Experimental evaluation of mechanical behavior of unsaturated silty sand under constant water content condition

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A R T I C L E   I N F O

Article history:
Received 13 July 2011
Received in revised form 24 April 2012
Accepted 28 April 2012
Available online 9 May 2012

Keywords:
Unsaturated silty sand
Shear resistance
Matric suction
Volume change
Constant water content triaxial test

A B S T R A C T

There are very few experimental data on the mechanical behavior of unsaturated soils, particularly in constant water content condition, because of the technical difficulties and time-consuming nature of measuring suction and deformation. This paper presents the results of a series of constant water constant triaxial tests on the specimens of an unsaturated silty sand. Constant water content tests correspond to a field condition where the rate of loading is much quicker than the rate at which the pore water is able to drain out of the unsaturated soil. The axis translation technique and a double-walled triaxial cell have been used to measure the soil matric suction and variation of pore air volume respectively. Test specimens were prepared at two different compaction conditions prior to testing to achieve different initial density. It is found that the mechanical behavior of the soil mainly depends on the initial density, the mean net stress and the initial matric suction. Also the volume and pore water pressure changes are significantly different in specimens with different initial condition. The results of tests indicated that the shearing strength of silty sand increases non-linearly with matric suction.

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1. Introduction

In geotechnical practice most soils are in unsaturated condition, for instance the compacted soils used in several engineering constructions (such as earth dams, highways, embankments, and airport runways). Many of these soil structures often do not attain fully saturated conditions during their design life. Testing of soil in unsaturated conditions is not common in soil mechanics laboratories. Conventional soil mechanics theory treats soil as either fully saturated or dry. However, a large number of engineering problems involve the presence of unsaturated soil zones where the voids between the soil particles are filled with a mixture of air and water. These zones are usually ignored in practice and the soil is assumed to be either fully saturated or completely dry. This is despite test results indicate significant differences between the mechanical behavior of unsaturated soils and the mechanical behavior of fully saturated or completely dry soils (such as Adams and Wulfsohn, 1998; Miao, 2002; Wang et al., 2002; Chiui and Ng, 2003; Ng and Chiui, 2003; Rahardjo et al., 2004; Kayadelen et al., 2007; Jotisankasa et al., 2009). So far many studies have been conducted on critical state and mechanical behavior of saturated soils (Schofield and Wroth, 1968; Wood, 1991; Maatouk et al., 1995; Newson, 1998) but not unsaturated soils.

In the 1950’s, research at Imperial College London, was directed toward a fundamental understanding of unsaturated soil behavior within the classical framework of saturated soil (Bishop et al., 1960). The research involved careful laboratory studies, primarily on the shear strength of unsaturated soil. These studies have provided the catalyst for further studies in various countries of the world. This interest has accelerated during the last 17 years, and has been accompanied by the development of extensive experimental laboratory testing programs leading to the formulation of various constitutive models for unsaturated soils.

It is well known that the mechanical behavior of saturated soils can be interpreted and explained by a single stress state variable, called the effective stress (Terzaghi, 1936). Conversely, unsaturated soils are characterized by the presence of air phase, water phase and air–water interface in voids. Due to the additional pore phase, there are difficulties in applying the same approach to unsaturated soils (Jennings and Burland, 1962) and it is thus difficult to define convenient stress state variables. During the past three decades there has been an increasing use of two independent stress variables to describe the behavior of unsaturated soils (Coleman, 1962; Bishop and Blicht, 1963; Burland, 1965; Atchison, 1967; Matyas and Radhakrishna, 1968; Barden et al., 1969; Brackley, 1971; Fredlund and Morgenstern, 1977).

