Hydro-mechanical behavior of collapsible soils in unsaturated soil mechanics context

S. Mohsen Haeri i)

i) Professor, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

ABSTRACT

This paper is related to the studies taken place during last decade to understand the intact behavior of a Collapsible Loess subjected to loading and wetting at Advanced Soil Mechanics Laboratory of Sharif University of Technology, Tehran, Iran. In this regard intact block samples are carefully taken from Hezar Pich Hill in the city of Gorgan, Iran, and various tests are performed on undisturbed specimens recovered from the intact block samples. In this way three automated unsaturated oedometer are built and a conventional triaxial apparatus is upgraded to a fully automated unsaturated triaxial device to accommodate rigorous and different stress and wetting path with continuous data acquisition of various parameters. The tests are conducted mainly on undisturbed samples, however, some tests are also performed on reconstituted specimens to observe the differences between the behavior of intact and reconstituted specimens. The results indicate that the hydro-mechanical behavior of intact Collapsible Loess is substantially different from that of the reconstituted specimens. Therefore, it is strongly recommended to perform undisturbed sampling and conduct tests on intact natural loess to be able to predict the collapse behavior, shear strength and hydro-mechanical behavior of this type of collapsible soil reasonably. Also in order to investigate on the type, optimized amount and methods of application of stabilizing agents a number of agents and improvement techniques are implemented. Various tests are conducted on the improved specimens as well and the results are compared with those of unimproved ones to verify the effectiveness of the used agents and methods.

Keywords: collapsible soil, loess, unsaturated soil, undisturbed sample, reconstituted specimen, hydro-mechanical behavior

1 INTRODUCTION

Loess as a type of collapsible soils is a well-known Aeolian deposit, which is characterized by some Specific Engineering Properties including high initial void ratio, relatively low natural density and water content, high percentage of fine-grained particles, and medium to low cohesion (Feda 1988; Estatiev 1988; Lawton et al. 1992; Haeri et al 2012a; Haeri et al. 2014a). In these Aeolian deposits, there usually exists a significant degree of cementation that is brittle and mostly crystalline-type (such as hydrants or calcite). In addition, the contribution of the suction resulted from their initial high negative pore water pressures can become quite significant, especially in a loess that have considerable amount of fine particles such as silt or clay (Houston and El-Ehwany 1991, Haeri et al 2012a, Haeri et al 2014a,b). Because of the cemented or bonded nature, loessial deposits appear to have a strong and stable condition in their natural unsaturated state; but when they are subjected to additional water from various sources such as heavy and continuous rainfall, excessive irrigation, broken water or sewer lines, or ground water rise, these relatively dry deposits may experience a large loss of suction and bond strength, allowing a great increase in compressibility or virtually collapse, when subjected to threshold loadings (Lawton et al. 1992, Haeri et al 2012a, Haeri et al. 2014a,b).

Heavy destructions in structures built in or on the loessial soil deposits, have encouraged many researchers to study the behavior of this kind of soils (Chen et al. 1999, Clevenger. 1958, Denisov. 1951, Feda. 1966, Gibbs and Holland. 1960, Haeri and Garakani. 2012, Haeri et al. 2012a, Haeri et al. 2012b, Handy. 1973, Nuntasarn. 2011, Popescu and Coric. 1998, Zhu and Chen 2009, Haeri et al. 2014, Garakani et al. 2015, Haeri et al. 2015c). However, the great majority of the works are on disturbed or reconstituted samples and very limited researches have investigated the matter implementing undisturbed samples. The reason could be difficulties involved in acquiring undisturbed samples and test specimens. However, because of bonded and unsaturated nature, and randomly distributed open pores of the natural loess, that cannot be reproduced, the responses of reconstituted and undisturbed specimens to wetting and loading have major differences (Haeri et al 2014b). Therefore, if the aim of a study is related to the response of a built structure or a future development on a loessial soil, tests should be conducted on undisturbed specimens.

The Aim of this paper is to discuss the hydro-mechanical behavior of a highly collapsible loess,
mainly in unsaturated soil mechanics context. The subject has been under investigation for about a decade at Sharif University of Technology. The tests are conducted mainly on undisturbed samples, however, some tests are also performed on reconstituted soil specimens to observe the differences between the behavior of intact and reconstituted specimens. Also in order to investigate on the type, optimized amount and methods of application of stabilizing agents for this collapsible soil, a number of agents and improvement techniques are implemented and tests are conducted on the improved specimens and the results are compared with those of unimproved ones to verify the effectiveness of the used agents and methods. Summary of the results of conducted tests presented in this paper are categorized as follows:

1. The physical characteristics of the tested loess
2. The Conventional Double Oedometer tests with different inundation stresses on undisturbed and reconstituted specimens.
3. The Unsaturated Oedometer tests under different stress and wetting paths.
4. Implementing different types of Remedial Measures, study the effectiveness of the measures, and study the behavior of stabilized soil using double conventional and unsaturated oedometers.
5. The Unsaturated Triaxial tests implementing different stress and wetting paths during isotropic compression stage on both intact and reconstituted specimens.
6. The Unsaturated Triaxial tests implementing different stress and wetting paths during both isotropic compression and shearing stages on intact and reconstituted specimens.

