Effects of freezing and thawing cycles on over-consolidated reconstituted structural loess

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\textbf{ABSTRACT:} The effect of freezing and thawing cycles on the behaviors of over-consolidated reconstituted structural loess was studied by routine uniaxial compression tests and uniaxial loading-unloading cyclic tests in this paper. Energy dissipation was used as a new way to investigate the structural damages during the freezing and thawing cycles. The change laws of strength, failure strain, modulus and the energy dissipation after different freezing and thawing cycles were investigated. It was found that under the experimental conditions used, freezing and thawing cycles lead a slight expansion in volume, and an obvious desiccation of the specimens. The failure strain and initial tangent modulus decreased gradually with freezing and thawing cycles, while the average resilient modulus decreased significantly after the first cycle, and then appeared impervious to a further increase of cycles. And based on that fact, the threshold value of Su1.0\% for the over-consolidated reconstituted structural loess was suggested as about 225 kPa or a little higher. The UC strength decreased most intensely after first 3 cycles and then recovered a little during the 5~10th cycles, which indicated a slight re-structuring effect during the cycles. The change trend of strength with freezing and thawing cycles was similar to that of the average energy dissipation, which further verified the structural damages induced by freezing and thawing cycles. The evolution laws of energy dissipation with axial strain could be described by parabolic curves, and the vertex of the fitting parabola usually appeared around the failure strain under various freezing and thawing cycles.
Keywords: Freezing and thawing cycles; Structural damages; Over-consolidated reconstituted soils; Uniaxial loading-unloading cyclic tests; Energy dissipation.

1. Introduction

Shen (1998) indicated that study on soil structures would be one of the core topics of geotechnical engineering in the century. Soil structures can essentially reveal the fundamentals of soil behaviors. Geotechnical properties, such as hydraulic permeability, compressibility, shear strength, resilient modulus and so on, always change not only with the mineral and particle compositions, water contents and densities of the soil itself, but also with the confining pressures, temperatures or other environmental factors of the circumstances in which the soil is, because of the changes in their structures or fabrics during external disturbances. The soils that are sensitive to structural disturbances are called structural soils. Regarding the fact that the strength of natural clays is usually much higher than that of the reconstituted soils under the same density and water content, Shen (1998) pointed out that natural clays are generally structural soils due to the existence of a strong inter-particle bonding.

