Hardening behavior of a hydro collapsible loessial soil

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ABSTRACT

Hydro collapsible soils are of kinds of problematic soils which show high shear strength at low degrees of saturation but due to wetting, their meta stable structure collapses and will be subjected to large deformation. In this study by applying isotropic triaxial loadings to undisturbed samples, mechanical behavior of a highly collapsible loessial soil has been assessed. During tests, matric suction of the samples was controlled as well as the mean net stress, and the variation of the degree of saturation was monitored continuously. Two types of stress paths were conducted on the samples namely “Isotropic induced collapse” under applying constant matric suctions and “wetting induced collapse” by decreasing matric suction while applying constant mean net stress. Results show increasing yielding stress of the samples by increasing the mean stress under constant matric suctions. By considering effective stress approach, a hardening model is introduced in this paper to interpret the behavior of the tested soil. Agreement obtained between the predicted and measured values of the yielding stresses during tests is promising and shows the efficiency of the presented model.

Keywords: Unsaturated collapsible loess, triaxial test, undisturbed samples, effective stress, hardening model

1 INTRODUCTION

Upon wetting, partially saturated loessial soils tend to experience significant volumetric decrease or collapse. This behavior is generally attributed to their unstable soil fabric and their weak inter-particle bonding forces, which together yield a soil void structure that is susceptible to collapse. Recent studies on the hydro-mechanical behavior of such soils revealed that the complicated stress-deformation properties of these soils are highly affected by the soil fabric, stress levels and the applied stress paths on the soil structure (e.g., Garakani 2013, Haeri et al. 2014a & b and Garakanei et al. 2015).

In this study, the hardening behavior of an undisturbed collapsible loessial soil is assessed under applying two different general isotropic hydro mechanical loadings. For this purpose, a conventional triaxial device was improved to a full digital unsaturated triaxial device with the capability of applying, controlling and recording the stress and strain parameters as well as the degree of saturation, pore water pressure and air pore pressure (Haeri et al. 2014a). Two different isotropic stress paths, namely “isotropic compression under constant matric suctions” and “wetting under constant mean net stress”, were applied to the loessial soil specimens and the behavior of the soil including collapse was monitored. By implementation of the effective stress approach, the hardening behavior of the tested soil is investigated and a constitutive relation is introduced which shows the relation between the coupled variation of the effective yield stress of the soil and the degree of saturation.

2 THE SOIL MATERIAL

The tested soil in this study is an Aeolian loessial deposit located in “Hezar-pich” hills, in Gorgan, northeast of Iran. Undisturbed monolithic samples were taken from this natural loessial deposit and then a special specimen sampler, including a 100-kN pushing jack and a supporting steel frame, was utilized to extract undisturbed cylindrical test specimens with a diameter of 5 cm and a height of 10 cm. More details about the sampling procedure are presented in Garakani (2013) and Haeri et al. (2014a). The tested soil is classified as a yellowish brown Silt (ML), in accordance with the Unified Soil Classification System (ASTM D2488-00), with very little fine sand and 20% to 35% clay size particles. The tested specimens have average initial values of void ratio, moisture content and dry unit weight of 0.77, 7.1%, and 15.07 kN/m³, respectively and the plasticity index for the soil is approximately 6.5%. The measurements of the SWRC for this soil using the filter paper technique (ASTM D2325-68) showed an average initial suction value of about 750 kPa (Fig. 1).
3 EXPERIMENTAL SETUP

A modified suction-controlled triaxial test device (Fig. 2) was used to investigate the hydromechanical behavior of the tested soil. In this test device, the axis translation technique (Hilf 1956) was implemented to control suction in the specimen using a high air-entry (HAE) ceramic disc, with an air-entry suction value of 1500 kPa. Water outflow from the specimen and the chamber of the cell during the application of subsequent increments of mean net stress and matric suction was measured using two automatic volume change apparatuses connected to the water drainage lines from the bottom of the specimen and the triaxial cell, respectively. Measurements from these systems are used to obtain changes in the degree of saturation and the volume of the specimen during loading. Three on-board digitized bias pressure regulators in conjunction with two air/water bladder systems were utilized to perform simultaneous control of the air and water pressures needed for each test. Three digital submersible pore pressure sensors incorporated into a pressure-feedback control loop were connected to the cell and pressure supply lines of the specimen to allow for accurate measurements of pore water, pore air and cell pressures during each test. More details about the testing system can be found in Haeri et al. (2014).

