Type of the Paper (Article)

Shearing with Infiltration Tests to Study Mechanical Behavior and Failure Mechanism of Shallow Slopes

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Abstract: An experimental series of shearing tests with water infiltration were performed on compacted unsaturated soil to simulate the behavior of shallow slope failures. Soil samples were compacted at moisture contents from dry to wet of optimum moisture content with the degree of saturation varying from 24.0% to 59.5% while maintaining the degree of compaction at 80%. Two series of shearing with infiltration tests were performed in this study. In Series-I, just before the start of shearing, matric suction was decreased by increasing pore water pressure to start water infiltration i.e. shearing is carried simultaneously with water infiltration. In Series-II, the soil was first sheared with drained pore air and undrained pore water to pre-defined value of deviatoric stress, after which matric suction was decreased by increasing pore water pressure to start water infiltration and shearing is performed by keeping deviatoric stress constant on specimen. The test results showed that the decrease in matric suction has an effect on volume of infiltrated water and degree of saturation. The soil slopes compacted on the dry side of optimum moisture content showed better performance than other soils, they require more decrease in matric suction to start water infiltration and showed higher deviatoric stress. In addition to this, water infiltration alone can cause the failure of shallow slopes without having to have any further loading.

Keywords: Shallow Slopes, Unsaturated Soil, Slope Stability, Deviatoric stress, Pore-water Pressure, Water Infiltration.

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1. Introduction

Natural slopes and man-made embankments are generally in unsaturated state, their failure causes a lot of damage to infrastructure and thus have a significant financial impact on the country's economy. Unsaturated slope failures are directly associated with rainfall and water infiltration, therefore, a detail and comprehensive seepage analysis is required to study their behvaior [1]. In order to study the behavior of unsaturated slope both the geotechnical and the hydrological properties are important e.g. the rate of water infiltration, development of pore water pressure, the volume deformation and rate of change in shear strength is affected by change in matric [2]. Previously, a number of experimental studies have been carried out to explore the unsaturated soil behavior [3–7]. The finding of studies carried by Brooks and Corey, 1964; Chenggang, Biwei and Liangtong, 1998; Gavin and Xue, 2007; Rahardjo et al., 2010; Fredlund, Rahardjo and Fredlund, 2012; Shin, Kim and Park, 2013 help in understanding the response of unsaturated soil slopes under water infiltration and the mechanism that lead to failure [8–13]. Some researchers investigated the shear strength and deformation characteristics of unsaturated soil by keeping shear strength constant at 80-90% of maximum shear strength and infiltrating the water in the soil [14–16]. However, all of the studies have been carried out at high net confining stresses. A thorough understanding of the mechanical behavior of unsaturated soils under low confining stresses is important for predicting the stability and deformations of the surface layer in natural slopes or embankments. Chae et al., 2010;

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Marinho and Oliveira, 2012; Kim et al., 2016 performed the research to study the shear strength behavior of unsaturated soil in unconfined conditions or low confining pressures [17–19]. Aubeny and Lytton, 2002; Kim and Lee, 2010; Ray, Jacobs and Ballestero, 2011 studied the stability of shallow slopes by considering seepage conditions with constant suction, preparing one-dimensional infiltration model and developing infinite slope stability methods respectively [20–22]. In previous researches, the effect of reduction in matric suction due to water infiltration is well known on slope stability. However, limited research is available describing how the mechanical behavior and instability of shallow slopes are affected due to change in matric suction on the soil prepared from dry to wet side of optimum moisture content with the same initial density.

The main goal of this research is to study the effect of increase in pore water pressure on behavior and stability of shallow unsaturated slopes and to investigate the mechanism leading to the failure. The soil specimens were prepared at the same initial void ratio but with the different initial degree of saturation. Mechanical behavior of is studied by starting water infiltration at zero deviatoric stress simultaneously with shearing whereas the failure mechanism is studied by infiltration water at 80-90% of maximum deviatoric stress by keeping it constant. The effect of decrease in matric suction has been reported on deformation behavior, shear strength, pore pressures and water infiltration etc. Finally, the effect of change in stress paths due to matric suction is also studied and discussed.

2. Materials and Methods

2.1. Physical Properties of the Soil

DL clay is a commercial name of the soil used in this study that is a fine material with no/low plasticity. The appearance of freshly and freely deposited DL clay is yellowish-brown. Dried and powdered DL clay is composed of Silica and Kaolinite. As per Unified Soil Classification System USCS (ASTM D2487-11, 2011), DL clay is classified as silt and clay with low plasticity (ML-CL) [23]. Table 1 shows the physical properties of the soil and the compaction curve is shown in Figure 1.

Table 1. Physical properties of the tested soil.

