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FACTORS AFFECTING MECHANICAL BEHAVIOR OF UNSATURATED SILTY SAND ON WETTING PATH

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ABSTRACT

This paper reports the results of suction-controlled triaxial tests performed on unsaturated compacted silty sand specimens subjected to various initial anisotropic stress states and suction states. A double-walled triaxial cell working in suction control condition by axis translation technique have been used to control matric suction and measure the variation of pore volume of the samples. All the specimens were initially subjected to specific values of initial suction and total anisotropic stress, and then, wetted by finite decreases of suction. During wetting, deformations with time were measured. It was found that wetting behavior of soil specimens depends on initial density, initial suction and initial anisotropic stress level. For a given density, the specimen deformation increases with initial suction and anisotropic stress state. Wetting from high level of initial suction or initial deviatoric stress state, leads to specimen collapse. For given initial suction and stress state, deformation of specimen, on wetting path, increases with decreasing in initial density. Finally, deformation rate on wetting path depends on the level of external loading, density and matric suction.

Key words: Unsaturated soil, wetting, collapse, silty sand, triaxial testing.

1. INTRODUCTION

In the majority of earth structures such as earth and rock fill dams and slopes, construction is generally under unsaturated states. According to the experimental results in the literature, there are significant differences between the shearing behavior of unsaturated soils and fully saturated or completely dried soils. For unsaturated soils, a change in the degree of saturation can cause significant changes in volume, shear strength and hydraulic properties. Due to wetting, the unsaturated compacted fills, may experience a large amount of deformation or in certain cases collapse can occur (Leonard and Narain 1963; Leonard and Davidson 1984; and Pereira and Fredlund 2000). Wetting effect on unsaturated soil depends on different factors such as soil type, initial matric suction, density, initial degree of saturation and confining pressure. There are numerous studies in literature concerning the influence of wetting on stress-strain behavior of unsaturated soils (Kato *et al*. 2000; Ferber *et al*. 2008; Airo Farulla *et al*. 2010; Lim *et al*. 2004; Sun *et al*. 2004 and 2007; Meilani 2005; Fredlund *et al.* 1991; Cerata *et al*. 2009; Escario *et al*. 1973; and Bishop 1961). The majority of these works have been executed through oedomertic apparatus. However application of this apparatus presents certain limitations concerning, stress and strain boundary conditions and matric suction measurement. For removing the above mentioned limitations, triaxial apparatus has been used by some authors such as Anderson and Sitar (1995), Sun *et al*. (2007), and Meilani *et al.* (2005). The effect of different factors affecting the wetting and collapse behavior of soils such as stress path, density, drainage conditions can be studied by triaxial apparatus.

An important issue corresponding to the majority of practical geotechnical problems is the wetting of compacted unsaturated soil under a constant anisotropic stress state and production of deformation during the time. This aspect is the aim of the present work. For this purpose, using a developed triaxial apparatus, wetting behavior of compacted unsaturated silty sand specimens in different initial matric suction, different initial density, and in various levels of constant anisotropic stress state was studied.

2. SOIL PHYSISICAL PROPERTIES AND SAMPLES PREPARATION

The used soil in this work is sand mixed with silt and clay. Its physical properties are presented in Table 1. The selection of soil was based on time-consuming nature of air and water equilibrium together with suction and deformation measurement that necessitated such percentage of sand, moderate probability of collapse occurrence of soil led to select such clay percentage, and finally silt percentage was necessary as an intermediate material between sand and clay. The particle size distribution curve of soil based on ASTM D-422 is shown in Fig. 1 and according to Unified Soil Classification System (USCS), it is classified as silty sand (SM). Two groups of specimens with different densities were prepared to study the effect of density on wetting behavior of soil. Initial void ratio for first and second groups is 0.46 and 0.61, respectively. The specimens were prepared using the moist tamping method. The purpose of using static wet compaction as opposed to dynamic compaction is to obtain a more homogenous specimen in terms of density and shear strength. This method is recommended by several authors such as Frost and Park (2003).

