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Hydro-mechanical behavior of undisturbed collapsible loessial soils under different stress state conditions

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ABSTRACT

A conventional triaxial test device was modified to characterize the hydro-mechanical behavior of a loessial soil during isotropic and shear loadings. This device is capable of precise and continuous measurements of water outflow during the application of loading. The tests were performed on "undisturbed" cylindrical specimens, which were taken from loessial deposits in Gorgan, a city in the northeast of Iran. Experimental measurements indicate that the hydro-mechanical behavior of loess is highly affected by the extent of applied mean net stress and the level of suction. During both isotropic and shearing stages of loading, the tested specimens may exhibit collapse, abrupt decrease in volume or sudden positive volumetric strain, upon wetting or applied loading. However, the magnitude and extent of collapse are different depending on the applied state of the stress and the hydro-mechanical loading path. The results of the experiments reveal that the peak shear strength of the soil increases, as the applied mean net stress during isotropic loading or the applied matric suction increases. The shearing test results are also used to investigate the efficiency of suction stress in describing the state of stress for unsaturated loessial soils. The outcome indicated a unique critical state line for unsaturated specimens under different stress paths and loading conditions. Furthermore, considering the effective stress concept, a hardening constitutive law is presented in this study to demonstrate the hardening/softening behavior of the collapsible loessial soils.

1. Introduction

The Caspian lowland of northern Iran is part of the Eurasian loess belt extending from northwest Europe to central Asia and China, with the most complete loess sequences located in the area between the Gorgan and Atrek rivers in Golestan province and on the northern foothills of the Alborz Mountains (Feiznia et al., 2005; Frechen et al., 2009). The loess sequences in these regions are mostly silt-rich sediments with particles loosely arranged in a soil void structure, an open, metastable soil fabric and weak inter-particle bonding forces (Garakani, 2013; Haeri et al., 2014a). These types of Aeolian deposits are known for their high potential of collapse behavior. Due to the rapid urban developments in this region, major projects are facing increasing problems related to the presence of unsaturated loessial deposits, leading to foundation settlements in residential buildings or water conveying canals, instability in the slopes supporting the structures, lifeline damage, and failure occurrence in the side walls of the dam reservoirs (*e.g.*, Nomal dam). The need for construction and development in the area has reverted to using a large number of pile foundations in the design and construction of structures or increasing the rigidity and strength of the super structures; without a comprehensive attention to the deformation behavior of the highly collapsible loessial soil which is the real cause of in admissible settlements. It is believed that a thorough and comprehensive study on the hydro-mechanical behavior of this problematic loessial soil, will lead to better understanding of the response of collapsible soils to different loading conditions.

In this study, a series of suction-controlled triaxial tests are performed on "undisturbed" specimens taken from the loessial soil of the "Hezar-pich" hills in the city of Gorgan to observe and characterize the behavior of this soil under hydro-mechanical loadings. The

Abbreviations: b, Double-hardening parameter; b_1 and b_2, Fitting parameters of the hardening model; d_{200}, Percent passing sieve No. 200; d_4, Percent passing sieve No. 4; d_c, Percentage of clay fraction; de^p, Increment of plastic change in void ratio; dS_e, Increment of change of effective saturation; e, Void ratio; e_o, Initial void ratio; M, Slope of critical state line; p', Mean effective stress; p_o', Initial mean effective stress; p_c', Mean apparent preconsolidation stress; p_n, Mean net stress; p_{no}, Initial mean net stress; p_s, Suction-stress; q, Deviator stress; S_e, Effective saturation; $S_{e,sat}$, Effective saturation at the matric suction of zero; S_r, Degree of saturation; $S_{r,res}$, Residual degree of saturation; S_{ro}, Initial degree of saturation; u_a, Pore air pressure; u_w, Pore water pressure; w_o, Initial water content; w_L, Liquid limit of the soil; w_P, Plastic limit of the soil; χ, Effective stress parameter; ε_v, Volumetric strain; ε_a, Axial strain; γ_{do}, Initial dry density; κ, Slope of the elastic rebound curve; λ, Slope of the virgin compression curve; ψ, Matric suction; ψ_e, Transition matric suction.

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experimental approach incorporates the axis translation technique (Hilf, 1956) for suction control, two independent digitized volume change measurement devices for the precise measurement of water volume change from the cell and specimen, a strain control electronic jack for imposing the shear stress, and three electronic pressure regulators and submersible pressure sensors to control the applied pressures separately during testing. In this study, specimens are initially subjected to isotropic loading and after reaching an equilibrium state, the shear stress is applied to measure the shear stress-deformation and collapse behavior of the loessial soil. During isotropic loading, two possible mechanisms of pore structure collapse are considered: isotropic compression collapse under constant matric suction, and wetting-induced pore collapse under a constant mean net stress.

The shearing test results are then used to measure the suction stress of collapsible loessial soils introduced by Lu and Likos (2006) to describe the state of stress in unsaturated soils. The suction stress, p_s, which depends on capillary inter particle and van der Waals attraction forces, electrical double-layer repulsion, and ionic bonds formed between the soil particles is considered as a material characteristic (Lu, 2008). Due to the collapse potential of the loess, and its complicated deformation behavior, it is quite difficult to define trends between suction stress and the soil suction for this type of soil and a soil-specific experimental testing approach may be useful to examine the available choices of relationships for p_s for loessial collapsible soils.

