The following publication Mu, Q. Y., Dong, H., Liao, H. J., Dang, Y. J., & Zhou, C. (2020). Water-retention curves of loess under wetting−drying cycles. Géotechnique Letters, 10(2), 135-140 is available at https://doi.org/10.1680/jgele.19.00025.

Water retention curves of intact, compacted and reconstituted loess under cyclic wetting-drying

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Abstract

Water retention curves (WRCs) of intact, compacted and reconstituted loess were investigated using a pressure plate extractor. All specimens were prepared to the same initial density and subjected to two cycles of drying and wetting in the suction range of 0 to 400 kPa. Furthermore, their pore size distributions were measured through mercury intrusion porosimeter (MIP) for explaining the measured WRCs. Results show that the air entry value (AEV) of reconstituted loess is 505% and 169% larger than that of intact and compacted loess respectively. This is because the reconstituted loess has more uniform pore size distribution and it is lack of large-size pores, as supported by the MIP measurements. On the other hand, the average degree of hysteresis of reconstituted loess during the second wetting-drying cycle decreases by 73% compared to that of the first cycle, attributed to the significant soil shrinkage (i.e., 28%) induced by the first wetting-drying cycle. On the contrary, the number of wetting-drying cycles shows negligible effects on the hysteresis of intact loess. In addition, the wetting-drying cycles influence the hysteresis of compacted loess only in a narrow suction range (i.e., 10-50 kPa).

Key words: Fabric/structure of soils; Suction; Laboratory tests

1. Introduction

Understanding the water retention curve (WRC) of unsaturated soils is essential for analyzing many geotechnical geo-structures such as embankments, slopes and landfill covers (Muñoz-Castelblanco et al., 2011; Xu et al., 2011; Zhou et al., 2013; Chen et al., 2019). The water retention behaviour is expected to be different from other soils, as it has much larger wetting-induced collapse. So far, the WRC of loess has been only investigated along a monotonic drying/wetting path or a single wetting-drying cycle. Experimental results under cyclic wetting-drying are limited, even though it is well-known that soil behaviour is greatly affected to suction and stress-history (Ng et al., 2009; Zhao et al., 2019). Huang et al. (2010) measured WRC of an intact loess along a drying path. This study focused on evaluating performance of existing models for predicting WRC of intact loess. To obtain a complete set of hysteretic WRCs, Muñoz-Castelblanco et al. (2012) studied WRC of an intact loess along a single wetting-drying cycle. Measured WRCs showed a specific shape, with no hysteresis observed around the initial water content (i.e., w = 14.4%) and two hysteresis loops on the wet and dry sides of the curves. The initial water content was determined through an intact loess at the in-situ state. Recently, Ng et al. (2016) measured WRCs of intact and compacted loess under a single wetting-drying cycle. It was found that intact and compacted loess exhibited different hysteretic behavior although these two specimens shared a similar dry density. In all of these studies, the WRC of loess under cyclic wetting-drying were not studied.

In the present work, the WRCs of intact, compacted and reconstituted loess were measured along two wetting-drying cycles. To compare measured WRCs consistently, all specimens were prepared with the same initial void ratio. The obtained WRCs were interpreted with the assistance of mercury intrusion porosimeter (MIP) measurements.

2. Test apparatus

Figure 1 shows the schematic diagram of the commercial pressure plate extractor (Soil-moisture Equipment Corporation. Santa Bahara, CA.) used in this study. A ceramic disc with an air entry value of 5 bar (1 bar=100 kPa) is mounted on the base of the air-tight chamber. The water pressure beneath the ceramic disc is open to atmospheric condition (u_w=0) and the air pressure (u_a) is elevated in steps through an air pump. It is therefore that the principle of axis translation is applied to control soil matric suction ($s=u_a-u_w$). During tests, the water flowing in or out of soil specimens is monitored through the water level mark of the ballast tube. Upon achieving the equilibrium condition, the specimens are removed from the chamber and weighed immediately. The changes of soil water content are determined by deducting the initial weight from the current weight. In addition, the burette is used to store or supply water to the ballast tube. The dissolved air that may diffuse through the ceramic disc is flushed with the air trap every 24 hours (Ng and Pang, 2000). On the other hand, the apparatus adopted for measuring the pore size distribution is Micromeritics Auto Pore IV 9500 V1.04.

