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Evaluation of unsaturated soil behavior based on consolidated-drained and constant water content tests results

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Abstract

The surficial soils in the majority of Iran‟s region are in unsaturated state, having negative pore-water pressure, which contribute to their strength. The main aim of this study is to investigate the effect of matric suction, net confining pressure and drained condition on the shear strength and volume change characteristics of silty sand. The shear strength and volume change behavior of soil, were studied in this work using triaxial compression tests including; consolidated-drained (CD) and constant water content (CW). The test results indicate that the matric suction has an important role in the mechanical behavior of soil. Also the shear strength of the compacted specimens obtained from the CW tests are completely different from the shear strength obtained from the CD tests for same initial matric suctions and confining pressures.

Keywords: Unsaturated soil, Silty sand, Shear resistance, Matric suction, Volume change

1. INTRODUCTION

Civil engineers build on or in the earth’s surface. Most of the earth’s land surface comprises notoriously hazardous geomaterials called “unsaturated soils”. These soils are a hazard to earth structures and earth-supported structures because on wetting, by rain or other means, they can expand or collapse with serious consequences for cost and safety. Unsaturated soils, which are the majority of surface or near-surface soils on the earth’s land surface, are introduced together with their characteristic of partial saturation giving rise to pore air as well as pore water and hence an air–water interface forming a contractile skin. The importance of stress state variables in defining the engineering behaviour of strength, deformability and transient flow is discussed and the selection of the two independent stress state variables (net normal stress and matric suction) is explained. The associated physics of surface tension and cavitation (and how to avoid it) are described. The case is made that saturated soil is a simplified special case of unsaturated soil and so there are fundamental differences between the two in terms of classification and analysis methods. This important distinction has major implications for practicing civil engineers. Also geotechnical engineers have been increasingly challenged by problematic soils around the word. Some soils which have been identified as problematic are expansive soils, collapsible soils and residual soils. These soils are generally unsaturated with three phase materials, containing soil particles, water and air that pore-water pressures of these soils are negative relative to atmospheric conditions. In unsaturated soils the negative pore-water pressure contributes to the shear strength of the soils, as the surface tension or soil suction pulls the soil particles together. During rainfall, rainwater that infiltrates into the soil causes reduction in suction, which in turn reduces the shear strength of the soil and eventually leads to slope failures.

It is incumbent upon the geotechnical engineer to know and understand the loading conditions for which the stability analysis is being performed to evaluate. All of these loading conditions apply to both natural and man-made fill and cut slopes, but each condition does not have to be analyzed in every case. In the other word, each of these loading conditions requires the selection of the appropriate soil strength parameters. Once the rate of loading (i.e. loading condition) is determined, the soil response should be determined (i.e. drained or undrained). The drained response of soil is determined by loading the soil slowly enough to allow for the dissipation of pore pressures. Conversely, the undrained response of a soil is determined by loading the soil faster than the pore pressures can dissipate.

Brand (1981) indicated two extreme slope failure conditions encountered in the field: (1) rapid failure, which occurs under constant water content conditions (pore-air pressure is assumed atmospheric and constant throughout the entire failure process); and (2) slow failure, which occurs under approximately constant suction conditions. The mechanism of slope failures in unsaturated soils has been studied mostly by conducting consolidated drained (CD) tests, which involve the control of both pore-water and pore-air pressures (Rahardjo et al., 1994). The time taken for these tests is substantial enough, however, to render them impractical and uneconomical in engineering practices.

The other difficulty associated with the use of the CD test procedure is that slope failures may occur rapidly under undrained conditions. One of the possible undrained conditions is the constant water content (CW) condition, in which the pore-air pressure remains constant and the pore-water pressure changes due to compression during sliding. Hence, the CD test condition does not always simulate the field condition correctly. In this study, the necessary formulations for describing the pore pressure and volume change behavior during undrained and drained loadings (e.g. consolidation) are derived.

