Experimental Study on the Effect of freeze-thaw cycle on Silty Clay Stress–Strain Behaviour

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Abstract. The area of seasonally frozen soil in China accounts for about 54% of the national territorial area. The property of seasonally frozen soil has a great influence on highway, railway and architectural foundation. The effect of freeze-thaw cycle for saturated silty clay in Northeast Area on stress-strain behaviour was investigated by triaxial test in this paper, where three different freezing temperature and five different freeze-thaw cycle times were considered. The results showed that silty clay exhibited strain softening characteristics for small number of freeze-thaw cycles, while strain hardening characteristics will appear with the increase in freeze-thaw cycles. The deviatoric stress-axial strain relationship shows the transitional form from strain softening to strain hardening. It will be helpful to understand the strain behaviour of soil under freeze-thaw cycle.

1. Introduction
The area of seasonally frozen soil in our country is about 5,137,000m$^2$, accounting for about 54% of the national territorial area [1]. After the seasonally frozen soil experience several times of frost heaving in winter and thawing in spring, the thermodynamic transformation of temperature may cause migration of water content [2]. The physical and mechanical property may also change, the corresponding parameters will change obviously [3, 4] along with the cycle number of freezing and thawing so as to affect the engineering characteristic of seasonally frozen area [5]. With the rapid development of China’s economy and the implementation of the old industrial base in Northeast China, the development of highway, railway, water conservancy and hydropower in large scale determines the physical and mechanical property of soil in seasonally frozen area under various environmental and human factors, which is extremely necessary and valuable to guarantee the stability and safety of the project [6].

Xiaojie Ma [7] studied the elastic behaviour of sandy soil and silty soil under the triaxial strain. The result indicated that the maximum compactness corresponded to maximum resilient modulus, while it was false for silty clay. Xuesong Mao [8] studied the resilient modulus under different water contents and cycle number of freezing and thawing. The results indicated that for the sample under optimum water content, the change in modulus of resilience was greatest when the water content changed for the first time, but he didn’t consider saturated sample.

Stress-strain curve of soil changes after freeze-thaw cycle and the change mode is greatly related with the soil quality and test type; The shearing strength of soil also appears different change trends to the freeze-thaw cycle. In the freeze-thaw cycle test of soil, the previous research only concerns about the influence of freeze-thaw cycle on the shear performance under optimum water content or nearby the optimum water content, while the mechanical property of saturated soil was not to paid enough
attention; another research only focuses on the number of freeze-thaw cycle, but ignores the influence of freezing temperature on the mechanical property of soil. Therefore, the influence of saturated soil on the soil stress-strain behaviour under different freezing temperatures and freezing times is still an outstanding problem.

2. Sample preparation and test method

2.1 Basic nature of soil sample
The soil sample in the test was taken from the foundation soil (the burial depth is 20m and below the underground water level) of library under construction in new campus of Northeast Electric Power University, Jilin. Due to the fact that the original soil contains non uniform sand particles, which easily causes the difference in the sample. Therefore, the test adopted remoulded sample for research. Drying of undisturbed soil and crushes the original soil and then sieving it with 2mm screen. Then a series of physical tests and compaction test were carried out. The related parameters are shown in Table 1.

| Parameter of soil            | Value | Parameter of soil            | Value   |
|------------------------------|-------|------------------------------|---------|
| Specific gravity of soil, $G_s$ | 2.72  | Plastic limit, $w_p$         | 25.27%  |
| Uniformity coefficient, $C_u$ | 58.75 | Plasticity index             | 11.31   |
| Bending coefficient, $C_c$   | 0.18  | Optimum moisture content, $w_{op}$ | 21%    |
| Liquid limit, $w_l$          | 36.58%| Maximum dry density, $\rho_{d,max}$ | 1.74 kg/m$^3$ |

2.2 Specimen preparation
Vacuum suction method [9, 10] was used to prepare saturated samples. The specific procedures are as below: (1) Lay two layers’ plastic film in the trough and then lay 3–5mm round gravel cushion and put 10mm thick geotechnical cloth on it; (2) After drying the excavated original silty clay, crush it and screen it so as to get rid of big gravel; Add distilled water and stir into mud and then pour it onto the geotechnical cloth; (3) Sealing the plastic film totally, turn on the vacuum pump, the water and gas in the soil samples were pumped into the pressure storage tank and make the soil consolidation for saturated soil sample.

2.3 Test method
The prepared remoulded saturated soil sample was cut off in cylinder with diameter of 39.1 mm and height of 80 mm for triaxial test. Then these cylindrical soil samples were put in the constant-temperature and humidity freeze-thaw test tank for 0-9 times freeze-thaw cycle. In order to avoid moisture loss of the soil samples or deformation during the process of freezing and thawing, the metal plates with 39.1mm diameter were added on the top and at the bottom of the samples and then the rubber membrane were wrapped on the sample, as shown in Figure 1.

Based on the annual temperature curve data in Jilin, the average lowest temperature is found in January, and the average temperature is -17.8°C. Therefore, we control the freezing temperature of sample within such range and select the freezing temperature of -3°C, -7°C and -12°C. The thawing temperature of the sample is set as 20°C, and the freezing and thawing process experiences 12h. Meanwhile, in order to consider the influence of freeze-thaw cycle number on the mechanical property
of soil, the samples were subjected to 0, 1, 3, 5, 7, and 9 freeze-thaw cycles respectively before the conventional triaxial test. To consider the interaction of confining pressure, cycle number of freezing and thawing and freezing temperature, 61 samples were prepared and tested, shown in Table 2.

