Experimental Research on Impact of Freeze-thaw Cycle on Geotechnical Properties of Compacted Loess

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ABSTRACT
Freeze-thaw experiments with external water supply have been conducted in laboratory to study the impact of freeze-thaw cycling on compacted loess's geotechnical properties, such as water redistribution, deformation and dry density. Results showed that the water content in loess sample increased after some freeze-thaw cycles, e.g. the water content reached a maximum of 28.47 % after 31 freeze-thaw cycles. And it gradually rose from bottom to top. During the first few freeze-thaw cycles, the amount of frost heave was greater than that of thaw settlement, and loess sample was expanded. However, the deformation remained stable after several freeze-thaw cycles because the amount of frost heave is equal to that of thaw settlement. The maximum accumulated deformation reached 12.16 mm, which accounted for 12 % of the initial height of loess sample. It was found that the dry density of loess decreased with increasing freeze-thaw cycle and water, and tended to keep constant after some freeze-thaw cycles. The density was reduced from an initial value of 1.86 g/cm^3 to 1.55 g/cm^3 after 31 freeze-thaw cycles. The main reason for this reduction was that freeze-thaw cycling and water rise re-structured the arrangement of soil grain, which led to bonding reduction and pore expansion.

RÉSUMÉ
Beaucoup d'expériences de gel-dégel avec l'approvisionnement en eau ont été menées dans le laboratoire pour étudier l'impact des cycles de gel-dégel sur les propriétés géotechniques de loess compacté, comme la distribution de l'eau, la déformation et la densité sèche. Les résultats montrent que la teneur en eau dans l'échantillon loess augmenté après quelques cycles de gel-dégel, qui a atteint un maximum de 28,47% après des 31 cycles de gel-dégel et a augmenté progressivement de bas en haut. Durant les premiers cycles de gel-dégel, le montant de soulèvement par le gel a été supérieure à celle du établissement au dégel, et la déformation de l'échantillon du loess présentaient une expansion. Cependant, la déformation est restée stable après quelques cycles de gel-dégel, car le montant de soulèvement par le gel est égale à celle du du établissement au dégel. La déformation maximale atteint 12,16 mm, ce qui représentait 12% de la hauteur initiale de l'échantillon de loess. De plus, la densité sèche de loess a diminué avec les augmentations des cycles de gel-dégel et de l'eau, et tend à maintenir constante après quelques cycles de gel-dégel. Il a été réduit d'une valeur initiale de 1,86 à 1,55 g/cm^3 après des 31 cycles de gel-dégel. La raison principal est que les cycles de gel-dégel et la augmentation de l'eau restructuré la voie d'arrangement des grains du sol, qui mène à la réduction de collage et de l'expansion des pores.

1 INTRODUCTION

Loess is a kind of wind-blown quaternary silt deposit which widely develops in arid and semi-arid regions. It is characterized by larger pore, more vertical fissure, and being more sensitive to water compared to other silts. Adequate water easily leads to larger settlement under the self-weight or external load. This specific property of loess is called collapsibility. And the settlement induced by water supply is called the collapsible deformation. Loess distributes widely in many countries such as Midwest of Americas, Southern Russia, Northern France, Canada, Australia, Central and Eastern Europe. It covers an area of 13,000,000 square kilometers, accounting for 9.3 % of the continent area. In China, loess appears with an area of 640,000 square kilometers, of which the collapsible loess accounts for 71%. Most of loess is widely distributed in seasonally frozen ground regions in China (Sun, 2005). It is densely compacted as building foundation and highway subgrade. They are often exposed to water immersion and/or repetitive freeze-thaw cycles. Such exposure makes the compacted loess loose and potentially leads to the differential settlement, even hazards, to the buildings. The impacts of water supply and freeze-thaw cycles on the geotechnical properties of compacted loess or other fine-grained soils had therefore been extensively studied.

Kim and Daniel (1992) found that the hydraulic permeability of soil compacted with optimum water content was increased two to six times by freezing while that of soil compacted wet of optimum increased about 100 times. Othman and Benson (1993) found from tests on post-thawed and unfrozen soils that the degree of change could be reduced by isotropic loading, as pressure may close the cracks induced by freeze-thaw cycles. As for the mechanism, Chamberlain et al. (1990)

and many others have inferred that the permeability increase was due to both micro-fissuring during freezing and thawing and the large pores that were left after thawing of ice crystals. Chamberlain and Gow (1979) also mentioned that fine particles might move out of large pores during freezing and thawing. Chamberlain and Gow (1979) and Eigenbrod (1996) found that freezing and thawing leaded to densification of soft, normally-consolidated clay samples, but other studies showed the opposite to occur for dense samples. But the quantitative relation between them was not yet well-established.