Properties	Unit	Value
Specific gravity	g/cm^3	2.635
Percentage of fine content	%	99
Consistency	-	Non-Plastic
Maximum dry density, ρ_{dmax}	g/cm^3	1.55
Optimum moisture content, OMC	%	20
Maximum particle size, d_{max}	mm	0.039
Coefficient of permeability k_s	m/s	6.68×10^{-7}

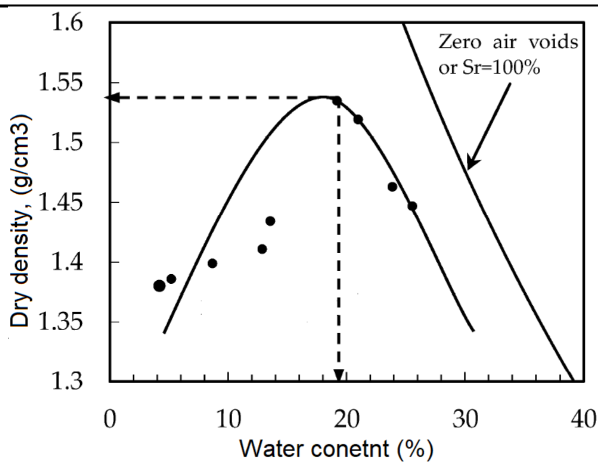

Figure 1. Compaction curve of DL clay

2.2. Specimen Properties

The optimum moisture content of the soil is 20% and the maximum dry density is 1.55 g/cm³. Homogenous specimens were prepared by compacting the soil with a static compaction machine in 5 layers, each layer being 2 cm thick [24]. Before compaction, water was added to the dry DL clay to prepare soil samples at water contents of 10%, 15%, 20% and 25% i.e. from dry side to wet side of optimum moisture content. The specimens had the constant void ratio of 1.10 and density of 1.25g/cm³ at different degrees of saturation (Sr) of 24%, 36%, 49% and 59.5%. The physical properties of the specimens are listed in Table 2.

Table 2. Properties of all specimens tested in this study

Properties	Values			
Water content, ω (%)	**10**	**15**	**20**	**25**
Specimen weight, m (g)	267.50	278.60	291.95	302.90
Specimen volume, V (cm³)	194.20	194.20	194.20	194.20
Dry density, ρ_d (g/cm³)	1.25	1.25	1.25	1.25
Degree of saturation, S_r (%)	24.00	36.00	49.00	59.50
Void ratio, e	1.10	1.10	1.10	1.10
Degree of compaction, D_c (%)	80	80	80	80

Degree of compaction of all specimens was maintained at 80%. The pressure applied to the soil at the time of sample preparation was higher than the applied stresses during the test phase hence the samples are considered to be over-consolidated. According to [25], unsaturated soils which exist nearby ground surface and soils compressed manually are generally over-consolidated due to environmental changes. The compaction pressure on the soil samples during preparation is shown in Figure 2.

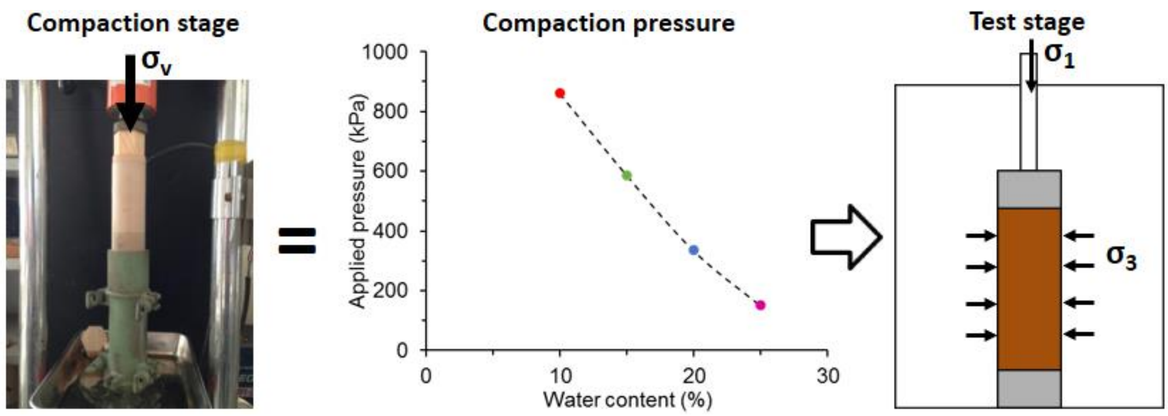

Figure 2. Compaction pressure on soil specimen

The nomenclature used in describing the test results is "S-I-X" and "S-II-X". Where "S-I" is for shearing with infiltration tests performed in Series-I and "S-II" is for shearing with infiltration tests performed in Series-II. "X" is the compacted water content of 10%, 15%, 20% and 25%. e.g. "S-I-15" is the shearing with infiltration tests in Series-I on the specimen with 15% water content.

2.3. Experimental Setup

Considering the requirements of unsaturated soil testing, this study has been performed on a modern triaxial test device. The schematic illustration of the triaxial test apparatus is shown in Figure 3. It consists of lucid acrylic cell, inner load cell, local vertical deformation transducer (LVDT), cell pressure transducer, pore air pressure transducer and pore water pressure transducer. The total volume change of the soil specimen was measured with low capacity differential pressure transducer (LCDPT). The procedure of measuring specimen volume change with LCDPT has been described in

Japanese Geotechnical Society standard (JGS 0527-2009) [26]. The top cap of 6 cm diameter has a solenoid valve to control drained/undrained air and a pore air pressure transducer. A polytetrafluoroethylene, known as Teflon (PTFE) sheet and a membrane filter has been used to isolate the paths for measurement and control of both pore pressures (i.e. air and water). The PTFE sheet allows the flow of air and resists the follow of water and pasted at the bottom of the top cap. The membrane filter with pore size of 0.45μm allows the flow of water and resists the flow of air and placed on the bottom pedestal. The membrane filter has air entry value (AEV) of 250 kPa. The pore water pressure was measured by pore water pressure transducer having a maximum capacity of 1 MPa.