**Table 2. Experimental program of triaxial test**

| Freezing temperature, \( t^\circC \) | Group No. | Cycle number, \( n \) | Confining pressure, \( \sigma_f/kPa \) |
|--------------------------------------|-----------|------------------------|--------------------------------------|
| 20                                   | A1        | 0                      |                                      |
|                                      | B1-B4     | 1                      |                                      |
|                                      | C1-C4     | 3                      |                                      |
| -3                                   | D1-D4     | 5                      |                                      |
|                                      | E1-E4     | 7                      |                                      |
|                                      | F1-F4     | 9                      |                                      |
| -7                                   | G1-G4     | 1                      | 100, 200, 300, 400                   |
|                                      | H1-H4     | 3                      |                                      |
|                                      | I1-I4     | 5                      |                                      |
|                                      | J1-J4     | 7                      |                                      |
|                                      | K1-K4     | 9                      |                                      |
| -12                                  | L1-L4     | 1                      |                                      |
|                                      | M1-M4     | 3                      |                                      |
|                                      | N1-N4     | 5                      |                                      |
|                                      | O1-O4     | 7                      |                                      |
|                                      | P1-P4     | 9                      |                                      |

3. Test result
Non consolidation and non-drainage (UU test) triaxial tests were carried out by TSZ-2 triaxial apparatus. Deviatoric stress-axial strain curves for different temperatures (-3, -7 and -12°C) under confining pressure of 100kPa are shown in Figure 2.

![Figure 2. Deviatoric stress-axial strain curves under different freeze-thaw cycles at \( \sigma_f=100kPa \)](image)

It can be seen that the silty clay has a certain softening characteristic after freeze-thaw cycles \( 1 \sim 5 \) times. However, the homogeneous soil presents a hardening curve form after 7 to 9 freeze-thaw cycles as Figure 3. It shows soils with more number of freeze-thaw cycles are more likely to behave strain hardening phenomenon.

Figure 3 shows the effects of different confining pressures and temperatures on the stress-strain curves at 9 times freeze-thaw cycles. The stress curves behave strain hardening when the confining pressures are 100, 200, 300 and 400kPa, respectively. But obviously when the confining pressure 300kPa and 400kPa, the \( (\sigma_f-\sigma_f) \sim \varepsilon \) curve is steeper and larger than the confining pressure at
100kPa and 200kPa. It can be found that the \((\sigma_i - \sigma_j) - \varepsilon\) curve hardening degree of high confining pressure is more obvious than the low confining pressure, the strain hardening phenomenon is more prominent.

Figure 3. Deviatoric stress-axial strain curves under different confining pressure at \(n=9\)

Figure 4 shows the deviatoric stress and strain curves for various freezing temperatures under confining pressure of 400kPa and different cycle times. Combine all curves to know that when the freeze-thaw cycle reaches 5 times, it appears strain hardening characteristic and the freezing temperature is \(-12^\circ C\). The process of soil freezing is from external to internal. There is a certain time gradient, which doesn’t conduct at the same time. The temperature is low when the initial freezing temperature is \(-12^\circ C\) and the time for soil precooling and congealing to ice is less than it at the initial temperature of \(-3^\circ C\) and \(-7^\circ C\). Moreover, after freeze-thaw cycle for many times, the strain hardening process is accelerated.

Figure 4. Deviatoric stress-axial strain curves under different freezing temperature at \(\sigma_i=400kPa\)

According to the \((\sigma_i - \sigma_j) - \varepsilon\) curve of the soil after freeze-thaw cycle, it can be known that under different confining pressures and at different freezing temperatures, when the number of freeze-thaw cycle is 1-3 times, 23 of 24 \((\sigma_i - \sigma_j) - \varepsilon\) curves appear strain softening and the occurrence rate of strain softening is 96%. When the number of freeze-thaw cycle is 5 times, strain softening happens 8 times among 12 \((\sigma_i - \sigma_j) - \varepsilon\) curves and the strain hardening occurs 4 times; and all of them happen at the freezing temperature \(-12^\circ C\). When the number of freeze-thaw cycle is 7-9 times, all the 24 curves appear strain hardening and the occurrence rate of strain hardening is 100%.

4. Conclusion

Through triaxial compression test of saturated clay and analysing and processing the test data, the paper summarizes the mechanical property of silty clay on different initial conditions as below:

1. When the number of freeze-thaw cycle is low, the silty clay exhibits strain softening property. After experiencing freeze-thaw cycle for 5 times, the curve turns into strain hardening gradually. When the number of freeze-thaw cycles increases, all of them show strain hardening characteristics.

2. The \((\sigma_i - \sigma_j) - \varepsilon\) curve hardening degree of high confining pressure is more obvious than the low confining pressure, the strain hardening phenomenon is more prominent.
(3) The deviatoric stress axial strain relationship is characterized by the transition from strain softening to strain hardening at three different freezing temperatures. Moreover, after 7 cycles of freeze-thaw strain hardening is most obvious.

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