Considerable laboratory work has been performed on factors affecting the resilient properties of soil, including studies on the effects of freeze-thaw. The basic understanding was that even a small number of freeze-thaw cycles might lead to a significant reduction in the resilient modulus. Simonsen et al. (2002) studied five soils from gravelly sand to marine clay. They found that the modulus decreased by 25 % to 60 %, depending on soil type, the larger the percentage of fine particles, the greater the change. Wang et al. (2007) found that freeze-thaw cycles caused reduction in resilient modulus and cohesion, and increase in friction angle in a fine grained clay. Qi and Ma (2007) studied variation in strength of two over-consolidated soils after freeze-thaw cycles. They found that change in cohesions was similar to the change obtained from Wang et al. (2007). But the friction angle changed in an opposite way. The effect of freeze-thaw on the undrained shear strength has been studied on natural soil samples as well as laboratory-prepared samples. Data for natural clays, for example, was reported by Graham and Au (1985) and Leroueil et al. (1991). It was found that the undrained shear strength decreased significantly after freeze-thaw. It was also found that change was greatest during the first few cycles (Yong et al., 1985). For the loosely compacted silt samples, research results showed an increase in the undrained shear strength after freeze-thaw (Alkire and Morrison, 1982). Edwin and Anthony (1979) found that freezing and thawing caused a reduction in void ratio and an increase in vertical permeability from the data of fine-grained soils. As discussed above, dense soils tend to dilate under freeze-thaw. On the other hand, loose soils are densified under freeze-thaw and show the corresponding properties.

The researches mentioned above provided a good understanding for the impact of freezing and thawing on geotechnical properties of compacted loess, such as water redistribution, variation in structure, void ratio, cohesion, friction angle, volume and permeability. However, there remained still a certain shortcoming in some aspects of these researches. Freeze-thaw tests, for instance, were conducted with quite limited cycle number, almost less than 20 cycles, which could not represent the whole process of variation in geotechnical properties. No definite relationship was established. In addition, some conditions of tests were simpler, such as unidirectional freezing at a constant temperature instead of periodic freezing and thawing cycling. Loess is sensitive to water, while some tests were conducted without considering its impact. So, in the current paper, lots of freeze-thaw experiments, with large number of freeze-thaw cycle and water supply, were conducted to study the impact of freezing and thawing on geotechnical properties of compacted loess, which was collected form the Loess Plateau, China. The result is expectedly to provide a good scientific basis for design, construction and maintenance of loess foundations, and a good understanding for both causes and mechanism of loess collapsibility.

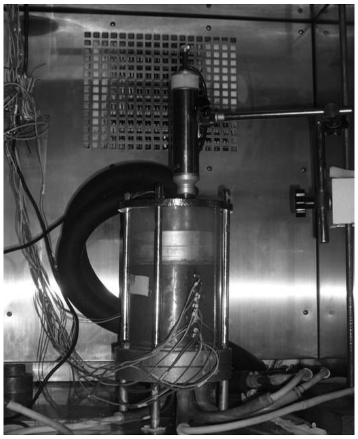
2 EXPERIMENTAL METHOD

Loess was collected at 36°36′34″ N, 103°22′05″ E, close to Yonydeng county, Gansu province, northwestern China. The collected loess is collapsible one. It was compacted layer by layer into loess samples with a water content and a large dry density, which approached the optimum water content of 11.6 % and a maximum dry density of 1.91g/cm^3, respectively. The cylindrical samples were 10.13 cm in height, 10.1 cm in diameter. They were always consolidated for 24 hours for a uniform water content. They were installed in a small PVC tubes placed in an experimental system for freezing and thawing tests in laboratory (See Figure 1). Temperatures at the top and bottom of loss sample were controlled by liquid coolant connected with cooling bath. The top temperature varied sinusoidal in the range of -6.7 to 27 degree Celsius according to the mean annual ground surface temperature of the nearest Lanzhou meteorological station for 30 years (during 1971 through 2000) (See Figure 2). The bottom temperature was set at 1 degree Celsius. A water reservoir was connected to the sample bottom to simulate the natural condition with water immersion. The environmental air temperature in experimental system also was also controlled at a temperature of 1 degree Celsius. A freeze-thaw cycle lasted one day. The PVC tube holding soil sample was insulated to avoid the impact of the environmental air on the temperature of loess sample. The loess temperature at a vertical interval of 10 cm was measured by thermal susceptible resistance sensors every 30 minutes, with a precision of ±0.1 degree Celsius. A dial gauge on the top was used to measure deformation with a precision of ±0.01mm.

