Water retention curves of intact and re-compacted loess at different net stresses

H. Sadeghi i), SK. B. Hossen ii), Abraham C.F. Chiu iii), Q. Cheng i) and C.W.W. Ng iv)

i) Ph.D Student, Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.
ii) MPhil Student, Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.
iii) Professor, Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, 1 Xikang Road, Nanjing 210098, China.
iv) Chair Professor, Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.

ABSTRACT

Water retention curves (WRC) of loess were investigated through conducting two series of tests on intact and re-compacted specimens. Modified pressure plate extractors were used to control net stress and matric suction. Compared to the re-compacted loess, higher rates of adsorption and desorption as well as larger area of hysteresis loop were observed for intact loess. The effect of net stress on WRC seems to be more pronounced for re-compacted loess than intact one. The higher the net stress, the lower the rate of adsorption, and desorption, and the area of hysteresis loop for re-compacted loess. This is due to the reduction in void ratio as a result of net stress. Drying-induced shrinkage is significant for the re-compacted loess, but not for the intact one. Furthermore, shrinkage increases with net stress.

Keywords: loess, intact, re-compacted, water retention curve, net stress

1 INTRODUCTION

Loess soil with aeolian origin is quite common and widespread in Northwest part of China (Peng et al., 2014; Wen and Yan, 2014; Jiang et al., 2012). Natural loess deposits with metastable structure experience seasonal climatic changes (Gao, 1988). The open structure of intact loess makes this category of problematic soils sensitive to mechanical loading as well as hydraulic paths. Either of these two factors can affect water retention curves (WRC) of loess as a result.

Muñoz-Castelblanco et al. (2012) studied water retention properties of a natural loess from Northern France by using a high capacity tensiometer (HCT) and filter paper technique. Specific retention curves with no hysteresis in the central part were obtained, which was postulated to be related to the natural variations of water content under seasonal climatic changes. Triaxial tests were conducted on intact and re-compacted loess by Jiang et al. (2014). Differences in shear strength and generated excess pore water pressure were observed for both samples.

The behavior of re-compacted loess was studied by Chen et al. (1999). Results indicated that compressibility indices for soil structure and the parameters corresponding to water volume change vary considerably in the low suction range. Based on the results of an experimental study on compacted silt, Chiu and Ng (2012) concluded that water retention curve is strongly influenced by the net stress and stress path. Having been spread all around the world, loess deposits could be considered as a promising resource for constructing engineered earth-fill structures (Zhan et al., 2014). In order to have a complete picture of loess behavior, it is important to do research not only on intact soil but also on re-compacted one. In other words, intact loess would not behave in the same manner as re-compacted loess because of different microstructure. According to the literature, previous studies were focused on water retention characteristics of either intact or re-compacted loess. To the knowledge of the authors, no study has been conducted so far on the water retention characteristics of both natural and re-compacted loess subjected to different net stresses. Therefore, this study aims at clarifying the differences between soil water retention properties of intact and re-compacted loess under different net stresses.

2 LABORATORY INVESTIGATION

2.1 Soil type and specimen preparation

High quality undisturbed block samples (0.25x0.25x0.25 m³) of loess were taken from Xi’an, Shaanxi province of China. Samples were collected at 1.5 m depth from an excavated pit. The average values

http://doi.org/10.3208/jgssp.HKG-04
of in-situ dry density and water content are 1.237 Mg/m³ and 10.9%, respectively. Based on the results of sieve and hydrometer analysis, the fractions of sand, silt, and clay are 0.1%, 71.9%, and 28.0%, respectively. The loess is classified as clay of low plasticity (CL) according to the Unified soil classification system.

Two types of specimens were considered in this study, namely, intact and re-compacted. Intact specimens were prepared by pushing an oedometer ring into block samples. Bottom and top of the specimens were trimmed by using a wire saw afterwards. This procedure was conducted inside a temperature/humidity-controlled room to reduce moisture exchange of soil specimens with the surrounding environment. Re-compacted specimens, on the other hand, were prepared from oven-dried, sieved loess soil mixed with natural water content. The mixture was passed through 2 mm-aperture sieve and was kept into a sealed plastic bag for 24 hours for moisture equalization. Cylindrical specimens of 62 mm in diameter and 20 mm in height were dynamically compacted into two layers. The first layer was scarified before compaction of the second one to provide better contact between two layers.

