Wetting-induced collapse of unsaturated recompacted loess at various temperatures

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ABSTRACT: Unsaturated loess has a metastable structure, which can be maintained temporarily by suction. Many experimental studies have demonstrated that when subjected to wetting under a certain load, collapse behaviour can be observed in unsaturated loess. However, most previous studies are conducted under room temperature. Wetting-induced collapse of unsaturated loess at different temperatures are seldom studied. In this study, a series of wetting tests were carried out on unsaturated loess at different temperatures of 5, 23 and 50°C. It is found that when wetting from 100 to 0 kPa at confining stress of 50 kPa, the wetting-induced volumetric strain of loess increases from 4.1% at 5°C to 11.7% at 50°C. This is because with a given suction decrease, reduction of the stabilizing inter-particle normal force is larger at a higher temperature. Consequently, the wetting-induced softening of yield stress is larger at a higher temperature, resulting in more significant yielding and volumetric collapse during wetting.

1 INTRODUCTION

Loess soil is one of the typical collapsible soil and widespread all over the world, which is generally metastable and have an open structure (Rogers, 1995; Ng and Menzies, 2007). When subjected to wetting under a certain load, loosely packed soil particles may undergo a marked increase in settlement (Barden et al., 1973). As far as wetting-induced collapse is concerned, most previous studies focused on stress effects (Lawton et al., 1989, Pereire and Fredlund, 2000; Sun et al., 2007; Munoz-Castelblanco et al., 2011; Vilar and Rodrifues, 2011, Jiang et al., 2012). It is found that the maximum collapse occurs when the mean net stress equals to the initial yield stress of unsaturated soil.

In loess area such as loess plateau of China, temperature always varies by dozens of degrees in a year. Although thermal effects on soil behaviour are well recognized (Campanella and Mitchell, 1968; Abuel-Naga et al., 2007; Uchaipichat and Khalili, 2009; Zhou et al., 2015; Ng et al., 2016a), as far as the authors are aware, only two studies have been reported to investigate thermal effects on wetting-induced collapse (Romero et al., 2003; Haghighi et al., 2011). Romero et al. (2003) found that, for recompacted loose Boom clay, wetting-induced volumetric strains measured at 22 and 80°C are almost the same. Haghighi et al. (2011) found that the collapse volumetric strain of recompacted Kaolin clay at 20°C is slightly larger than that at 50°C and the maximum difference is about 4%. Unfortunately, the yielding behaviour are not reported in the above two studies, and therefore the observed thermal effects on soil collapse cannot be properly interpreted and fully understood within elastoplastic framework.

2 TEST PROGRAM AND TEST APPARATUS

The principal objective of this research is to study wetting-induced collapse of unsaturated recompacted loess at various temperatures (5, 23 and 50°C). Three suction- and temperature-controlled wetting tests were carried out on recompacted loess at temperatures of 5, 23 and 50°C, respectively (T5, T23 and T50). Details of the test programme are summarised in Table 1.

Table 1. Details of stress and temperature controlled wetting tests.

Test ID	T (°C)	e (initial)	Stress path (See Fig. 3)
T5	5	1.17	A→B→C→D1→E2
T23	23	1.18	A→B→C→E1
T50	50	1.17	A→B→C→D2→E3

A suction- and temperature-controlled double cell triaxial apparatus (Ng et al., 2016a) was utilised in this study. Figure. 1 shows the photograph of the apparatus. This apparatus mainly consists of four parts:

matric suction and stress control system, total volume change measurement system, water volume measurement and flushing system and temperature control system. Matric suction ($u_a - u_w$) of soil specimen is controlled using the axis translation technique (Hilf, 1956).The pore-air pressure u_a is controlled through a low air-entry value (AEV) porous stone and the pore-water pressure u_w is controlled through a saturated high AEV (5 bar) ceramic disk. The total volume change of soil specimen is measured by using double cell volume change measuring system (Ng et al., 2012). By adopting the high accuracy differential pressure transduced (DPT), the volumetric strain measurement has an accuracy of 0.03% for the tested specimens (76 mm in diameter and 20 mm in height). The water volume change of the soil specimen is measured by the water flow in and out through a ballast tube connected with an air trap and a burette. The temperature control system includes a heating/ cooling bath connected with a spiral copper tube installed between the inner cell and outer cell. The heating/ cooling bath consists of a thermostat, a heating/ cooling unit, a water bath, an inbuilt pump and a thermocouple. Water in the water bath is heated/ cooled by using the heating/ cooling unit and then circulated in the spiral copper tube with the help of the pump. Soil specimen is then heated/ cooled by heat transfer. The thermocouple is installed in the water of the inner cell to measure temperature and give feedback to the thermostat. The thermostat is able to adjust the output of the heating/ cooling unit according to current and target temperatures. In this study, 48 hours are allowed to reach the target temperature and to achieve the thermal equilibrium. After reaching thermal equilibrium, the temperature fluctuation is less than 0.2°C. More details of the temperature control system were reported by Ng et al. (2016a).

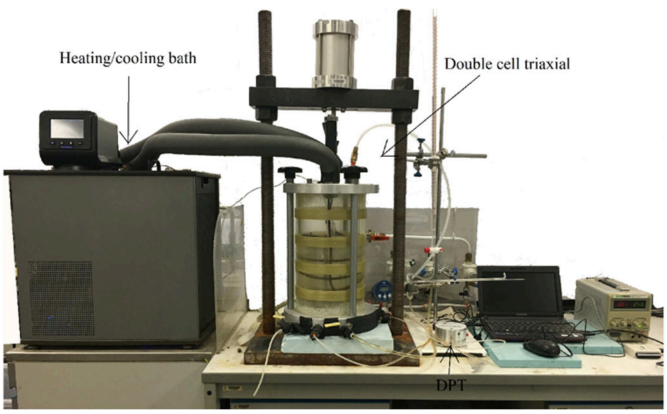

Figure 1. Photograph of the suction- and temperature-controlled double-cell triaxial apparatus

3 SOIL TYPE AND SPECIMEN PREPARATION

The soil tested in this paper is loess from the Shaanxi Province of China. Figure. 2 shows the particle size distribution of tested loess, determined by wet sieving and hydrometer (Ng et al., 2016c). The fractions of sand, silt and clay are 0.1%, 71.9% and 28.0%, respectively. The plastic and liquid limits are 19% and 36%, respectively. The maximum dry density and optimum water content determined from standard Proctor test are 1680 kg/m^3 and 18.1%, respectively (Ng et al., 2016b). According to the Unified Soil Classification System (ASTM, 2011), the tested loess soil is classified as a clay of low plasticity (CL).

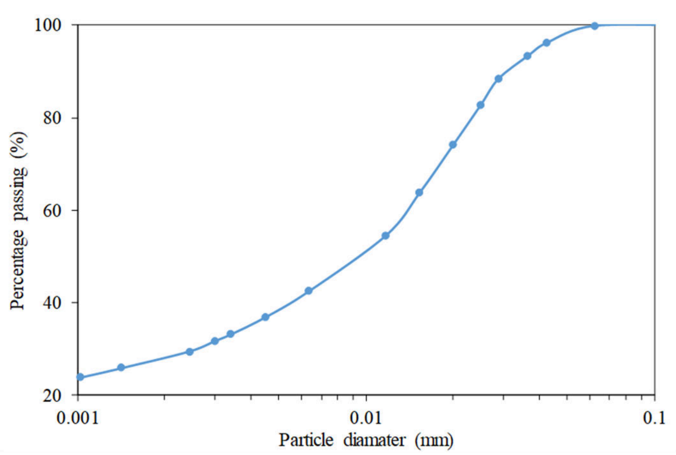

Figure 2. Particle size distribution of tested loess

Recompacted specimen is prepared from disturbed samples. The disturbed soil samples cut from block samples were first broken down into smaller lumps. Then, the aggregation of soil particles was broken down mechanically by a rubber pestle and was oven-dried at a temperature of 105°C for 24 hours. Thereafter, the oven-dried soil was passed through a 2 mm-aperture sieve. Recompacted specimen was prepared with compaction water content and void ratio of 10.9% and 1.17, respectively. The initial water content and void ratio kept the same as intact loess. Based on the targeted water content, the required amount of de-aired water was added to the sieved, oven-dried soil step by step. After mixing, the mixture was sieved through a 2 mm-aperture sieve again. After sieving, the soil was then sealed inside a plastic bag and kept in a temperature- and humidity-controlled room for 48 hours to ensure the moisture equalization.