4 LABORATORY TEST PROCEDURE

To investigate the effect of stress conditions on the deformation and hydraulic characteristics of loessial specimens, two possible mechanisms of pore structure collapse were examined during the isotropic loading stage: pore collapse induced by an increase in mean net stresses under a constant matric suction (for total of 10 specimens), defined as isotropic compression collapse (Fig. 3a), and pore collapse induced by a decrease in matric suction under a constant mean net stress (for total of 8 specimens), defined as wetting-induced collapse (Fig. 3b).

For the specimens experiencing isotropic compression collapse, a given test specimen was first subjected to a sufficiently low value of seating pressure, \( p_n = 10 \text{ kPa} \) to avoid any significant compression or collapse of the soil specimens. At a constant back-pressure of 50 kPa, the air and cell pressures were increased equally to the respective target values. The specimen was then allowed to come to equilibrium under the applied stresses.

For the soil specimens that experienced wetting-induced collapse, an isotropic confining pressure of 10 kPa was first applied to the soil specimen as the seating load. Based on the initial degree of saturation of the soil specimens and the SWRC of the undisturbed soil samples (Fig. 1), an initial matric suction of 750 kPa was introduced to the boundaries of the specimen by applying an air pressure of 800 kPa to the top and a constant water pressure of 50 kPa to the bottom of the specimen. After reaching equilibrium state at the desired \( p_n \) value, the wetting-induced collapse was initiated by maintaining a constant air pressure at the top of the specimen, while increasing the water pressure at the bottom of the specimen. For each suction level, sufficient time was permitted for hydraulic equilibrium of the specimen.

5 TEST RESULTS

The isotropic compression collapse test results at various constant matric suction values are presented in Figs. 4a and 4b. Fig. 4(a) shows volumetric strain, \( \varepsilon_v \), as a function of the applied mean net stress, \( p_n \), and Fig. 4(b) illustrates changes in degree of saturation, \( S_r \), with \( p_n \). The isotropic compression test consists of two stages: the suction-equilibrium stage (Dashed lines), and the isotropic compression stage (Solid lines). As shown in Figs. 4a and 4b, for suction levels of 100 kPa and 400 kPa, three different target levels of mean net stress were considered.
During the isotropic compression collapse stage of testing, as shown in Fig. 4, the soil specimens experienced a decrease in volume and increase in water volume (to keep the internal suction constant as volume decreases) in a way that resulted in an increase in the corresponding degree of saturation (Fig. 4b).

The results from the wetting-induced collapse tests, conducted at various mean net stresses are presented in Figs. 4(c) and 4(d). As presented in these figures, for each mean net stress level of 50 kPa or 200 kPa, three different target suction values were considered for testing, while for mean net stress level of 400 kPa, two different target levels of suction were chosen. During wetting, considerable collapse deformation was observed in all specimens as suction decreased from its initial value to the desired matric suction (Fig. 4c). The rate of change in volume decreased as \( \psi \) reached values of 10 kPa or smaller (Fig. 4c). As illustrated in Fig. 4(d), during the wetting process, the degree of saturation of all specimens increased with negligible impact of the applied \( p_n \). During wetting-induced collapse, the soil specimens that were subjected to higher levels of \( p_n \) experienced larger collapse deformation with a decrease in matric suction.
6 DOUBLE HARDENING BEHAVIOR

In this study, results reported in Fig. 4 have been assessed by implementation of the effective stress concept to describe the double hardening behavior of the unsaturated collapsible soils.

Lu and Likos (2006) developed an effective stress definition for unsaturated soils as an extension of Bishop’s effective stress by modifying the matric suction contribution to the effective stress as follows:

\[ p' = p_n + p_s \]  (1)

where \( p' \) is the effective stress and \( p_n \) is the mean net stress. \( p_s \) is the "suction stress", which is also described as effective stress under the conditions of no external stress. Lu et al. (2010) developed a closed-form equation for the suction stress as follows:

\[ p_s = \frac{S_r - S_{r,\text{res}}}{1 - S_{r,\text{res}}} \psi \]  (2)

where \( S_r \) and \( S_{r,\text{res}} \) are respectively the degree of saturation of the soil specimen and the residual degree of saturation of the soil specimen, both under the condition of zero external loads.