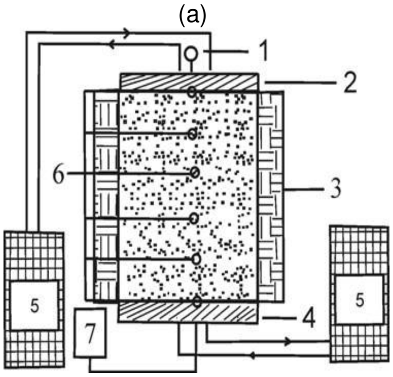
3 EXPERIMENTAL RESULTS

3.1 Loess properties

Grain size distribution, liquid and plastic limits, and specific density were measured in laboratory prior to freeze-thaw experiment. Grain size distraction was showed in Table 1. The liquid and plastic limits were 26.9 % and 18.7 %, respectively. The specific density is 2.704. The collected loess is a kind of silt with a lower liquid limit. Meantime, the maximum dry density and the optimum water content were measured, which were 1.91 g/cm^3 and 11.6 %, respectively (See Figure 3). The laboratory-prepared samples should approach the maximum dry density and the optimum water content as close as possible. The loess samples were prepared with a maximum dry density of 1.86 g/cm^3 and an optimum moisture content of 11.58%.



(a)



(b)

Figure 1. Schematic drawing of experimental system for freezing and thawing.(a) Photo of freeze-thaw experiment system; and (b) Simplified model of components in the experimental system. 1-Deformation sensor, 2-Top plate, 3-Insulation layer, 4-Bottom plate, 5-Cooling bath, 6-Temperature sensors, and 7-Water reservoir.

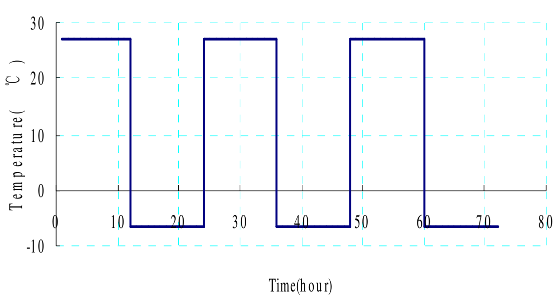


Figure 2. Chang in temperature on the top plate of samples

Table 1. Grain-size distribution of the collected loess

Diameter (mm)	0.1 ~ 0.07	0.07 ~ 0.05	0.05 ~ 0.01	0.01 ~ 0.005	0.005 ~ 0.002	< 0.002
Percentage (%)	0.1	10.2	49.2	37.2	1.2	2.0

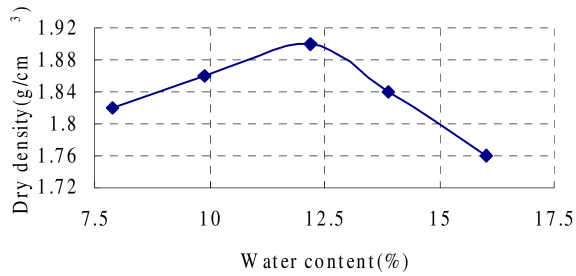


Figure 3. Results of compaction tests of collected loess

3.2 Deformation process

The loess samples were subjected to freeze-thaw cycles with a water supply from the bottom. They showed a frost heave when the top temperature was negative, and a thaw settlement when the top temperature became positive. From Figure 4, we found that the deformation kept a constant at the starting of experiments as the top temperature was positive. When the top temperature turned negative, the upper part of loess samples was frozen and the deformation increased. Then, the deformation decreased gradually when the top temperature became positive. During the first few freeze-thaw cycles, the deformation induced by frost heave was greater than that induced by thaw settlement. So soil sample exhibited an increase in deformation. After some freeze-thaw cycles, it remained constant because the deformation induced by frost heave was equal to that induced by thaw settlement. The maximum accumulated deformation induced by frost heave reached 10.65 mm, 11.71 mm, and 12.16 mm after 5, 11 and 31 freeze-thaw cycles, respectively. The deformation did not get stable after 5 and 11 freeze-thaw cycles. However, the sample suffering from 31 cycles kept stable after its deformation reached a maximum value. During the last few freeze-thaw cycles, the deformation decreased slightly because freezing and thawing leaded to redistribution of soil particle, increase in void ratio, and reduction in bonding, and these changes caused a low bearing capacity.