Static compaction method is used to prepare recompacted loess specimen. Each specimen is 76 mm in diameter and 20 mm in height and statically compacted in two layers. Each layer was statically compressed at a fixed displacement rate of 1.0 mm/min. After compaction, the initial suction of soil specimen was measured to be about 180 kPa (Ng et al., 2016a).

4 TEST PROCEDURE

Figure. 3 shows the stress path of each wetting test. Each specimen was first isotropically compressed to confining stress of 50 kPa at drained condition (A→ B). Then, each specimen was wetted to 100 kPa (B→

C). This stage needs 7-10 days for reaching suction equilibrium. The third stage was to change soil temperature to target value. The soil specimens in tests T5 and T50 were cooled and heated to 5 and 50°C, respectively (C→D1, C→D2). For the test T23 conducted at room temperature, the temperatures were kept constant. Two days were needed for each specimen to achieve thermal equilibrium. The final stage is wetting from suction of 100 to 0 kPa (D1→E2, C→E1, D2→E3) at constant stress and temperature condition. During the wetting process, soil suction was decreased step by step (100-50-10-1-0 kPa). At each suction, the equilibrium state was regarded as being reached when the water flow rate is less than 0.1 ml/day. The stress paths of all tests are summarized in Table 1.

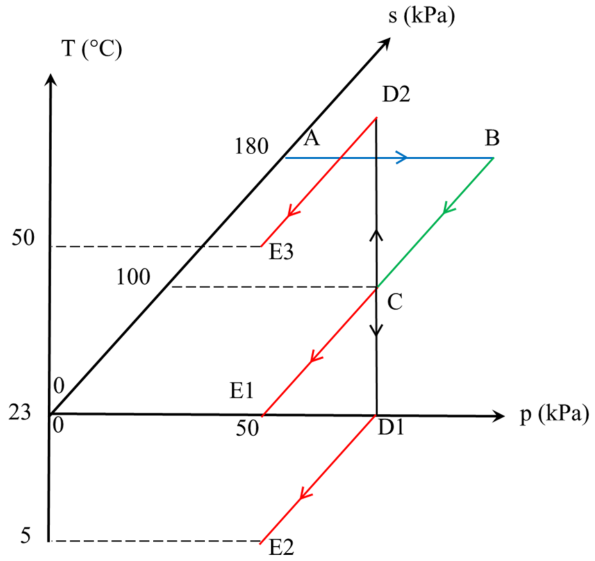

Figure 3. Thermo-hydro-mechanical path of each wetting tests

5 INTERPRETATION OF EXPERIMENTAL RESULTS

Figure. 4 shows wetting-induced collapse of recompacted loess during wetting from 100 to 0 kPa at different temperatures of 5, 23 and 50°C. The volumetric strain ε_v during this process is calculated using the following equation:

$$\varepsilon_v = -\frac{e_{100} - e_i}{1 + e_{100}} \tag{1}$$

where e_{100} is the void ratio at suction of 100 kPa; e_i is the void ratio at a given suction value during the wetting process. Before wetting from 100 to 0 kPa, contractive volumetric strains of about 9% have been observed in the three specimens during the process of compression to 50 kPa and wetting from initial suction to 100 kPa. It is reasonable to assume that all the three specimens are normally consolidated at the stress state with suction of 100 kPa and confining stress of 50 kPa.