Using the framework proposed by Lu et al. (2010) for the effective stress of unsaturated soils, the data presented in Figs. 4a to 4d are used to calculate the variation of volume change with respect to \( p' \) as illustrated in Figs. 5a and 5b. The solid lines in the figures show the pore collapse stage of the tests during an isotropic compression collapse or wetting induced collapse. The dashed lines represent the suction equilibrium stage at the beginning of the tests. As shown, for the specimens experiencing an isotropic compression collapse, the effective stress increases as the mean net stress is increased from its initial value to the desired value. These changes in effective stress result in a decrease in the volumetric strain of the test specimens. However, the behavior is different during the wetting-induced collapse tests. When wetting occurred in the loess specimens, two different deformation processes may occur under different conditions: collapse and reduction in the volume of the specimen as a result of suction decrease, and an elastic rebound happening due to the effective stress decrease. In the specimens tested in this study, the amount of volume decrease due to pore collapse is observed to be much higher than the amount of dilation and elastic rebound due to the effective stress decrease. Therefore, the resultant is volume decrease while effective stress decreases at the same time.

The results presented in Fig. 5 also show that the soil specimens may experience hardening or softening during the test, depending on the level of applied mean net stress or matric suction. For the specimens that are wetted to lower levels of suction before compression, flooding of voids with water may result in reduced stability of the soil skeleton. As a result of this softening, an inward movement of the compression curve occurs. However, for the specimens experiencing wetting-induced collapse, an initial increase in the applied net stress may result in a plastic decrease in the volume of the specimen. This phenomenon has the effect of shifting the volumetric strain curve to the right.

Wheeler et al. (2003) and Tamagnini (2004) described a double hardening mechanism to explain the hardening/softening behavior that soils experience under unsaturated conditions. Based on this mechanism, the soil specimen may experience a hardening/softening behavior due to either plastic deformation of the soil skeleton under a change in the mean effective stress or due to changes in matric suction during drying or wetting.

Using the data presented in Fig. 5, the effective yield stress during isotropic loading tests are calculated and illustrated in Fig. 6 (as point data). As shown in this figure and comparing the mean effective yield stresses with the wetting cycle of SWRC (Fig.1), due to the small changes in \( S_r \) for the range of the values of suction less than 10 kPa, only small changes in \( p' \) are expected. However, for the values of suction greater than 10 kPa, changes in \( p' \) happen at a greater rate as the changes in \( \psi \) lead to significant changes in \( S_r \).

In order to properly capture the nonlinear behavior
of $p'_c$ (the effective yield stress) with matric suction, in this study, an empirical equation (which relates the effective stress, matric suction and degree of saturation in a coupled form) was established as follows:

$$p'_c = \frac{(p'_c - p'_c0) × (S_{r0} - S_{r})}{S_{r0}} + p'_c0$$  \hspace{1cm} (3)$$

where $p'_c0$ and $p'_cd$ are the mean effective yield stress values for the saturated and oven dried specimens respectively, $S_{r0}$ and $S_{r}$ are the degrees of saturation for saturated and unsaturated specimens respectively, and $k$ is the fitting parameter related to the tested soil material properties. The values of $p'_c0$, $S_{r0}$ and $S_{r}$ are obtained from the test results directly. Also $p'_cd$ could be either obtained from the test conducted on an oven dried specimen or by applying curve fitting and extrapolation over the other effective yield stress data. In this study, the value of $p'_cd$ was estimated using a curve fitting procedure. By implementation of least square fitting method and considering the values of $p'_c0$ and $S_{r0}$ equals to 22 kPa and 0.96 respectively (from the data presented in Fig. 6), the predicted model on the values of effective yield stress versus matric suctions is drawn as a dashed line in Fig. 6. As illustrated in this figure, a very good agreement between the test results and the prediction curve is obtained which shows the rational trend between the matric suction, the effective yield stress and the degree of saturation during isotropic loadings.

**Fig. 6.** Predicted and tested values of $p'_c$, with matric suction ($\psi$).

The main advantage of the presented model is that the constitutive parameters in Eq. 3 can be estimated with no need for performing difficult, delicate and time consuming laboratory efforts, as $p'_c0$ and $S_{r0}$ can be obtained from conventional saturated triaxial test, $p'_cd$ is obtained from a non suction controlled triaxial test and performing filter paper test on the unsaturated samples can result in $S_{r}$. 

## 7 CONCLUSIONS

In this study, hardening behavior of a collapsible loessial soil was investigated. For this purpose, data presented by Haeri et al. (2014a) were implemented. Two sets of unsaturated triaxial tests were conducted on undisturbed unsaturated loessial soil namely, isotropic induced collapse tests and wetting induced collapse tests. By considering the effective stress approach, the effective yield stresses of the tested soil at different matric suctions were calculated and a coupled constitutive model was presented to show the relation between the values of mean effective yield stress, degree of saturation and matric suction. The model shows desirable efficiency to predict the behavior of the soil where associated parameters could be obtained by conducting simple laboratory tests.

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