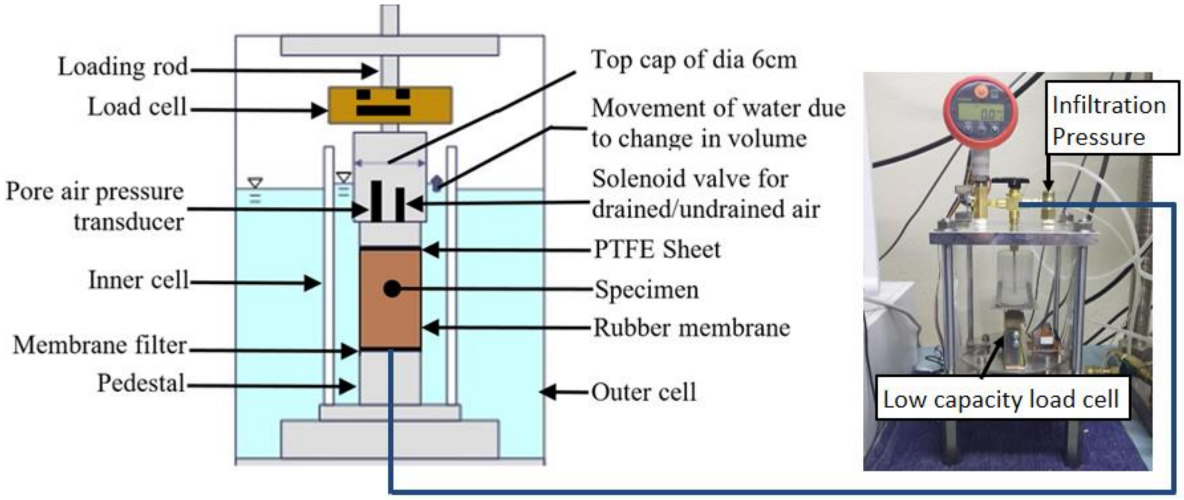

Figure 3. (a) Schematic figure of triaxial cell: (b) external load cell for water infiltration

Various tests performed on unsaturated soils are, fully drained, undrained and constant water content tests [27]. In fully drained tests, both pore air and pore water pressures are controlled and the drainage valves are kept open for both air and water so that no excess pore pressure is developed. In this research, the pore air pressure was controlled with an air regulator which was also used to ensure the continuous supply of air throughout the test. The pore water pressure was controlled by applying air pressure on top of the chamber shown in Figure 3(b). The water in the soil sample was infiltrated from the bottom pedestal which was connected to a beaker and the pore water pressure transducer through the waterline. Figure 3(b) shows a beaker placed on an external load cell and encased in a pressure chamber. The infiltration rate was controlled by regulating the pressure of air which was applied on top of the water surface in the beaker [14,28].

2.4. Test Procedure

Shear with infiltration test performed in this study is a type of fully drained shear test in which matric suction is decreased just before starting the shear process to start water infiltration and then kept constant throughout the test. In these tests water infiltration is performed starting at zero deviatoric stress and is designed to study the mechanical behavior of unsaturated soil slopes. Two types of shearing with infiltration tests are performed. In the first series (Series-I), the water infiltration was executed simultaneously with shearing (starting from zero deviatoric stress until failure is achieved).

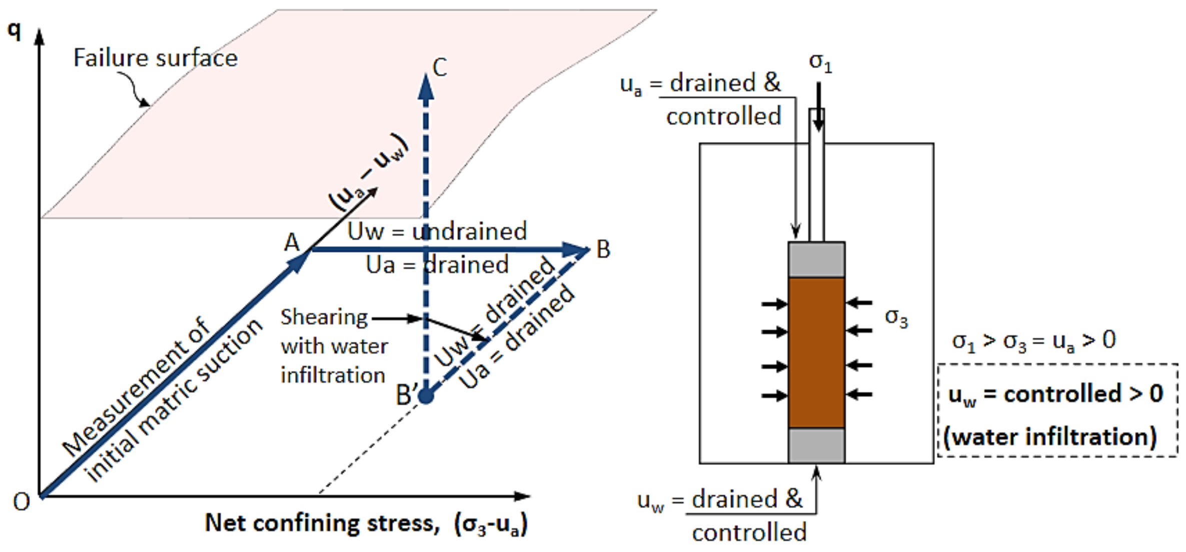

Figure 4. Schematic illustration of Series-I when water infiltration carried simultaneously with shearing

Figure 4 shows the schematic illustration of tests performed in Series-I. After measurement of initial matric suction (OA) the axis translation technique was applied [29]. After that, the specimens were first isotropically consolidated at a confining pressure of σ_3 with undrained pore water uw and drained/controlled pore air pressures ua. The net confining pressure and matric suction on soil samples at the end of consolidation was recorded as (σ_3 – ua) and (ua – uw) respectively at point B. Just before the start of the shear process, valve for pore water pressure was opened and pore water pressure was increased to allow water infiltration, the pore water pressure was then kept drained and controlled throughout the test process (BC). The path from B to B′ occurred within no time. During the shearing process, specimens had constant net confining pressure (σ_3 – ua) and matric suction (ua – uw) whereas deviator stress increases during shearing until failure conditions were achieved. Tests in Series-I are performed to study the mechanical behavior unsaturated soil slopes.