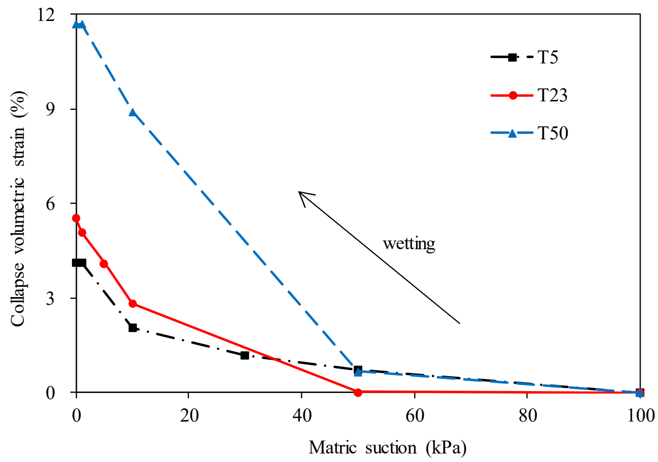

Figure 4. Wetting-induced collapse of recompacted loess during wetting from 100 to 0 kPa at different temperatures

It can be seen from the figure that, with decreasing suction, the wetting-induced volumetric strain of recompacted loess increases, at an increasing rate. Moreover, with increasing temperature, the cumulative collapse strain increases. When wetting to 0 kPa, the cumulative collapse volumetric strain at 5°C is about 4%, which is 20% less than that at room temperature (about 5%). The collapse volumetric strain at 50°C is around 12%, which is three times of that at 5°C.

The thermal effects on wetting-induced collapse can be explained using existing elasto-plastic theory. According to one of the elasto-plastic models for unsaturated soil (e.g. Alonso et al., 1990), there is a positive relationship between incremental volumetric strain $d\varepsilon_v$ and incremental yield stress:

$$d\varepsilon_v = \frac{\lambda(0)}{1+e}\frac{dp_c^0}{p_c^0} \tag{2}$$

where $\lambda(0)$ is the plastic compressibility index at zero suction; e is void ratio; p_c^0 is the initial yield stress at zero suction and dp_c^0 is the incremental yield stress at zero suction. The initial yield stress at zero suction at each temperature is reported by Ng et al. (2017). It is found that yield stress at a given suction decreases with increasing temperature (thermal softening), as shown in Figure 5. This may be able to be explained using suction-dependent inter-particle normal force ΔN. According to the analytical solution proposed by Fisher (1926), ΔN can be expressed as:

$$\Delta N = \frac{\pi T_s^2}{s}\frac{\left(\sqrt{9+\frac{8Rs}{T_s}}-3\right)\left(\sqrt{9+\frac{8Rs}{T_s}}+1\right)}{4} \tag{3}$$

where T_s is the surface tension coefficient of water; s is matric suction of soil; and R is the radius of spherical particles. According to Gittens (1969), surface tension T_s decreases with increasing temperature. For example, when temperature increases from 23 to 50°C, T_s decreases from 72.3 to 67.9 mN/m. At 5°C,

T_s is 74.9 mN/m. With increasing temperature, R increases. The variation of R can be estimated by using the thermal expansion coefficient of soil particles. According to Horseman and McEwen (1996), for clay particles, the thermal expansion coefficient is about 2.9×10^{-3}%/°C. According to Equation (3), when suction decreases from 100 to 0 kPa, ΔN decreases by about 8.4%, 9.9% and 10.3% at 5, 23 and 50°C, respectively. With a larger reduction of the stabilizing inter-particle normal force at a higher temperature, the wetting-induced softening becomes larger at 50°C than at 5°C.

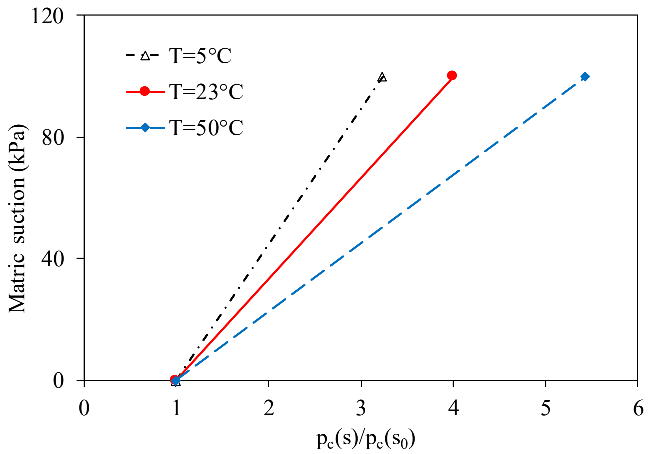

Figure 5. Wetting-induced softening of yield stress of recompacted loess at different temperatures