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Table 1 Physical properties of the soil

Soil type	Sand content (%)	Silt content (%)	Clay content (%)	Specific gravity	LL	PL
SM	51	20	29	2.68	16	–

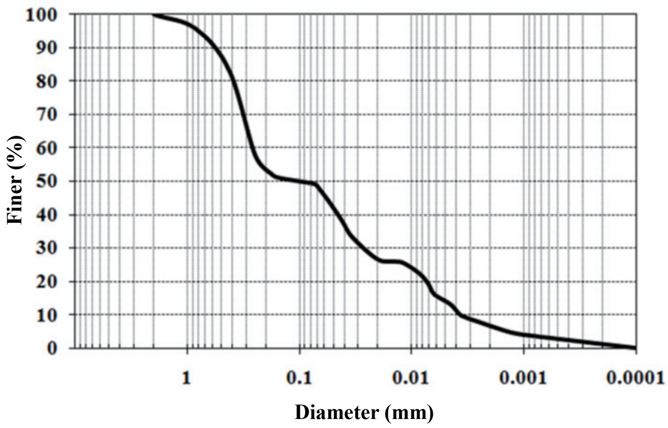

Fig. 1 Particle size distribution curve of the soil specimen

3. TESTING APPARATUS

The load controlled triaxial test apparatus developed at Bu-Ali Sina University, was used to achieve the aim of this work. The matric suction in this apparatus is controlled using the axis translation technique. The pore-water pressure was controlled through a saturated ceramic disc with an air entry value of 500 kPa. The apparatus has ability to control and measure the pore-air and pore-water pressures in the soil specimen independently by using axis translation technique. A schematic design of triaxial cell, used in the present study is shown in Fig. 2.

4. TESTING PROCEDURE

The initial anisotropic stress states of specimens were selected as a percentage of their maximum supported deviatoric stresses. For this, firstly a set of classical drained triaxial tests with different value of initial suction (50, 100, and 162 kPa) and under net confining stress equal to 100 kPa were carried out. In these tests, all specimens were in the state of equilibrium concerning pore air and pore water before shearing. The stress-strain curves for different tests are shown in Figs. 3(a) and 3(b). In these Figures, vertical axis presents deviatoric stress defined by difference between major and minor principle stresses ($q = \sigma_1 - \sigma_3$) and horizontal axis shows axial strain of specimen during shearing. It is obvious from Fig. 3 that increasing in initial matric suction results in increasing in shear strength of soil. Different values of deviatoric stress states for wetting tests are listed in Table 2. In the first column of this table, different type of test are presented. For example G2-S50-100 represent a test of second group with initial suction of 50 kPa and confining pressure of 100 kPa. Maximum deviatoric stress, selected from Fig. 3, has been listed in second column. In the third and fourth columns, applied anisotropic stresses in wetting process have been presented. The unsaturated specimens, for wetting effect study, were

Table 2 Definition of different type of tests

Test	q_{max} (kPa)	$0.7q_{max}$ (kPa)	$0.5q_{max}$ (kPa)
G1-S162-100	658	460.6	329.0
G1-S100-100	603	422.1	301.5
G1-S50-100	540	378.0	270.0
G2-S162-100	539	377.3	269.5
G2-S100-100	526	368.2	263.0
G2-S50-100	455	318.5	227.5

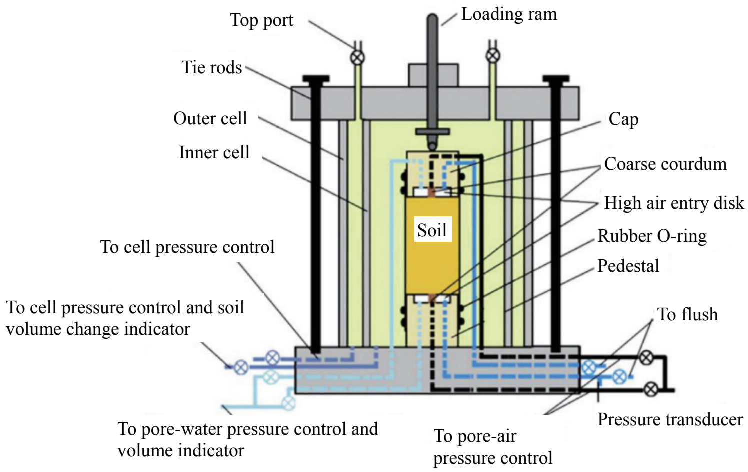

Fig. 2 Schematic design of triaxial cell, used in present study (Maleki & Bayat 2012)