Critical state frameworks for unsaturated soil mechanics have been proposed and compared with those of saturated soil mechanics (Alonso et al., 1990; Maatouk et al., 1995; Wheeler and Sivakumar, 1995). The smooth transition from the two stress state variables for
an unsaturated soil, net stress (σ - u_a) and matric suction (u_a - u_w), (where, σ is the total stress, u_a is the pore air pressure, and u_w is the pore water pressure) to the single stress variable effective stress (σ - u_w) for a saturated soil (Fredlund and Morgenstern, 1977), forms the basis for the extension from saturated to unsaturated soil behavior. The concepts of yielding, hardening, and critical state are the key elements comprising the critical state framework for saturated soils. These concepts can be extended using two independent stress state variables, (σ - u_a) and (u_a - u_w), to build a critical state framework for unsaturated soils. These variables have been suggested as the critical state variables for unsaturated soils by several researchers (Maatouk et al., 1995; Wheeler and Sivakumar, 1995; Rampino et al., 1998). Given the diversity of results from previous research, more study is required on the behavior of soils with varied values of water content (or matric suction), initial density and net stress to investigate their influence on shear strength and volume change behavior.

This paper presents test data from triaxial tests on an unsaturated silty sand with measurements of matric suction. It summarizes the findings from an experimental program concerning the mechanical behavior of two groups of silty sand with different initial density tested under low mean net stress. Constant water content triaxial tests were carried out on unsaturated specimens. In addition, consolidated undrained tests on saturated samples were performed to study soil behavior in saturated condition. The mechanical behavior of unsaturated specimens is studied and compared with the behavior pattern for saturated specimens and their variation is considered with respect to matric suction.

2. Testing apparatus

The stress–strain behavior of unsaturated soils is often interpreted from results of triaxial or direct shear tests. These tests are generally performed by controlling matric suction (Alonso et al., 1990; Fredlund and Rahardjo, 1993; Aversa and Nicotera, 2002) in the soil specimen by using the axis translation technique. In this technique, the pore-air pressure is artificially raised above atmospheric pressure to increase the pore water pressure by the same amount to a positive value. In this way, the cavitation of water in the measuring system is prevented (Fredlund and Rahardjo, 1993).

In the current study, the triaxial compression apparatus developed at Bu-Ali Sina University is used to study the mechanical behavior of unsaturated soils. The details of the triaxial including its top cap and base plate are presented in Fig. 1. High-air entry ceramic disks, with 500 kPa of air entry values are sealed into the base pedestal and top cap using epoxy resin along their periphery. The two-way water flow (i.e. through ceramic disks in the cap and pedestal) causes a considerable decrease in test time and also create a more uniform distribution of moisture in the specimen. Two ceramic disks connected to the measuring system water compartment. The grooves inside the water compartment run as water channels for flushing air bubbles accumulated due to diffusion. The diffused air volume was measured by using the diffused air volume indicator (DAVI) proposed by Fredlund and Rahardjo (1993), and the measurement of pore-water volume change was corrected accordingly.

3. Testing program and procedures

3.1. Experimental details

In this work two groups of triaxial tests under saturated and unsaturated conditions were carried out for investigating the influence of initial density, matric suction and net confining pressure on soil behavior. The differences between the two groups are the specimen’s initial density and compaction water contents. The initial physical properties of specimens are given in Table 1. The values in this table are average values obtained from all specimens in this study. The

| Table 1 |
| - Physical properties of compacted soil specimen. |
| Group-1 | Group-2 |
| wet (KN/m^3) | 19.11 | 17.24 |
| dry (KN/m^3) | 17.94 | 16.26 |
| (S_r) initial (%) | 37.73 | 28.26 |
| e | 0.46 | 0.61 |
| G | 2.67 | 2.67 |
| (w) initial (%) | 6.5 | 6 |