2. Background

Improvements in experimental unsaturated soil mechanics have led to a better understanding of the behavior of loessial soils. Early experimental works on the behavior of unsaturated loessial soils focused on their stress-deformation characteristics during an isotropic compression collapse at a constant matric suction, or a wetting-induced collapse at a constant mean net stress (*e.g.*, Maâtouk et al., 1995; Wheeler and Sivakumar, 1995, 2000; Habibagahi and Mokhberi, 1998; Chen et al., 1999; Pereira and Fredlund, 2000; Kato and Kawai, 2000; Sivakumar and Wheeler, 2000; Sun et al., 2000, 2004, 2007; Jotisankasa, 2005; Zhu and Chen, 2009; Jiang et al., 2012; Gallipoli and D'Onza, 2013; Haeri et al., 2014a).

For example, Sun et al. (2007) utilized a modified suction-controlled triaxial test setup to perform a series of wetting-induced collapse tests on compacted clayey specimens. Results showed a great impact of matric suction, ψ, and applied mean net stress, p_n, on the deformation behavior of collapsible soils, and three distinct phases of volume reduction were observed as suction was decreased from its initial value to zero. Specimens initially experienced a small volumetric strain at higher suction levels. Changes in soil volume happened at higher values of mean net stress when the suction was reduced to lower levels. After reaching the air expulsion suction, due to negligible changes in the degree of saturation of the soil specimen, the volumetric strain became very small or even negative (swelling). The specimens subjected to higher values of p_n were observed to experience larger deformation due to pore collapse during wetting (Sun et al., 2007). Similar results were reported by Alonso et al. (1990), Maâtouk et al. (1995), Pereira and Fredlund (2000), and Haeri et al. (2014a).

Maâtouk et al. (1995) utilized a modified suction-controlled triaxial test device to perform a series of unsaturated drained shearing tests to study the behavior of a reconstituted collapsible silty soil during shear. The tests were performed by applying mean net stresses ranging from 10 to 310 kPa and matric suctions varying between 80 kPa and 600 kPa. At small values of p_n, the shear stress–axial strain curves followed an increasing path during shear, tending toward a plateau at an axial strain between 12% and 20%. The volumetric strain–axial strain curves approached a constant value as the tested soil reached its critical state at large strains. At high values of mean net stress, the shearing test results indicated no significant change in the shear behavior when matric suction was increased in the specimens. Maâtouk et al. (1995) applied the concepts of yielding and critical state originally developed for saturated clays to examine the influence of suction on the stress-deformation behavior of unsaturated collapsible silty soils. Results showed different critical state lines for the tested material at different applied matric suctions. Similar results were reported by other researchers (*e.g.*, Wheeler and Sivakumar, 1995; Cui and Delage, 1996; Geiser, 1999).

A challenge encountered in the characterization of the behavior of natural loess is a non-homogenous distribution of macro- or micropores which results in the presence of void spaces with different degrees of collapse potential in the soil matrix. Due to this unique characteristic, the collapse phenomenon in natural loess is mostly a continuous-stepwise reduction in volume rather than a sudden drop as water enters the voids. Haeri et al. (2014a) revealed that this continuous variation in volume will change the internal capillaries which could dramatically disturb the suction equilibrium inside the soil mass and also pressures applied to the system, complicating the pressure control when testing an undisturbed specimen of a natural loess under strain control conditions. This observation shows the need for using an unsaturated testing approach for natural loessial soils which is capable of making precise and continuous measurements of volume change and water outflow during both isotropic and shear loadings.

3. Sampling procedure and general soil properties

Undisturbed samples were taken from the natural loessial deposit of the "Hezar-pich" hills, in Gorgan, northeast of Iran. The monolithic samples, with an approximate size of 30 cm × 30 cm × 30 cm, were taken from a depth of 1.0 m at different locations in this wide Aeolian land. The sample cubes were carefully transported to the laboratory, 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). Almost all particles in the soil samples fall in the silt range with very little fine sand and 20% to 35% clay sized particles. As shown in Table 1, each of the soil specimens is classified as a yellowish brown Silt (ML), in accordance with the Unified Soil Classification System (ASTM D2488-00).

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/m^3, respectively. The plasticity index for the soil is approximately 6.5% and the representative specific gravity of soil particles taken from 10 triaxial specimens yielded an average value of 2.72. Initial measurements using the filter paper technique (ASTM D2325-68) showed an average initial suction value of 750 kPa for the specimens (Haeri et al., 2014a). Table 1 provides some index properties of the soil.

4. Experimental setup

A modified suction-controlled triaxial test device (Fig. 1) was used to investigate the impact of unsaturated stress states, mean net stress and matric suction, on the stress-deformation behavior of highly collapsible loessial soils. 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. To ensure a uniform distribution of water to the HAE ceramic disk and prevent stress concentrations beneath the disc, a 0.2 cm deep spiral-shaped groove was created in the bottom platen of the triaxial setup.

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