Figure 5 shows the schematic illustration of tests performed in Series-II. In the second series (Series-II), after measuring the initial suction (OA) and applying the axis translation technique, the specimens were isotropically consolidated (AB). The net confining pressure and matric suction on soil samples at the end of consolidation was recorded as (σ_3 – ua) and (ua – uw), respectively at point B. The shearing in this test series was performed in two stages. In the 1st shear shown in Figure 5(b) the specimens were sheared up to the predefined value of deviatoric stress i.e. (80-90% of qmax) with drained pore air and undrained pore water pressure (BD). Once the required value of deviatoric stress was achieved the specimens in 2nd shear was sheared by keeping the deviatoric stress constant (DE) as shown in Figure 5(c). Just before the start of 2nd shear, valve for pore water pressure was opened and pore water pressure was increased to allow water infiltration, the pore water pressure was then kept drained and controlled afterwards. During 2nd shear the specimens had constant net confining pressure (σ_3 – ua) and matric suction (ua – uw) whereas the deviator stress was kept constant and water infiltration alone caused the failure of specimen (D′E). The tests in Series-II are performed to study the failure mechanism of unsaturated soil slopes.

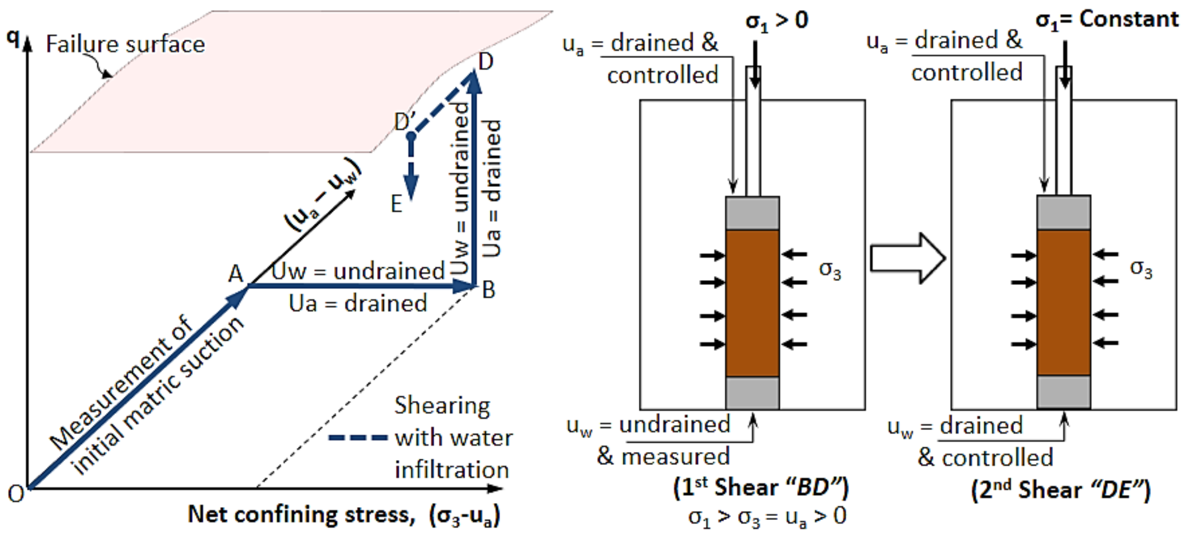

Figure 5. Schematic illustration of Series-II when water infiltration carried by keeping deviatoric stress constant at 80-90% of q_{max}

3. Experimental Results

3.1. Measurement of Initial Suction

The soil compacted at different water contents lead to a difference in initial matric suction. The previous studies also show that the behavior of unsaturated soil is influenced by initial suction [30]. However, the distribution of pore water and degree of saturation are factors affecting initial suction. Figure 6 illustrates the change in initial suction of soil samples compacted at w = 10, 15, 20 and 25%.

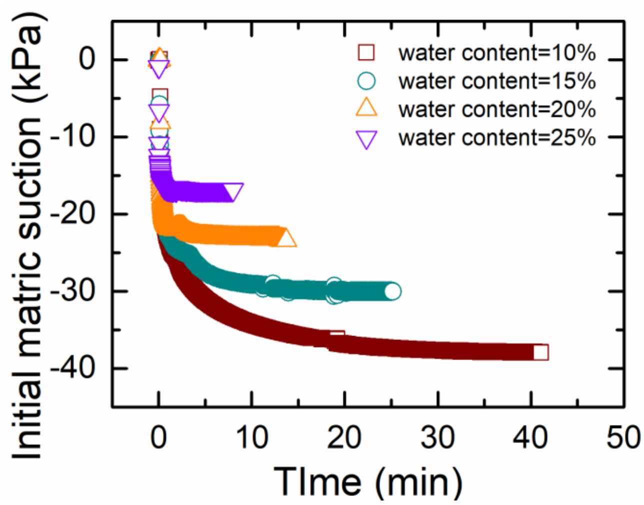

Figure 6. Variation of initial matric suction of specimens prepared with different water content against time