The adoption of matric suction, (u_a-u_w), and the excess of total stress over air pressure, that is, net normal stress, $(\sigma-u_a)$, as relevant stress state variables, has facilitated the modelling of key features of unsaturated soil behavior via suction controlled testing using axis-translation technique. It is the relative success of this technique that has prompted researchers in the unsaturated soil discipline to devote countless hours to fine-tuning the myriad details of the existing testing devices and keep the focus of their efforts on expanding their testing capabilities.

In this work, with the aim of study of unsaturated soil behavior, three series of triaxial tests have been conducted; namely (i) constant water content tests on unsaturated specimens with suction measurements and (ii) consolidated drained tests on unsaturated specimens. In the other word, this study was carried out to investigate the shear strength characteristics of soils associated with rainfall-induced slope failures.

2. SOIL PROPERTIES

The soil index properties are shown in Table 1 and according to Unified Soil Classification System (USCS), it is classified as silty sand (SM) and the grain size distribution of used soil is shown in Figure 1. Proctor compaction tests gave a maximum dry density of 1930 kg/m^3 and optimum moisture content of 10.2 %. Triaxial specimens, 38 mm in diameter and 70 mm high, were prepared by wet tamping technique. The samples were compacted in 7 layers, slightly under-compacted each, as suggested by Ladd (1978), so that the final specimens had a uniform density. All samples were compacted to a dry density of the Proctor maximum, which corresponds to a void ratio (e) of 0.46 and a degree of saturation of 38 %.

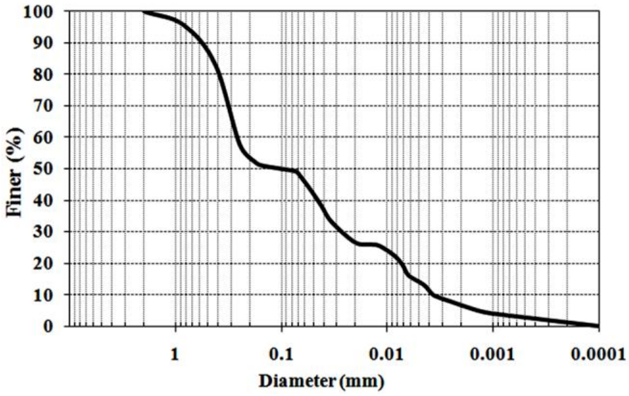


Figure 1. Grain size distribution curve

Table 1- Classification properties of soil

Liquid limit %	16
Plastic limit %	-
Plasticity index %	NPI
Specified gravity (G_s)	2.67
Clay percent %	29
Silt percent %	20
Soil type: (unified system)	SM

3. TRIAXIAL TESTING EQUIPMENT

In the current study, the triaxial compression test apparatus developed at Bu-Ali Sina university, used to determine the mechanical behavior of unsaturated soils. Triaxial tests were conducted using two conventional triaxial cells made for unsaturated soil testing (Fredlund and Rahardjo, 1993). The apparatus has ability to control and measure the pore air and pore-water pressure in the soil specimen independently by using axis translation technique. The pore-water pressures (u_w) was controlled through two saturated ceramic disks. For that purpose, two ceramic disks with air entry value of 500 kPa were sealed onto the base and upper pedestals of the triaxial cell. The constant pore air pressure was applied to the base and upper pedestals by coarse corundums that were sealed in the middle of ceramic disks. This two-way flows of water and air causes an acceptable decrease in test time and also production of homogeneous specimen.

4. TESTING PROSEDURE

Figure 2 shows the main procedures followed to prepare the soil specimens. As shown in this Figure, for unsaturated triaxial test, soil specimens were enclosed in two rubber membranes with two slotted aluminium sheets separated by layer silicon grease between the membranes. In this way, air which is diffused into cell water through the rubber membrane was eliminated (Alonso et al., 1990). After placing and sealing the specimen inside the triaxial chamber, the wetting process was then started by decreasing the value of matric suction until the specimen was achieves to initial matric suction of 50 or 100 kPa. In this stage, water was absorbed by the soil specimen so that volume of the water in the soil specimen remained constant (i.e. after 3-5 days). After the equalization stage the soil specimen is first consolidated by applying matric suction and net confining. During this consolidation stage, the moisture content of the specimen is reached the equilibrium state. In constant water content tests, unsaturated specimens were sheared to failure under constant gravimetric water content conditions. In these tests the pore-water valve was shut off while pore-air was allowed to drain freely from the specimen. During CW tests, matric suction will vary if significant changes in pore-water pressure occur during shearing. In consolidated drained (CD) tests, unsaturated specimens were sheared at a low strain rate with both pore-air and pore-water drainage valves open. In CD tests, excess pore-water and pore-air pressures are dissipated and equalized so that the matric suction remains constant.

