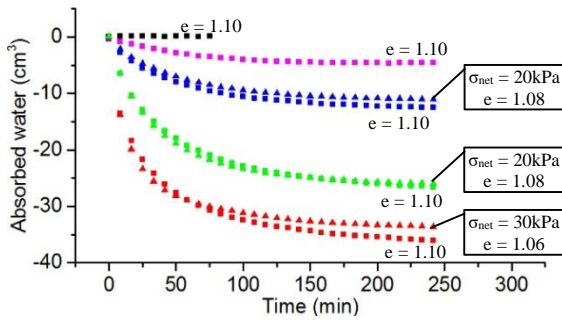


Fig. 7 Flow of water into specimens during wetting

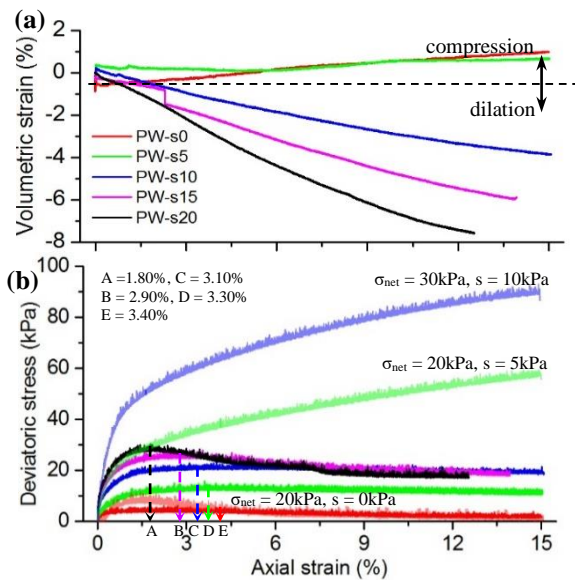


Fig. 8 Pre-wetting shear test results: (a) volume change; (b) deviator stress

The plots of volume change and deviatoric stress versus axial strain relationship for five variable suction pre-wetting shear test is shown in Fig. 8. It can be seen that both stiffness and strength decreases with a decrease in matric suction. This behavior can be related to the influence of matric suction on inter-packet contact forces, which tends to stabilize the soil structure. Specimens with matric suction value of 5kPa or less showed stress-strain behavior typical of normally consolidated soils without a marked reduction of shear strength after attaining peak value, as compared to specimens with matric suction of more than 5kPa which showed stress-strain behavior typical of overconsolidated soils. The different shapes of stress-strain curves during shearing can be explained by looking at how the soil samples were prepared using static compaction technique. The compacted soil behavior was similar to the overconsolidated soil as ~300kPa of vertical stress was applied during sample preparation and tested under zero net stress. This behavior is attributed to dilation of compacted soil [9]. Such specimens show a brittle stress-strain and dilative volume change behavior at a relatively high matric suction as shown by specimen PW-s20, PW-s15 and PW-s10. However, with a decrease in suction the volume of water flow into specimen increases, as a result, stress-strain behavior becomes typical of ductile material and compressive soil behavior was observed in specimen PW-s5 and PW-s0. When specimens with a matric suction of 5kPa and 10kPa were sheared under net confining stress of 20kPa and 30kPa, no peak curve was obtained and specimens showed high strength at the end as compared to unconfined conditions. However, specimens with 0kPa matric suction and net confining stress of 20kPa did not show any remarkable difference. A relationship between water content, mean net stress and matric suction at failure is plotted in 3D space as shown in Fig. 9. It can be seen that mean net stress decrease with increasing water content and a decrease in suction, which shows that water content and suction independently controls the shear strength of soil.

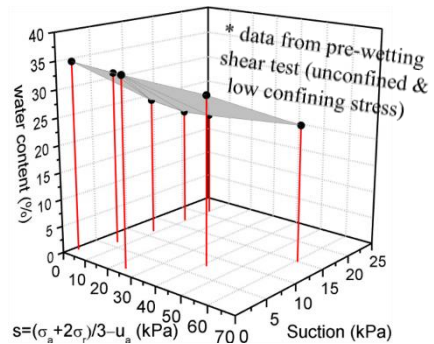


Fig. 9 Relationship between water content, mean net stress, and matric suction

The cohesion of unsaturated soils at a certain level of matric suction can be estimated more efficiently by using extended Mohr-Coulomb failure envelope [3]. The Mohr-Coulomb failure envelope for the study soil was obtained from a series of soil specimen and has a peak angle of shearing ϕ' of 32° and apparent cohesion c' (for a specimen with 0kPa matric suction) 1.7kPa, shown in Fig. 10(a). The cohesion changed with matric suction, however, ϕ remained constant. The angle of the rate of strength due to matric suction ϕ_b is shown in Fig. 10(b) which is ϕ_b 22° for the study soil. This shows that the cohesion of unsaturated soils is reduced due to water infiltration from the surface.

