Geomechanics and Engineering, *Vol. 19, No. 5 (2019) 435-445*
DOI: https://doi.org/10.12989/gae.2019.19.5.435

Shear infiltration and constant water content tests on unsaturated soils

Ali Murtaza Rasool[1a] and Mubashir Aziz*[2]

[1]National Engineering Services Pakistan (NESPAK), Lahore, Pakistan
[2]Department of Civil Engineering, National University of Computer and Emerging Sciences (NUCES), Lahore, Pakistan

(Received September 21, 2019, Revised November 19, 2019, Accepted November 27, 2019)

Abstract. A series of element tests with different drainage conditions and strain rates were performed on compacted unsaturated non-plastic silt in unconfined conditions. Soil samples were compacted at water contents from dry to wet of optimum with the degree of saturation varying from 24 to 59.5% while maintaining the degree of compaction at 80%. The tests performed were shear infiltration tests in which specimens had constant net confining pressure, pore air pressure was kept drained and constant, just before the shear process pore water pressure was increased (and kept constant afterwards) to decrease matric suction and to start water infiltration. In constant water content tests, specimens had constant net confining pressure, pore air pressure was kept drained and constant whereas pore water pressure was kept undrained. As a result, the matric suction varied with increase in axial strain throughout the shearing process. In both cases, maximum shear strength was obtained for specimens prepared on dry side of optimum moisture content. Moreover, the gradient of stress path was not affected under different strain rates whereas the intercept of failure was changed due to the drainage conditions implied in this study.

Keywords: unsaturated soil; shear strength; matric suction; pore water pressure; water infiltration; constant water content tests; drained shear tests

1. Introduction

Natural soils may be subjected to different strain rates in numerous geotechnical engineering conditions. Loading rate may be significantly higher than the strain rate employed in standard laboratory element tests. Some examples of rapid loading include blast loading, impact loading, or earthquake loading (Mohamed *et al.* 2013, Mun *et al.* 2016). The strain rate effects can be described as the difference between the soil resistance under rapid and slow strain rates. Strain controlled triaxial tests with pore water pressure measurements are carried out in most of the previous studies depicting the impact of axial strain rate on mechanical behaviour of saturated soils (Richardson and Whitman 1963, Zhu and Yin 2000). It has been reported that the soil becomes stiffer which leads to a smaller axial strain at failure with increase in the axial strain rate. In research carried out by Svoboda *et al.* (2013), shear strength behaviour of sand compacted at dry side of optimum water content and tested at relatively low confining pressure was explored. The results showed that the strain rate did not affect the friction angle of soil and had negligible effects on the soil behaviour. The behaviour of sand under triaxial compression at dry conditions was investigated by Martin *et al.* (2013) with different confining pressures, axial strain rate, and initial density showing that the sand behaviour is independent of the strain rate but depends on the confining pressure. Unsaturated soils are composed of two stress state variables i.e., net stress and matric suction. Due to degree of saturation effects on the stress state, matric suction, development of excess pore water pressure and pore air pressure, degree of compaction and hydraulic conductivity, the effects of strain rate on mechanical behaviour of unsaturated soils becomes difficult to study as compared to saturated soils. A number of experimental studies have been carried out to explore the unsaturated soil behaviour (Rahardjo *et al.* 1995, Gasmo *et al.* 1999, Goual *et al.* 2011, Estabragh and Javadi 2012). However, only few studies are available focusing on drained or undrained shear strength of unsaturated soils subjected to different strain rates (Peters *et al.* 2011, Svoboda and McCartney 2014, Li and Zhang 2015). Although the change in strain rate may affect the unsaturated soil behaviour, however, the effect is difficult to estimate due to the compression of the air phase. The apparatus used for testing of unsaturated soil should be able to control and measure pore-air and pore-water pressures separately. It has been reported as well that the unsaturated soil behaviour is also affected by variations in the stress state i.e. net stress and matric suction (Bolzon and Schrefler 1995, Lu *et al.* 2010).

Numerous studies have shown that the variation of shear stress is nonlinear with matric suction (Sáez and Escario 1986, Vilar 2006, Nam *et al.* 2011, Lin *et al.* 2018). The unsaturated soil shear strength along with saturated shear strength parameters can be predicted with soil-water characteristic curve (SWCC). Hanasimbi and Nishimura (2018) conducted SWCC tests on a silty soil in one-dimensional stress conditions, and isotropic confining stress conditions. They concluded that different stress conditions

*Corresponding author, Associate Professor
E-mail: mubashir.aziz@nu.edu.pk
[a]Ph.D.
E-mail: ali.murtaza@nespak.com.pk
ali_eng@hotmail.com

http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

have an influence on SWCC. The unsaturated soil behaviour is also affected by the compaction water content due to variation in matric suction. Compacting the clayey soil at different water contents changes its associated behaviour from flocculated to dispersed structure. The flocculated soil samples compacted at dry side of optimum water content (OWC) has higher shear strength than for dispersed specimen compacted at the wet of OWC. It was also observed that the soil structure has significance effects on the rate effect of unsaturated soils. Olson and Parola (1967) performed unconsolidated undrained (UU) tests in triaxial test apparatus on Goose lake clay prepared at various initial water contents to study the influence of strain rate on shear stress. The tests were performed by varying rates from 0.2 to 4.0×10^5 %/min. It was observed that the specimens prepared with less water content and sheared at same strain rates showed more undrained shear strength at failure and strength reduced with increase in water content. The effects of grain size and the moisture content on the dense Eglin sand under confining pressure at higher strain rates was studied by Luo *et al.* (2014). It was found that the breakage factor followed a linear relationship with moisture content. Whereas, Barr *et al.* (2018) focused on high strain rate compressibility due to the effect of water content and particle fracture in loose sand and concluded that the full saturation of specimens results in development of pore water pressure and a major decrease in particle breakage. Present research involves the evaluation of strain rate effects on the compacted unsaturated silty soil behaviour prepared at the same initial void ratio but with different initial degree of saturation. The samples have been tested under undrained and drained conditions for pore water in unconfined conditions. The influence of strain rate has been reported on volume change, shear strength and water infiltration. Finally, the influence of strain rate on stress paths has also been discussed.

2. Materials and methods

2.1 Physical properties of test soil

DL clay is commercial name of the soil used in this study which 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 with low plasticity (ML) comprising of 90% silt and 10% clay. Table 1 shows the physical properties of the soil. The optimum water content of soil is 20% and the maximum dry density is 1.55 g/cm^3. The compaction curve of DL clay has been shown in Fig. 1.