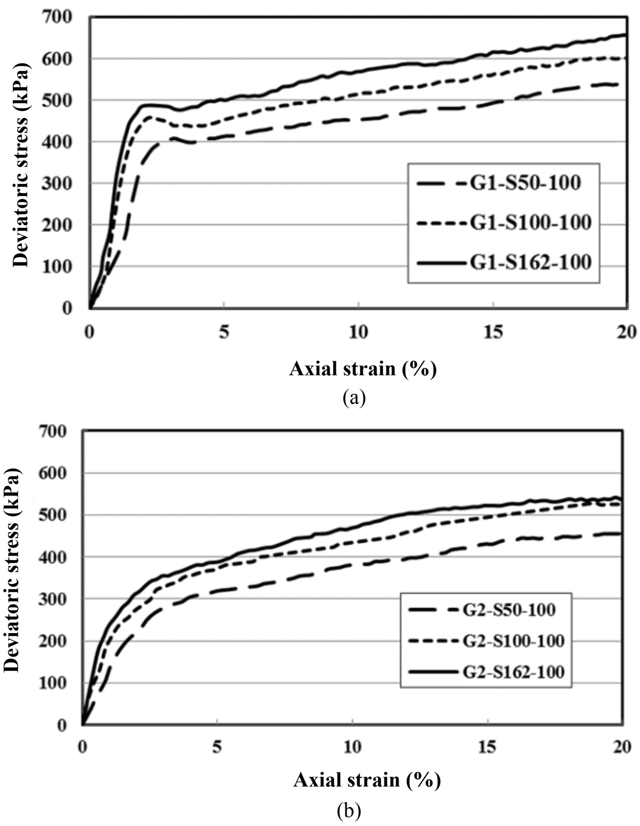

Fig. 3 Stress-strain curves of triaxial tests for different initial matric suctions; (a) group 1, and (b) group 2

prepared in the second step. They were afterward subjected to selected initial anisotropic stress states and initial suctions. In this experimental program, pore-air pressure was constant equal to 250 kPa for all of the tests. The term of suction is the difference between pore-air and pore water pressures. Therefore, for inducing the initial suction, air and water pressures were imposed on the specimen. After achieving the equilibrium state between pore-air and pore-water pressures for attaining given initial suction, the wetting phase were started with decrease in suction incrementally.

Figures 4(a) and 4(b) show the tests results for equilibrium phase, after applying the stress states and before applying wetting. It was observed an instantaneous behavior due to applied external stresses and a delayed behavior under constant loading for achieving equilibrium state. In the wetting phase, the specimens were subjected to decrease in matric suction incrementally, and specimen deformations were recorded during the time.

5. RESULTS AND DISCUSSIONS

The wetting tests of two groups of specimens were performed for three values of initial suction (50, 100 and 162 kPa) at two levels of initial anisotropic stress states (50 and 70% of maximum deviatoric stress, respectively, according to Table 2). For all of the tests, suction was decreased by increasing pore water pressure incrementally and axial and volumetric deformations were recorded during the time. The selected increment for decreasing matric suction during wetting process was 50 kPa and the time position of decrease in matric suction has been marked on the Figs. 5, 6, and 7. The obtained results for two groups of specimens are presented separately, that provides a good interpretation and discussion on the results.