2 PHYSICAL CHARACTERISTICS OF THE TESTED LOESS

The tested loess was obtained from the “Hezar-pich” Hills area in suburb of the city of Gorgan, northeast of Iran. The soil in this region belongs to a highly collapsible Aeolian loessial deposit, which was created by severe silt and sand storms blowing in from north of the Gorgan plate, in the northeast of Iran. These storms, which carried sandy silty materials, tended to form sandy hills while blowing over the Turkmenistan deserts; this pattern of deposition tended to change after reaching the Alborz Mountains, where a decrease in transmissibility led to deposition of the finer silty particles. This pattern of deposition yielded a wide plane of suspended silt particles in the form of hills, mounds, and plates in the Gorgan region. The distribution of different types of the loessial deposit in Gorgan Plain is shown in Fig. 1. (Pashaei, 1997)

“Undisturbed” block samples of soil having an approximate size of 30 cm x 30 cm x 30 cm were taken from the “Hezar-pich Hills” site in Gorgan, from a depth of about 1m below the ground surface. A special specimen sampler utilizing a 100 kN pushing jack and a supporting steel frame was then utilized to extract “undisturbed” cylindrical specimens with a diameter of 5 cm and a height of respectively 2 cm and 10 cm for oedometer and triaxial tests. Tests are conducted in the Advanced Soil Mechanics Laboratory of Sharif University of Technology (SUT). Additional details about undisturbed sampling, handling process and laboratory specimen preparation are available in Haeri and Garakani (2012), Garakani (2013), and Haeri et al (2014a).

The soil is a kind of loess composed mainly of silt size grains with some clays and a small fraction of fine sand. The bonds between the silts of this loess are mainly clay bridges, although some minerals like calcite are present as well. The physical properties of the soil are given in Table 1 and the soil grain size distribution is shown in Fig. 2. The material texture is a porous media with randomly distributed voids of very different sizes; some root size and some very small. SEM photos taken from undisturbed samples shown in Fig. 3 give very good insight about the natural texture of the tested loess.

![Fig. 1. Microzonation of Loessial sediments in Golestan Province, Iran (Pashaei, 1997)](image)

3 CONVENTIONAL DOUBLE OEDOMETER TESTS FOR COLLAPSE POTENTIAL DETERMINATION

Undisturbed specimens were prepared and tested in three groups of initial water content: 3-4% (natural water content), 8-9%, and 13-15%. (Haeri et al 2012a)

| Property                  | Value  |
|---------------------------|--------|
| Specific gravity          | 2.72   |
| Natural void ratio        | 0.67-0.79 |
| Natural dry density (gr/cm3) | 1.57-1.64 |
| Natural water content (%) | 2.9-3.6 |
| Liquid limit (%)          | 33     |
| Plastic limit (%)         | 24     |
| Plasticity index (%)      | 9      |
| Soil classification (USCS)| ML     |

Table 1. Physical properties of soil tested in this study (Haeri et al 2012a)
The results of the tests conducted on undisturbed specimens with water contents of about 3-4% and subjected to wetting at different levels of inundation stresses are presented in Fig. 4. The results indicate that the higher the inundation stresses the higher the amount of collapse at that stress. However, if after inundation the loading continues, to 16 kg/cm² or so, the final volume change increases with decrease in inundation stress. This is clearly shown in Fig. 4. The unloading curves are the lines with very mild and similar slop and their final void ratio is a function of the final void ratio of the loading path. Similar tests that conducted on other specimens with different initial water contents indicate that the initial water content has a considerable effect on the final void ratio of the specimens when they are subjected to wetting collapse under the same inundation pressure. Also, the results indicate that the final void ratio of the specimens with higher initial water content is higher in comparison with the specimens with lower initial water content, meaning that the amount of collapse increases as the initial water content decreases.

The collapsibility of a soil can be represented by the Collapse Potential Index ($I_c$) at each inundation pressure, as expressed by Equation 1 in which $\Delta H$ and $H_0$ stand for the variation of the sample height due to inundation and the sample height just before inundation, respectively. The variation of $I_c$ with inundation pressure is shown in Fig. 5 for undisturbed specimens having different initial water contents. For the tested specimens, at the same inundation stress, collapse potential index increases with decrease in initial water content.

$$I_c = \frac{\Delta H}{H_0} \quad (1)$$

Critical pressure is the pressure at which the dry loess changes from a low compressibility response to a high compressibility with different initial water content. Critical pressure is strongly influenced by initial water content. Table 2 represents the critical pressure of undisturbed loess samples. Increase in initial water content reduces the strength of the bond between the loess particles and eventually decreases the critical pressure. For the same initial water content, an increase in stress below critical pressure leads to a greater collapse potential. However, beyond the critical pressure at which the effect of stress alone causes significant soil collapse, the collapse potential decreases with a further increase in stress.