2.2 Specimen properties

Homogenous specimens were prepared by compacting soil in 5 layers, each layer being 2 cm thick, with a static compaction machine with a hydraulic jack (Rasool and Kuwano 2018). Before compaction, water was added to the dry DL clay to prepare soil samples at water contents of 10,

Table 1 Physical properties of the tested soil

Properties	Unit	Value
Density of soil particle, ρ_s	g/cm^3	2.635
Consistency	-	Non-Plastic
Maximum dry density, ρ_{dmax}	g/cm^3	1.55
Optimum water content, OWC	%	20
Maximum particle size, d_{max}	mm	0.039
Saturated coefficient of water permeability, k_s	m/s	6.68×10^{-7}

Table 2 Properties of all specimens tested in this study

Properties	Values			
Water content, w (%)	10	15	20	25
Dry density, ρ_d (g/cm^3)	1.25	1.25	1.25	1.25
Degree of saturation, S_r (%)	24.0	36.0	49.0	59.5
Void ratio, e	1.10	1.10	1.10	1.10
Degree of compaction, D_c (%)	80	80	80	80

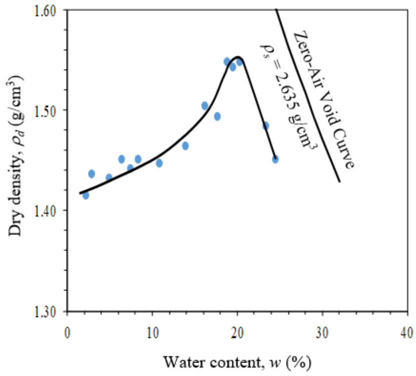
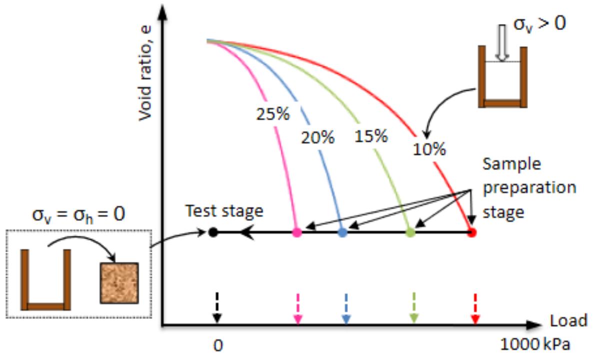
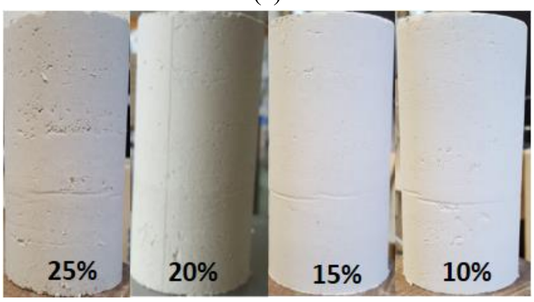


Fig. 1 Compaction characteristics of DL clay



(a)



(b)

Fig. 2 (a) Sample preparation under different compaction pressures and (b) the prepared soil specimens

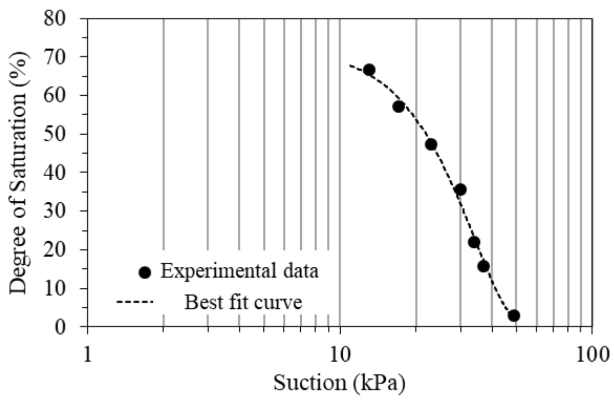


Fig. 3 Soil water characteristic curve for the studied soil

15, 20 and 25% i.e., from dry side to wet side of optimum water content. The specimens had the constant void ratio of 1.10 and density of 1.25g/cm^3 at different degrees of saturation (S_r) of 24, 36, 49 and 59.5%. The physical properties of the specimens are listed in Table 2.

Degree of compaction of all specimens was maintained at 80%. The pressure applied to soil at the time of sample preparation was higher than the applied stresses during the test phase and hence the samples are considered to be over-consolidated. According to Nishimura *et al.* (1999), 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 sample preparation has been presented in Fig. 2. In the present paper, results obtained from tests for soil samples prepared on the dry and wet side of the optimum water content are expressed as “dry specimen” and “wet specimen” respectively. The test results obtained for the specimens prepared at optimum water content are expressed as “optimum specimen”.

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. 3 shows the results i.e. the suction decreases as the saturation ratio increases.

2.4 Test apparatus

The triaxial apparatus used in this study consists of a double cell, pore air pressure transducer, pore water pressure transducer and cell pressure transducers made by Tokyo Instruments and an axial loading device as shown in Fig. 4(a). The confining pressure was applied on the top of double cell chamber filled with the water by controlling the air pressure with a regulator. Supre precision regulator (RS/RR series) made by Fujikura Inc. Japan has high

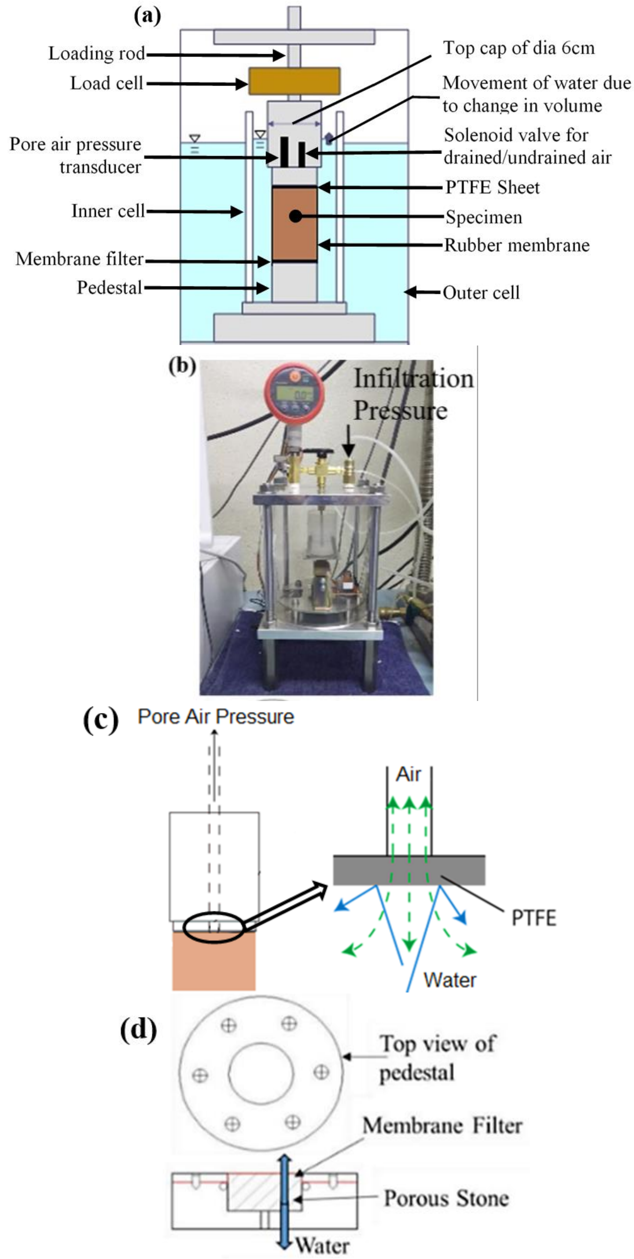


Fig. 4 (a) Schematic figure of the triaxial cell, (b) external load cell, (c) top cap and (d) bottom pedestal

accuracy of keeping the air pressure and hence the cell pressure constant throughout the shear process. The apparatus has features of measuring pore air pressure and pore water pressure independently. To give continuous supply of air to the specimen during the test process, pore air pressure is fitted in the top cap which is also attached to an air regulator. The volume of soil samples was measured by a Low Capacity Differential Pressure Transducer (LCDPT) made by Fuji Electric. The LCDPT measures specimen volume change as the variation in the water level in the inner cell. The change in water level was recorded by a computer, which was then calculated as total volume change of specimen as per relations given in Japanese Geotechnical Society standard JGS0527-2009. The vertical deformation of specimen was measured by LVDT made by