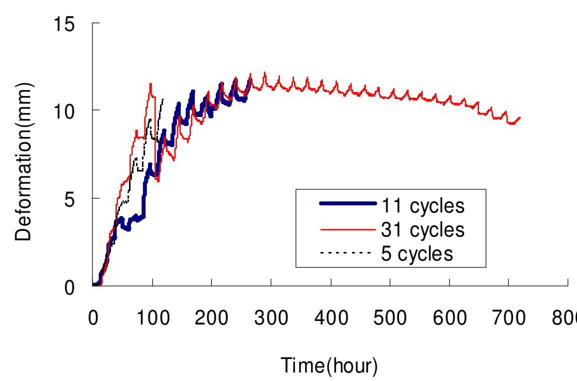


Figure 4. Changes in deformation of loess samples exposed to different freeze-thaw cycles

It is therefore concluded that loess is a kind of frost-susceptible soil. The loess foundation should be carefully treated and keep water off to avoid the larger differential deformation which is potentially induced by the impact of freeze-thaw cycles and of water supply.

3.3 Water redistribution

The soil samples in a frozen state were taken off from the PVC tubes after some freeze-thaw cycles. The water content was immediately measured layer by layer at an interval of 10 mm to analyze water distribution along height of the sample. Figure 5 showed variations in water content after 5, 11 and 31 freeze-thaw cycles, respectively. It could be found that the soil samples had a higher water content compared to the initial value of 11.6 %. The water content increased gradually from bottom to top. After freeze-thaw cycles, there was no significant difference in bottom water content among three samples. However, in the middle and upper part of samples, such difference is great. Water content increased with increasing number of freeze-thaw cycle. The maximum values reached 26.87 %, 27.52 % and 28.74 %, respectively, after different freeze-thaw cycles.

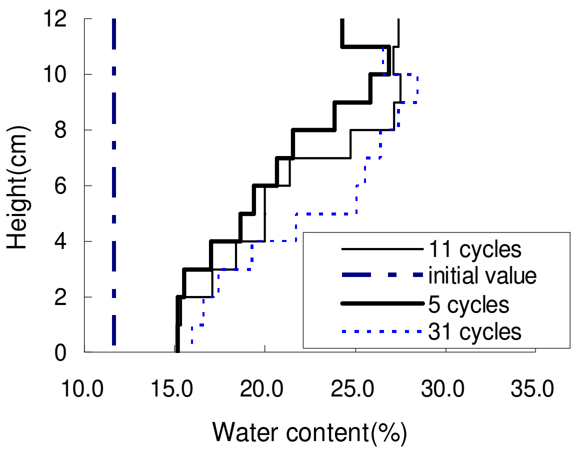


Figure 5. Water content distribution after different freeze-thaw cycles

As for the causes and mechanism of water redistribution, the following explanation, schematically shown in Figure 6, could be referred to for further understanding. When the upper part of sample was frozen, water moved from the lower part of sample (in an unfrozen state) to the upper part (in a frozen state) due to temperature gradient. When the top temperature turned positive, the upper part started to thaw downward, and the middle part near freezing-thawing interface also started to thaw upwards. Water in upper part began to migrate downwards due to gravity. It halted when reaching the frozen layer. Only when the frozen layer was thawed completely did the water continue to migrate smoothly downward. The water in the middle and upper part of soil was accumulated and increased if the water migrating upward was more than that downward. After lots of repeated freeze-thaw cycles, water redistribution was formed as shown in Figure 5. Loess is sensitive to water. So water increase and redistribution would lead to the larger settlement of loess foundation, the building on which would be damaged possibly.