To determine the values of p_c^0 and dp_c^0 in equation (3), the yield stress of recompacted loess before and after wetting are shown in Figure. 6. Before wetting from 100 to 0 kPa, contractive volumetric strains of about 9% have been observed in the three specimens during the process of compression to 50 kPa and wetting from initial suction to 100 kPa. It is reasonable to assume that all the three specimens are normally consolidated at the stress state with suction of 100 kPa and confining stress of 50 kPa. The stress states of each specimen should be located on the corresponding loading collapse (LC) curves. In the current study, it is assumed that the shape of loading collapse curve remains the same before and after wetting. This assumption is supported by the experimental results of Nowamooz and Masrouri (2008) on a bentonite/silt mixture. It was found that the loading collapse curves are almost parallel in a similar suction range (0 to 100 kPa) as that in current study. Under this assumption, the LC curves before wetting from 100 to 0 kPa are obtained by parallelly shifting the initial LC curves obtained from Ng et al. (2017). During the following wetting process, all the three LC curves at different temperatures shift to the right. After wetting to 0 kPa, the stress state at each stress and temperature condition is on the corresponding LC curves. Then, the ratios dp_c^0/p_c^0 can be obtained and are 1.38, 1.50 and 1.78 at temperatures of 5, 23 and 50°C, respectively. It is found that dp_c^0/p_c^0 induced by the wetting process increases with increasing temperature. Consequently, based on equation (2), the wetting-induced yielding and volumetric contraction are larger at a higher temperature, as shown in Figure. 6. This observation implies that at a higher temperature, wetting-induced soil contraction and ground movement would be much larger.

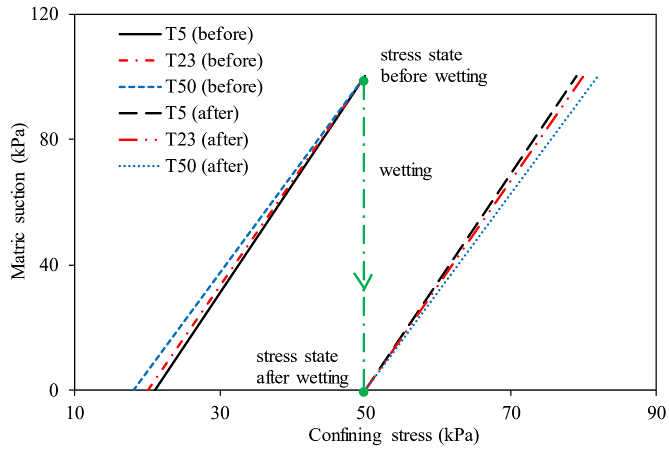

Figure 6. Thermal effects on the evolution of loading collapse curves of recompacted loess during wetting from 100 to 0 kPa

6 CONCLUSIONS

Under wetting from 100 to 0 kPa at a confining stress of 50 kPa, the wetting-induced volumetric strain of recompacted loess increases from 4.1% at 5°C to 11.7% at 50°C. The results of wetting tests were at various temperatures were interpreted using the measured yield stress at various suctions and temperatures. It is found that yield stress decreases with decreasing suction (wetting-induced softening). The wetting-induced softening of recompacted loess is more significant at a higher temperature. The observed thermal effects on wetting-induced softening are likely because with decreasing suction, the stabilizing inter-particle normal force decreases more at a higher temperature. On the other hand, when the applied stress reaches the yield stress during wetting, yielding and plastic volumetric contraction can be observed. Thus, the larger contraction at 50°C is mainly because the wetting-induced softening is larger at a higher temperature. This observation implies that at a higher temperature, wetting-induced soil contraction and ground movement in loess area would be much larger.

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