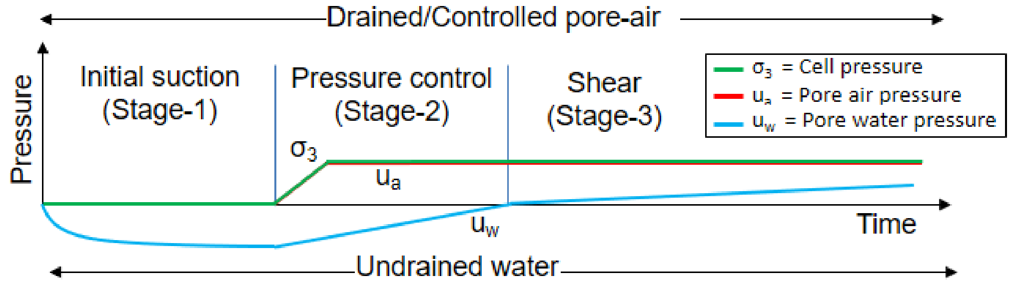


Fig. 5 Schematic illustration of the constant water content (CW) test series

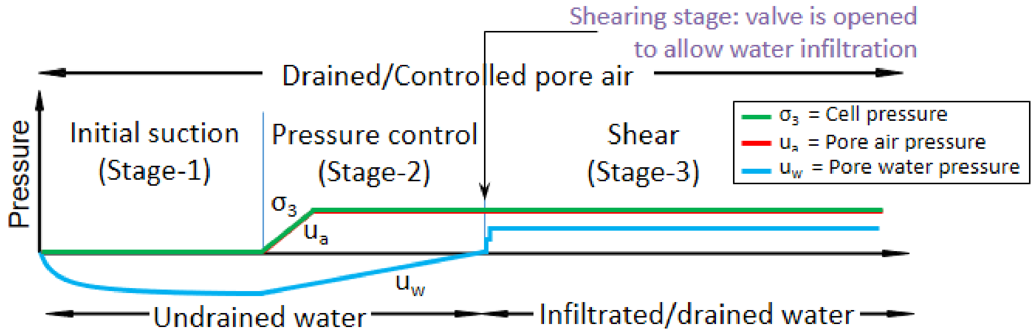


Fig. 6 Schematic illustration of the shear infiltration (SI) test series

Tokyo Instruments. A thin membrane and a PTFE sheet were used to separate the supply of pore water and pore air for effective measurement and control of these pressures. Fig. 4(c) shows the sheet of PTFE pasted to the surface of top cap to resist the flow of water. Fig. 4(d) shows the thin membrane type "Supor 450" from Pall Corporation. The Membrane filter has pore size of 0.45 μm, member thickness of 140 μm and provided air entry value of 250 kPa. The same membrane has been used by Habasimbi & Nishimura (2019) and Nishimura (2014). The membrane was installed in the lower pedestal which permits the flow of water and resists the air flow. In addition, a solenoid-controlled valve to control the exhaust air was also installed inside the top cap to minimize the air volume in drainage line of pore air. The pore air pressure was kept atmospheric throughout the test and water infiltration increased only the water pressure (Farooq *et al.* 2004). The water in the soil sample was injected from the bottom pedestal which was connected to a beaker and the pore water pressure transducer through the water line. Fig. 4(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 (Farooq *et al.* 2004, Melinda *et al.* 2004).

2.5 Test procedure

The negative pore water pressure (also known as matric suction) strongly influences unsaturated soil behaviour as it attracts the soil particles together. In a rainfall event, the infiltration of rainwater into the ground causes a reduction in matric suction. The reduction in matric suction also reduces the soil shear strength which may result in slope failures. The unconfined compression is a type of triaxial compression test under no confining pressure and in constant water content condition. Because the stress states in natural slopes or in a surface layer of the embankment are under very low confining pressure conditions, the unconfined compression (UC) test can simulate this type of unsaturated condition. From a practical standpoint, the UC test plays a significant role to understand the mechanism of shallow failure problem in natural or engineered earth slopes (Kim *et al.* 2016).

This research simulates two slope failure situations in unconfined conditions that come across in the field: (i) rapid failure, this type of failure occurs in constant water content conditions i.e., pore-air pressure is assumed atmospheric and remain constant throughout the whole failure process; and (ii) slope failures induced by water infiltration i.e., both pore air pressure and pore water pressure are drained throughout the entire failure process.

Fig. 5 illustrates the schematic representation of constant water content (CW) tests. In these tests, pore air u_a and cell pressures σ_3 were increased using axis translation technique after measurement of the initial matric suction to keep pore water pressure u_w above atmospheric. After wards, isotropic consolidation is performed by controlling pore air pressure. The net confining pressure and matric suction on soil samples at the end of consolidation were recorded as $(\sigma_3 - u_a)$ and $(u_a - u_w)$, respectively. In shear process, the valve for pore air pressure is kept open while the valve for pore water is closed. In other words, specimens have constant net confining pressure $(\sigma_3 - u_a)$ whereas the matric suction $(u_a - u_w)$ changes with increase in axial strain during the shear process.

Unsaturated soil shear strength parameters in drained conditions can be obtained by performing shear infiltration (SI) tests. Fig. 6 shows the schematic illustration of shear infiltration (SI) tests. The axis translation technique (ATT) is applied after measurement of initial suction. Afterwards, the specimens are first isotropically consolidated at a confining pressure of σ_3 with controlled pore water u_w and controlled pore air pressures u_a. The net confining pressure and matric suction on soil samples at the end of consolidation were recorded as (σ_3 – u_a) and (u_a – u_w), respectively. In shear process, the valve for pore air and water pressure are kept open. In other words, specimens have constant net confining pressure (σ_3 – u_a) and matric suction (u_a – u_w) whereas the deviator stress increases during shearing until failure conditions are reached.

2.6 Strain rates during shearing

The shear strength tests in unsaturated conditions are usually carried out at constant strain rate. The selection of a suitable strain rate is very important prior to the commencement of the test. The selection of strain rate in the constant water content test which is also a type of undrained test must guarantee equalization of induced pore pressure in the specimen (Fredlund and Rahardjo 1993). Test data presented by Gibson and Haenkel (1954) and Bishop and Henkel (1962) show the variation in shear strength with strain rate. The effect of variation of strain rates was studied by Satija and Gulhati (1979) and concluded that deviatoric stress is not sensitive to strain rate. However, no research data is available to show the effect of strain rate when the soil is tested in drained conditions. The authors have performed a separate series of constant water content tests and shear infiltration tests at a strain rate of 0.025, 0.05, 0.08 and 0.11 mm/min to observe the influence of strain rate on the mechanical behavior of unsaturated DL clay. The selected strain rates were corresponding to the motor speed of 100, 200, 300 and 400 rpm of strain-controlled loading system.