Fig. 1. Details of: (A) used triaxial cell for testing unsaturated soils; (B) base plate of unsaturated triaxial test apparatus.
water into the air-dried soil. Water spraying and soil agitation were done simultaneously to ensure a uniform distribution of water. The soil was transferred to plastic bags and placed without further agitation in a controlled environment room for about 5 days to achieve moisture equilibration before preparing samples for testing. Triaxial soil specimens were formed by statically compacting soil at low water content of 6 or 6.5% in seven uniform layers, using a specially fabricated unit. The low water content is selected for achieving desired initial suctions without any drying process. Suitable thickness of soil of each layer is necessary for achieving uniform specimen. Layer thickness depends upon type of soil, dimensions of specimen and compaction method. In this study, a layer thickness about 1 cm is optimum for achieving material homogeneity. The loose soil is confined in a mold and compacted using the gradual movement of a piston. In the used compaction method a static force is gradually applied to each layer until the required thickness (volume) is achieved. This procedure produced uniform 38 mm diameter by 70 mm long cylindrical specimens all having the same material fabric. A length to diameter ratio of about 2 was selected in order to minimize the frictional effects due to the end platens of the apparatus and to reduce the likelihood of buckling during testing.

3.2. Saturated triaxial compression tests

Consolidated undrained triaxial compression tests were performed under saturated conditions. The saturated stress–strain behavior of soil specimens was measured by means of a conventional triaxial compression test apparatus. Prior to the tests, the soil specimens were saturated until a pore pressure coefficient ($B_w$) exceeding 0.95 (ASTM D 854-02, 2002) was measured. For this purpose, after placing and sealing the specimen inside the triaxial chamber and taking measurements of diameter and height, the specimens were first subjected to a flow of CO$_2$ from the bottom to the top for at least 3 h and then saturated by deaired water. Then a cell pressure and a saturation back pressure were applied and increased gradually. A difference of 10 kPa between cell pressure and back pressure was maintained so that accidental swelling of the specimen resulting from a high back pressure or consolidation of the specimen due to high cell pressure is prevented. At the end of the saturation process, the soil specimens were consolidated under a confining pressure ($\sigma_3$). Then, they were sheared at a constant strain rate. In consolidated undrained triaxial tests with pore water pressure

<table>
<thead>
<tr>
<th>Test</th>
<th>$\sigma_3$</th>
<th>$u_a$</th>
<th>$u_{uw}$</th>
<th>$\sigma_3 - u_a$</th>
<th>$u_a - u_{uw}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(G1$ or $G2)$-S 25-25</td>
<td>275</td>
<td>250</td>
<td>225</td>
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<td>25</td>
</tr>
<tr>
<td>$(G1$ or $G2)$-25-50</td>
<td>300</td>
<td>250</td>
<td>225</td>
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</tr>
<tr>
<td>$(G1$ or $G2)$-25-100</td>
<td>350</td>
<td>250</td>
<td>225</td>
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</tr>
<tr>
<td>$(G1$ or $G2)$-50-25</td>
<td>300</td>
<td>250</td>
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<td>$(G1$ or $G2)$-S 50-50</td>
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<td>$(G1$ or $G2)$-S 50-100</td>
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<tr>
<td>$(G1$ or $G2)$-S 100-25</td>
<td>275</td>
<td>250</td>
<td>150</td>
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<td>100</td>
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<tr>
<td>$(G1$ or $G2)$-S 100-50</td>
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<td>250</td>
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<tr>
<td>$(G1$ or $G2)$-S 100-100</td>
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<tr>
<td>$(G1$ or $G2)$-S 162-25</td>
<td>275</td>
<td>250</td>
<td>88</td>
<td>25</td>
<td>162</td>
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<tr>
<td>$(G1$ or $G2)$-S 162-50</td>
<td>300</td>
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<td>$(G1$ or $G2)$-S 162-100</td>
<td>350</td>
<td>250</td>
<td>88</td>
<td>100</td>
<td>162</td>
</tr>
</tbody>
</table>
measurements, the rate of strain ranges from 0.05 to 1%/min. We used a strain rate of 0.07%/min for consolidated undrained (CU) tests on saturated specimens.