![Fig. 2. Grain size distribution of the representative collapsible soil specimens (Haeri et al 2012a)](attachment:fig2.png)

![Fig. 3. SEM pictures of collapsible soil structure at different scales: (a) Zoom X16; (b) Zoom X100; and (c) Zoom X1000(Haeri et al. 2014a).](attachment:fig3.png)

| Initial moisture content (%) | 3-4 | 8-9 | 13-15 |
|-----------------------------|-----|-----|-------|
| Critical Pressure (Kg/cm²)  | >16 | 8   | 4     |

Table 2. Critical pressure of the tested undisturbed loess (Haeri et al 2012a)
4 UNSATURATED OEDOMETER TESTS ON INTACT LOESS UNDER DIFFERENT STRESS AND WETTING PATHS

In this part of the investigation, the collapse potential and the volumetric water change of undisturbed specimens of 20mm in height and 50 in diameter taken from highly collapsible loessial soil of Gorgan, have been studied using Unsaturated Oedometers built at Sharif University of Technology in which matric suction, water content, and vertical displacement have been controlled under K_0 condition (K_0 is taken as unity in this study), as shown in Fig. 6 (Haeri et al 2012b). In order to evaluate the collapsibility and the effects of stress-suction paths on the mechanical behavior of the tested loess, eight oedometer tests with the capability of controlling matric suction have been performed (Haeri et al 2012b). Tests have been conducted in two groups, namely, constant matric suction with varying net mean stress (loading and unloading), and constant net mean stress with varying matric suction (wetting and drying). The suction-loading pattern in each test is shown in Table 3. Moreover, two saturated oedometer tests (with zero matric suction) have been performed by applying loading and unloading mean net stresses of 5, 12.5, 50, 100, 200, 400, 800, 1600, 2400, 400 and 100 kPa on the soil specimens. (Haeri et al 2012b, Khorshidi 2012)

Variations of specific volume (ν) versus vertical net stress (P_{vn}) corresponding to the first group of tests are depicted in Fig. 7. Parameter P_{vn} is defined in Eq. 2 where \( \sigma_v \) is total vertical stress and \( u_a \) is air pressure. If the lateral pressure at rest (K_o) is assumed to be unity then P_{vn} can be taken as P_n or mean net stress. In this case the graphs shown in Fig. 7 can be taken as specific volume (ν) versus mean net stress (P_n).

\[
P_{vn} = \sigma_v - u_a
\]  

Table 3. Suction-loading pattern in unsaturated oedometer tests on Gorgan Loess. (Haeri et al 2012b, Khorshidi 2012)

| Type 1: Constant Matric Suction –Variable Mean Net Stress (Loading and Unloading) |
|-----------------|-----------------|-----------------|
| Test No.        | Target constant matric suction (kPa) | Net mMean net stress in loading path (kPa) | Net mMean net stress in unloading path (kPa) |
| 1               | 50              | 50, 150, 200, 400, 800, 1600, 2400 | 2400, 1600, 400, 100                       |
| 2               | 100             | 50, 100, 200, 400, 800, 1600, 2400 | 2400, 1600, 400, 100                       |
| 3               | 200             | 50, 100, 200, 400, 800, 1600, 2400 | 2400, 1600, 400, 100                       |
| 4               | 400             | 50, 100, 200, 300, 400, 600, 800, 1200, 1400, 1600, 2000, 2400 | 2400, 2000, 1600, 800, 200                   |

| Type 2: Constant Net Mean Net Stress –Variable Matric Suction (Wetting and Drying) |
|-----------------|-----------------|-----------------|
| Test No.        | Constant net mean net stress (kPa) | Matric suction in wetting path (kPa) | Matric suction in drying path (kPa) |
| 5               | 100             | 400, 300, 200, 50, 25, 0 | 0,50, 100, 200, 400                    |
| 6               | 200             | 400, 200, 100, 50, 25, 0 | 0,100, 200, 400                       |
| 7               | 250             | 400, 300, 200, 100, 50, 25, 0 | 0,100, 200, 400                      |
| 8               | 400             | 400, 200, 100, 50, 0 | 0,100, 200, 400                       |
It can be seen that reduction in the matric suction results in decrease in specific volume. Also, the dependency of soil compression to matric suction can be obtained from Fig. 7. The larger the matric suction, the steeper the slope of normal compression line ($\lambda(s)$). Futai & Almeida (2002), Machado (1998), and Vilar & Davies (2002) also observed this behavior in other soils. In oedometer tests with controlled matric suction, collapse potential ($C_p$) as given in equation (3) is obtained on the basis of double oedometer test. In other words, $C_p$ is the difference between compression curves of the sample with specific matric suction and that of saturated sample (zero matric suction); which was firstly presented by Jennenigs and Knight (1975).

\[
C_p(\%) = (e_{in} - (e_{on} - e_{ow}) - e_{ow}) \times 100 \tag{3}
\]

where:
- $e_{in}$: void ratio of a specimen at a defined matric suction and any mean net stress
- $e_{on}$: initial void ratio of a specimen at a defined matric suction
- $e_{ow}$: initial void ratio of a specimen at saturated condition (Zero suction stress)
- $e_{ow}$: void ratio of a specimen at saturated condition (Zero suction stress), and any mean net stress.

As it can be observed from Figure 8, the tested soil has a high collapsibility with $C_p$ varying from 5% to 23%, depending on the applied mean net stress and matric suction. The specimens with larger matric suctions show greater collapse potential, as expected. The rate of increase in collapse potential before a specific net stress, which can be analogous to critical pressure as stated above, is very high. However, after that specific or critical pressure, the collapse potential decreases with increase in mean net stress.