5.1 Variation of Axial Deformation

Figure 5 shows variation of axial strain versus time in wetting phase for the first and second groups. In all tests matric suction was diminished incrementally and axial and volumetric deformations were recorded during time. Comparison between Figs. 5(a) ~ 5(c) and 5(d) ~ 5(f) shows the effect of density on wetting behavior of tested soil, so that, for a given initial deviatoric stress and initial suction, specimen with lower density has experienced more axial strain. For example, in the case of $q = 0.5q_{max}$, for two initial matric suctions of 50 and 100 kPa, increase in axial deformations for first group, in comparison with second group, are 650% and 191% respectively. However for initial suction of 162 kPa the specimen of second group was collapsed. As it is obvious from Fig. 5 the level of initial deviatoric stress for two groups of specimens, plays an important role in deformation. In the other word increase in initial deviatoric stress led to increase in axial strain of specimen. Based on tests results, the effect of initial anisotropic stress on wetting phase is more significant in comparison with equilibrium phase. For example, according to Fig. 5(a), difference between axial deformations for two levels of initial anisotropic stress $0.5q_{max}$ and $0.7q_{max}$ is near 0.15% before wetting and 3.7% after wetting. The other important point is the form of evolution of axial strain rate during time. According to presented results, we can distinguish different types of behavior. The whole of specimens experience a near constant strain rate in first steps of wetting process. Afterward, strain rate is increased

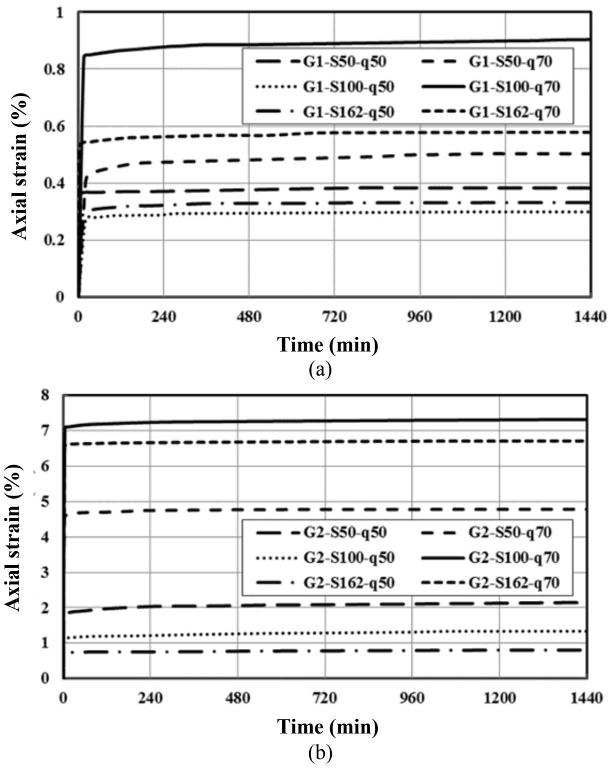

Fig. 4 Instantaneous and delayed behaviour of specimens before wetting phase for (a) group 1, and (b) group 2

and depending on the level of initial stress and initial density presents two different behaviors during time. For lower value of constant initial stress, axial strain reaches to the stationary state (Figs. 5(a), and 5(d), and Figs. 5(b), 5(c) and 5(e) for $q = 0.5q_{max}$). However, for high level of initial deviatoric stress, increasing of strain rate is continued until the failure of specimen (Figs. 5(c) and 5(f), and Figs. 5(b) and 5(e) for $q = 0.7q_{max}$). In the Figs. 5, 6 and 7 the term of "To failure" means specimen was ruptured or experienced large deformation under constant external loading. The level of initial suction is also one of the influencing factors in wetting process. According to the test results, for a given density and external deviatoric stress state, specimen with high level of initial suction during wetting experiences a great value of axial deformation. This is clearly indicated in Fig. 5. For example, comparison between Fig. 5(a) (initial suction of 50 kPa) and Fig. 5(d) (initial suction of 162 kPa) for $0.5q_{max}$ shows 300% difference between axial deformations. This can be important in evolution of collapse settlement of undisturbed natural soil. In fact, one of the most important points in wetting behavior is the manifestation of specimen failure which occurs in certain case of triaxial test path. For a given soil, level of initial deviatoric stress state, initial density and suction and confining pressure influence on occurrence of failure state. According to Fig. 4, initial suction of 100 kPa and initial stress state of $0.7q_{max}$ led to failure for two groups of specimens. Similarity for initial suction of 162 kPa, the specimens experiment failure state during the wetting process. However, for initial suction of 50 kPa all of the specimens experiments a stationary state at the final step of wetting. It should be noted that due to special boundary conditions of oedometric test in deformation, the failure state can't be occurred. However different criteria for evaluation collapse potential of soils exist