3. Results and discussions

3.1 Measurement of initial suction

The soil compacted at different moisture contents lead to a difference in initial matric suction. The previous studies also show that the behaviour of unsaturated soil is influenced by initial suction (Olson and Langfelder 1965). However, the distribution of pore water and degree of saturation are factors affecting initial suction. Fig. 7 illustrates the change in initial suction of soil samples compacted at w = 10, 15, 20 and 25%. It can also be observed that the values of initial suction when the specimens were set in triaxial apparatus and it can be seen that initial suction 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 Constant water content (CW) tests

The stress state of specimens during constant water content (CW) test process is shown in Table 3. The cell pressure was increased to 20kPa during isotropic consolidation process. The pore air pressure equal to cell

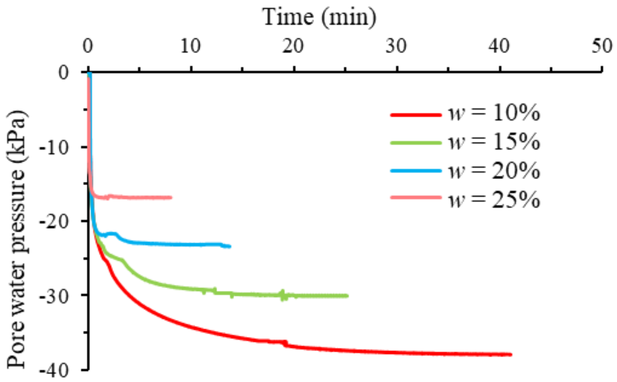


Fig. 7 Variation of initial matric suction of specimens prepared with different water content against time

Table 3 Stress state of specimen during CW tests

Specimens with water content (%)	Cell pressure, σ_3 (kPa)	Pore air pressure, u_a (kPa)	Pore water pressure, u_w (kPa)
10	20	20	Varied during shearing
15			
20			
25			

pressure was applied during axis translation technique and kept drained and constant afterwards. The pore water pressure was undrained and measured during the shear process.

Fig. 8 illustrates the relationship between the volumetric strain and axial strain of specimens prepared at w = 10, 15, 20 and 25% and tested at strain rates of 0.025, 0.5 and 0.08 mm/min in unconfined conditions. Less volumetric strains are developed in specimens because of unconfined conditions. The volumetric strain is the ratio of total volume change to original volume of the specimen. The negative volumetric strain shows the dilatant behavior of the specimen. It can be seen that the specimen volume is increased with increase in axial strain. The increase in volume is because of high pressure at preparation stage and a high degree of compaction. The peak shear strength falls within axial strain range of 0-2.75%. The volumetric strain of soil samples prepared at w = 10% did not vary within this range. However, some change was observed afterwards for specimens prepared at 15, 20 and 25% water content due to the post peak shear stress response.

Fig. 9 shows the relationship between deviatoric stress and axial strain for compacted specimens sheared at different strain rates. It can be seen that for all specimens deviatoric stress increased with axial strain up to a peak value and after that it decreases showing post peak behavior. In the stress-strain curve, the peak and post peak failure behavior is due to the effect of over-consolidation. The measured initial suction of soil samples prepared at a water content of 10, 15, 20 and 25% were 17, 24, 32 and 40 kPa, respectively. The curve showed that the sample prepared with w = 10% presented more brittle behavior as compared to other specimens. The trend appears to be

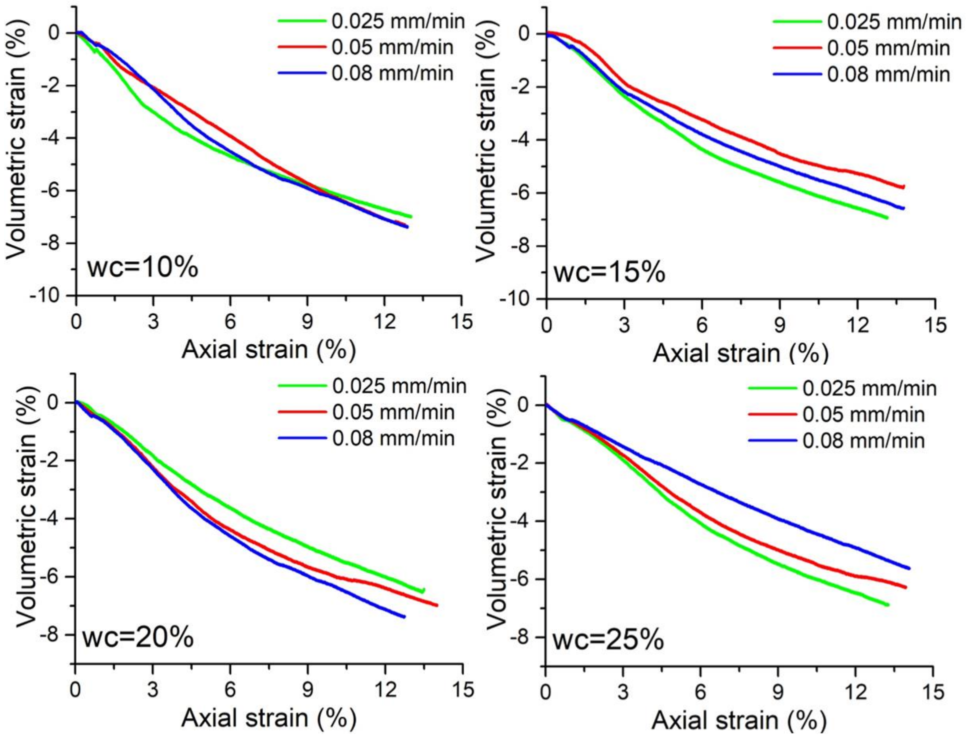


Fig. 8 Influence of strain rate on volume change behavior of specimens prepared with different water content in constant water content test series

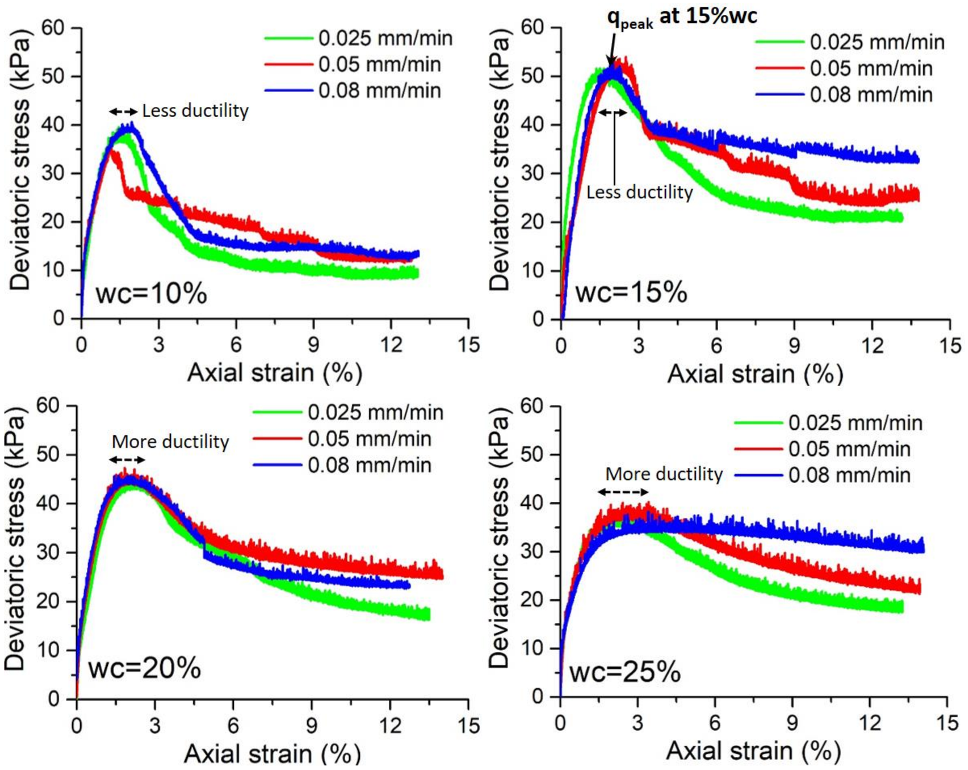


Fig. 9 Influence of strain rate on stress-strain behavior of specimens prepared with different water content in constant water content test series

affected by high matric suction, as the stiffness of soil increased with matric suction. The same response was also perceived by Chae *et al.* (2010) and Kim and Jeong (2017). However, the brittleness also decreases due to decrease in suction with increase in water content. The shear strength of soil also varied with matric suction. The soil sample prepared on the dry side of optimum water content i.e., at 15% water content showed maximum shear strength. The peak stress value of all specimens falls within axial strain range of 0-2.75%. The residual shear strength or post peak