Figure 7. Relationship between mean net stress and specific volume (Haeri et al 2012b, Khorshidi 2012)

Figure 9 shows the changes in degree of saturation versus mean net stress in the tests type 1 (Table 3) on Gorgan Loess. In all tests, the degrees of saturation of the specimens increase with increase in mean net stress, and the slopes of the curves associated with different constant matric suctions are nearly identical. The higher the matric suction, the lower the degree of saturation.

Figure 8. Collapse potential measurement under constant matric suction and varying mean net stress (Haeri et al 2012b, Khorshidi 2012)

Changes of the degrees of saturation versus matric suction in constant mean net stress tests are illustrated in Fig. 10. In all tests, the degree of saturation increases by decreasing matric suction. At low matric suction levels, all specimens have nearly the same degrees of saturation.

As shown in Figs. 9 and 10, for the same amount of matric suction and mean net stress in two types of tests, the samples have different degrees of saturation indicating stress-suction path dependency of the unsaturated behavior of this collapsible soil. (Haeri et al 2012b, Khorshidi 2012)
5 IMPROVEMENT OF THE COLLAPSIBLE LOESS

The main goal of most soil improvement techniques used for reducing collapse potential is to avoid large deformation of the soil during increasing water content while the soil is under loading. This goal can be achieved by various methods including adding stabilizers to the soil. By considering the Gorgan loessial characteristics, two stabilizers namely Lime and a Nanomaterial were chosen to examine their positive effects on the collapsibility of this soil. Lime as one of the most common and affordable materials for soil improvement purposes, applied on reconstituted and undisturbed specimens. However, nanomaterial was only utilized as a bonding agent on the undisturbed samples.

5.1 Lime stabilization of reconstituted specimens

Several tests on reconstituted specimens improved by lime have been conducted (Haeri et al 2012d, Roohparvar 2012). Double Oedometer tests were first conducted on untreated and treated reconstituted specimens to find the best percentage of lime mixture. Based on this work, as shown in Figure 11, 3% lime was found to be the optimum mixing amount.

In an extension to this study, unsaturated tests were performed under constant matric suction while net stresses was the variable for unimproved and improved with 1, 3, and 5% lime by weight. The applied suction-stress path of these tests is shown in Fig 12. Some of results of this type of tests are shown in Figs. 13 and 14.
As shown in Figs. 13 and 14, for the same constant matric suction in two types of tests, the improved specimens by 3% lime showed considerably lower amount of decrease in void ratio compared to that of unimproved ones. Fig. 14 also indicates that stabilization by lime has controlled the effects of wetting or reduction in matric suction on the collapsibility of the soil (Haeri et al. 2012d, Roohparvar 2012).

A number of unsaturated oedometer tests under controlled matric suction on reconstituted specimens with and without stabilizing lime were also conducted in another set of stress path as given in Fig. 15 (Haeri et al. 2013, Zabihi 2013). The amount of lime was chosen to be 3% by weight of the base material based on the author’s previous works (Haeri et al. 2012d, Roohparvar 2012). All samples were tested under constant vertical net stress and varying matric suction. The results showed that addition of lime to the soil changed the water retention behavior of the soil. Also, the results of unsaturated oedometer tests under varying matric suction on both unimproved and improved specimens indicated that vertical net stress level (or mean net stress level with the assumption of $K_0 = 1$) significantly affects the volume change and water retention behavior of the untreated reconstituted specimens (Fig. 16) in a way that for low values of mean net stress (100 kPa), no collapse is observed by wetting. However, for high values of mean net stress (400 kPa) the soil collapses drastically upon wetting or matric suction reduction. An intermediate value of mean net stress like $p_\text{n}=200$ kPa presumably is not enough for mobilization of a huge collapse, and only partial collapse is envisaged for this condition of the tested soil. As can be seen from Fig. 17, stabilization changes the behavior of the soil from a collapsible to a normal soil in which not only collapse is not observed, but also swelling is observed during wetting or reduction of matric suction, even for a mean net stress of 400 kPa. Also, note that for both untreated and treated specimens drying, which increases the effective stress, results in positive volume change (decrease in void ratio) with a constant gradient, similar to the behavior of normal soils (Haeri et al. 2013, Zabihi 2013).
5.2 Stabilizing undisturbed samples by lime and nanomaterials

5.2.1 Method of improvement

A method by implementing Electrokinetics is developed in our recent research, in which Undisturbed samples are stabilized and improved by adding Nanomaterials and Lime in two sets of experiments. In this method, lime or nanoparticle migrates in the pores of the soil and stabilizes the intact collapsible soil samples. Electrokinetics is a technique especially developed for removal of contaminants in soil, sediments, and sludge, although it can be applied to any solid porous material. Electrokinetics method is based on the application of a direct electric current to the porous matrix (Reuss 1809). The effect of the electric field induces the mobilization and transportation of added materials through the pores of the soil towards the electrodes, where they are supposed to crystalize and stabilize the soils (Casagrande 1952a, b; Bjerrum et al. 1967; Shang et al. 1996). Main electrodes, anode and cathode, should be inserted into the soil matrix. In our experiments, anode inserted at the center of the undisturbed sampling chamber, and the chamber itself stays as cathode. The aim of this process is to increase the bonds of the intact soil in order to reduce the collapse potential significantly.