As a special form of weathering, freezing and thawing cycles have a considerable impact on the physical and mechanical properties of both natural soils and reconstituted soils, while the effects on different types of soils are usually not the same. Applying freezing and thawing cycles on natural clays usually results in a decrease in density, strength and stiffness. John and Alan (1979) carried out a 1-D compression test on an undisturbed silty soil and found that the strength of the post-thawed soil tended towards to zero at a water content between 35% and 42%. Graham and Au (1985) and Leroueil et al. (1991) tested on natural soils and showed that natural soils exhibited remarkable peaks on the stress-strain curves from triaxial test, while the peaks would gradually reduce or even disappear after 5 freezing and thawing cycles. And a freeze-thaw induced drop of pre-consolidation pressure on one-dimensional oedometer consolidation curve was also observed by Graham and Au (1985), which verified the weaken effect of freezing and thawing cycles on natural soils. However, for reconstituted soils, the effects of freezing and thawing cycles are more complicated and largely depend on the initial states of soil samples. Generally, over-consolidated samples behave consistently with the natural soils and tend to be weakened after freezing and thawing cycles, while the normally-consolidated or loose ones tend to be strengthened. Qi and Ma (2006) tested on two over-consolidated reconstituted clayey soils and showed an decrease of strength after freezing and thawing cycles. While Ono and Mitachi (1997) found that the post-thawed strength of reconstituted specimen was about 20% stronger than that of unfrozen ones and thus they proposed a re-structuring effect due to freezing and thawing cycles. Chamberlain and Gow (1979) and Eigenbrod (1996) found that freezing and thawing cycles lead to densification of soft, normally-consolidated clay samples. Viklander (1998) proposed a conception of "residual void ratio", which means both kinds of soils may reach a same void ratio after a number of freezing and thawing cycles. The conclusion that freezing and thawing cycles have a dual effect on reconstituted soils can also be drawn from many other researches. (Alkire and Morrison 1982, Aubert and Gasc-Barbier , 2012).
That is to say, for most of the natural clays and the over-consolidated reconstituted clays with a strong initial structural bonding, freezing and thawing cycles induce a micro-structural damage; while for the less bonding or bondless soils (like most of the normally-consolidated reconstituted clays), the cycles inversely induce a re-structuring effect of reinforcement. The changes of inter-particle bonding (structural damage or reinforcement) can be confirmed indirectly by routine soil tests and can be directly observed using scanning electronic microscopes (SEM), computed tomography (CT) scanners and other test methods. Many researchers have conducted routine tests as well as micro-structural observations on various soils and under various test conditions. Ma et al. (1999) used nuclear magnetic response (NMR) and SEM tests to investigate the micro mechanisms of the strength and the creep characteristics of frozen soils under different confining pressures. And CT scanner was also used by Ma et al. (1997) to dynamically monitor the structural changes during creep process and to investigate the influence of confining pressure on strength and deformation characteristics of frozen loess. Hohmann-Porebska (2002) carried out SEM tests and permeability experiments on several cohesive soils that were used as impermeable walls for waste deposits to assess the effect of freezing and thawing on micro and macro structural transformations and their impact on the permeability. Makusa et al. (2014) observed cation exchange concurrent with freezing and thawing cycles, which had an effect on the chemical bonding among soil particles and thus on the hydraulic conductivity of a geosynthetic clay liner. Comparatively, continuum damage mechanics (CDM) is relatively a new way that investigates the mechanical response and reliability of materials weakened by changes of microstructures. The degeneration of macro mechanical properties is defined as damage. The damage is usually irreversible and is accompanied with energy dissipation. Energy dissipation is an apparent index to describe the extent of damage and the changes of internal meso/micro structures. Moreover, it is very cheap and convenient to investigate energy dissipation by cyclic loading test. In this study, energy dissipation from the uniaxial loading-unloading cyclic (ULUC) tests, rather than the expensive SEM or CT results, combined with routine uniaxial compression (UC) tests are adopted to investigate the change laws of strength, failure strain, modulus and the damage extent of a structural soil after different freezing and thawing cycles. Specially, based on the fact that over-consolidated reconstituted specimens behave similarly with the natural samples under freezing and thawing cycles, over-consolidated reconstituted specimens were used to avoid the uncertainties of initial differences between the specimens, rather than the natural intact samples, which are susceptible to disturbances during the sampling processes. The purpose of the present study is to examine how the properties of the over-consolidated reconstituted structural loess are changed after different freezing and thawing cycles.

2. Materials and methods

2.1. Soil material and sampling

The test material was Xi'an loess taken from Bailuyuan town in Xi'an city, which is a typical structural soil. It has a natural moisture content of 24.3% and a specific gravity of 2.71. The
grain size distribution of this soil is shown in Table 1. After being air-dried to 10% of moisture content, the soil was added with an appropriate amount of distilled water to bring the water content to the demanded value of 19.2%, which was nearly the saturation moisture content at the target dry density of 1.78 g/cm$^3$. After 24 hours in an airtight container, when the moisture had distributed evenly in the soil, an appreciated quantity of soil was put into a cylindrical mold and compacted into cylinders on a particular sampling machine. The maximum compacting load during sampling was about 8kN to make the specimens over-consolidated. All the specimens were made at a time to ensure the minimum differences between them, and they all had a diameter of 39.1 mm, a height of 80 mm, and an expected dry density of 1.78 g/cm$^3$.

