Acta Technica *62* (2017), No. 5B, 539–550

Effect of freeze-thaw action on mechanical properties of unsaturated clay

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Abstract. To investigate the variation in the mechanical properties of the canal soil in the Xinren irrigation district of Harbin after freeze-thaw, experiments were conducted on Harbin silty clay. The temperature range and time in the freeze-thaw process were defined by the similarity ratio of the modified coefficient α and freezing index C_I. Samples with different dry densities and water contents were prepared for different kinds of freeze-thaw cycles. The samples were measured on a low-temperature permafrost triaxial apparatus under different confining pressures using the unconsolidated-undrained (UU) triaxial test, and partial stress-strain curves were used to obtain the elastic modulus. The results show that :(1) with the increase in the number of freeze-thaw cycles, the cohesion decreased and the internal friction angle increased slightly, but the change in the internal friction angle was not obvious and fluctuated up to 4 °. (2) The decrease in the elastic modulus after 1 freeze-thaw was the most obvious change. The elastic modulus began to increase after the 5th freeze-thaw cycle, and then decreased at a slower rate after the 9th cycle. (3) Under the same number of freeze-thaw cycles, the cohesion, internal friction angle and elastic modulus were affected by the initial dry density and water content conditions. When the water content was constant, the dry density and cohesive force increased. When the modulus of elasticity decreased, the dryness and water content increased, and the cohesion value and internal friction angle decreased. The opposite trends were observed when the elastic modulus increased. (4) The modulus of elasticity was related to the confining pressure and increased with the increasing confining pressure.

Key words. Freeze-thaw cycle, Unsaturated soil, Cohesive force, Internal friction angle,Elastic modulus.

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[1] Acknowledgement - This work was supported by the National Natural Science Foundation of China(51541901), the Application Technology Research and Development Plan in Heilongjiang Province(GZ16B009,GZ16B020) and the National Natural Science Foundation of Heilongjiang Province(E201405).

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1. Introduction

Under natural conditions in cold regions, freeze-thaw cycling of the surface rock and soil will occur more than 100 times a year [1-3]. Freeze-thaw action is essentially a strong weathering process, which changes the original internal structure of the soil. Freeze-thaw also causes the expansion and contraction of the base soil volume of a canal in cold regions, and finally leads to the cracking and collapse of the water transmission channel, which seriously affects the water conveyance efficiency and utilization ratio of the channel [4,5]. Therefore, studying the mechanical properties of soil under freeze-thaw is very important to the engineering safety and stability of cold regions [6].

Frozen soils are a four-phase system and are mostly in an unsaturated state. The freeze-thaw effect changes the size and strength of the soil within the loess in the earth, which is the main cause of loess engineering degradation [7, 8]. The freeze-thaw cycle process is essentially the transformation process of soil from an unstable state to a stable state [9, 10]. At present, studies on the shear strength of soil have mainly focused on the cohesion and internal friction angle of two basic indexes. The effect of freeze-thaw on cohesion is significantly greater than that of the internal friction angle [10,12]. Results from the different experimental materials used in previous studies suggest that after the initial freeze-thaw, the cohesive force clearly decreased and after 9-12 freeze-thaw cycles the cohesive force value became basically stable. The internal friction angle was reduced to a minimum after 7 freeze-thaw cycles [13]. Freeze-thaw experiments on the silt of the Qinghai-Tibet Plateau are consistent with the above conclusions [14]. In addition, in earlier studies, the cohesion of the northeastern silty clay decreased after freeze-thaw, and the internal friction angle was positively correlated with the water content of the sample [15, 16]. After experimental freeze-thaw cycles of clay, the cohesion decreased, and the internal friction angle did not clearly stabilize [17].