3.3. Unsaturated triaxial compression tests

Soil specimens were enclosed in two rubber membranes with a layer of silicon grease between them. In this way, air diffusion into cell water through the rubber membrane was eliminated (Alonso et al., 1990). After placing and sealing the specimen inside the triaxial chamber, the specimen is consolidated prior to shearing by applying matric suction and net confining pressure. A wetting process was then started by decreasing the value of matric suction to different levels of 25, 50, 100 and 162 kPa.

As shown in Table 2, specimens are referred to according to the conditions in which they were tested (initial density, matric suction prior to shearing and net confining pressure). For example, G1-S50-100 represents a specimen of group-1 that was tested under constant water content at a matric suction prior to shearing of 50 kPa and net confining pressure of 100 kPa.

4. Results and discussions

4.1. Equalization stage

In order to confirm whether or not equilibrium has been reached during suction equalization, the moisture content of the specimen is monitored with respect to time. Fig. 3 shows the volumetric water content with respect to time and indicates that specimens have reached equilibrium after a certain time. In Fig. 3, the specimen with the initial matric suction of 25 kPa takes longer to equalize than the others, at suctions of 50, 100, and 162 kPa. Also, for the specimens of group-2, the equilibrium time is generally shorter than for the specimens of group-1. By comparing the two figures (i.e. Fig. 3(a) and (b)), we find that the specimens of group-1 absorb more water than the specimens of group-2 at the same matric suctions. These differences indicate of influence of initial density on soil capillarity.

4.2. Shearing behavior

After consolidation, the specimen is subjected to deviator stress. Specimens were sheared until 30% axial strain under constant gravimetric water content (CW). In these tests the pore-water valve was shut off while pore-air was allowed to drain freely from the specimen. We used a strain rate of 0.01%/min for these constant water content tests. This value of strain rate cases a suitable coherence between pore water pressure of specimen and pressure transducer in every moment. During CW tests, matric suction varies as changes in pore-water pressure occur during shearing. Figs. 5–8 and 10–13 show the variation of deviator stress, volume change and suction against the axial strain during the shearing stage for the unsaturated specimens of group-1 and group-2, respectively. Also Figs. 4 and 9, show the
deviator stress and pore-water pressure versus axial strain for the saturated soil specimens of group-1 and group-2, respectively.

For a given density, the deviatoric stress increases with an increase in net confining pressure at a given level of suction (the (a) sections of Figs. 4–13). Also, for the same net confining pressure, the strength of the unsaturated specimens is significantly greater than the strength of a saturated specimen. The general trend for all tests (group-1 and group-2) is that the specimens with higher initial suctions were stiffer and they experienced higher ultimate deviatoric stresses. Although matric suction does not have important influence on the general shape of the stress–strain curve, it does influence the maximum and final values of shear stress. Many other similar results about the relationship between suction and shear strength have been presented in the literature (Miller and Nelson, 1993; Melinda et al., 2004; Rahardjo et al., 2004; Indrawan et al., 2006; Oh et al., 2008).

Fig. 14 shows the peak shear strength of all unsaturated specimens versus initial matric suction. This figure suggests that there is a nonlinear increase in peak shear strength of specimens as a result of increase in initial suction. Also, equal increases of suction and net confining pressure do not produce equal increases of shear resistance. In particular, an increase of net confining pressure produces a greater increase of resistance than an equal increase of suction. A comparison between the two groups shows that the shear strength of specimens is affected by initial density. The shear strength for the specimens of group-1 is greater than the shear strength of the specimens of group-2 at a given level of suction for all confining pressures. Also this figure shows that the specimens in group-1 show a larger increase of peak shear strength for a given increase of suction than the specimens in group-2.