It shows that the values of initial suction when the specimens were set in triaxial apparatus varied with water content. Note that when the water content is low matric suction is high and more time is required to stabilized suction and vice versa. The reduction in initial suction stabilizing time is because of using a thin membrane

3.2. Shearing with infiltration Tests Results

In Series-I, the cell pressure was increased to 20 kPa during the isotropic consolidation process. The pore air pressure was increased equal to cell pressure i.e 20 kPa during the axis translation technique and kept drained and constant afterwards. Just before starting the shear process, pore

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water pressure was increased to 12 kPa, 7 kPa and 5 kPa for specimens with water content 15%, 20% and 25% which decreased the matric suction to 22 kPa, 17 kPa and 12 kPa respectively. In some initial trial tests, it was tried to infiltrate water into the specimens without increasing pore water pressure. However, a small volume of water infiltrated into the specimens. The infiltrated volume of water was not enough to change the soil behavior; therefore, in further test series water was infiltrated by decreasing the matric suction. The pore water pressure was increased by applying infiltration pressure on the top of the chamber. The infiltration chamber is shown in Figure 3b.

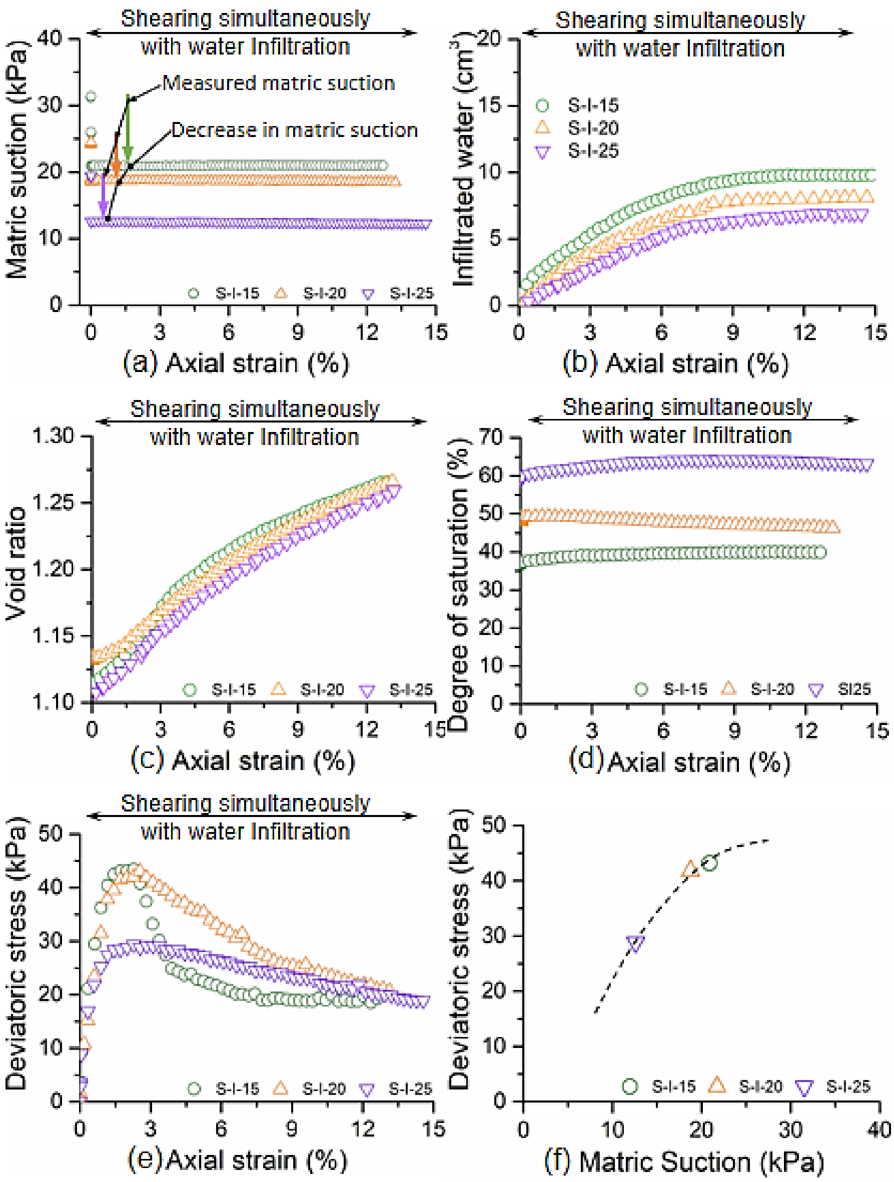

Figure 7. Results of Series-I (a) matric suction, (b) infiltrated water, (c) void ratio, (d) degree of saturation, (e) deviatoric stress, (f) non-linear relation between maximum deviatoric stress and matric suction.