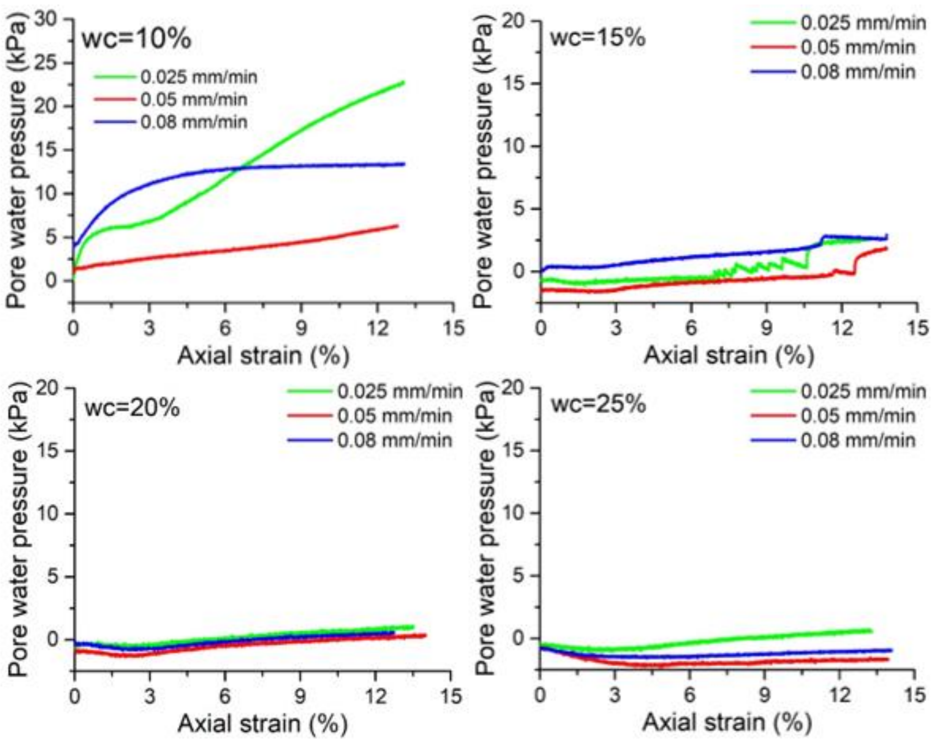


Fig. 10 Effect of strain rate on development of pore water pressure in specimens prepared with different water content in Constant water content test series

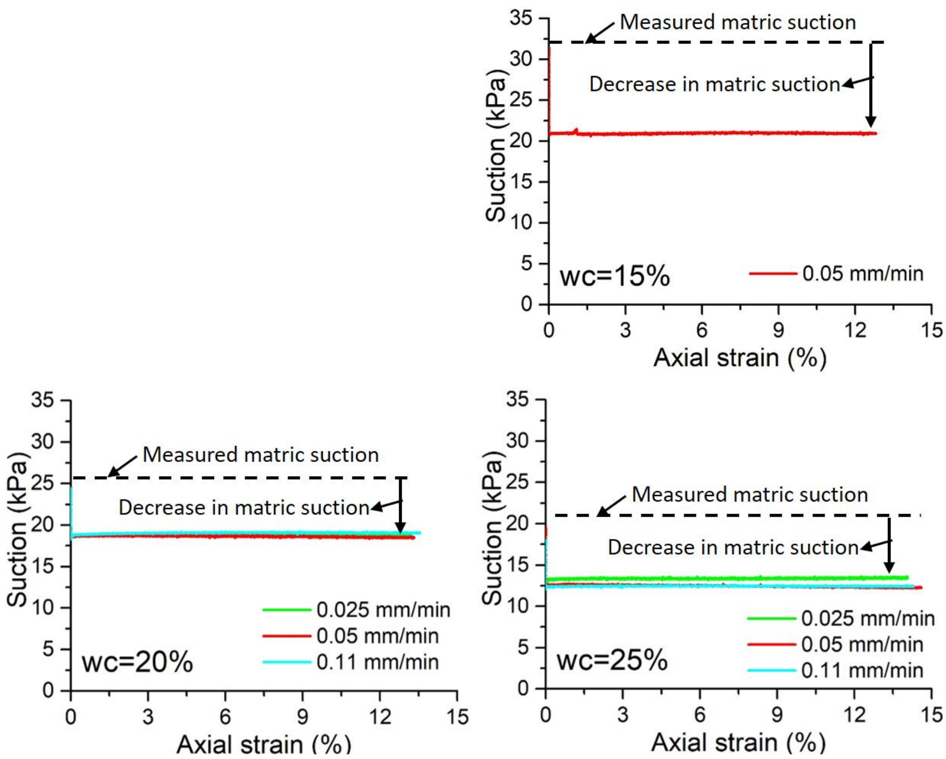


Fig. 11 Effect of decrease in matric suction in specimens prepared with different water content in SI tests

strength curves were merged except for the case of the specimen with w = 10%. The peak shear strength of soil prepared at water content e.g. of 10, 15, 20 and 20% is not affected by the strain rate. This shows that the strain rate practically has no influence on shear strength response of the soil used in this study.

The pore-water pressure behavior of compacted specimens during the shear process is plotted against axial strain in Fig. 10. It can be observed that more pore water pressure was developed in specimens prepared on the dry side of OWC i.e. 10% water content, and maximum pressure was developed when the specimen was sheared at