Fig. 15 presents the shape of the two specimens of group-1 at the end of test. As shown in the figure, the unsaturated specimens showed a barrel failure mode at lowest suction (i.e. 25 kPa) similarly to saturated specimens, while they showed a brittle failure mode accompanied with a shear zone at highest suction (i.e. 162 kPa). This figure shows that the stiffness and brittleness of the specimens of group-1 increased as their initial matric suctions increased. In other words, the stiffness and brittleness of the specimens of group-1 increased as their initial matric suctions increased at the same net confining pressure. Conversely, the shear stress of the unsaturated specimens of group-2 stabilizes at an axial strain between 20 and 30%, without distinct failure planes being observed for all initial suctions.
4.3. Volumetric behavior

The changes in volumetric strain of unsaturated specimens during shearing are shown in the (b) section of Figs. 5–8 and 10–13 (dilation is plotted here as positive). These figures show clearly that a constant-volume condition was achieved at the end of test. All specimens in group-1 started to dilate after continued shearing regardless of their suction. For all specimens of group-1, an increase of net confining pressure reduces the dilation rate. In other words, during constant water content shearing, there was a tendency for reduced volume changes under higher net confining pressures. This is largely attributed to the fact that higher net confining pressure caused a greater reduction of the pore spaces (i.e. compaction) during the preceding isotropic compression stage (such as Herkal et al., 1995; Adams et al., 1996). An explanation in terms of soil structure is that more closely packed particles result in reduced interconnections between pore spaces as well as reduced porosity. The maximum value of dilation in specimens of group-1 occurred at specimens with initial water content equal to optimum water content (i.e. 10.2%) at a given net confining pressure. Conversely, in group-2, increasing water contents reduced the dilation rate and the specimens with higher initial water content tended to compress more. In other words, the general trend for this group is that the higher the suction, the greater was the dilation. This shows that initial density, matric suction and net confining pressure are all important factors in the volume change of unsaturated soil.

4.4. Changes of suction or pore water pressure

Water is normally thought to have little tensile strength and may start to cavitate when the magnitude of gauge pressure approaches −1 atm. As cavitation occurs, water phase becomes discontinuous, making the measurements of suction unreliable or impossible. Hilf (1956) introduced the axis-translation technique of elevating pore air pressure $u_a$ to increase pore water pressure to be positive, preventing cavitation in the water drainage system. Total stress, $\sigma$, is increased together with air pressure of the same amount so the net stress, $(\sigma - u_a)$, remains unchanged. The variation of matric suction under constant water content conditions during the shearing stage is investigated here. This variation is caused by the fact that pore-air pressure is maintained at a constant value while the pore-water pressure changes continuously during shearing of the specimen. The (c) section of Figs. 5–8 and 10–13 show the variation of matric suction during constant water tests for the two groups with four different initial matric suctions (25, 50, 100 and 162 kPa) and three confining pressures (25, 50 and 100 kPa). In most cases, the suction changes tend to stabilize close to the end of loading (i.e., 30% strain). Suction increases for all specimens except for the highest matric suction in group-1 (i.e. G1-S162). For group-1, as shown in Fig. 8(c) the variation of matric suction becomes negative for the matric suction of 162 kPa, whereas for the initial matric suctions of 25, 50 and 100 kPa, the variation of matric suction remains positive. It should be noted that a matric suction of 162 kPa...
is close to the initial matric suction of the compacted specimens. This decrease of suction did not occur in the tests of group-2 for which matric suction increases to a relatively high value during shearing for all tests. The results indicate that the initial density of the specimen plays an important role in the variation of matric suction during loading and this effect is particularly significant in the specimens with highest suction value (i.e. 162 kPa). Also, in the first group of tests, as shown in Fig. 16(a) the relative variation of matric suction in the case of tests conducted at 25 kPa initial suction is larger than in those conducted at other values of suction for all confining pressures (i.e. 25, 50 and 100 kPa). Conversely, as shown in Fig. 16(b), for specimens of group-2 the largest percentage variation occurs for an initial suction 50 kPa at all values of confining pressure. In all specimens of groups-1 and 2, the variation of matric suction is dependent on the confining pressure. In addition, it can be seen from Fig. 16(a) that under the same initial matric suction condition, the variation in matric suction for specimens of group-1 under higher net confining pressures is more pronounced than for specimens under lower confinements. In other words, in all specimens of this group, there is a direct relationship between the value of the variation of matric suction and the net confining pressure. However, high net confining pressures during constant water content shearing lead to a reduction in the volume of the specimen. Different results of relationship between variation value in matric suction and net confining pressure are shown in Fig. 16(a) and (b), so that this relationship is direct for of group-1 and indirect for group-2. These different results show the importance of initial density of unsaturated soil in pore water pressure change during undrained loading. In other words, the variation of matric suction under constant water content is more sensitive to the initial density of specimens than to the net confining pressure and the initial matric suction.