As the main parameter used to characterize the stiffness of soil, the modulus of elasticity is closely related to the deformation of soil. The measurement of the elastic modulus of soil is usually based on a triaxial test, in which the elastic modulus is obtained from the stress-strain relationship [18]. Previous results have shown that the elastic modulus increases with the increase in the dry density for samples with constant initial moisture content. Under the same freeze-thaw conditions, the elastic modulus of the soil increases with the confining pressure. However, under the same confining pressure, the dynamic modulus of elasticity clearly decreases with the increase in the number of freeze-thaw cycles, and the effect of the freezing temperatures on the dynamic elastic modulus is small [19]. The elastic modulus essentially reflects the bonding strength of a material. Many factors affect the bonding strength, such as the bonding mode, crystal structure, chemical composition, microstructure, and temperature. Therefore, the change in the elastic modulus before and after freeze-thaw is related to the size of the soil particles; the larger the particles are, the smaller the change in the elastic modulus is. These studies are often unable to meet the demand of the engineering construction projects in each region and have not been conducted for the vast expanses of permafrost and seasonal permafrost that are distributed in the northeast of China. Relevant studies of the loess in the northeast region have not been conducted. Therefore, this study on repeated freeze-thaw soil strength will provide a reference for enhancing the relevant theory and engineering practices.

2. The basic physical properties of soil

For this study, undisturbed soil was collected from the Xinren irrigation district of Harbin, and the depth of the excavation was 1.5-2 m. According to the Standard for soil test method , the soil samples are classified as low-liquid-limit clay, and the parameters are shown in the below.

Table 1.Physical parameters of soil indicators

Particle analysis	0.25-0.075	%	0.7
	0.005-0.075	%	66.7
	<0.005	%	32.6
proportion			2.69
Liquid limit		%	44.9
Plastic limit		%	23.0
Plasticity index			21.9
Maximum dry density		g/cm^3	1.69
Optimum moisture content		%	18.1

3. Test apparatus and test method

3.1. Research description

Under increasing freeze-thaw cycles, the main tests of this study are as follows: (1) the effects of different water content and different dry density values on the soil cohesion (c), (2) the effects of different moisture content and different dry density values on the internal friction angle (ψ) of the soil, (3) the effects of different moisture content and different dry density values on the elastic modulus (E) of the soil, and (4) the effects of different confining pressures on the elastic modulus (E) of the soil.

3.2. Test instruments

The freeze-thaw cycles were conducted in a low-temperature environment simulation test chamber. A low-temperature environment simulation test chamber of 5 m×4 m×5 m (length × width × height) was used to simulate the mechanism of unidirectional freezing and bidirectional melting in seasonal frozen soil. An XSL-D180LMV0 patrol instrument was used to collect the temperature data automatically and the instrument was made in Tianjin Jianuode limited company; the precision of the temperature collection and sensor was ± 0.1. The shear tests of the soil samples were carried out using a low-temperature permafrost triaxial apparatus.

3.3. Test methods

The soil samples were crushed and passed through a 2mm sieve, and the initial moisture content was measured. Different water contents were prepared by water mixing. The water content was added to the airtight testing container and left for 24 h so that the water content was evenly distributed. The sample size was 10 cm × 20 cm (diameter × height), and a total of 162 samples were prepared. According to the Irrigation Canal Lining Engineering Technical Specification , the size of the compact design in the large-scale channel was 0.95, and the water content of the sample was set according to the optimal moisture content of 5% to determine the dry density of the sample. The water content was 18%, 20% and 22% and the dry density was 1.55 g/cm^3, 1.60 g/cm^3 and 1.65 g/cm^3. The number of freeze-thaw cycles tested was 0, 1, 3, 5, 7, 9, was 11 cycles at seven levels. The sample was wrapped with a piece of plastic film, and a 1-mm thick iron sheet was tightened around the sample with a cloth strip after the sample was prepared to prevent changes in surface moisture content and lateral deformation in the soil sample during the freeze-thaw cycles. The samples were placed in batches into the reserved insulation holes in the low-temperature environment simulation test chamber. The temperature simulations were referenced to the ground-based meteorological observation standards. From the top of the test chamber to the surface of the sample, 1.5 m, the temperature sensor accuracy was ± 0.1 centigrade, which was representative of the ambient temperature change . After the samples were subjected to different freeze-thaw cycles, the samples were taken out, and the triaxial shear tests were conducted with an experimental shear rate of 1.5 mm / min and confining pressures of either 50 kPa, 100 kPa or 200 kPa. When a peak in the results was observed, 15 % of the maximum strain was taken as the damage point. When a peak was not observed, 15 % of the maximum strain was used as the estimated point of destruction.