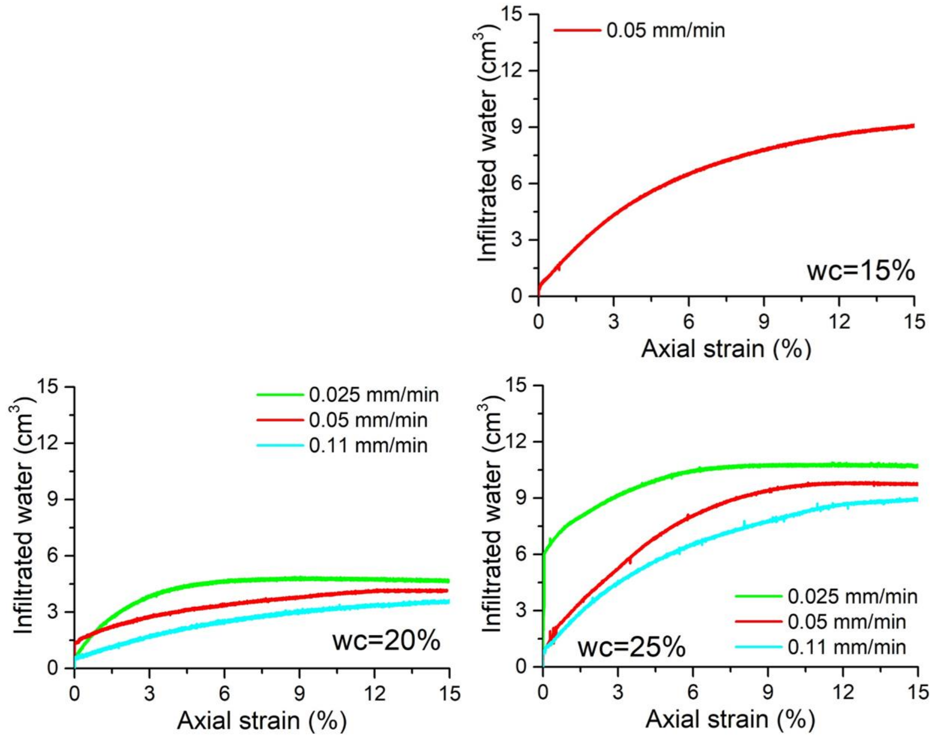


Fig. 12 Effect of strain rate on water infiltration in specimens prepared at different water content in SI tests

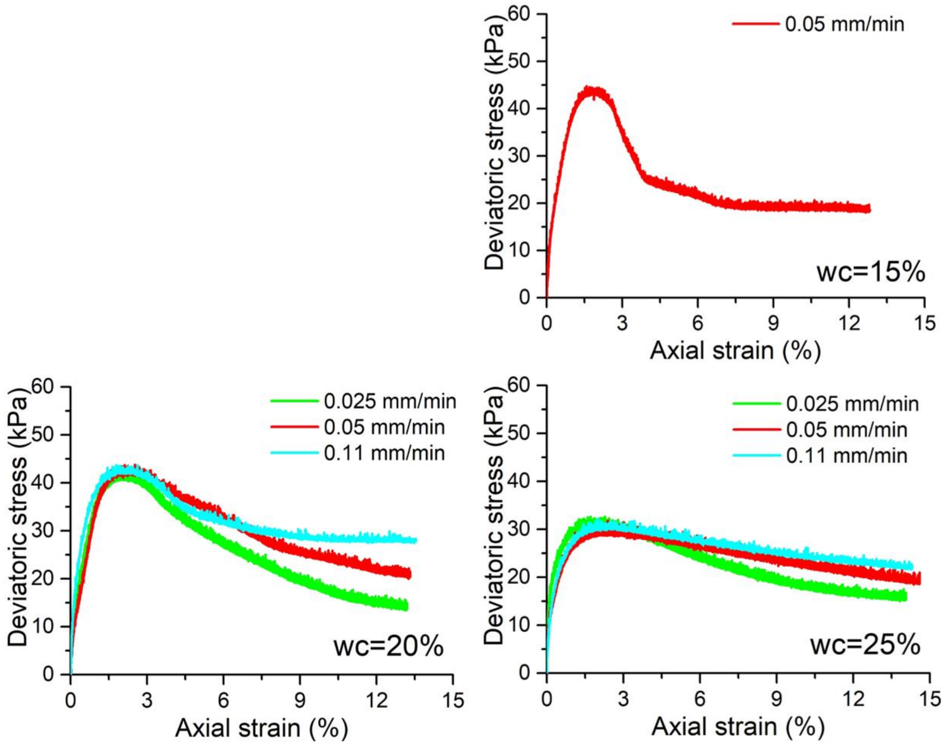


Fig. 13 Strain rate influence on stress-strain behavior of specimens in SI tests

Table 4 Stress state of specimen during SI tests

Specimens with water content (%)	Cell pressure, σ_3 (kPa)	Pore air pressure, u_a (kPa)	Pore water pressure, u_w (kPa)
15	20	20	11
20			10
25			9

0.025 mm/min. The trend shows a quick increase in pore water pressure, whereas, the specimens prepared at 10% water content and sheared at a strain rate of 0.05 and 0.08 mm/min showed a gradual increase in pore water pressure. The development of high pore-water pressure in case of specimens prepared at w = 10% was due to the dissolution of pore air into pore water, due to the presence of large air

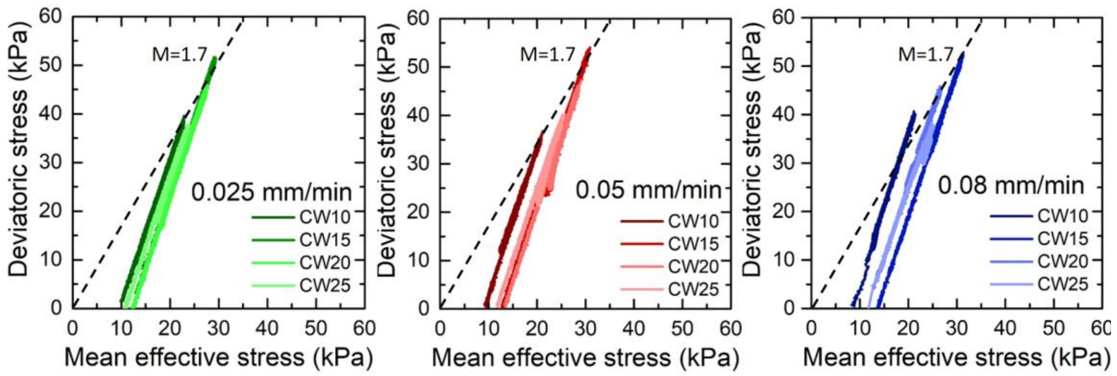


Fig. 14 Effect of strain rate on stress paths of specimens prepared with different water content in CW tests

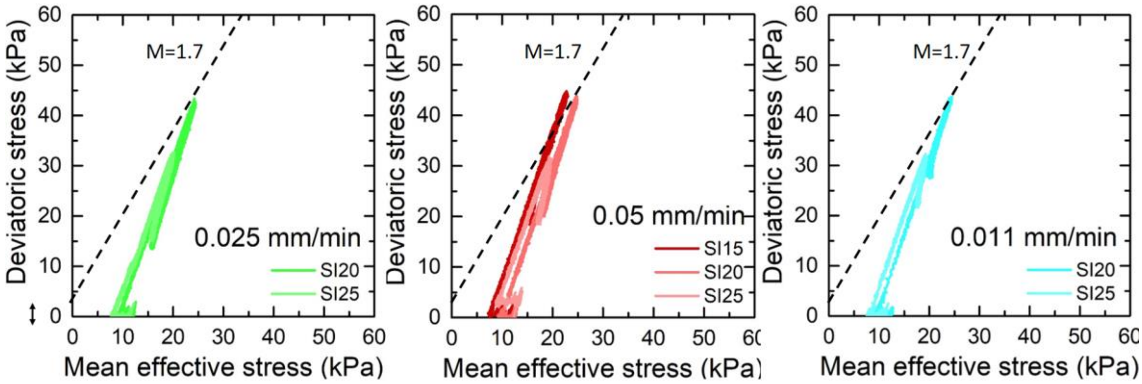


Fig. 15 Effect of strain rate on stress paths of specimens prepared with different water content in SI tests

voids in dry specimens. The specimen prepared at 15% water content showed the same trend when tested at different strain rates. The specimens prepared at optimum water content (w = 20%) initially showed a decrease instead of an increase in pore water pressure with shearing, the specimens showed the same trend when tested at different strain rates. The specimens prepared on the wet side of OWC i.e., w = 25% showed a decrease in pore water pressure only. It can be concluded that the strain rate affects only the pore water pressure in specimens prepared at w = 10%.