Fig. 17. Mean net stress effects on void ratio changes under varying matric suction for treated reconstituted samples by 3% Lime (Haeri et al 2013, Zabihi 2013)

5.2.2 Verification of improvement and the behavior of undisturbed improved loess

Unsaturated Oedometer tests on undisturbed specimens taken from untreated and treated samples were performed to evaluate the effectiveness of this method. The tests plan is outlined in Fig. 18. The tests results show that the improved soil experienced considerably lower amount of collapse or volumetric changes under the same mean net stresses in comparison with that of the unimproved specimens. As observed from Figs. 19 and 20, leaving the data for the tests under $p_n=100$ kPa in which collapse was nothing or small, depending on the applied mean net stress the Lime can reduce collapse by 34% and Nanomaterial by 78%. Another advantage of Nanomaterial to lime is the time needed for effectiveness of the stabilizing agent. Nanomaterial needs only three days to strengthen the formed bonds whereas Lime needs 7-14 days (Haeri et al 2015a)

In order to assess the effectiveness of the implemented method, unsaturated oedometer tests were used for undisturbed specimens taken from treated samples by Lime and Nanomaterial. As shown in Fig. 20 the amount of collapse decreased drastically in treated specimen in comparison to that of the unimproved specimens. As observed from Figs. 19 and 20, leaving the data for the tests under $p_n=100$ kPa in which collapse was nothing or small, depending on the applied mean net stress the Lime can reduce collapse by 34% and Nanomaterial by 78%. Another advantage of Nanomaterial to lime is the time needed for effectiveness of the stabilizing agent. Nanomaterial needs only three days to strengthen the formed bonds whereas Lime needs 7-14 days (Haeri et al 2015a)

Fig. 18. suction-loading pattern of the tests of this section (Mohammad Hosseini 2014, Haeri et al 2015a)

Fig. 19. Void ratio changes under varying matric suction on the wetting path for undisturbed unimproved samples (Mohammad Hosseini 2014, Haeri et al 2015a)
The stabilization of the soil in this manner also changes the soil water retention curves of the soil in a way that for the same matric suction, the stabilized soil samples have greater volumetric water content (Fig. 21). Chemical changes in the soil due to Electrophoresis current (Electrophoresis is the transport of charged particles due to the application of a low direct current or voltage gradient to the soil) as well as bonding of the soil particles by added materials, can be two of the reasons for differences in obtained SWRCs.

6 UNSATURATED TRIAXIAL TESTS

6.1 Unsaturated triaxial tests

A modified triaxial apparatus used in this research (Fig. 22) was developed at Sharir University of Technology. A 500kPa high air entry ceramic disk was installed into the especially designed and made base plate of the triaxial apparatus. A digital volume change device was connected to the single-walled cell to measure the total volume change of the sample and another digital volume change device was connected to the base of the pedestal, just beneath the high air entry ceramic disk, to measure the water volume changes of the sample. The variations of the volume of cell and connecting pipes with respect to the different pressure levels have been measured to calibrate the volume change assessments. To control the air pressure, water pressure and confining pressure independently, three high resolution electronic pressure regulators adjoined with three pressure sensors were implemented, to apply any type of stress path to the specimen.

![Fig. 22. Unsaturated triaxial device, upgraded at SUT (Haeri and Grakani 2012c, Garakani 2013)](image)

6.2 Specimen preparation and triaxial testing procedure

Laboratory tests to assess the effect of soil structure on hydro-mechanical behavior of loessial soils were performed on two separate sets of specimens. In the first set of tests, the behavior of loess was examined using undisturbed cylindrical specimens with a diameter of 50 mm and a height of 100 mm. The specimens were extracted in the SUT laboratory from the monolithic intact samples taken from Hezar Pich site in Gorgan. The prepared specimens had an average initial void ratio of 0.770, an average initial moisture content of 7.12%, and an average initial dry unit weight of 15.07 kN/m³. Five isotropic compression triaxial tests, followed by applying deviator stresses, were performed on undisturbed specimens under drained condition. Each test was performed by applying constant matric suction using the axis translation technique and rising the net confining pressure in steps.
At the end of the last step, the deviator stress was applied to the sample. The stress and wetting paths for tests on undisturbed specimens are depicted in Fig. 23. Each test lasted 20 to 35 days to complete. At the end of each test, the water content was measured. The second group was reconstituted specimens and prepared in the laboratory in such a way that their initial physical characteristics were tried to be identical to the undisturbed specimens. The loading and wetting path of tests on reconstituted specimens are given in Fig. 24.

6.3 Effect of stress and suction levels on volumetric strain of undisturbed loess specimens

Figure 25 presents the results from the isotopic compression tests that were conducted at various constant suction values; Fig. 25(a) shows volumetric strain, $\varepsilon_v$, as a function of the applied mean net stress, $p_n$, and Fig. 25(b) shows how the degree of saturation, $S_r$, changes with the applied mean net stress, $p_n$. The dashed lines in Fig. 25 represent the initial suction equilibrium period that each specimen was subjected to, prior to isotropic compression. Depending upon the level of suction applied to the specimen, different deformation behaviors were observed during the suction-equilibrium stage (Fig. 25a). At a mean net stress of 10 kPa, specimens subjected to higher values of suction (e.g., $\psi = 100, 200$ and $400$ kPa) experienced a small amount of swelling during the suction equilibrium stage. This behavior is due to a decrease in matric suction, which caused a decrease in mean effective stress that yielded a fairly small increase in void ratio. Other specimens that were tested at lower values of suction (e.g., $\psi = 0$ and $50$ kPa) exhibited pore collapse, and consequently a considerable reduction in their volume was observed during the suction equilibrium stage.