3. Test material and specimen preparation

3.1. Test material

The tested loess was extracted from an excavation pit in Xi’an, China. Intact blocks (0.3m ×0.3m ×0.3m in size) were collected at a depth of 5.5 m. As shown in Figure 2, the clay and silt fractions of the tested loess are 18.4% and 81.3%, respectively. The loess has a liquid limit of 35.7% and a plastic limit of 16.2%. According to ASTM D2487-11, the tested loess is classified as clay of low plasticity (CL). More soil physical properties are summarized in Table 1.

X-ray diffraction (XRD) test was carried out to identify mineral compositions of the tested loess. Figure 3 shows the measured soil XRD pattern. The peaks in the range of 5°-20° and 20°-40° represent clay and non-clay minerals, respectively. It can be seen that the peaks in the range 20°-40° are larger than those in the range 5°-20°, indicating that non-clay minerals dominate the composition of tested loess. Non-clay minerals, such as quartz (Q), albite (A) and calcite (Ca) are identified. It should be noted that the calcite is a cementation material which is probably acquired from the initial wind deposition or reprecipitation (Liu et al., 2015). On the other hand, clay minerals of the tested loess include nimite (N) and muscovite (M).

3.2. Specimen preparation method

Intact, compacted and reconstituted specimens were tested in this study. The intact specimen was obtained by pushing a steel oedometer ring into the loess block. The dry density and water content of intact specimen were 1.52 g/cm^3 and 16.6%, respectively. For the compacted specimen, the loess was first oven-dried for 24 hours and then passed through a 2 mm aperture sieve. Dried soil was mixed with water to reach the same water content as the intact specimen and then sealed inside a plastic bag for moisture equalisation. The prepared soil was statically compacted into a steel oedometer ring with target dry density similar to the intact specimen. For the reconstituted specimen, oven-dried loess was mixed with de-aired water to a water content 1.5 times the liquid limit. The mixed slurry was then consolidated one dimensionally to the same dry density as the intact and compacted specimens (i.e., 1.52 g/cm^3). It should be noted that the initial water content of reconstituted specimen was at saturated state at the beginning of water retention tests. In this study, the WRC of intact, compacted and reconstituted specimens was measured and compared at the same initial void ratio.

4. Test program and test procedure

Intact and compacted specimens were firstly placed in the chamber. The initial suction controlled in the specimens was 24 kPa, which is approximately equal to their initial suctions. The initial suction of intact and compacted specimens was determined based on the null-type axis translation technique (Fredlund and Rahardjo, 1993). The intact and compacted specimens were wetted in steps from 24 to 0 kPa by reducing the air pressure. After finishing the first wetting path for intact and compacted specimens, the reconstituted specimen was placed in the chamber (see in Figure 1). Following the first wetting path was the first drying path that the air pressure was increased in steps from 0 to 400 kPa and then re-wetting and -drying afterwards. In total, two wetting-drying cycles were performed on all specimens. At each step, suction equalisation was assumed to be achieved when the variation of water content is less than 0.04%/day (Sivakumar, 1993). After equalisation at each suction condition, specimens were taken out of the pressure plate extractor. Their height and diameter were measured using a vernier caliper with a resolution of 0.01 mm. The measured diameter and height were used to calculate soil axial and radial strains, respectively. It was found that in the suction range considered in this study (i.e., 0 to 400 kPa), the shrinkage of intact and compacted specimens was almost negligible. No gap was observed between intact/compacted specimen and the oedometer ring, so the radial strain is zero. For the reconstituted specimen, however, its radial strain is not zero due to its more significant shrinkage. In addition, to check those calculated volume changes, volume of soil specimens was also determined by employing the wax method (ASTM D 4943-08) at suctions 0, 200 and 400 kPa during the first drying path. It was found that the differences in the void ratios determined by using the above two methods were less than 4%, as shown in Figure 5. At a given suction stage, the soil volumetric water content is calculated through the measured soil volume and water content.