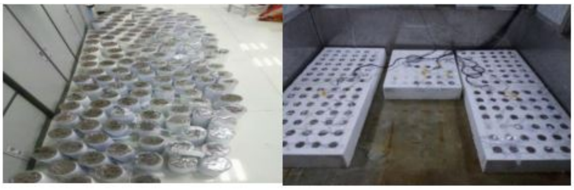

Fig. 1. Part of the samples and test arrangement

3.4. Temperature control mode

According to the field observations and analysis of the meteorological data from the Harbin Wanjia Experimental Station (Fig. 2), the 2010-2012 three-year average of the depth of frozen soil was 1.8 m, and the sample height was 0.2 m; therefore, the sample size to the actual freezing depth was 1:9, and the experimental to measured temperature was 1:1. According to the similarity analysis, the experimental time scale was determined to be 1:81 of the natural time scale, since the average freezing index of three years was1773.25 centigrade•d. The measured three-year daily average temperature trend was simplified for the simulations, and the freeze-thaw cycle was simplified into 4 stage.

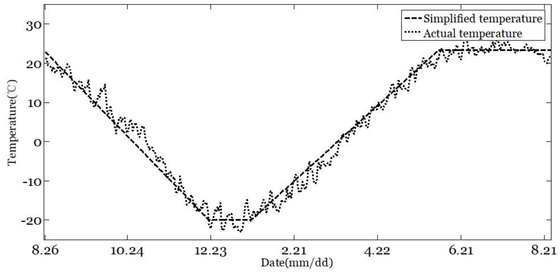

Fig. 2. The 2010-2012 three-year average of temperature

To improve the accuracy of the simplified temperature control strategy and the actual operation of the low-temperature laboratory, a laboratory correction coefficient (K) and freezing index similarity (C_I) were proposed. This study used K and C_I to subdivide each stage. Since the moisture content and dry density were tested at three levels, the mean values of the three levels in the initial sample states (a moisture content of $\omega = 20$ % and dry density of $\rho_d = 1.60$ g/cm^3) were used to determine K and C_I. According to the laboratory ambient temperature, the experimental freeze-thaw cycle freezing index was 17.30 centigrade • d.

The relationship between the freezing depth and freezing index is as follows :

$$H = \alpha\sqrt{I_0} \tag{1}$$

where H is the standard freezing depth (cm) of the project location, I_0 is the average of the freezing index after many years (°C • d), and α is a multifactor function.

According to the relationship between each scale and the actual freezing index I, the corresponding α, K and C_I were obtained using (1), (2) and (3), respectively, where K is the laboratory correction factor, C_I is the freezing index similarity ratio, and α_p, I_p, and H_p represent the parameters corresponding to the simplified laboratory test.

$$K = \frac{\alpha_P}{\alpha} \tag{2}$$

$$C_I = \frac{I_P}{I} \tag{3}$$

The correlation expressions between the two equations are deduced as follows:

$$\frac{H_P}{H} = \frac{1}{C_L} = K\sqrt{\frac{I}{I_P}} \tag{4}$$

$$C_I = \frac{1}{C_L^2 K^2} \tag{5}$$

$$C_I = \frac{1}{K^2 C_T} \tag{6}$$

For the calculation of the freezing depth of the model, the actual meteorological data were used to determine the laboratory correction factor K value of 1.13. From equations (4) and (5), the freezing index was similar to the C_I value of 1:135. It can be deduced from equation (6) that the time period of each stage was adjusted by the size of the K value when the freezing coefficient was similar to that of the C_I value of 1:135.

Table 2 different temperature control mode table

Freeze-thaw stage	Practical date	Practical days(d)	After adjusted duration (h)
Cooling stage	8.26-12.22	119	27.58
Constant negative temperature stage	12.23-1.22	30	6.95
Temperature rising stage	1.23-6.5	135	31.25
Constant positive Temperature stage	6.6-8.25	81	18.75

Before the start of the test, in order to ensure a uniform internal temperature in the soil within the test chamber at 23.3 centigrade, the samples were held under constant temperature for 12 h before entering the cooling stage.