Figure 2. Steps used for preparing the unsaturated silty sand specimens.

5. SHEARING BEHAVIOR

The specimens were designated using the symbol XX-S Y-Z, in which XX denotes type of test, Y is the matric suction, and Z is the net confining pressure applied in the test.

The (a) section of Figures 3-6 are the stress–strain curves for the unsaturated specimens. As shown in these figures, an increase in soil suction increased the shear strength and increases in soil suction affect the general shape of the stress–strain relationship.

The stress-strain curves for two sets of the CW tests (i.e., CW-S 50-x and CW-S 100-x) are presented in the (a) section of Figures 3 and 5. The suction and net confining pressure values indicated in the graphs correspond to the suctions at the beginning of the shearing process. These figures show that the stress–strain curves exhibited evidence of post-peak strain softening and the higher the initial matric suction of the specimens, the more distinct the peak deviator stress will be. It is known that whether a landslide can move rapidly is affected by many factors. The most important factor is, during landslide motion, whether the sliding surface is in undrained condition or in drained condition. The result indicated that deviator stress increased rapidly at commencement of shearing in the all tests but after this stage, CW specimens have a greater potential for undergoing flow (strain-softening behavior) during axial compression. The terminology of soil “softening” is referred to, after soil reaches peak strength, the soil strength would decrease with the increasing deformation. This softening behavior can be often observed from conventional laboratory tests, specifically for triaxial test (Lade and Prabucki, 1995; Chu et al. 1996; Yoshida and Tatsuoka, 1997; Suzuki and Yamada, 2006).

The stress-strain curves for two sets of the CD tests (i.e., CD-S 50-x and CD-S 100-x) are presented in the (a) section of Figures 4 and 6. Based on result of the CD and CW tests, deviatoric stress of specimens increases with an increase in net confining pressure at a given level of suction. The general trend for the results of tests is that the specimens with higher initial suctions were stiffer, they experimented higher ultimate deviatoric stresses. On the other hand, matric suction does influence the maximum and termination values of the shear stress. Many other similar results on unsaturated soils and relationship between suction and characteristics of shear strength have been presented in literature (Maleki and Bayat, 2011; Melinda et al., 2004; Indrawan et al., 2006; Oh et al., 2008).