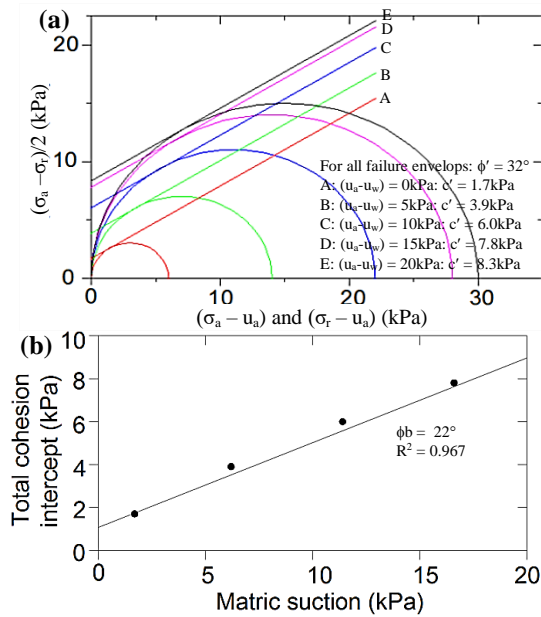


Fig. 10 Pre-wetting shear test results: (a) failure envelope; (b) angle indicating the rate of increase in shear strength with respect to changes in $(u_a - u_w)$

4. DISCUSSION

The results from the shear infiltration tests are compared with the results from the pre-wetting shear tests and are plotted in Fig. 11. Initially, all specimens have almost the same saturation ratio. In the shear infiltration test, due to the flow of water into specimen during shearing process, the saturation ratio increases till residual stage. Due to this increase in the degree of saturation a decrease in deviator stress was observed, the decrease which is small for matric suction values 15kPa and 10kPa and bigger for 5kPa and 0kPa, can be seen in Fig. 11(b). The change in deviator stress with matric suction is non-linear. In the case of pre-wetting shear test the water infiltration was completed before shearing, therefore, a small change in saturation ratio was observed at the start, peak and

residual deviator stress. The amount of water absorbed by the specimen at residual deviator stress stage in shear infiltration test is almost the same as the pre-wetting shear test wetting stage. Due to this, the specimens have almost the same water content and saturation ratio, as a result almost identical peak deviator stresses were observed in pre-wetting shear test as the residual deviator stress in the shear infiltration test, shown in Fig 11(b). The change in the degree of saturation is not only due to the flow of water but also due to the volume of specimen, at matric suction of 15kPa and 20kPa the amount of water infiltration was very small and specimen showed dilatant behavior so a decrease in saturation ratio was observed in both series. When the suction is about zero or at a small value, the saturation ratio is between 80% and 85%. That means the specimens could not be fully saturated even at zero suction. The incompletely full saturation may be attributed to the trapped air in the pores inside soil specimens or in the testing system.

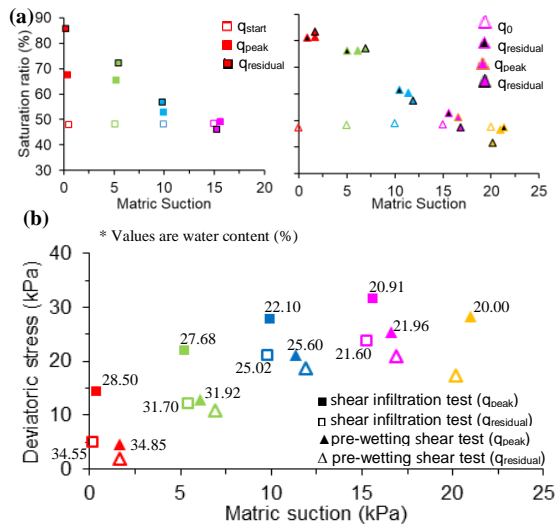


Fig. 11 Comparison of test results: (a) saturation ratio; (b) deviator stress

5. CONCLUSION

A series of laboratory element tests were conducted to examine the instability of unsaturated soil subjected to water infiltration. It was found that under the same matric suction, the soil sheared to failure with pre-wetting condition possessed a lower shear strength than soil sheared to failure under infiltration conditions. The maximum reduction in shear strength due to water infiltration observed in case of SI test was 55% and PW test was 85%. The water infiltration causes excessive deformation changing the soil behavior from dilatant to compression. The slope instability problems, which were always been treated as a shear strength problem, also appeared to be a volume change problem. It seems that a better way

of preventing rainfall-induced slope failures is to limit the excessive development of soil deformation rather than just trying to increase the shear strength of slope.

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