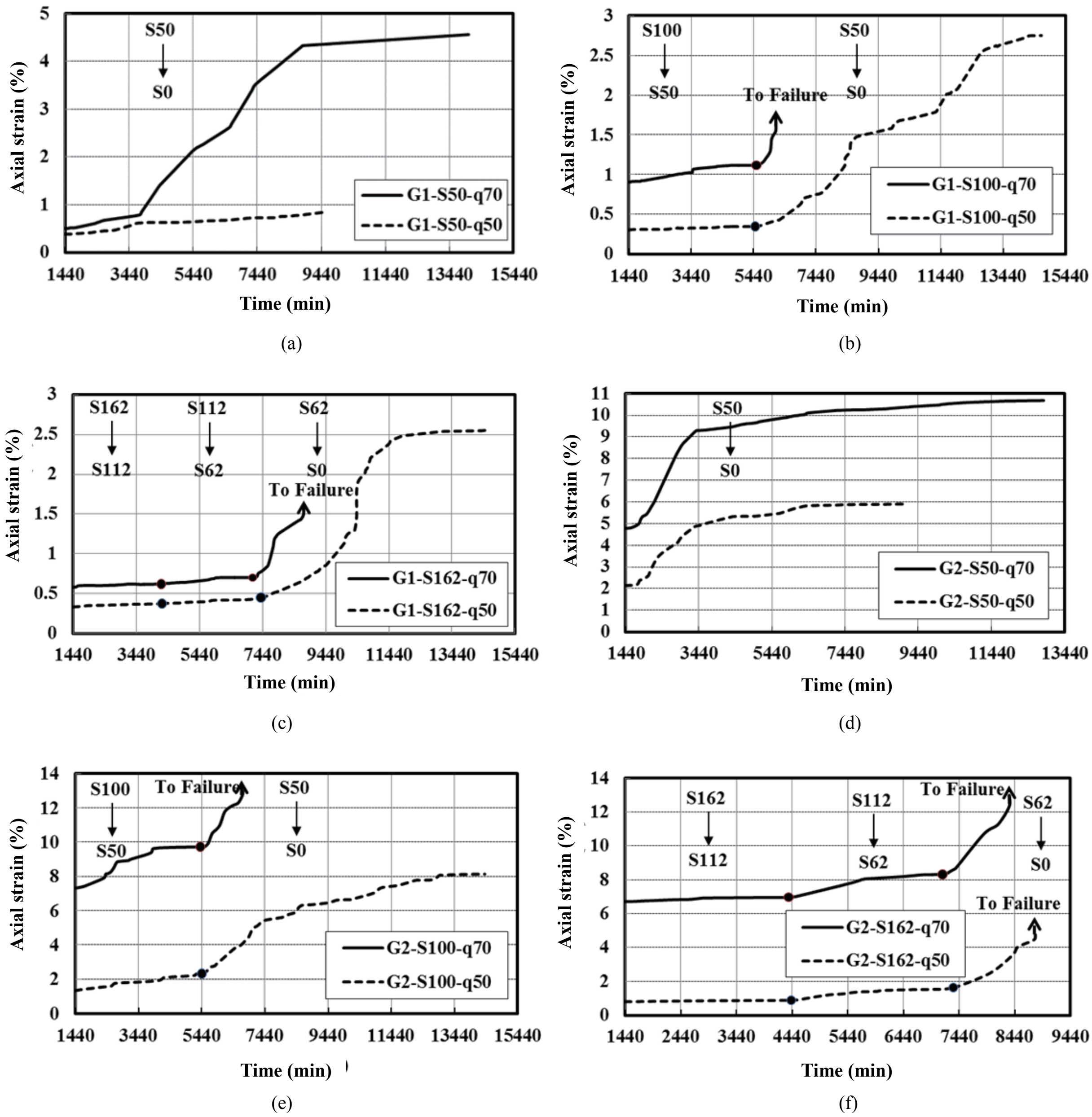

Fig. 5 Variation of axial strain versus time for two groups of specimens during wetting process; for group 1 (a) ~ (c), and for group 2 (d) ~ (f)

based on oedometric test. As it was mentioned, applied anisotropic stress state is constant during wetting of specimen. However, deformation is generated during time. This deformation is due to creep, and variation of pore water and pore air pressures for achieving the equilibrium state. The rate of deformation depends on different factors such as the level of applied stress state, initial suction, and density. According to the tests results in Fig. 5 the time parameter play an important role for describing behavior of soil during wetting. For example, failure of specimen occurs in different time position. This means that for describing mechanical behavior of unsaturated soil, it is more realistic to introduce viscosity in constitutive equations.

5.2 Variation of Volumetric Strain

Variation of volumetric strain of specimens during time is presented in Fig. 6. As can be seen from this figure, wetting of unsaturated specimen under a constant stress state generates the volumetric strain. For all tests, specimens have been shown a contractive behavior. Figures 6(a) to 6(d) show that for specimens under high level of deviatoric stress ($0.7q_{\max}$), volume change is less than those under low level of deviatoric stress ($0.5q_{\max}$). The reason behind it is that for the first group of specimens, lateral strain is more than the second group of specimens. It should be noted that the total net cell pressure was 100 kPa. Figures 6(e) and 6(f) show that for tests of second group, with initial suction of 100 and 162 kPa and under anisotropic stress of $70\%q_{\max}$, specimens experienced a few swelling in the equilibrium phase. This is due to high level of suction and fewer value of initial density in comparison with first group tests. The comparison between Figs. 5 and 6 indicate that volumetric strain is less influenced by the initial suction than axial strain.

5.3 Saturation Degree

Saturation degree is calculated from the basic relation of $eS_r = wG_s$. In this relation, void ratio (e) is calculated using $\varepsilon_v = (e - e_0) / (1 + e_0)$, and changes in water content and volume of specimen during wetting is directly measured from the tests. Variation of saturation degree versus time for two groups of specimens has been presented in Fig. 7. It is obvious that for all specimens, saturation degree increased during wetting process. However, at the final step of wetting, saturation degree is less than 100%. This is due to air trapped in the specimen void and dissolving air into the water. It seems that variation of saturation degree during wetting, for given initial density and initial suction, is independent of the level of initial deviatoric stress state, as shown in Fig. 7.