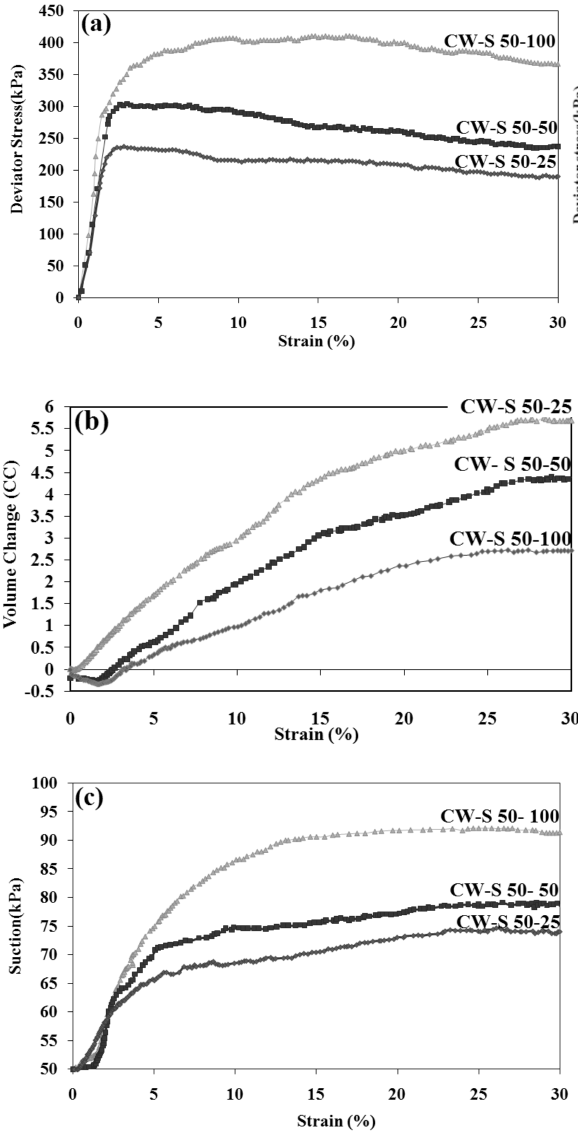
7. CHANGES OF VOLUME AND PORE WATER PRESSURE DURING LOADING STAGE

The overall and water volume changes were monitored throughout the shearing process. Compression of the specimen during shearing is expressed using a negative sign, and a positive sign is used for dilation of the specimen in the graph of the total volume change versus axial strain. It appears that the total volume change of specimens becomes stable at certain values of strain. This behavior shows that the soil specimens have a tendency to critical state condition as defined by Toll and Ong (2003) as the state achieved by a soil when it exhibits no changes in volume when it is sheared.

The total changes in volumetric of unsaturated tests (CD and CW tests) during shearing are shown in the (b) section of Figures 3-5 (dilation is plotted here as positive). These figures showed clearly that a constant-volume condition was achieved at the end of test. All of the specimens in the unsaturated tests after continued shearing the specimens started to dilate regardless of their suction. As shown these figure, for all the specimens, increasing of net confining pressure reduces the dilation rate. In the other word, during the shearing stage of tests, there was a tendency for reduced volume changes under higher net confining pressures. Also, the total volume change of CW test is more than CD test for given suction and net confining stress.

The (c) section of Figures 3 and 6 show the variation of matric suction during CW tests with two different initial matric suctions (i.e. 50 and 100 kPa) and three confining pressures (i.e. 25, 50 and 100 kPa). In most cases, the suction changes tend to stabilize close to the end of loading (i.e., 30% strain). As shown in these figures, the increase of suction appears to all specimens. In the other word, pore water pressure of unsaturated specimens reduced because pore air pressure is constant during shearing stage. In the all CW tests, the variation of matric suction is dependent on the net confining pressure and initial matric suction. As, it can be seen from results that under the same initial matric suction condition, the variation in matric suction of specimens under higher net confining pressures is more pronounced than the variation for specimens under lower confinements. In other word, there is a direct relationship between variation of matric suction and net confining pressure. However, it seems that using high net confining pressures during the constant water content shearing stage reduced the volume of the specimen.

The water volume changes of unsaturated test (CD test) during shearing are shown in the (b) section of Figures 4 and 6. The signs for the water volume change are expressed as positive for water entering into the specimen and negative for water being squeezed out of the specimen. As expect of the increase of suction in the CW test during shearing stage, the all specimens of CD tests absorbed water during shearing stage. The results indicated a direct relationship between variation of suction in CW test and water volume change in CD test. On the other hand, the specimen with more total volume change has more absorbed water at the end of test for a given initial matric suction.