Figure 7(a) shows that matric suction was decreased from the initial measured value just before the start of the shearing process and then kept constant throughout the test. So no further change in matric suction was observed with increase in axial strain. Figure 7(b) shows the corresponding infiltrated water due to decrease in matric suction. It can be observed that as soon as matric suction was decreased, water started infiltrating into the specimens and water infiltration increased gradually with axial strain. In case of specimen S-I-15, matric suction was decreased from 34 kPa to 22 kPa and 10 cm^3 of water was infiltrated. In case of specimen S-I-20, matric suction was decreased from 24 kPa to 17 kPa and 8 cm^3 of water was infiltrated. In case of specimen S-I-25, matric suction

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was decreased from 17 kPa to 12 kPa and 6 cm^3 of water was infiltrated. Although the difference in volume of infiltrated water is observed to be very small, however, it can be seen that water infiltration increased with decrease in matric suction i.e water infiltration was more for the dry specimen. Figure 7(c) shows the relationship between the void ratio and axial strain. For all specimens the void ratio increases from 1.10 to 1.25. The increase in void ratio is due to dilative behavior of specimens which occurred because of high pressure at specimen preparation stage and a high degree of compaction. The small increase in void ratio is due to low confining stress applied during the shear process. The change in degree of saturation due to change in volume of specimens is shown in Figure 7(d). As the water was infiltrated during the shearing process, therefore, degree of saturation increased with increase in axial strain. The maximum water was infiltrated in specimen S-I-15 which increased degree of saturation from 35% to 40%. In case of specimen S-I-20 and S-I-25, as less amount of water was infiltrated in the specimens, therefore, degree of saturation first increased and with further shearing it decreased due to decrease in volume of specimen. Figure 7(e) shows the influence of water infiltration on deviatoric stress. The specimens S-I-15 and S-I-20 showed the peak deviatoric within axial strain range of 0-2.5% followed by post-peak softening. The post-peak drop in deviatoric stress was more for specimen S-I-15 and S-I-20, while no peak deviatoric stress was observed in the stress-strain curve of specimen S-I-25. The peak deviatoric stress increased with matric suction and the specimen S-I-15 showed the maximum shear strength. Figure 7(f) shows the deviatoric stress increased non-linearly with respect to decrease in matric suction. The effect of matric suction on deviatoric stress increment declines gradually when the suction exceeds the range of 15 kPa. In this part of research, The mechanical behavior of shallow slopes was studied by performing water infiltration starting at zero deviatoric stress simultaneously with shearing. The test results showed that decrease in matric suction has its effect on volume of infiltrated water, degree of saturation and deviatoric stress. The soil compacted on dry side of optimum moisture content (w = 15%) showed better performance as compared to other soils, it required more decrease in matric suction i.e. 12 kPa to start water infiltration and showed higher deviatoric stress. However, the deformation behavior in terms of void ratio is not affected much by decrease in matric suction.

In Series-II, the cell pressure was increased to 20 kPa during the isotropic consolidation process. The pore air pressure was increased equal to cell pressure during axis translation technique and kept drained and controlled afterwards. During shearing process, the specimens were first sheared to 80-90% of maximum deviatoric stress obtained from constant water content tests (performed in another series by the author). Once the required value of deviatoric stress was obtained, the specimens were infiltrated with water by keeping the deviatoric stress constant, until the failure is achieved. The stress state of specimens in Series-II is shown in Table 3.

Table 3. Stress state of the specimen during the shear process in Series-II

Specimens with water content (%)	Cell pressure, σ_3 (kPa)	Pore air pressure, u_a (kPa)	Pore water pressure, u_w (kPa)	
			1st Shear	2nd Shear
10	20	20	undrained	25
15	20	20	undrained	16
20	20	20	undrained	10
25	20	20	undrained	5

The concept of water infiltration in Series-II is shown as schematic representation in Figure 8(a). The curve ① in Figure shows a typical stress-strain curve with peak and residual deviatoric stress. Whereas, curve ② shows the water infiltration performed at constant deviatoric stress in which the rate of decrease in deviatoric stress depends on amount of water infiltrated into the specimen. The tests in Series-II are performed in two stages, in the first stage (indicated as 1st Shear in Figures) the specimens were first sheared to predefined values of deviatoric stress and in second stage (indicated as 2nd Shear in Figures) the water was infiltrated by keeping deviatoric stress constant. The first shearing was carried out in constant water content conditions so no water was infiltrated into the specimens. The deviatoric stress increased with increase in axial strain and predefined value of all

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specimens was achieved within axial strain range of 0-1.5%. Due to small axial strain range no change in matric suction occurred and specimens showed small change in void ratio and some decrease in degree of saturation. Once required value of deviatoric stress was achieved the matric suction was decreased in order to start water infiltration.