4. Test results and analysis

4.1. The influence of the number of freeze-thaw cycles, moisture content and dry density on the cohesion (c) of the soil

Soil cohesion can include van der Waals forces, Coulomb forces, cementing forces, and so on. Fig. 5 shows the different initial states of the cohesive force and the number of freeze-thaw cycles tested. With the increase in the number of freeze-thaw cycles, the soil cohesion and rate of cohesion gradually decreased. It was concluded that the main reason for the deterioration of the cohesive force is that the water in the pores froze into ice crystals during the freezing process, the volume of the sample expanded due to the frost heave, and the melting of the ice crystals during the thawing process shrank the volume of the soil. In the process, the height of the sample after each freeze-thaw cycle was always greater than the initial height, that is, the total frost heave of the soil sample was always larger than the shrinkage. After freeze-thaw, the cementing force between the particles decreased and adversely affected the stability of the original structure. Hence, the distance between the particles increased and reduced the Coulomb force, resulting in the decrease in the cohesion.

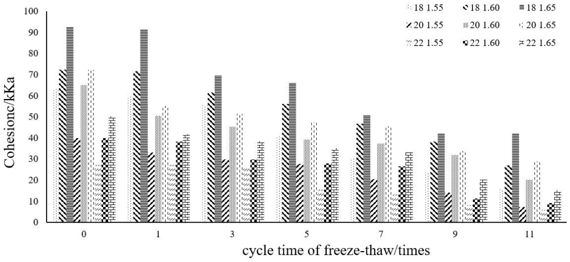

Fig. 3. Adhesion of water content and dry density to soil (c) impact curve

Note: In the legend, 18 indicates the moisture content (%) and 1.55 indicates the density (g/cm^3) in the table below.

With the increase in the number of freeze-thaw cycles, the following conclusions can be drawn from Fig. 5:

(1) Because of the increase in the water content in the soil, the arrangement and coupling effect of the soil particles were weakened. With greater water content, the water dissolved part of the cementation. Therefore, the soil strength was sensitive to water because the particle bonding decreased and the matric suction was reduced, allowing for easier deformation in the soil skeleton. Because the matric suction was part of the cohesive force of the unsaturated soil, the moisture content of the soil directly affected the magnitude of the cohesive force.

(2) Under certain water content conditions, the cohesive force increased with the increase in the dry density. This result occurred because with a greater dry density, the contact between the soil particles increased and caused greater effective friction, strengthening the soil skeleton and improving the stability of the soil, which increased the soil cohesion.

4.2. Effect of the number of freeze-thaw cycles, moisture content and dry density on the internal friction angle (ψ) of the soil

Fig. 6 shows that for samples with different initial states, the internal friction angle generally increased with the increase in the number of freeze-thaw cycles. The increase in the internal friction angle after 11 freeze-thaw cycles for different moisture contents and dry densities is shown in Table 3. However, the magnitude of the change was not significant, and the maximum increase in the internal friction angle was 3.26 °. After 5 freeze-thaw cycles, the change in the internal friction angle was not obvious. This shows that the effect of more freeze-thaw cycles on the internal friction angle of the soil was not significant. The internal friction angle reflects the friction characteristics of the soil, which mainly includes the friction between the soil particles and the degree of mutual embedding between the particles. The analysis shows that the freeze-thaw cycle changed the pore structure inside the soil and that the overall size of the particles decreased with the increasing number of free-thaw cycles so that the contact area between the particles and the number of particles increased[20,21]. After the freeze-thaw, the friction between the particles increased, which was reflected in the gradual increase of the internal friction angle under repeated freeze-thaw cycles.

Table 3 The internal friction angle increment table after11 times the freeze-thaw cycle

ω=18 %			ω=20 %			ω=22 %		
1.55	1.60	1.65	1.55	1.60	1.65	1.55	1.60	1.65
2.10	3.26	2.58	3.00	1.64	1.58	2.43	2.43	2.59

With the increase in the number of freeze-thaw cycles, the following conclusions can be drawn from Fig. 6:

(1) For samples with the same dry density, the higher the moisture content was, the smaller the internal friction angle was. This is because the water film thickened, reducing the friction of the soil particles so that external forces were more likely to produce relative movement between the particles, ultimately leading to a weaker degree of occlusion between the particles. The moisture content was substantially reduced by the sliding friction and occlusal friction between the soil particles, which in turn changed the friction angle in the soil sample.