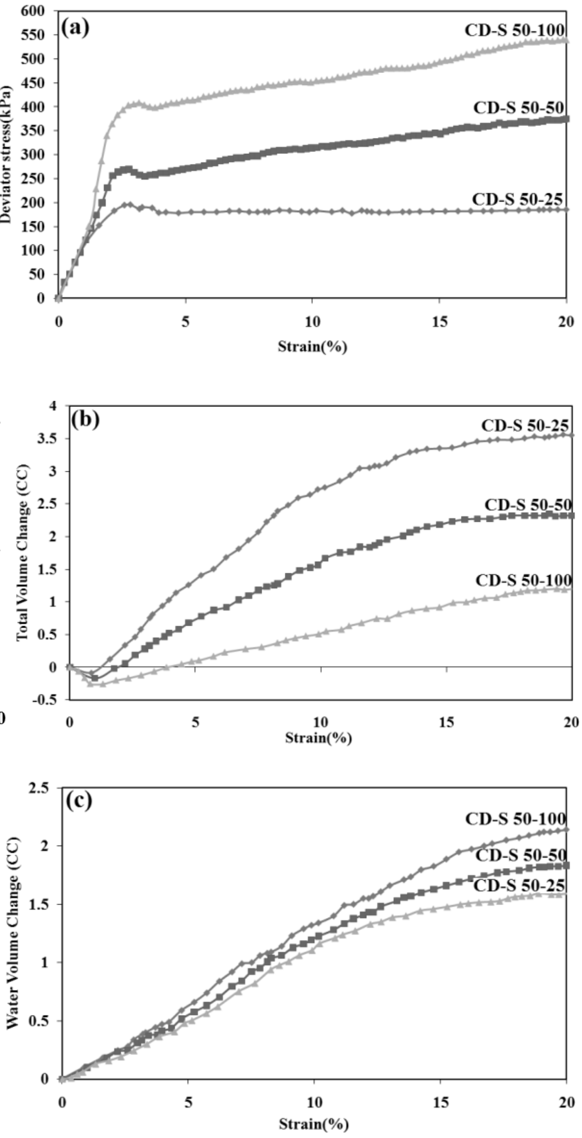
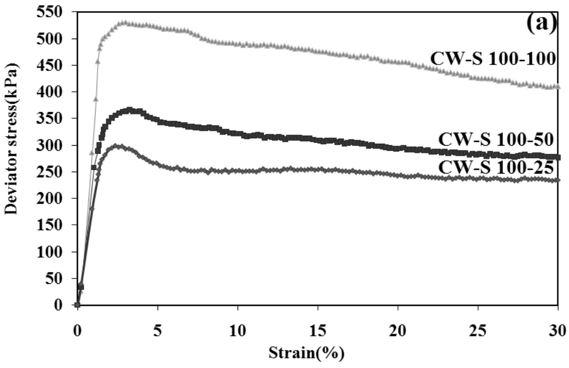
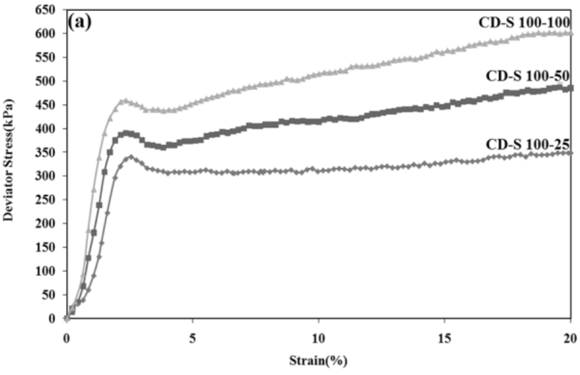


Figure 3. Results of CW tests at the initial matric suction of 50 kPa, plotted against axial strain: (a) deviator stress, q; (b) volume change; (c) suction.

Figure 4. Results of CD tests at the initial matric suction of 50 kPa, plotted against axial strain: (a) deviator stress, q; (b) total volume change; (c) water volume change.