3.3 Shear infiltration (SI) tests

In shear infiltration tests, the cell pressure was increased to 20kPa during isotropic consolidation process. The pore air pressure was increased equal to cell pressure during axis translation technique and kept drained and constant afterwards. Just before starting the shear process, infiltration pressure was applied to the infiltration chamber to increase pore water pressure and decrease matric suction. Measured initial matric suction for specimens prepared at 10, 15, 20 and 25% was 40, 34, 24 and 17 kPa, respectively. In some trial tests, water was infiltrated into the specimens without increasing pore water pressure i.e., by decreasing matric suction. However, only a small volume of water infiltrated into the specimens. The infiltrated volume of water was not enough to change the soil behavior; therefore, water was infiltrated by decreasing matric suction. An increase in pore water pressure decreases matric suction. The pore water pressure was increased by applying infiltration pressure on the top of the chamber. The infiltration chamber has been shown in Fig. 4b. The stress state of specimens during Shear Infiltration (SI) test process is explained in Table 4.

Fig. 11 shows that the specimens prepared on the dry side of OWC require 10 kPa pore water pressure to start water infiltration, whereas, specimens prepared at the optimum and wet side of optimum water content required 5 kPa pore water pressure to start water infiltration process. It was also observed that strain rate had no effect on the decrease in matric suction.

The influence of strain rate on water infiltration due to the decrease in matric suction is shown in Fig. 12. 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. For specimens prepared at w = 15%, matric suction was decreased from 34 kPa to 22 kPa in order to start water infiltration. 9 cm^3 of water were infiltrated when the same specimen was sheared at a strain rate of 0.05 mm/min. For specimens prepared at w = 20% and 25%, matric suction was decreased from 24 to 17kPa and 17 to 12kPa, respectively in order to start water infiltration process. The soil samples were then sheared at a strain rate of 0.025, 0.05 and 0.11mm/min. It was found that water infiltration decreased with increase in strain rate. This illustrates that the strain rate has significant influence on the water infiltration process.

The influence of strain rate on deviatoric stress due to water infiltration has been shown in Fig. 13. The specimens prepared at w = 15% and sheared in drained conditions at a strain rate of 0.05 mm/min showed a peak shear strength of 45 kPa. In contrast, the specimens prepared at w = 15% and sheared in constant water content conditions at a strain rate of 0.05 mm/min showed a peak strength of 55 kPa. It was also observed that peak shear strength of specimens prepared at w = 20 % is not affected when sheared at strain rates of 0.025, 0.05 and 0.11 mm/min in drained conditions. However, the peak shear strength of specimens sheared in drained conditions was less than the specimens sheared in constant water content conditions. Similar behavior was observed for specimens prepared at w = 25%. This shows that strain rate does not affect deviatoric stress of soil when sheared in drained or undrained conditions for pore water pressure, however, the deviatoric stress decreases due to water infiltration.

3.4 Comparison of CW and SI test results

The influence of stain rate is equally important to study the mechanical behavior of saturated as well as unsaturated soils. However, only a few studies have been published on the effects of strain rate on unsaturated soil behavior. This is possibly due to the fact that it is quite difficult to perform constant water content and fully drained tests to study the time dependency separately from that due to the pore fluid flow. The influence of strain rate on stress paths of constant water content tests and shear infiltration tests has been shown in Figs. 14 and 15. From the stress paths (deviatoric stress versus mean effective stress plot) in Figure 14, the peak stress envelopes of constant water content tests yield a gradient of 1.7 with zero intercept which shows that the gradient of the failure line is not affected by the strain rate. Similarly, the peak stress envelopes of the shear infiltration tests also yield a gradient of 1.7 with an intercept of 3kPa (Fig. 15). It can be stated that drainage conditions affect the mechanical behavior of unsaturated soils.

4. Conclusions

Constant water content (CW) and shear infiltration (SI) triaxial tests were performed at increased loading rates to investigate the effects of strain rate on the mechanical behavior of a non-plastic silt at different initial compaction water contents. The following conclusions are drawn from this study:

• Specimens tested in constant water content conditions exhibit higher shear strength as compared to shear infiltration conditions. Peak deviatoric stress was obtained for the specimens compacted at dry of optimum water content.

• The soil compacted at dry of optimum experienced positive excess pore water pressure generation during shearing whereas the soil compacted at wet of optimum experienced negative excess pore water pressures.

• The strain rate effects were observed to be similar regardless of the compaction water content indicating the same net effect on the effective stress.

• The ratio of deviatoric stress to mean effective stress (stress ratio) is observed to be independent of confining pressure and strain rate. The stress ratio for both cases is 1.7, however, the intercept varies. This demonstrates that the strain rate has little effect on mechanical behavior of unsaturated soils whereas the drainage conditions considerably affect the shear strength of an unsaturated soil.

• Finally, the soil compacted on dry side of OWC showed better performance as compared to wet soil under same conditions. It showed high initial matric suction, dilative behavior, high shear strength during shear and require more decrease in suction to start water infiltration. This suggested that soil should be compacted on the dry side of optimum moisture content to get better performance during the service life of slope or embankment.

Acknowledgments

The Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) is gratefully acknowledged for research facilities and financial assistance.

References

ASTM D2487-11 (2011), *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Barr, A.D., Clarke, S.D., Tyas, A. and Warren, J.A. (2018), "Effect of moisture content on high strain rate compressibility and particle breakage in loose sand", *Exper. Mech.*, **58**(8), 1331-1334. https://doi.org/10.1007/s11340-018-0405-4.

Bishop, A.W. and Henkel, D.J. (1962), *The Measurement of Soil Properties in the Triaxial Test*, Edward Arnold Publishers Limited.

Bolzon, G. and Schrefler, B.A. (1995), "State surfaces of partially saturated soils: an effective pressure approach", *Appl. Mech. Rev.*, **48**(10), 643-649. https://doi.org/10.1115/1.3005044.

Chae, J., Kim, B., Park, S.W. and Kato, S. (2010), "Effect of suction on unconfined compressive strength in partly saturated soils", *KSCE J. Civ. Eng.*, **14**(3), 281-290. https://doi.org/10.1007/s12205-010-0281-7.

Estabragh, A.R. and Javadi, A.A. (2012), "Effect of suction on volume change and shear behaviour of an overconsolidated unsaturated silty soil", *Geomech. Eng.*, **4**(1), 55-65. https://doi.org/10.12989/gae.2012.4.1.055.

Farooq, K., Rolando, O. and Towhata. I (2004), "Response of unsaturated sandy soils under constant shear stress drained condition", *Soils Found.*, **44**(2), 1-13. http://dx.doi.org/10.3208/sandf.44.2_1.

Fredlund, D.G. and Rahardjo, H. (1993), *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons, Inc. http://dx.doi.org/10.1002/9780470172759.