5. Experimental results

5.1. Pore size distributions

Figure 4 shows the pore size distributions (PSDs) of intact, compacted and reconstituted loess at the initial state. The intact loess is characterized by a tri-modal PSD with dominated large, medium and small pores around 17.3 μm, 0.3 μm and 0.05 μm, respectively. The tri-modal PSD of intact loess is different from existing results which showed that intact loess exhibited a bi-modal (Ng et al., 2016) or a mono-modal PSD (Muñoz-Castelblanco et al., 2012). The different aeolian deposition processes are probably responsible for these different PSDs of intact loess. In addition, extra-large pores (>500 μm) are observed in the intact loess through visual observation (see photograph in Figure 4). For the compacted loess, a bi-modal PSD defining a population of large (13.9 μm) and small (0.05 μm) pores is obtained as the soil was compacted at the dry side of optimum (Delage et al., 1996). The PSD of reconstituted loess shows a similar bi-modal curve but with a smaller dominated size for large pores (1.3 μm) than compacted loess. According to previous studies (Tarantino, 2009; Burton et al., 2014), soils reconstituted from slurry exhibited a mono-modal PSD in contrast to the bi-modal PSD observed by soils compacted on the dry side of optimum water content. Recently, the PSD of reconstituted loess reported by Ng et al. (2019) was also characterized as a mono-modal curve. In this study, however, a bi-modal PSD curve is observed for the reconstituted loess. This is likely because the loess tested in the current study has calcite (see in Figure 3), which imposes cementing effects to soil aggregates. Cemented aggregates which contain intra-aggregate pores (i.e., 0.05μm) may not be completely destroyed during mixing the slurry. In addition, according to previous studies (Garcia et al. 1991; Kristof et al. 1993), high-energy or intensive dry grinding can alter the crystalline structure of fine-grained clay minerals. The differences in measured PSDs among intact, compacted and reconstituted loess may also arise in the different soil compositions. Further studies need to be carried out to investigate the effects of dry grinding efforts on soil water retention behavior.

5.2. Water retention curves and deformation behavior

Figure 5 shows the WRCs of intact, compacted and reconstituted loess together with their deformation under two wetting-drying cycles. Parameters of measured WRCs are summarized in Table 2. The AEV is estimated by extending a line from the constant slope portion (i.e., from 10 to 50 kPa, 20 to 100 and 50 to 200 kPa for WRC of intact, compacted and reconstituted loess, respectively) of the drying curve to intersect the suction axis at saturation state (Ng and Pang, 2000). At suction ranges mentioned above, the slope of the drying and wetting curves is defined as desorption and adsorption rates, respectively. For the reconstituted loess, the AEV determined from the first drying path is 505% and 169% larger than that of intact and compacted loess, respectively. It is evident from MIP measurements that the reconstituted loess has a smaller dominated size for large pores than intact and compacted loess and hence exhibits a larger AEV. The differences in the AEV of intact, compacted and reconstituted loess confirm that soil WRC is not only influenced by the overall dry density but also the pore structure (Romero et al., 2011; Zhou and Ng, 2014). On the other hand, the reconstituted loess shrinks 28% during the first drying path while the void ratio of intact and compacted loess decreases by less than 3% under the same drying path. Although the three specimens have a similar void ratio, the pore sizes in the reconstituted loess are generally smaller than those in the intact and compacted loess. Due to the enhanced capillarity (Romero et al., 2011; Mu et al., 2018), the reconstituted loess has the strongest water retention ability (see in Figure 5). Given the same increment in suction, the reconstituted loess has the highest Sr and hence the largest increase in average skeleton stress (σ') $\sigma_{net}+S_r*s$, where σ_{net}, S_r and s are the net stress, degree of saturation and suction, respectively (Bishop, 1959; Alonso et al., 2013). With the largest increase in average skeleton stress, the reconstituted loess therefore has the most significant shrinkage. On the other hand, the intact, compacted and reconstituted loess show a progressively larger shrinkage during wetting-drying cycles. This could also be attributed to the increasing damage to the initial inter-grain bonding of loess (e.g., calcite) during specimen preparation (i.e., intact, compacted and reconstituted).

The AEV of intact loess determined from the second drying path (1.9 kPa) is similar to that from the first drying (2.0 kPa). The constant AEVs of intact loess are because that the intact loess has been subjected to numerous wetting-drying cycles in the past. For the compacted loess, the AEV determined from the first drying path (i.e., 4.5 kPa) is also very close to that from the second drying path (i.e., 3.1 kPa). The small reduction of AEV is negligible considering the existence of experimental errors. This is because volumetric contraction of the compacted loess is only 3% during the drying and wetting processes. However, the AEV of the reconstituted loess determined from the second drying path (i.e., 20.2 kPa) is much larger than that from the first drying path (i.e., 12.1 kPa), mainly because the reconstituted loess shrinks by 28% during the first drying-wetting cycle. The specimen with a smaller average pore size requires a larger air pressure to allow air to break into soil pores (Ng and Pang, 2000; Tarantino, 2009). In addition, for the intact and compacted loess, the wetting-drying cycle has minuscule effects on desorption and adsorption rates (i.e., 0.02). On the contrary, the desorption rate of reconstituted loess decreases by 100% with increasing wetting-drying cycles, mainly because of the shrinkage of reconstituted loess (i.e., 28%) occurred in the first wetting-drying cycle.