![Fig. 23. Loading path for undisturbed samples (a) Isotropic compression tests at various constant suction values (b) Wetting-induced collapse tests at various constant mean net stresses for undisturbed samples (Garakani 2013 and Haeri et al. 2014a).](image)

The changes in $S_r$ during the period of suction equilibrium (Fig. 25b), indicates that all of the test specimens experienced an increase in their degree of saturation, with lower amounts of water being absorbed by specimens that were subjected to higher values of suction (e.g., $\psi = 100, 200$ and $400$ kPa). These results also showed that it is not possible to fully saturate a soil specimen (e.g., $S_r = 1.0$) at a zero suction value; this phenomenon occurs because of the existence of some air bubbles that are trapped between the soil particles. During the isotropic compression phase of testing, all of the specimens that were tested exhibited a decreasing volume as the mean net stress was increased (Fig. 25a). Not surprisingly, those soil specimens that were subjected to higher levels of suction exhibited a smaller amount of volumetric compression under a given applied mean net stress. During an isotropic compression test, due to collapse of the air voids in the pore space, the soil specimen experienced a decrease in volume with increasing mean net stress. As a result of changes in volume of the specimen, the water pressure applied to the specimen changes too. To maintain constant induced matric suction in the specimen, the soil specimen experienced a relative increase in the water volume, and consequently, the corresponding degree of saturation of the test specimens increased (Fig. 25b).
6.4 Effect of stress path dependency on the SWRC and volumetric behavior of undisturbed specimens

Figure 26 compares the deformation behavior of undisturbed soil specimens subjected to different paths of loading, with the dashed lines corresponding to the isotropic compression tests and the solid lines corresponding to the wetting-induced collapse tests. Representative volumetric compression results for the specimens tested at mean net stresses of 50 and 250 kPa along with their corresponding SWRCs for the wetting path are respectively presented in Figs. 26a and 26b. For the specimens subjected to wetting-induced collapse, the SWRC curves at different mean net stresses were obtained by measuring the degree of saturation after equilibrium was reached under the applied matric suction conditions. For the specimens experiencing isotropic compression, however, since the matric suction is kept constant during the test, the SWRC curve for each specimen was obtained by plotting the Sr values for each test at a constant mean net stress versus their corresponding matric suction values. For comparison purposes, the wetting path of the SWRC measured using the pressure plate/filter paper techniques is also shown on these figures. The results presented in these figures indicate that the hydro-mechanical behavior of loessial soils is considerably stress path dependent. As shown, for the same values of mean net stress, the deformation measurements of specimens subjected to isotropic compression are often larger than those subjected to wetting-induced collapse. In those cases where larger volumetric strain was observed, there was also a correspondingly higher degree of saturation in the SWRC. As also shown in this figure, the SWRCs at different values of $p_n$ are generally different, with the soil specimens subjected to higher values of $p_n$ having higher rates of water adsorption during wetting. With their greater ability for water adsorption, the soil specimens subjected to higher mean net stresses are expected to have a different number of water menisci between the particles and consequently different inter-particle contact stresses and collapse deformation for a given value of suction. Based on the results presented in this figure, the effect of mean net stress on the SWRCs is also more pronounced for the specimens that were subjected to isotropic compression.
6.5 Effect of disturbance on the hydro-mechanical behavior of loess

To investigate the effect of disturbance on the wetting-induced collapse behavior of Gorgan loess, results of 12 tests were conducted, 6 tests for undisturbed and 6 tests for reconstituted specimens. Representative data recorded during this stage of testing is presented in Fig. 27 for both undisturbed and reconstituted specimens tested under different mean net stresses of 50 kPa and 200 kPa.

In Figs. 27a and 27b the variations of matric suction vs. time, in Fig. 27c the variations of water volume change vs. time and in Fig. 27d the variations of specimen volume change vs. time are depicted for both types of undisturbed and reconstituted specimens tested under mean net stresses of 50 kPa and 200 kPa, respectively.

Based on the data presented in Fig. 27, the undisturbed and reconstituted soil specimens experience different behaviors with respect to water volume change, specimen volume change and degree of saturation during wetting as matric suction changes with time. This kind of behavior can be attributed to different structures and fabrics of these two types of specimens (Haeri et al. 2014a & b). As observed in Figs. 27c, regardless of the amount of applied mean net stress, the rates of water absorption for undisturbed specimens, except for the early times, are significantly higher than those for reconstituted specimens. Also the water volume change curves are stepwise for undisturbed specimens compared to those for reconstituted specimens. Such behavior can be generally attributed to the size and size distribution of the voids, the initial structure of the tested specimens, amount or the level of applied mean net stress and the level of matric suction at that time.