Fig. 17 shows the relationship between volume change and matric suction change of the specimens at critical state. As shown in Fig. 17(a), the magnitude of matric suction change generally decreased with increasing dilation rate for the specimens of group-1. But the specimens of group-2 show different behavior in this respect. According to Fig. 17(b), there is direct relation between the magnitude of suction

**Fig. 10.** Results of CW tests of group-2 at the initial matric suction of 25 kPa, plotted against axial strain: (A) deviator stress, q; (B) volume change; (C) suction.

**Fig. 11.** Results of CW tests of group-2 at the initial matric suction of 50 kPa, plotted against axial strain: (A) deviator stress, q; (B) volume change; (C) suction.
change and increasing dilation rate or reducing soil compaction of specimens at critical state. This means that the initial density of the soil is a decisive factor in the variation of matric suction during fast loading.

Finally, the changes of pore water pressure in the saturated tests are investigated. Figs. 4(b) and 9(b) show the pore water change of saturated specimens during shearing. As shown in these figures, a rapid increase of pore water pressure occurred at the start of loading. The test results indicate that the confining pressure has an important role in the variation of pore water pressure during loading, so that excess pore water pressure increases as confining pressure increases.

5. Conclusions

Triaxial experiments have been performed to investigate the variation of pore pressure, volume change and axial strain in unsaturated soils samples with different values of initial matric suction. The matric suction was controlled by the axis translation technique and volumetric behavior of specimens was measured by using a double-walled triaxial cell. The tests include consolidated undrained tests on saturated specimens and constant water content tests on unsaturated specimens. Based on results, the following conclusions can be deduced.

1. Soil suction does play a role toward increasing the shear strength of an unsaturated soil and the shear strength increases as a result of increasing matric suction. The test results indicate a non-linear relationship between shear strength and matric suction.
2. The shear strength increases as net confining pressure increases for both saturated and unsaturated conditions. The increase in shear strength with respect to matric suction is smaller than the increase with respect to the net normal stress.
3. 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. An increase of confining pressure reduces the dilation while matric suction does not have univocal effect on volume change of soil.
4. Results of constant water content triaxial tests show that the relationship between pore water pressure and total volume change during shearing is more complicated than that found in saturated undrained triaxial tests. In other words, the change in pore water pressure during shearing is not directly related to the overall volume change of the specimen.

References


Fig. 14. Relationship between peak shear strength and initial matric suction: (A) in the specimens of group-1; (B) in the specimens of group-2.

Fig. 15. The failure modes in the unsaturated specimens of group-1: (A) barrelling in specimens at lowest suction value; (B) shear zone in specimens at highest suction value.
Fig. 16. Relationship between initial matric suction and suction change in critical state: (A) group-1; (A=B) group-2.

(a) \( \sigma_z - \gamma_a \) = 25 kPa

(b) \( \sigma_z - \gamma_a \) = 50 kPa

(c) \( \sigma_z - \gamma_a \) = 100 kPa
Fig. 17. Relationship between volume change and suction change for a given initial matric suction: (A) group-1; (B) group-2.