**Table 1.** Grain size distribution of the test material.

| Soil name   | Grain size distribution /% | Cu | Cc  |
|-------------|----------------------------|----|-----|
| Xi’an loess | 0.005-0.01mm               | 6.68| 7   |
|             | 0.01-0.1mm                 | 80.91| 3.3 |
|             | >0.1mm                     | 2.36|     |

2.2. Freezing and thawing procedure

In this study, the temperature gradient, water migration, ice crystals growth and other cryogenic phenomena during the individual process of freezing or thawing are not observed in real-time. But the comprehensive effects of freezing and thawing cycles on soil properties would be tested after specific cycles. No load is applied and no water is supplied during freezing and thawing process. The procedures of freezing and thawing used in this study are as follows. When all the specimens were ready, each specimen was sealed in a plastic membrane and then put into a copper mold to prevent moisture evaporation during freezing and thawing process. After that, the sealed specimens were placed into the chamber of a programmable environmental freezing and thawing device, which can automatically control the temperatures of the closed chamber. The specimens were all-around freezing and thawing in a closed system without water supply during all the cycles. It was verified that the specimens can completely freeze in 4 hours at the temperature of -20°C, and completely thaw in 4 hours at 20°C. Therefore, a freezing and thawing cycle lasted for 8 hours, the first 4 hours at -20°C for freezing and the later 4 hours at 20°C for thawing. The specimens were divided into 8 groups, of which 7 groups were respectively applied with 1, 3, 5, 7, 10, 15, 20 times of freezing and thawing cycles, and the other one group was considered as a reference group to provide the initial properties of the specimens and does not undergo freezing and thawing cycles (the cycle number is 0). After specified times of freezing and thawing cycles, each group was taken out from the freezing and thawing device. And then the copper mold, plastic membrane and the water on the membrane (lost from the specimen during freezing and thawing cycles) were carefully removed. The dimensions and weight of each specimen were measured before and after freezing and thawing cycles to calculate the changes of volume and moisture content after the cycles, for the weight reduction was totally due to water loss.
2.3. UC and ULUC tests

UC and ULUC tests were run on a GDS advanced digital controller, which controls the test process and records the test data programmatically by a computer. Both the two kinds of tests were conducted with a loading rate of 1% axial strain per minute (0.8mm/min). Different from dynamic cyclic loading, ULUC test is static loading mode and can be used to investigate changes of resilient modulus and energy dissipation according to the unloading-reloading hysteresis loops. The specific procedures of ULUC test were as follows: Firstly, pack the specimen with a rubber membrane and dock the specimen on the base in the pressure chamber. After that, the axial load was applied to the specimen to increase the axial strain to 2%, and then unload at the rate of -0.8mm/min to the initial value (an insignificant docking stress). Cyclically, a following reloading began to make the axial strain 3% and then unload again. The loading-unloading cycles repeated until the peak point appeared. The specimens used in this study generally have the peak points at the strains of 4~8%, and thus usually have at least 4~8 loading-unloading cycles.

3. Results and discussion

3.1. Change ratio of volume and moisture content

A dimensionless variable was defined to analyze the change rates of volume and moisture content, given by

$$\varepsilon_i = \frac{x_i - x_0}{x_0} \times 100\%$$

where $\varepsilon_i$ is the change ratio, $x_0$ is the average heights or moisture contents of specimens without freezing and thawing, $x_i$ is the average heights or moisture contents of specimens undergone $i$ times of freezing and thawing cycles, and $i=1, 3, 5, 7, 10, 15$ and 20.

Figure 1 shows the change ratios of volume and moisture content with freezing and thawing cycles. It can be seen that volume increases mostly during the first 3 cycles, then increases slightly with further increase of freezing and thawing cycles, and levels off after 7~10 cycles. Whereas, moisture content decreases gradually with increasing cycles and levels off after 15 cycles.

Aubert and Gasc-Barbier (2012) studied behavior of clayey soil blocks subjected to freezing and thawing cycles. They indicated that freezing and thawing cycles lead a desiccation and thus a hardening of clayey soil blocks. Their test results showed that freezing and thawing cycles lead a marked increase in the uniaxial compressive strength and the initial tangent modulus. In this study, specimens' desiccation during freezing and thawing cycles is obviously observed. However, a "softening" phenomenon, rather than the hardening, is verified by the following UC tests and ULUC tests.
Figure 1. Change ratio of volume and moisture content with freezing and thawing cycles.