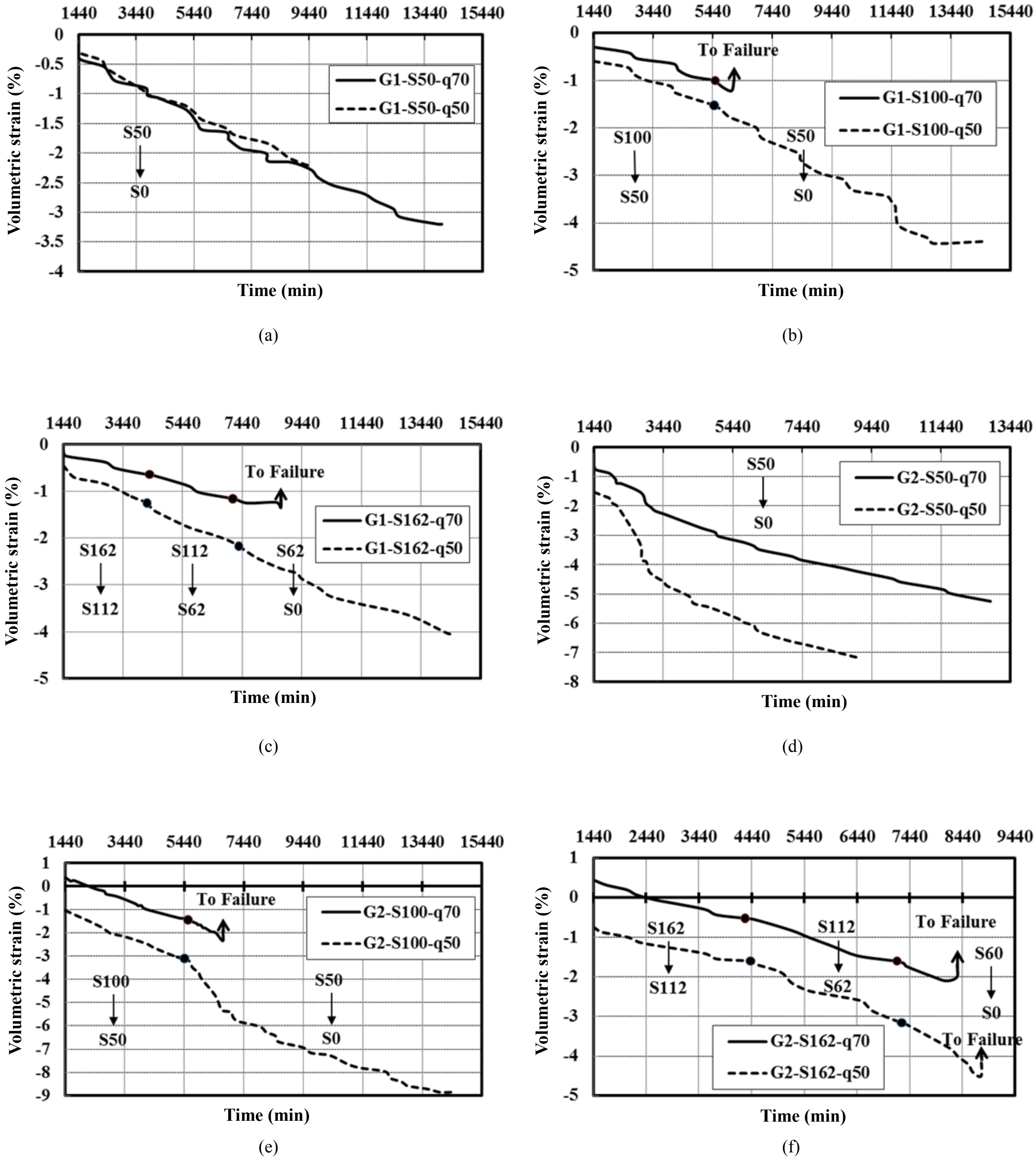

Fig. 6 Variation of volumetric strain versus time for two groups of specimens during wetting process; for group 1 (a) ~ (c), and for group 2 (d) ~ (f)