Gasmo, J., Hritzuk, K., Rahardjo, H. and Leong, E. (1999), "Instrumentation of an unsaturated residual soil slope", *Geotech. Test. J.*, **22**(2), 134-143. https://doi.org/10.1520/GTJ11272J.

Gibson, R.E. and Henkel, D.J. (1954), "Influence of duration of tests at constant rate of strain on measured 'drained' strength", *Géotechnique*, **4**, 6-15. https://doi.org/10.1680/geot.1954.4.1.6.

Goual, I., Goual, M.S., Taibi, S. and Abou-Bekr, N. (2011), "Behaviour of unsaturated tuff- calcareous sand mixture on drying-wetting and triaxial paths", *Geomech. Eng.*, **3**(4), 267-284. https://doi.org/10.12989/gae.2011.3.4.267.

Habasimbi, P. and Nishimura, T. (2018), "Comparison of soil–

water characteristic curves in one-dimensional and isotropic stress conditions", *Soil Syst*., **2**(43), 1-15. https://doi.org/10.3390/soilsystems2030043.

Habasimbi, P. and Nishimura, T. (2019), "Soil water characteristic curve of an unsaturated soil under low matric suction ranges and different stress conditions", *Int. J. Geosci*., **10**(1), 39-56. https://doi.org/10.4236/ijg.2019.101004.

Kim, Y. and Jeong, S. (2017), "Modeling of shallow landslides in an unsaturated soil slope using a coupled model", *Geomech. Eng*., **13**(2), 353-370. https://doi.org/10.12989/gae.2017.13.2.353.

Kim, B.S., Park, S.W., Takeshita, Y. and Kato, S. (2016), "Effect of suction stress on critical state of compacted silty soils under low confining pressure", *Int. J. Geomech*., **16**(6), 1-11. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000665.

Li, L. and Zhang, X. (2015), "A new triaxial testing system for unsaturated soil characterization", *Geotech. Test. J*., **38**(6), 823-839. https://doi.org/10.1520/GTJ20140201.

Lin, H.D., Wang, C.C. and Wang, X.H. (2018), "A simplified method to estimate the total cohesion of unsaturated soil using an UC test", *Geomech. Eng*., **16**(6), 599-608. https://doi.org/10.12989/gae.2018.16.6.599.

Lu, N., Godt, J.W. and Wu, D.T. (2010), "A closed-form equation for effective stress in unsaturated soil", *Water Resour. Res*., **46**(5), W05515. https://doi.org/10.1029/2009WR008646.

Luo, H., Cooper, W.L. and Lu, H. (2014), "Effect of particle size and moisture on the compressive behavior of dense eglin sand under confinement at high strain rates", *Int. J. Impact Eng*., **65**, 40-55. https://doi.org/10.1016/j.ijimpeng.2013.11.001.

Martin, B.E., Kabir, M.E. and Chen, W. (2013), "Undrained high-pressure and high strain-rate response of dry sand under triaxial loading", *Int. J. Impact Eng*., **54**, 51-63. https://doi.org/10.1016/j.ijimpeng.2012.10.008.

Melinda, F., Rahardjo, H., Han, K.K. and Leong, E.C. (2004), "Shear strength of compacted soil under infiltration condition", *J. Geotech. Geoenviron. Eng*., **130**(8), 807-817. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:8(807).

Mohamed, F.M.O, Vanapalli, S.K. and Saatcioglu, M. (2013), "Generalized Schmertmann equation for settlement estimation of shallow footings in saturated and unsaturated sands", *Geomech. Eng*., **5**(4), 343-362. https://doi.org/10.12989/gae.2013.5.4.343.

Mun, W., Teixeira, T., Balci, M.C., Svoboda, J. and McCartney, J.S. (2016), "Rate effects on the undrained shear strength of compacted clay", *Soils Found*., **56**(4), 719-731. https://doi.org/10.1016/j.sandf.2016.07.012.

Nam, S., Gutierrez, M., Diplas, P. and Petrie, J. (2011), "Determination of the shear strength of unsaturated soils using the multistage direct shear test", *Eng. Geol*., **122**(3/4), 272-280. https://doi.org/10.1016/j.enggeo.2011.06.003.

Nishimura, T. (2014), "Influence of seepage event on cyclic triaxial behavior of a compacted unsaturated soil", *Proceedings of the 6th International Conference on Unsaturated Soils*, Sydney, Australia, July.

Nishimura, T., Hirabayashi, Y., Fredlund, D.G. and Gan, J.K. (1999), "Influence of stress history on the strength parameters of an unsaturated statically compacted soil", *Can. Geotech. J*., **36**(2), 251-261. https://doi.org/10.1139/cgj-36-2-251.

Olson, R.E. and Langfelder, L.J. (1965), "Pore water pressures in unsaturated soils", *J. Soil Mech. Found. Div*., **91**(4), 127-160.

Olson, R.E. and Parola, J.F. (1967), "Dynamic shearing properties of compacted clay", *Proceedings of the International Symposium on Wave Propagation and Dynamic Properties of Earth Materials*, Albuquerque, New Mexico, U.S.A., August.

Peters, S., Siemens, G. and Take, W. (2011), "Characterization of transparent soil for unsaturated applications", *Geotech. Test. J*., **34**(5), 445-456. https://doi.org/10.1520/GTJ103580.

Rahardjo, H., Lim, T.T., Chang, M.F. and Fredlund, D.G. (1995), "Shear strength characteristics of a residual soil", *Can. Geotech. J*., **32**(1), 60-77. https://doi.org/10.1139/t95-005.

Rasool, A.M. and Kuwano, J. (2018), "Influence of matric suction on instability of unsaturated silty soil in unconfined conditions", *Int. J. GEOMATE*, **14**(42), 1-7. https://doi.org/10.21660/2018.42.7115.

Richardson, A.M. and Whitman, R.V. (1963), "Effect of strain-rate upon undrained shear resistance of a saturated remolded fat clay", *Géotechnique*, **13**(4), 310-324. https://doi.org/10.1680/geot.1963.13.4.310.

Sáez, J. and Escario, V. (1986), "The shear strength of partly saturated soils," *Géotechnique*, **36**(3), 453-456. https://doi.org/10.1680/geot.1986.36.3.453.

Satija, S. and Gulhati, S.K. (1979), "Strain rate for shearing testing of unsaturated soil", *Proceedings of the 6th Asian Regional Conference on Soil Mechanics and Foundation Engineering*, Singapore, July.

Svoboda, J.S. and McCartney, J.S. (2014), "Impact of strain rate on the shear strength and pore water pressure generation of saturated and unsaturated compacted clay", *Proceedings of the Geo-Congress 2014*, Atlanta, Georgia, U.S.A., February.

Svoboda, J.S. and McCartney, J.S. (2014), Shearing Rate Effects on Dense Sand and Compacted Clay, in *Dynamic Behavior of Materials, Volume 1. Conference Proceedings of the Society for Experimental Mechanics Series*, Springer, Cham, Switzerland, 389-395.

Vilar, O.M. (2006), "A Simplified procedure to estimate the shear strength envelope of unsaturated soils", *Can. Geotech. J*., **43**(10), 1088-1095. https://doi.org/10.1139/t06-055.

Zhu, J.G. and Yin, J.H. (2000), "Strain-rate-dependent stress-strain behavior of over-consolidated Hong Kong marine clay", *Can. Geotech. J*., **37**(6), 1272-1282. https://doi.org/10.1139/cgj-37-6-1272.

CC