To explain and understand the mechanism, one should carefully look at the variations of the set of parameters given in Fig. 27, altogether. As shown in Fig. 3, the pores and pore size distribution in undisturbed specimen are heterogeneous. The pore sizes in undisturbed specimens vary from very small to very large compared to those of reconstituted specimens that are of almost the same size (Haeri et al 2014b, Haeri et al 2015b). When the undisturbed specimen is subjected to wetting with relatively high matric suction (e.g., ψ = 400 kPa), the smallest pores (that are much smaller than pores inside the reconstituted specimen) start to absorb the water due to their higher potential of surface tension and suction. Hence the amount of water absorption in an undisturbed specimen in early stages of wetting (i.e., at higher matric suctions) is very small and is less than that for reconstituted one which has larger voids and consequently absorbs more water (Fig. 27c). According to Fig. 27d the specimen volume decrease in undisturbed specimens is also small at this stage, proving that only small pores are engaged in wetting and associated volumetric collapse. When the wetting of small pores are complete and soil specimen is subjected to lower matric suction (e.g., ψ = 200 kPa), a stepwise rise in water absorption happens especially in undisturbed specimens tested under lower mean net stresses (e.g., p_n = 50 kPa). This change in amount of matric suction activates the suction in pores that are relatively larger in size and consequently a rise in water volume can be observed in both cases of p_n = 50 kPa and p_n = 200 kPa. The higher confinement and stepwise decrease of matric suction from 400 kPa to 200 kPa in case of p_n = 200 kPa, result in a partial stepwise, longer time, and smaller amount of absorbed water volume in this case compared to the case associated with p_n = 50 kPa (Figs.27a, 27b and 27c). When the matric suction decreases from 200 kPa to 50 kPa, there are other steps of pore size involvement in water absorption in undisturbed specimens, and associated water volume are increased stepwise in undisturbed specimens (Figs. 27a, 27b and 27c).

The wetting test conducted under applying p_n = 200 kPa, continued by decreasing the matric suction down to 10 kPa and zero for reconstituted and undisturbed specimens, respectively. In this case, a large amount of water absorption and associated collapse take place in undisturbed specimen during the reduction of matric suction from 50 kPa to zero. In these steps, large pores are encountered and consequently the volume of absorbed water as well as the associated collapse is large (Figs. 27c and 27d). This kind of collapse in voids can approach the degree of saturation to unity on wetting path in undisturbed specimens, unlike the regular soils or the reconstituted specimens (with uniformly distributed pores). In other words, large volumetric collapse in undisturbed specimen tested under p_n =200 kPa, causes the occluded air bubbles to be replaced by water and the pore spaces become almost filled with water that in turn results in a S_r of nearly unity.

The pores in reconstituted specimens are of relatively the same size and their distribution is almost uniform. Hence an almost constant rate in the volume of water absorption is achieved (Fig. 27c). However, there is a ramp up in the curves associated with the reconstituted specimen. This ramp can be related to a local arching in the reconstituted specimens that has been vanished while applying p_n = 200 kPa and decreasing the matric suction from 50 kPa down to 20 kPa.

Figure 28a compares changes in the SWRC curves of undisturbed and reconstituted soil specimens subjected to different mean net stresses prepared the data used in Fig. 27c. The lines with white markers in the figure correspond to the SWRC curves of undisturbed specimens and the lines with black markers
correspond to the SWRC curves of reconstituted soil specimens.

Fig. 27. Representative of data that was recorded during the response-to-wetting collapse stage of testing; (a) matric suction vs. time for $p_n = 50$ kPa, (b) matric suction vs. time for $p_n = 200$ kPa, (c) water volume change vs. time for $p_n = 50$ kPa and 200 kPa, (d) specimen volume change vs. time for $p_n = 50$ kPa and 200 kPa (Haeri et al 2014b, Haeri et al 2015b).

Depending upon the applied mean net stress and the nature of the soil specimen, the SWRCs of reconstituted and undisturbed soil specimens were observed to differ in shape. For the same values of mean net stress, reconstituted specimens showed a lower rate of water absorption during wetting and a correspondingly lower degree of saturation in the SWRC. This observation is believed to be due to differences in the soil pore size and pore size distribution of undisturbed and reconstituted soil specimens which results in different rates of water adsorption under change in mean net stress and matric suction. As presented in Fig. 28a, the differences between the $S_r$ measurements of undisturbed and reconstituted specimens were more pronounced in the specimens subjected to lower values of mean net stress. Different $S_r$ values in undisturbed and reconstituted specimens is the effect of different number of the air-water menisci and amount of occluded water between the particles and consequently the state of stress applied to the specimens (Wheeler et al. 2003; Tamagnini 2004; Khalili and Zargarbashi 2010; Khosravi and McCartney 2012). The deformation behavior of the soil specimens may be therefore different during the process of loading. Fig. 28b shows changes in the volumetric strain of undisturbed and reconstituted specimens with matric suction during wetting process.

As shown in this figure, following a similar trend, both undisturbed and reconstituted specimens experienced a decrease in volume (i.e., compression, which
corresponds to positive volumetric strain) as the matric suction decreased. Comparing the results of undisturbed and reconstituted specimens (Fig. 28b), at a lower value of mean net stress ($p_n = 50$ kPa), volumetric strain measurements of undisturbed specimens were consistently lower than those of reconstituted soil specimens with the reason as discussed above describing Fig. 27. At higher values of mean net stress ($p_n = 200$ kPa), the mechanical stress significantly affects the natural composition of the soil matrix, and the bonds that are present in the intact specimens may be more destroyed. As a result, the effect of non-homogeneity in the distribution of pores on the deformation behavior of collapsible soils is less pronounced and therefore, both undisturbed and reconstituted soil specimens showed similar wetting-induced volumetric strain measurements during wetting-induced collapse (Haeri et al 2014b, Haeri et al 2015b).