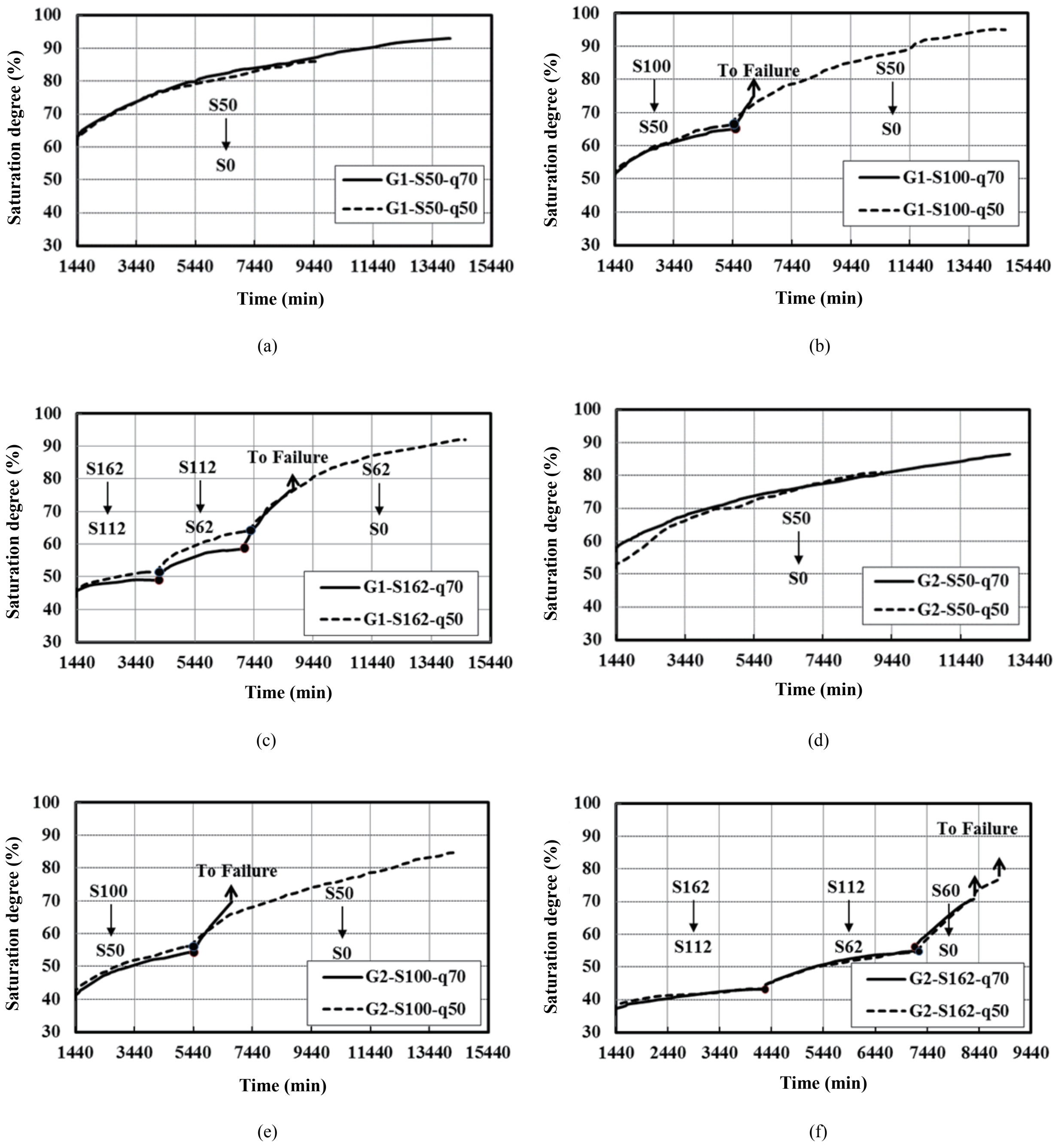

Fig. 7 Variation of degree of saturation versus time for two groups of specimens during wetting process; for group 1 (a) ~ (c), and for group 2 (d) ~ (f)

6. CONCLUSIONS

In this study, an experimental program has been carried out to investigate the effect of initial anisotropic stress, initial density and initial suction on behaviour of unsaturated clayey silty sand during wetting path. The following conclusions can be drawn from this research:

1. For a given density, the deformation due to wetting of unsaturated soil, depends mainly on the initial suction, and the stress state under which wetting is occurred.
2. Tested unsaturated soil, under more values of initial suction, experienced more amount of deformation. Besides, for greater value of initial deviatoric stress state in given initial density, decrease in suction due to wetting, leads to specimen failure.
3. For a given initial deviatoric stress state under which wetting process occurs, lower values of density leads to the larger strain or failure of soil.
4. Deformation due to wetting depends on time. On the other hand behavior of unsaturated soil during wetting is of viscous nature.
5. Volumetric strains during wetting, in comparison with deviatoric strains, are less dependent on initial suction.

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