(2) For samples with the same water content, as the dry density of the soil samples increased, the internal friction angle increased. The analysis suggested that as the dry density increased, the contact area between the particles increased, and the soil particle skeleton became more connected. This enhanced the ability of the soil particles to resist relative sliding under the external forces, and therefore, the internal friction angle increased.

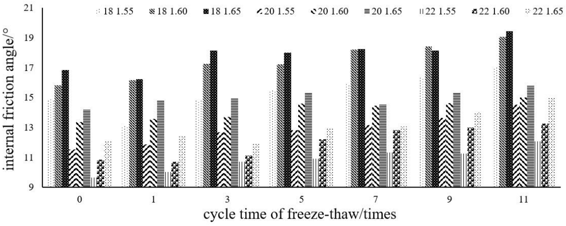

Fig. 4. Curve of water friction and dry density on soil internal friction angle

4.3. The Influence of the Number of Freeze - thaw Cycles on the Elastic Modulus (E) of Soil under the Confining Pressure

To accurately characterize the change in the modulus of elasticity, a dimensionless D_E is defined to represent the deterioration ratio.

$$D_E = \frac{D_i - D_{i+1}}{D_i} \tag{7}$$

where D_E is the elastic modulus deterioration ratio and i is the number of freeze-thaw cycles.

The results of the triaxial test were then processed. According to the confining pressure $\sigma 3$ and corresponding axial load $\sigma 1$, the partial stress (σ_1-σ_3) as determined, and the partial stress-strain curve was drawn. A straight line was used to fit the curve, and the corresponding slope is the elastic modulus.

Under the confining pressure of $\sigma_3 = 50$ kPa, the corresponding elastic moduli are shown in Fig. 7 for the different sample moisture contents, dry densities, and numbers of freeze-thaw cycles. From the figure, we can observe the following rules: regardless of the initial water content and dry density of the sample, under the freeze-thaw action the general trend of the soil elastic modulus first decreased, then increased, and then exhibited a certain volatility with more cycles. After the 1st free-thaw cycle, the reduction rate was most obvious for the sample with $\omega = 18$ % and $\rho_d = 1.55$ g /cm^3. As an example, the values of D_{Ei} were 54.07 %, 31.36 %, 21.56 %, 10.09 %, 3.96 %, and 2.5% (for I = 1, 3, 5, 7, 9, and 11, respectively). The increase in the elastic modulus was more extreme for the 5th cycle and 7th cycle, but the amplitude of attenuation was not the same for the 5th and 7th cycles.

For the same number of freeze-thaw cycles, the elastic modulus of the soil was affected by the moisture content and dry density. With equal water content in the samples, the elastic modulus increased with the increase in the dry density. The elastic modulus decreased with the increasing water content. The magnitude of the elastic modulus reflects the ability of the object to resist deformation. From a microscopic point of view, it reflects the atomic, ionic or molecular bonding strength. Therefore, the factors that affect the bond strength will indirectly change the size of the elastic modulus. The increase in the moisture content reduced the thickness of the weakly bound water film due to the van der Waals forces, and its breaking strength and fracture energy were less than those of the chemical bond strength between the original soil skeleton when the water content was low. Therefore, the moisture content essentially changed the bond strength between the particles and reduced the modulus of elasticity.

4.4. Influence of Different Confining Pressure on Soil Elastic Modulus (E)

Fig. 6, Fig. 7, and Fig. 8 show the elastic modulus results from tests with samples with $\rho_d = 1.55$ g /cm^3 under different confining pressures and moisture contents.