5.3. Hysteresis characteristics

At a given suction, water contents during the drying and wetting paths were determined. The ratio of their difference to their average value is used to quantify the degree of hysteresis, following the definition proposed by Lu and Khorshidi (2015). Figure 6 show the degree of hysteresis of intact, compacted and reconstituted loess during two wetting-drying cycles. During the first wetting-drying cycle, the intact loess shows apparent hysteresis at low (0.1~6kPa) and high (50~400kPa) suctions and negligible hysteresis at medium (10-24kPa) suctions. More importantly, at a given suction, the degree of hysteresis of intact loess changes slightly when the number of drying and wetting cycle increases. The shape of WRC measured by Muñoz-Castelblan et al. (2012) (see in Figure 5a) is similar to the measurement in this study, with no hysteresis observed around medium suctions and two hysteresis loops on both low and high suctions. The hysteresis in the WRC is known to be caused by the following: irregularity effects known as the "ink-bottle effects", differences of contact angle at the soil particle-pore water interfaces, entrapped air and thixotropic regain due to the wetting-drying history (Pham et al., 2005). For the WRC of intact loess, the hysteresis in the middle suctions is erased due to the thixotropic regain. As revealed in MIP measurements, the pore size of intact loess varies from several dozens of nanometers to several hundred millimeters. The permanent hysteresis at low and high suctions is probably due to ink-bottle effects induced by the significant non-uniformity of pore sizes.

For the compacted loess, pronounced hysteresis is exhibited during the first wetting-drying cycle. Compared to the hysteresis pattern of intact loess, the medium zone with small degrees of hysteresis is not observed in the WRC of compacted loess. This hysteretic behavior of compacted loess is expected as compacted loess hasn't been subjected to any wetting-drying cycles in the past. Furthermore, the degree of hysteresis at medium suctions (10-50 kPa) decreases by 33%-69% with increasing wetting-drying cycles while the hysteresis at low (0.1-6kPa) and high (100-400 kPa) suctions change slightly. It is also worthwhile to note that the hysteresis pattern in the WRCs of compacted loess seems to converge asymptotically to that of intact loess if the compacted loess was continually subjected to wetting-drying cycles.

For the reconstituted loess, apparent hysteresis was also observed during the first wetting-drying cycle. This hysteresis is mainly contributed by the “non-return” first wetting path (see in Figure 5c) because of significant soil shrinkage induced by the first drying path. Furthermore, the average degree of hysteresis decreases by 73% with an increase in wetting-drying cycles. This is because that the reconstituted loess becomes 28% denser after the first wetting-drying cycle. According to previous studies (Ng and Pang, 2000; Tarantino, 2009), a smaller hysteresis would be expected for soil specimens with smaller pore sizes.

6. Conclusions

(1) The AEV of reconstituted loess determined from the first drying path is 505% and 169% larger than that of intact and compacted loess, respectively. This is due to the fact that the pore size distribution of the reconstituted loess is more uniform than those of intact and compacted loess, as revealed by the results of MIP tests. Hence, the largest pore size in the reconstituted soil is smaller than that in the intact and compacted loess, even though they have the same initial density.

(2) The wetting-drying cycles have minuscule effects on the AEV of intact and compacted loess. For the reconstituted loess, however, the AEV determined from the second drying path is 40% larger than that from the first drying path. The larger AEV along the second drying path can be explained by soil shrinkage (i.e., 28%) induced by the first wetting-drying cycle.

(3) The WRC of intact loess retains a constant hysteresis pattern under wetting-drying cycles, with apparent hysteresis observed at low (0.1-6 kPa) and high (50-400 kPa) suctions and negligible hysteresis at medium (10-24 kPa) suctions. For the reconstituted loess, the average degree of hysteresis decreases by 73% with increasing wetting-drying cycles, due to its shrinkage with a volumetric strain of 28%. In addition, wetting-drying cycles influence the hysteresis of compacted loess at medium (10-50kPa) suctions but not at low (0.1-6 kPa) and high (100-400 kPa) suctions.

Acknowledgement

This work was supported by the National Science Foundation of China (51909205, 41630639, 51279155), the Chinese Postdoctoral Science Foundation (2018M631166;

2019T120914), the Fundamental Research Funds for the Central Universities of China (xjj2018250), the innovative talents promotion plan in Shaanxi Province, China (2018KJXX-033) and the Research Grants Council (RGC) of the Hong Kong Special Administrative Region (HKSAR) for research grant 16207918.

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