3.2. Stress-strain curves
The comparison of ULUC and UC stress-strain curves of the reference group (the group without freezing and thawing cycles) is shown in figure 2. It can be seen from figure 2 that it is not exactly but closely coincident between the UC test curve and the ULUC envelope curve. The peak strength, failure strain and initial tangent modulus on the two curves of the parallel specimens (specimens undergoing the same freezing and thawing cycles) are roughly the same and thus the differences between the two curves are neglected in this study. UC stress-strain curves under various freezing and thawing cycles are shown in figure 3. It is found that those curves all exhibit a property of strain softening, with an obvious peak point.

Figure 2. ULUC and UC stress-strain curves of specimens without freezing and thawing
cycles.

**Figure 3.** UC stress-strain curves of specimens under different freezing and thawing cycles.

### 3.3. Compressive strength and failure strain

Figure 4 presents the results of the peak strength and the corresponding failure strain from the UC curves of specimens under different freezing and thawing cycles. The results show that freezing and thawing cycles lead a decrease both in compressive strength and failure strain, but in two different ways. Strength and failure strain both decline sharply in the first 3 cycles. Strength decreases to the minimum value (less than 50% of the initial strength) after 3 cycles, then recovers to 70% of the initial strength at 5 to 10 cycles, at last decreases to 55% of the initial strength and tends to be stable after 15 cycles. Comparatively, after a sharp decrease in the first 3 cycles, failure strain does not recover with the further increase of freezing and thawing cycles like strength, but continues to decrease at a slower rate and gets to stabilization at 15 to 20 cycles.
3.4. Modulus

The resilient modulus can be obtained from ULUC test curves by connecting the upper endpoints and the lower endpoints of the hysteresis loops by a straight line, and the slope of the line is resilient modulus (see in figure 2). The values of resilient modulus ($M_R$) at different unloading strains under various freezing and thawing cycles are shown in Table 2. The change of average $M_R$ with freezing and thawing cycles is shown in figure 5. It is indicated that average $M_R$ is significantly affected by freezing and thawing cycles with a reduction of about 30% after the first cycle, and then appears impervious to a further increase of cycles. On the other hand, for a specific specimen, the $M_R$ changes irregularly and insignificantly with the increase of strains. In addition, figure 6 shows the initial tangent modulus (MIT) under various freezing and thawing cycles. Unlike $M_R$, MIT decreases gradually with freezing and thawing cycles and tends to be stable after 7 cycles.

Table 2. $M_R$ under different freezing and thawing cycles.

| Freezing and thawing cycles | $M_R$ at different strains /MPa | 2%  | 3%  | 4%  | 5%  | 6%  | 7%  | 8%  | average |
|-----------------------------|---------------------------------|-----|-----|-----|-----|-----|-----|-----|---------|
| 0                           |                                 | 60.6| 62.3| 56.0| 59.4| 57.8| 53.5| 56.6| 58.0    |
| 1                           |                                 | 42.4| 41.5| 47.1| 45.1| 48.6| 45.8| 49.0| 45.6    |
| 3                           |                                 | 43.5| 41.2| 41.8| 46.7| 44.6| 43.1| 46.7| 43.9    |
| 5                           |                                 | 44.0| 45.4| 47.2| 45.1| 44.4| 45.0| 44.1| 45.0    |
Lee et al. (1995) advised to take the stress at 1.0% strain of the UC test (Su1.0%) as an indicator of the resilient modulus. They reported that for a soil with Su1.0% less than 55 kPa, the effect of freezing and thawing cycles on $M_R$ was negligible, while for a soil with Su1.0% larger than 103 kPa, the change of $M_R$ was more than 50%. The effect of freezing and thawing cycles on $M_R$ increases as Su1.0% increases. The specimens used in this study has an initial Su1.0% of about 300 kPa (see in figure 2), which is much more than the threshold value of 55 kPa, however, the change of resilient modulus is only about 30%. The reason for this unusual phenomenon is attributed to the different samples used. The specimens used in Lee's study were high-quality natural soils while the specimens used in this study were laboratory compacted soils. The reconstituted specimens used in this study, although they were compacted from a typical strong structural soil and were over-consolidated during sampling, are not as sensitive as the natural ones when confronted with freezing and thawing disturbances. Therefore, Lee's threshold value of 55 kPa for field samples is not suitable for the reconstituted over-consolidated specimens. Considering that the $M_R$ of specimens used in this study keeps nearly unchanged with the increase of freezing and thawing cycles except an obvious reduction after the first cycle, and that the Su1.0% values of specimens under all freezing and thawing cycles are less than 225 kPa (see in figure 3), a conclusion can be drawn that the threshold value of Su1.0% for the over-consolidated reconstituted specimens is about 225 kPa or a little higher, but lower than 300 kPa.