2.2 Testing devices

Modified one-dimensional, stress-controllable volumetric pressure plate apparatuses (Ng and Pang, 2000) were used to measure the soil water retention curves of studied materials at different stress states. The axis translation technique was adopted to measure and control the matric suction of soil specimens. The original setup for the measurement of soil water retention properties was further modified by connecting a pressure transducer to the water drainage compartment beneath the high AEV ceramic disk. This modification makes the apparatuses capable of determining the initial suction of soil specimens. Fig. 1 shows the experimental setup for the measurement of initial suction before proceeding to the wetting sequences. After determination of the initial suction, the pressure transducer was replaced with a set of hysteresis attachments, including an air trap, a ballast tube and a burette, to measure the water volume change along wetting and drying paths. Pore air pressure is controlled through a pressure line connected to the pressure cell while the pore water pressure is kept constant at the atmospheric pressure via a 5-bar high AEV ceramic disk mounted at the bottom of pressure plate.

2.3 Experimental procedure and test program

Two series of tests were carried out on natural and compacted loess specimens. Tests on intact specimens were run in the Hong Kong University of Science and Technology while experiments on re-compacted samples were conducted in the Hohai University. Details of the test program are summarized in Table 1.

| Test ID | Sample type | Sampling depth (m) | Initial ratio | void Net stress (kPa) | vertical stress (kPa) |
|---------|-------------|-------------------|--------------|----------------------|---------------------|
| I-0     | Intact      | 1.5               | 1.19         | 0                    | 50                  |
| I-50    | Intact      | 1.5               | 1.12         | 50                   | 50                  |
| R-0     | Re-compacted| NA                | 1.18         | 0                    | 50                  |
| R-50    | Re-compacted| NA                | 1.09         | 50                   | 50                  |

The first series include two tests conducted on intact loess at zero and 50 kPa net vertical stress under $K_0$ conditions. Testing procedures for intact samples consists of three stages: (i) measurement of the initial suction, (ii) application of net vertical stress and (iii) wetting of soil specimens to saturated state followed by drying process. Prior to the tests, the ceramic disk of each volumetric pressure plate apparatuses was saturated and its AEV (5 bar) was checked accordingly. An intact specimen inside the oedometer ring was then placed on the ceramic disk and its initial suction was determined by incorporating the null-type axis translation technique. The air pressure of 450 kPa was applied to the pressure cell while the water drainage path connected to the pressure transducer was kept closed. In order to keep the top cap in contact with the soil sample, the upward air pressure applied to the rod was counterbalanced by dead load (Fig. 1). Water pressure was monitored time to time and suction was calculated by deducting $u_w$ from $u_a$. Fig. 2 indicates the evolution of matric suction with time for intact loess samples. Results show that equilibrium of suction for both specimens was reached after 48 h. The initial suction is 182 and 178 kPa for I-0 and I-50, respectively. The configuration of test setup was changed after the first stage by replacing the pressure transducer with hysteresis attachments. A net vertical stress was then applied according to test conditions in Table 1 under the controlled initial suction. Wetting process was proceeded from the initial suction in several steps by reducing the applied air pressure, followed by drying process in which suction was increased in several steps by increasing air pressure.
The maximum applied suction was 400 kPa. Water pressure was controlled at atmospheric level in the second and third stages. For a given suction stage, the water inflow/outflow rate and vertical deformation of soil specimen were monitored every 12 h. The inflow/outflow rate of 0.07 cm/day was set as the criterion for suction equalization. According to the results, 5 to 15 days are required to satisfy this criterion.

![Graph showing water retention curves](image.png)

**Fig. 2.** Measurement of the initial suction by using the null-type axis translation technique.

The second series of tests were run on re-compacted material under zero and 50 kPa net vertical stresses. These tests consist of three stages: (i) saturation, (ii) application of vertical stress, and (iii) drying sequences followed by wetting. Soil specimens installed on 5-bar AEV ceramic disks were submerged in de-aired water inside a desiccator under the maximum vacuum for 24 h to accomplish the saturation process. Thereafter, saturated specimens were transferred to the pressure cell and consolidated to the corresponding vertical stress (Table 1). Drying sequences were proceeded in several steps up to 400 kPa suction followed by several wetting intervals. The same protocols as the first series of tests were taken for suction equalization and measurements. Suction was equalized within 2-10 days for re-compacted loess.

### 3 INTERPRETATION OF TEST RESULTS

Results of the experimental program are presented and discussed in this section in terms of both water retention characteristics and volume change behavior of soil tested.