### 6.6 Shear strength of unsaturated collapsible soils based on effective stress approach and suction stress concept

Based on the results of shear strength tests, reconstituted specimens appear to experience strain softening and dilatancy after failure, while undisturbed specimens are highly contractive and experience mostly ductile shear strength behavior. Reconstituted specimens are also have smaller axial strain at failure, higher shear strength, a greater reduction in shearing resistance with further straining, and smaller shear-induced volumetric strain. These observations suggest that using reconstituted loess specimens instead of undisturbed specimens may lead to underestimation of volume changes and overestimation of strength during shear (Garakani 2013, Ghazizadeh 2013, Haeri 2014a, Haeri et al 2014b, Haeri et al 2015b).

Fig. 29a shows the drained stress paths for the reconstituted and undisturbed specimens tested under different net stresses and matric suctions along with their steady state deviator stress values. In this plot, the effective stress, $p'$, was defined using a definition of effective stress based on the concept of suction stress proposed by Lu and Likos (2006) as follows:

$$p' = p_n + p_s$$

where $p'$ is the effective stress, $p_n$ is the net stress, and $p_s$ is the suction stress. One of the limitations of the use of Bishop’s effective stress approach (Bishop 1959) for describing the state of stress of loessial soils in unsaturated state is the necessity to define the effective stress parameter, $\chi$, which is highly dependent on the type of soil, soil structure, degree of saturation and stress history and varies from none or extremely small for soils in their relatively dry state to 1 for soils in their saturated state (Coleman 1962; Nuth and Lalou 2008; Khocevri and McCartney 2009; Khosravi and Zargarbash 2010, Haeri et al 2014a).

The suction stress is a stress variable that describes the tensile or cohesive strength between the particles due to all the possible interparticle stress phenomena such as cementation attraction, capillarity, double layer repulsion and Van der Waals forces. It can be defined from shear or tensile strength test data (Lu and Likos 2006; Oh and Lu 2014). In this study, shear strength failure envelopes are interpolated to the normal stress axis to define the suction stress of undisturbed and reconstituted specimens (Haeri et al 2015b) to define $p_s$ to be used in Equation 4 and calculate effective stress shear strength parameters.

The results shown in Fig. 28 indicate the significant influence of disturbance on the deformation behavior of specimens that are tested at lower values of mean net stress.

### 6.7 Critical state of the hydro-collapsible soils based on effective stress approach

Referring back to Fig. 29, the shear strength values at steady state condition can be used to define the steady state conditions during shear for reconstituted and undisturbed specimens. Regression lines through the steady state data points in Fig. 29a can be used to define the Critical State Line (CSL) of reconstituted and undisturbed specimens (Fig. 29b).

![Fig.29. a) Effective stress paths, b) deviator stress relationship with mean effective stress for both reconstituted and undisturbed samples in triaxial tests (Haeri et al 2014b, Haeri et al 2015b)](image-url)
As observed in this figure, CSLs for both reconstituted and undisturbed specimens are straight lines through the origin but with different M values of 1.56 for reconstituted specimens, and 1.15 for natural undisturbed specimens where M is the slope of CSL. This observation reflects the looser structure of the undisturbed specimens in shear due to differences in the pore size and pore size distribution of these two types of specimens and the higher values of S in undisturbed vs reconstituted specimens (see Fig. 28a) at the beginning of shear tests. This fact suggests that the use of a critical state line generated based on reconstituted specimens to assess the field performance is not suitable for natural loessial soils.

The hardening behavior of this soil is studied as well and is discussed in another paper (Haeri et al 2015c)

7 CONCLUSIONS

The summary of a decade study for understanding the hydro-mechanical behavior of a Collapsible Loess is presented in this paper. The tests apparatus include ordinary and unsaturated oedometers and unsaturated triaxial device. The summary of the main conclusion that can be highlighted are as follows:

The tested soil is highly Collapsible Loess with heterogeneous pores and pore size distribution while the pores in reconstituted specimens are of almost the same size with nearly uniform distribution.

The tests on undisturbed specimens, recovered in the laboratory from the intact block samples taken from the site, indicate that the hydro-mechanical behavior of intact Collapsible Loess is substantially different from that of the reconstituted specimens. The water absorption and associated volume change or wetting collapse of the intact specimens is stepwise and generally greater, while that of reconstituted specimens is almost linearly increasing upon wetting and smaller. Also the SWRCs for intact specimens are not unique and are both stress and path dependent.

The shear tests on reconstituted specimens reveal higher critical state line (CSL) compared to that for the natural intact loess, namely the shear test on reconstituted specimens overestimates the shear strength of the natural Loess. Therefore it is not recommended to use reconstituted specimens of loess to predict the behavior of natural loess. It is strongly recommended to perform undisturbed sampling and conduct the tests on intact natural loessial soils to predict accurately the collapse potential, hydro-mechanical behavior and shear strength of this type of collapsible soil. The results of tests on improved reconstituted specimens and intact samples indicate that application of appropriate stabilizing agent and method can considerably improve hydro-mechanical behavior, collapse potential and shear strength of the natural loess.

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