|    | 44.7 | 43.4 | 43.5 | 44.3 | 44.2 | 43.9 | 44.0 |
|----|------|------|------|------|------|------|------|
| 10 | 42.5 | 42.0 | 42.8 | 42.7 | 42.4 | 40.7 | 42.2 |
| 15 | 47.7 | 44.9 | 46.2 | 43.7 | 45.6 |      |      |
| 20 | 44.3 | 43.1 | 46.0 | 44.3 | 43.3 |      | 44.2 |

Figure 5. Average $M_R$ under various freezing and thawing cycles.
Figure 6. Initial tangent modulus with freezing and thawing cycles.

3.5. Energy dissipation
The existence of hysteresis loops of ULUC tests indicates the occurrence of energy dissipation during the compression and deformation process. The evolutions of microstructures cause the energy dissipation phenomenon of the specimens under compression. Therefore, energy dissipation is considered as an important factor to reflect the changes of internal structures. The value of energy dissipation ($E_d$) is calculated by the formula of $E_d=\int \sigma \cdot d\varepsilon$, and is equal to the area of the closed hysteresis loop with a dimension of J/m$^3$ in this study. Table 3 gives $E_d$ at different unloading strains and the average values under various freezing and thawing cycles. It is found that the specimens without freezing and thawing cycles have the highest average $E_d$, and the ones under 3 cycles have the lowest. That means during the loading-unloading compression process, the structural damages of the specimens without freezing and thawing cycles are much higher than that of specimens under other various cycles. The reason is that freezing and thawing cycles have already destroyed part of the initial structures before the compression is applied to the specimens. That is to say, part of the damages has already happened during the freezing and thawing cycles, and the value of $E_d$ from loading-unloading process reflects the rest damage potential after freezing and thawing cycles. The specimens without freezing and thawing cycles do not undergo the damages caused by the cycles, and thus exhibit the highest damage potentials and consequent highest $E_d$ under loading-unloading process. Similarly, specimens under 3 cycles have the lowest $E_d$, and this indicates that 3 cycles of freezing and thawing would cause the most damages and that a further increase of freezing and thawing cycles would inversely induce a slight re-structuring effect on the specimens. This is consistent with the change trend of compression strength, which has the highest initial value, then decreases to the lowest at 3 freezing and thawing cycles and recovers a little with further increasing cycles. The fact that the change trend of average $E_d$ with freezing and thawing cycles is generally similar to that of the compression strength further verifies that energy dissipation
can better explain the structural damages induced by freezing and thawing cycles. A higher $E_d$ corresponds to a higher damage potential, accordingly means a lower damage extent caused by freezing and thawing cycles, and consequently a higher strength.