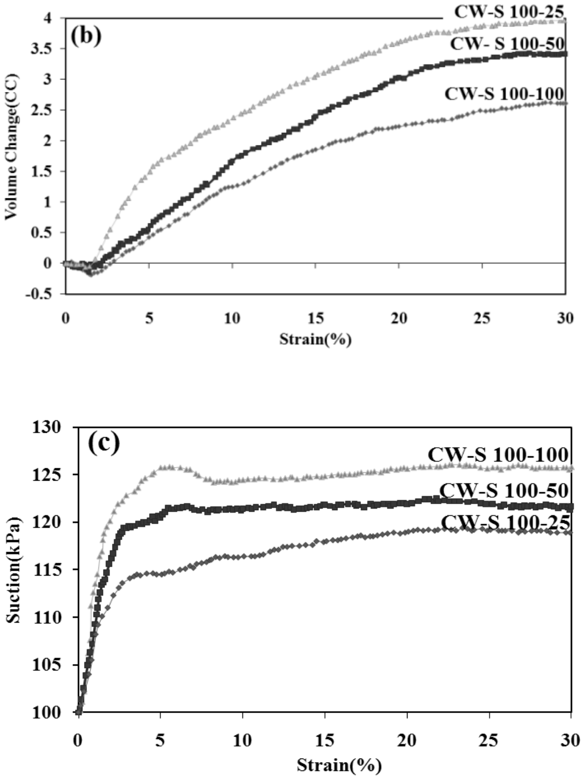


Figure 5. Results of CW tests of at the initial matric suction of 100 kPa, plotted against axial strain: (a) deviator stress, q; (b) volume change; (c) suction.

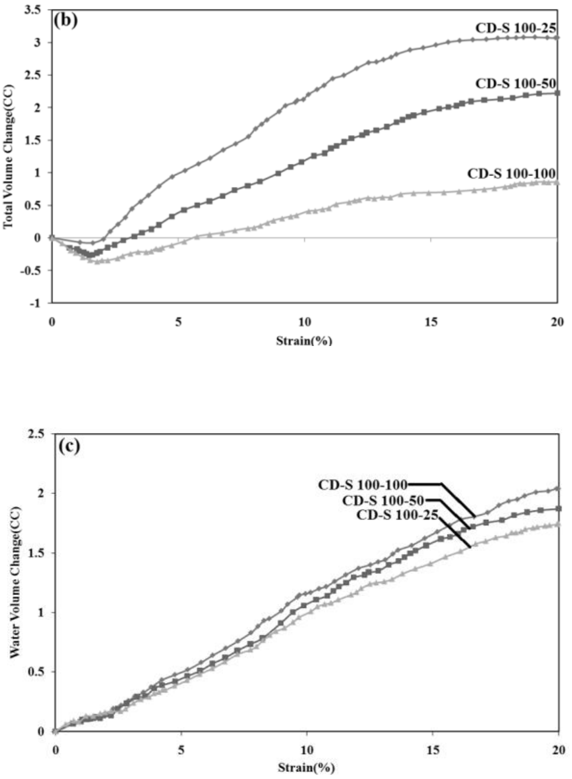


Figure 6. Results of CD tests at the initial matric suction of 100 kPa, plotted against axial strain: (a) deviator stress, q; (b) total volume change; (c) water volume change.

9. CONCLUSIONS

Based on the triaxial drained and undrained shear tests on the soil used in this research for unsaturated state, the following conclusions can be deduced:

1. Soil suction does play a role towards increasing the shear strength of an unsaturated soil and the shear strength of the specimens increases as a result of increasing matric suction both drained and undrained condition. The test results indicate a non-linear relationship between shear strength and matric suction.
2. The shear strength of unsaturated specimens increases as net confining pressure increases for both drained and undrained conditions. Also the increase in shear strength with respect to matric suction is then becomes less than the increase with respect to the net normal stress.
3. Based on the results of CW tests, there is a reciprocity relation between the variation in initial matric suction and net confining pressure.
4. Matric suction and net confining pressure have significant influence on the volumetric behavior of soil. The volume change of an unsaturated soil during shearing is more sensitive to the confining pressure compared to the initial matric suction of the specimen. Increasing of confining pressure reduces the dilation rate and specimens show the contraction behavior. Also matric suction has the same effect on total volume change of soil both for CD and CW tests.
5. Drained condition plays an important role in stress-strain path of silty sand. As shearing drained exhibit characteristics of a dilation behavior associated with strain hardening. Also undrained loading case hardening behavior in first steps of shearing and after this stage show a strain-softening behavior during shearing stage.

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