#### 3.1 Water retention properties

Water retention curves of loess soil are depicted in Fig. 3 for different net stresses. Fig. 3a and b. show the degree of saturation versus suction for natural and re-compacted soil specimens, respectively. According to Fig. 3a, tests were initiated from the initial suction of around 180 kPa. Having moved from the initial state along the wetting path, water retention curves slope up mildly in the scanning region followed by a drastic increase in degree of saturation, implying a shift from scanning curve to the main wetting path. In fact, the existence of two kinks along the wetting paths at matric suction of 6 and 35 kPa for I-0 and I-50 tests, respectively, is a sign of transition from scanning curve to the main wetting curve. In case of I-0 test, degree of saturation at saturation state (s=0.1 kPa) is less than one as expected due to the volume of entrapped air. It is not the case for I-50 test, however, in which degree of saturation goes marginally beyond the unity. A possible explanation could be the inevitable deformation of pressure cell, which directly affects the vertical displacement and sample volume changes. Apparatus compliance due to the application of vertical load and air pressure results in the overestimation of sample volume change, which in turn delivers a higher degree of saturation than the actual one. Tests were further continued along the drying path with a gentle slope until the air entry value followed by a clear steepening of the trends afterwards. Regarding the re-compacted loess, drying process was initiated from the fully saturated state (Fig. 3b). A distinct air entry value of around 10 kPa can be observed for both R-0 and R-50 tests. Tests were carried on to the maximum achievable suction followed by the wetting process.

In order to investigate the retention behavior of loess in a more systematic manner, comparisons are
made based on the parameters of WRC (Pham et al., 2005). Four parameters are selected as follows: the rate of desorption, \( m_d \), the rate of adsorption, \( m_s \), \( R_{SL} \), and \( A_{SL} \) (Chiu and Ng, 2012). \( R_{SL} \) is the ratio between the rate of desorption and the rate of adsorption. \( A_{SL} \) is the normalized area of the hydraulic hysteresis loop in the plane of \( S_r \)-log (s). The mathematical expressions for \( R_{SL} \) and \( A_{SL} \) are defined in the following equations:

\[
R_{SL} = \frac{m_d}{m_s} \tag{1}
\]

\[
A_{SL} = 1 - \frac{\int_{100}^{S_r} S_r(s) \, ds}{\int_1^{100} S_r(s) \, ds} \tag{2}
\]

Suction values of 1 and 100 kPa were selected as lower and upper integration limits. This range of suction is common for all the tests conducted in this study. Therefore, it is possible to make a consistent and fair comparison on hysteresis properties of loess soils. Table 2 summarizes the WRC parameters of intact and re-compacted loess at two different net stresses.

Table 2. Quantitative parameters for water retention curves of intact and re-compacted loess.

| Test ID | Net vertical stress (kPa) | AEXV (kPa) | AEV (kPa) | \( m_s \) (log\(^{-1} \) kPa) | \( m_d \) (log\(^{-1} \) kPa) | \( R_{SL} \) | \( A_{SL} \) |
|---------|---------------------------|------------|------------|-----------------|-----------------|-------------|-------------|
| I-0     | 0                         | 2          | 9          | 1.049           | 0.468           | 0.45        | 0.362       |
| I-50    | 50                        | 7          | 6          | 0.907           | 0.427           | 0.47        | 0.290       |
| R-0     | 0                         | NA         | 9          | 0.335           | 0.379           | 1.13        | 1.063       |
| R-50    | 50                        | NA         | 8          | 0.160           | 0.256           | 1.60        | 1.27        |

Air expulsion value; *Air entry value

Based on the results presented in Table 2, air expulsion value of intact loess increases with net stress. Since tests on re-compacted samples were terminated at suction of 1 kPa, AEXV cannot be determined for them and no conclusion can be drawn. On the other hand, the AEV of both intact and re-compacted soils is not significantly affected by the stress state. This might be due to the limited range of vertical net stress (up to 50 kPa) considered in this study.

Graphical representation of WRC parameters in Fig. 4, makes the comparison more convenient. Fig. 4a shows the rate of adsorption and desorption for all the tests. \( R_{SL} \) and \( A_{SL} \) of conducted tests are indicated in Fig. 4b. All parameters except \( R_{SL} \) decrease with an increase of net stress from zero to 50 kPa. The application of stress, in fact, results in a lower rate of adsorption and desorption along with a lower area of hysteresis loop. In terms of physical meaning, an intact or a re-compacted loess specimen compressed to a higher net stress would have higher potential for retaining water compared to a specimen under lower stress state. It is noted that the effect is more pronounced for re-compacted samples compared to the intact ones. It is then postulated that intact loess has a higher yield stress compared to re-compacted one. The opposite trend was observed for \( R_{SL} \) which increases with net stress. It is interesting that \( R_{SL} \) values are more than one for the re-compacted loess and less than one for the intact ones (Fig. 4b). The former trend was also reported by (Chiu and Ng, 2012) for compacted silt. The latter one which implies higher adsorption rate than the desorption rate has not been reported for similar material so far. A possible reason could be the hydraulic path followed for intact soil specimens. Unlike the tests on re-compacted specimens in this study and most of WRC tests by other researchers, wetting path was directly followed from the initial state rather than after the first drying. It is important to be aware that first wetting curve was usually neglected and not measured due to the direct saturation of soil samples as a prerequisite to the test. This conventional procedure for measuring WRC was not adopted in this study for intact loess to prevent the unintended collapse of soil structure during saturation procedure.