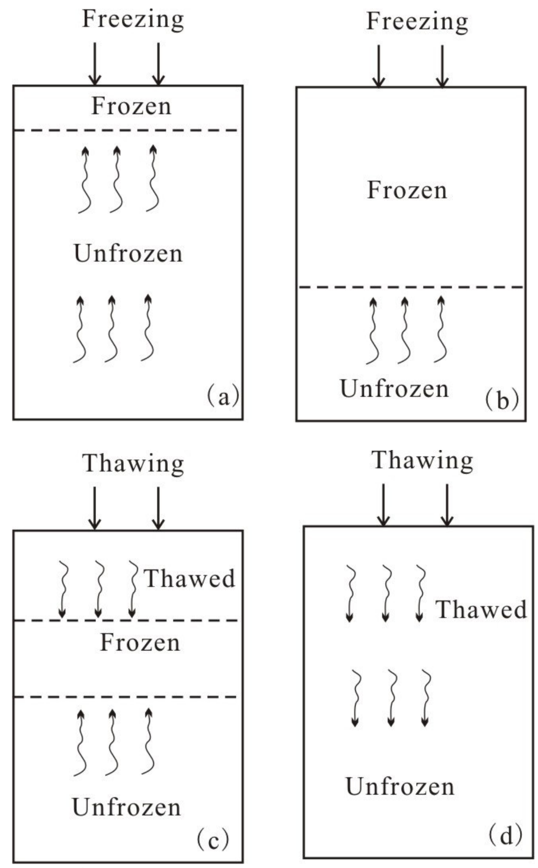


Figure 6. Schematic drawing of water migration under freeze-thaw cycle
(a) starting of freezing; (b) at maximum freezing depth; (c) starting of thawing; (d) thawed completely

3.4 Variation in dry density

Dry density of the upper part (post-thawed) and the lower part (unfrozen) of sample was measured after freeze-thaw cycles. Results were shown in Figure7. It was found that dry density decreased with increasing number of freeze-thaw cycles. Dry density of upper part decreased quickly during the first few freeze-thaw cycles. Then it tended to keep constant. It changed from an initial value of 1.86 g/cm^3 to 1.55 g/cm^3 after 21 freeze-thaw cycles and to 1.57 g /cm^3 after 31 freeze-thaw cycles. Additionally, dry density of the upper part was less than that of the lower part. It was because the upper part suffered from more strongly freezing and thawing. But the bottom part did not, which only suffered from water immersion.

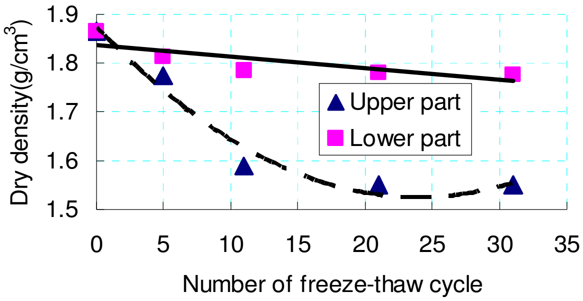


Figure 7. Change in dry density with increasing number of freeze-thaw cycle

4 CONCLUSIONS

The following was concluded according to results from freeze-thaw experiments on compacted loess:

(1) The compacted loess exhibited frost heave when it was frozen with water supply, and thaw settlement when being thawed. During the first few freeze-thaw cycles, the amount of frost heave was greater than that of thaw settlement. The volume of soil sample expanded. After several freeze-thaw cycles, the amount of heave frost was equal to that of thaw settlement. The volume retained stable. The maximum accumulated frost heave reached 12.16 mm, which account for 12 % of the initial height of soil sample.

(2) Water content in compacted loess increased with increasing freeze-thaw cycles, particularly apparent in the middle and upper parts. The maximum water content reached 28.47 % compared to an initial value of 11.58 %. Along the height of loess sample, water content increased gradually from bottom to top because the amount of water migrating upwards was greater than that of water downwards

(3) Dry density decreased with increasing number of freeze-thaw cycles as a result of freeze-thaw cycling and water increase. It varied from an initial value of 1.86 g/cm^3 to 1.55g/cm^3 after 31 freeze-thaw cycles. The main reason was that freeze-thaw cycling and water immersion restructured the arrangement pattern of loess particle, reduced bonding among particles, and expanded the pore. During the first few freeze-thaw cycles, dry density decreased sharply. After some freeze-thaw cycles, it tended to be stable. The dry density of the compacted loess exposed to freeze-thaw cycling was less than that of the loess unexposed to freeze-thaw cycling.

ACKNOWLEDGEMENTS

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