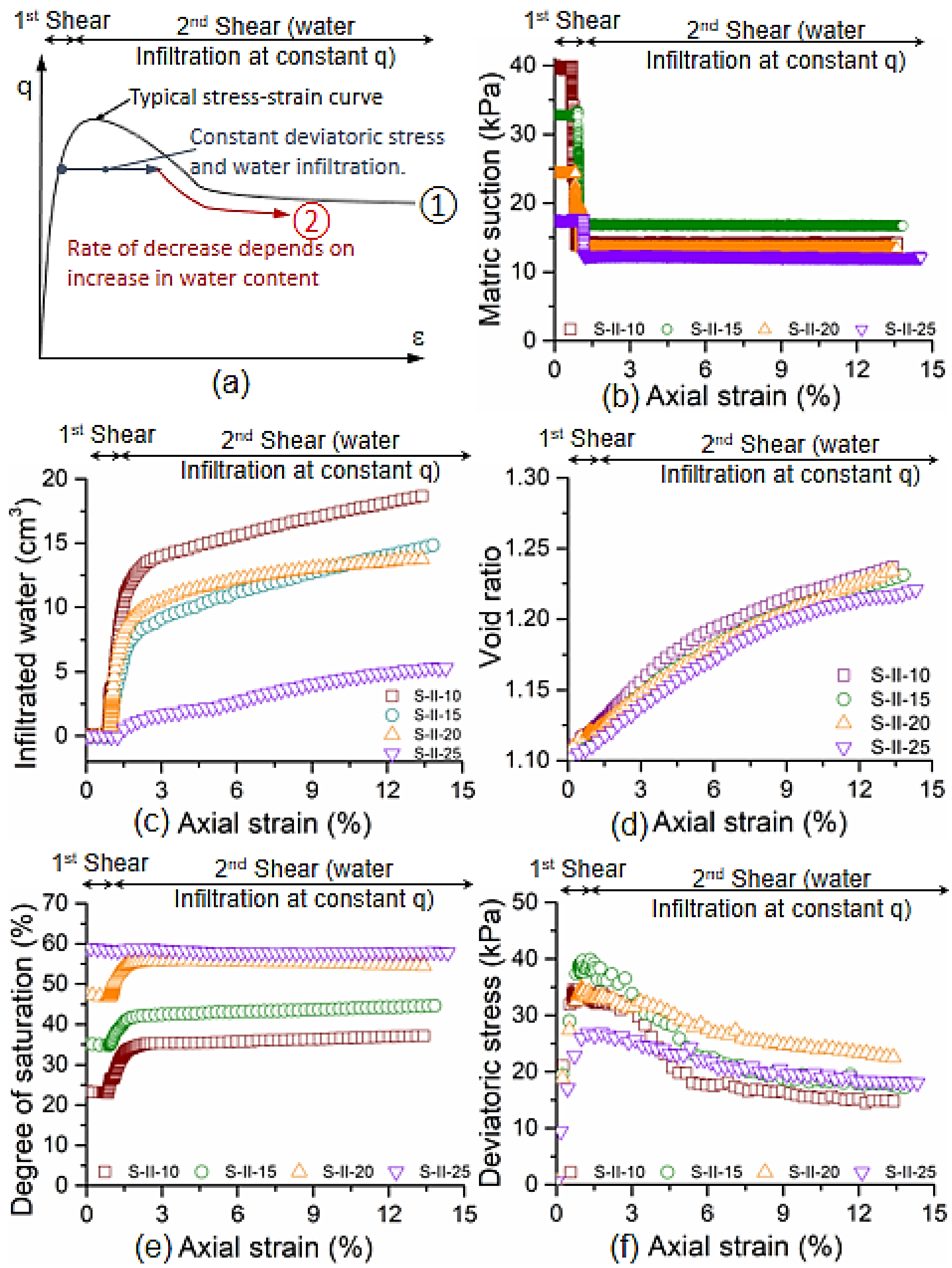

Figure 8. Results of Series-II (a) schematic representation, (b) matric suction, (c) infiltrated water, (d) void ratio, (e) degree of saturation, (f) deviatoric stress

It can be seen from Figure 8(b) that once matric suction was decreased from the initial measured value it is kept controlled throughout the test so no change occurred in matric suction with increase in axial strain. The matric suction was decreased by increasing pore water pressure. In case of specimen S-II-10, matric suction was decreased from 30 kPa to 15 kPa and 18 cm^3 of water was infiltrated into the specimens which increased the degree of saturation from 22% to 38%. In case of specimen S-II-15 matric suction was decreased from 33 kPa to 17 kPa and 15 cm^3 of water was infiltrated into the specimen which increased the degree of saturation from 35% to 45%. In case of specimen S-II-20, matric suction was decreased from 24 to 14 kPa and 14 cm^3 of water was infiltrated into the specimens that increase the degree of saturation from 45% to 55%. Whereas, in case of

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specimen S-II-25, matric suction was decreased from 18 kPa to 11 kPa as a result 5 cm^3 of water was infiltrated into the specimen, however, no increase in degree of saturation was observed in that specimen because increase in void ratio was more than infiltrated water. Figure 8(c) shows that water infiltration gradually increases with axial strain. Maximum volume was infiltrated in specimen S-II-10, as a result, it showed a maximum decrease in deviatoric stress because the rate of decrease in decrease depends on increase in water content. Whereas, almost same volume of water was infiltrated in specimen S-II-15 and S-II-20 although decrease in matric suction for specimen S-II-15 was much more than specimen S-II-20. Figure 8(d) showed that deformation behavior in terms of void ratio was not affected much by decrease in matric suction. In Series-II the failure mechanism of shallow slopes was studied by performing water infiltration at constant deviatoric stress. The tests results showed that decrease in matric suction has its effect on volume of infiltrated water and degree of saturation. Similar to test results in Series-I, the soil compacted on dry side of optimum moisture content (= 15%) showed better performance as compared to other soils, it required more decrease in matric suction to start water infiltration and showed higher deviatoric stress. In addition, water infiltration alone caused the failure of specimens without any further increase in deviatoric stress.