3.2 Volume change behavior

Fig. 5 shows the volume change behavior of intact and re-compacted loess. Results are depicted in terms of void ratio versus suction. According to Fig. 5a, the
change of void ratio for intact specimens is less than 2% during the whole wetting/drying processes. Collapse of the loess structure was not observed for the intact samples. This is probably because the yield stress for intact loess is beyond 50 kPa due to bonding. As a result, soil remain within the elastic range for the two net stressss considered here. On the other hand, considerable amount of shrinkage was observed during drying of re-compacted loess (Fig. 5b). Unfortunately, the volume change of soil specimens during the saturation process and wetting path was not measured.

4 SUMMARY AND CONCLUSIONS

Water retention and shrinkage curves of intact and re-compacted loess samples taken from Northwestern China were measured under different net stresses. It was observed that re-compacted loess has higher retention capability than intact loess, i.e. lower adsorption and desorption rate as well as smaller hysteresis loop. Unlike intact loess, rate of adsorption is lower than rate of desorption for re-compacted loess. Test results also showed that re-compacted loess can retain more water under a higher net stress. On the other hand, a net stress of 50 kPa does not induce significant difference in the water retention properties of intact loess. Considerable shrinkage was observed during drying of re-compacted loess resulting in a denser specimen. Shrinkage increases with increasing net stress. Hence, a lower rate of adsorption was observed during subsequent wetting path.

ACKNOWLEDGEMENTS

The financial support provided by the Research Grants Council of the Hong Kong Special Administrative Region (HKSAR) through the research grant No. 616812 is acknowledged.

REFERENCES

1) Chen, Z.H., Fredlund, D.G., and Gan, J.K.M. 1999. Overall volume change, water volume change, and yield associated with an unsaturated compacted loess, Canadian Geotechnical Journal, 36(2): 321-329.
2) Chiu, C.F. and Ng, C.W.W. 2012. Coupled water retention and shrinkage properties of a compacted silt under isotropic and deviatoric stress paths, Canadian Geotechnical Journal, 49(8): 928-938.
3) Gao, G. 1988. Formation and development of the structure of collapsing loess in china, Engineering Geology, 25(2-4): 235-245.
4) Jiang, M., Hu, H., and Liu, F. 2012. Summary of collapsible behaviour of artificially structured loess in oedometer and triaxial wetting tests, Canadian Geotechnical Journal, 49(10): 1147-1157.
5) Jiang, M., Zhang, F., Hu, H., Cui, Y., and Peng, J. 2014. Structural characterization of natural loess and remolded loess under triaxial tests, Engineering Geology, 181: 249-260.
6) Muñoz-Castelblanco, J.A., Pereira, J.M., Delage, P., and Cui, Y.J. 2012. The water retention properties of a natural unsaturated loess from northern france, Geotechnique, 62(2): 95-106.
7) Ng, C.W.W. and Peng, Y.W. 2000. Experimental investigations of the soil-water characteristics of a volcanic soil, Canadian Geotechnical Journal, 37(6): 1252-1264.
8) Peng, J., Fan, Z., Wu, D., Zhuang, J., Dai, F., Chen, W., and Zhao, C. 2014. Heavy rainfall triggered loess-mudstone landslide and subsequent debris flow in tianshui, china, Engineering Geology.
9) Pham, H.Q., Fredlund, D.G., and Barbour, S.L. 2005. A study of hysteresis models for soil-water characteristic curves, Canadian Geotechnical Journal, 42(6): 1548-1568.
10) Wen, B.P. and Yan, Y.J. 2014. Influence of structure on shear characteristics of the unsaturated loess in lanzhou, china, Engineering Geology, 168: 46-58.
11) Zhan, T.L.T., Yang, Y.B., Chen, R., Ng, C.W.W., and Chen, Y.M. 2014. Influence of clod size and water content on gas permeability of a compacted loess, Canadian Geotechnical Journal, 51(12): 1468-1474.