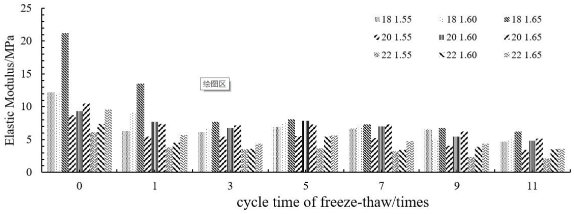

Fig. 5. Adhesion of water content and dry density to soil (c) impact curve

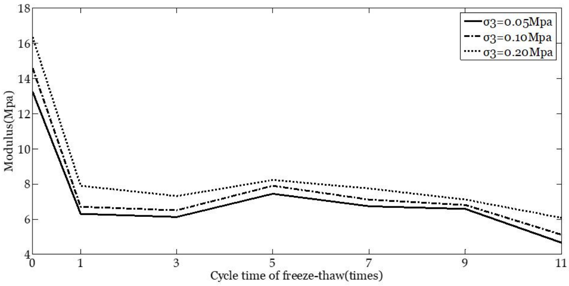

Fig. 6. ω=18 %, ρ_d=1.55 g/cm^3

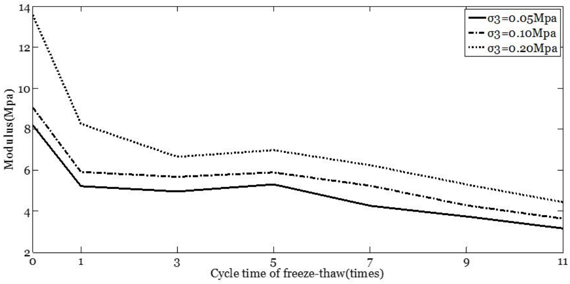

Fig. 7. $\omega = 20\%$, $\rho_d = 1.55$ g/cm^3

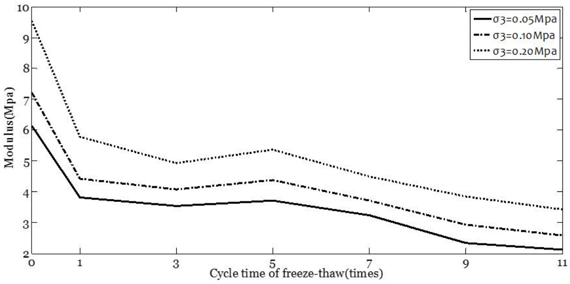

Fig. 8. ω=22 %, ρ_d =1.55 g/cm^3

It can be observed that the higher the confining pressure was, the greater the modulus of elasticity was for the samples with consistent water contents and dry densities. Because of the increase in the confining pressure, the lateral deformation of the soil was constrained so that the ability to resist deformation was stronger. Under the same dry density conditions, as the water content increased, the elastic modulus decreased. With water contents of $\omega = 18$ %, $\omega = 20$ % and $\omega = 22$ %, the D_E values of the corresponding D_{E1} were 51.75 %, 39.10 % and 39.44 %, respectively, and the maximum pressure was 0.2 kPa. Since only three water content levels were tested in this study, the relation between the size of the D_{E1} and the water content should be further validated.

5. Conclusion

Freeze-thaw cycles of unsaturated silty clay (0-11) were carried out using an indoor simulation test. The results show that the cohesion, internal friction angle and elastic modulus of each sample varied under different initial conditions. The influence of different initial states and cycles of freeze-thaw action was analyzed, and the following conclusions were drawn:

(1) After freeze-thaw, the unsaturated remolded silty clay cohesion decreased, and the internal friction angle increased. However, the increasing trend in the internal friction angle was not obvious, and the change was always less than 4 °.

(2) The elastic modulus increased with the first freeze-thaw cycle, and then, after a certain number of cycles, it had a decreasing trend. The elastic modulus magnitude decreased the most after the first freeze-thaw cycle, increased after the 5th freeze-thaw cycle, and then decreased after the 9th cycle.

(3) After the same number of freeze-thaw cycles, the cohesion, internal friction angle and soil elastic modulus were affected by the moisture content and dry density. When the water content was constant, the dry density and cohesion values were greater. The smaller the internal friction angle was, the larger the elastic modulus was. When the dry density was constant, the higher the water content was and the lower the cohesion value was. The smaller the internal friction angle was, the smaller the elastic modulus was.

(4) Under the same number of freeze-thaw cycles, the cohesion, internal friction angle and soil elastic modulus were affected by the water content and dry density. When the moisture content is certain, the larger the dry density was, the higher the cohesive force value was; the smaller the inner friction angle was, the greater the elastic modulus was; the higher the moisture content was, the lower the cohesive force value was; and the smaller the inner friction angle was, the smaller the elastic modulus was.

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Received November 16, 2017