3.3. Comparision and discussion

The stress paths of shearing with infiltration tests are plotted in 3D stress state surface in Figure 9. A stress path is a plot of a theoretical or experimental relationship between two stress parameters. The stress paths are plotted against mean effective stress $p' = (\sigma_1' + 2\sigma_3')/3 + Sr(u_a - u_w)$ which is a combination of mean net stress and suction stress. Figure 9(a) shows the movement of stress paths in Series-I. In Series-I, the valve for pore water pressure was opened just before the start of shearing to increase the pore water pressure. Change in point *B* to *B′* occurred within no time and showed the decreased in matric suction along with mean effective stress which occurred due to increase in pore water pressure. The shearing thus continued simultaneously with water infiltration and deviatoric stress increased with mean effective stress and approached the reference failure plane from *B′* to *C*. As the soil used in this study was over-consolidated, therefore, after attaining the maximum deviatoric stress the stress path revered its direction and showed decrease in deviatoric stress along with mean effective stress. Figure 9(b) shows the movement of stress paths in Series-II. In Series-II, the specimens were first sheared in constant water content conditions to the predefined value of deviatoric stress. *B* to *D* showed the path when the specimens were sheared in constant water content conditions. The deviatoric stress increased with mean effective stress and stress path reached the predefined value of deviatoric stress. As soon as the predefined value of deviatoric stress was reached the value of pore water pressure was opened to increased pore water pressure and decrease matric suction and stress path moved from point *D* to *D′*. *DD′E* shows the stress path when water infiltration was carried out by keeping the deviatoric stress constant and it was observed that water infiltration alone induced the shear failure in the soil specimen without having to have any additional loading.

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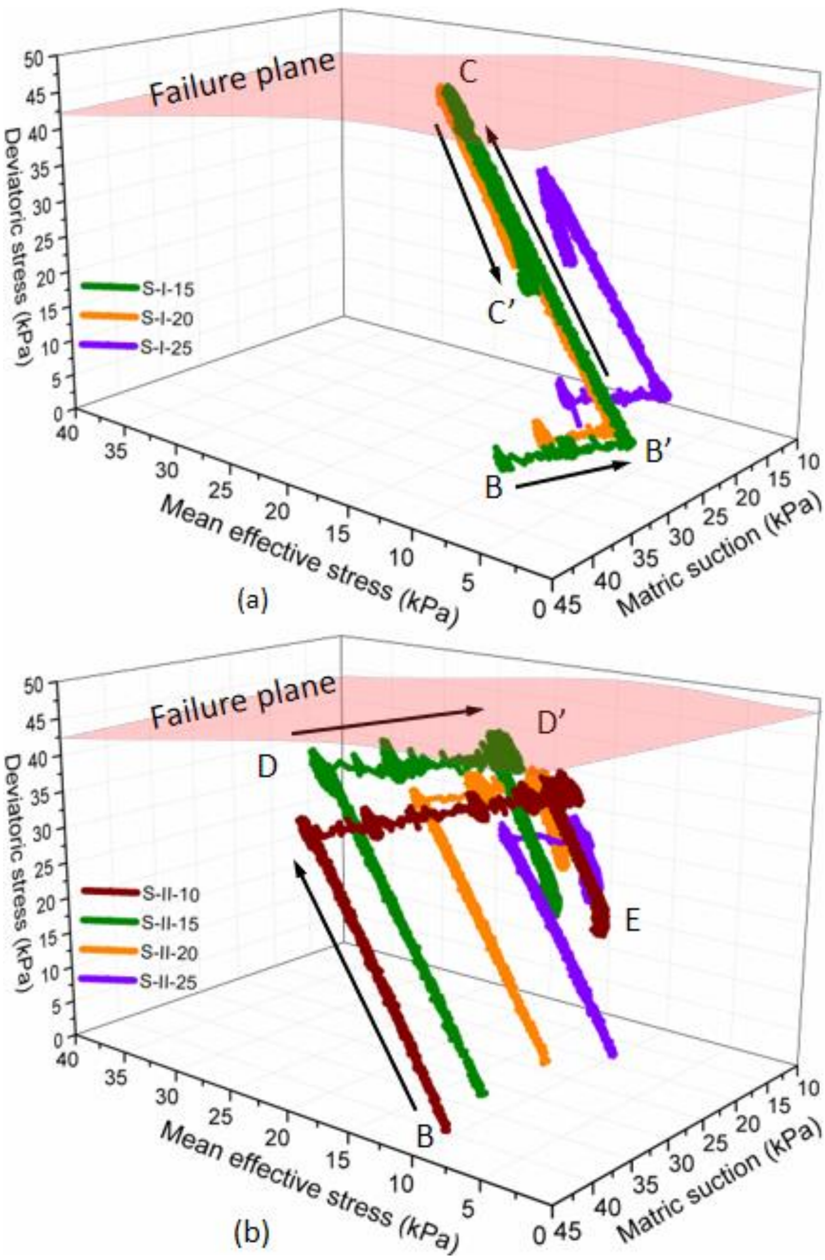

Figure 9. Change in stress paths due to decrease in matric suction (a) Series-I, (b) Series-II

4. Conclusions

A series of shearing with infiltration tests were conducted to examine the mechanical behavior and failure mechanism of shallow unsaturated slopes. The following conclusions have been obtained:

- The deformation behavior of shallow slopes compacted on dry to the wet side of optimum moisture content is not much affected by decrease in matric suction.
- The decrease in matric suction has effect on the volume of infiltrated water & degree of saturation. The soil slopes compacted on dry side of optimum moisture content (ω = 15%) showed better performance than other soils, they require more decrease in matric suction to start water infiltration & showed higher deviatoric stress.
- A decrease in matric suction has a significant effect on stress paths in stress state space. Water infiltration alone can cause the failure in shallow slopes without having to have any further loading.

Acknowledgments: The Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Department of Civil and Environmental Engineering, Saitama University, Japan are gratefully acknowledged for research facilities and financial assistance.

Conflicts of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

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