Table 3. Energy dissipation of specimens under various freezing and thawing cycles at different strains.

| Feezing and thawing cycles | energy dissipation at different strains / J/m$^3$ |
|---------------------------|-----------------------------------------------|
|                           | 2%         | 3%    | 4%    | 5%    | 6%    | 7%    | average |
| 0                         | 641        | 831   | 988   | 1072  | 1086  | 1202  | 1155    | 996    |
| 1                         | 248        | 277   | 342   | 393   | 399   | 409   | 379     | 349    |
| 3                         | 127        | 177   | 225   | 241   | 217   | 154   | 111     | 179    |
| 5                         | 161        | 295   | 380   | 452   | 512   | 533   | 321     | 379    |
| 7                         | 256        | 417   | 515   | 575   | 486   | 174   | 404     |        |
| 10                        | 135        | 242   | 342   | 378   | 352   | 226   | 279     |        |
| 15                        | 274        | 394   | 398   | 420   |       |       | 372     |        |
| 20                        | 171        | 302   | 366   | 414   | 398   |       | 330     |        |

Moreover, for a specimen under a specific freezing and thawing cycles, it is found that the change of energy dissipation with axial strains during unloading-reloading process firstly increases to a maximum value and then decreases. figure 7 shows that parabolic curves can fit the data well under various freezing and thawing cycles. Thus a quadratic polynomial is used to describe the evolution laws of energy dissipation with axial strains, given by

$$E_d = a \varepsilon_a^2 + b \varepsilon_a + c$$

where $\varepsilon_a$ is the unloading axial strain, $E_d$ is the corresponding energy dissipation, $a$, $b$ and $c$ are fitting coefficients. The numerical values of $a$, $b$ and $c$ under different freezing and thawing cycles are listed in Table 4.

What cannot be ignored is that the vertex of the fitting parabola always appears around the failure strain under various freezing and thawing cycles. An explanation for this phenomenon is that the highest energy dissipation indicates the maximum damages of soil structures. As a result, the specimen would begin to lose strength when the energy dissipation reaches to its climax, and maximum energy dissipation occurs just before the failure strain.

Table 4. The numerical values of $a$, $b$ and $c$ under different freezing and thawing cycles.

| Freezing and thawing cycles | $a$      | $b$   | $c$   |
|-----------------------------|----------|-------|-------|
| 0                           | -18.245  | 230.93| 437.61|
| 1                           | -7.9012  | 88.681| 152.79|
| 3                           | -13.074  | 100.97| 36.413|
| 5                           | -24.708  | 236.55| -72.72|
| Step | Energy Dissipation (J/m²) |
|------|--------------------------|
| 7    | -55.568                  |
| 10   | -29.881                  |
| 15   | -24.586                  |
| 20   | -22.272                  |

![Energy Dissipation Curves](image)

**Figure 7.** Fitting curves of energy dissipation under various freezing and thawing cycles.

### 4. Conclusions

The effect of freezing and thawing cycles on the behaviors of over-consolidated reconstituted structural loess is studied in this paper. Several conclusions are drawn as follows:
a) Under the experimental conditions used, freezing and thawing cycles lead a slight expansion in volume, and an obvious desiccation of the specimens.
b) The stress-strain curves of UC and ULUC tests are closely coincident, and they all exhibit a property of strain softening with obvious peak points, although the peak points appear at different axial strains and the peak values are different under various freezing and thawing cycles.
c) The failure strain and initial tangent modulus decrease gradually with freezing and thawing cycles, while the average resilient modulus decreases significantly after the first cycle, and then appears impervious to a further increase of cycles. And based on that fact, the threshold value of Su1.0% for the over-consolidated reconstituted structural loess is suggested as about 225 kPa or a little higher.
d) The UC strength decreases most intensely after first 3 cycles and then recovers a little during the 5–10th cycles, which indicates a slight re-structuring effect during the cycles. The change trend of strength with freezing and thawing cycles is similar to that of the average energy dissipation, which further verifies the structural damages induced by freezing and thawing cycles.
e) The evolution laws of energy dissipation with axial strain can be described by parabolic curves, and the vertex of the fitting parabola usually appears around the failure strain under various freezing and thawing cycles.

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