Study of shear strength of silty clay under freeze-thaw cycle

Yan Lv, Haoxu Wang* and Chengke Gu
Construction Engineering College, Jilin University, Changchun, Jilin, 130026, China
*1060865617@qq.com

Abstract. Silty clay is a common subgrade soil with a wide distribution in northeast China. The construction in the seasonal frozen area of silty clay in northeast China has become the norm. In the engineering construction, the shear strength characteristics of silty clay under different water content, different freezing temperatures and different cycle times of freeze-thaw should be considered. Based on the study of remolded silty clay, cohesion and internal friction angle are used as the shear strength indexes, and the influence of water content, freezing temperature and cycle time of freeze-thaw on the shear strength is analyzed by combining with the Gray Theory. The results show that the grey correlation degree of water content, freezing temperature and cycle time of freeze-thaw to cohesion is 0.97, 0.47 and 0.47, and to internal friction angle is 0.95, 0.45, 0.47, the water content towards cohesion and internal friction angle are linear negative correlation, freezing temperature has a best valuable impact on the shear strength, cycle time of freeze-thaw towards cohesion is linear positive correlation, and has little relationship with the internal friction angle.

1. Introduction
Northeast China has a temperate continental monsoon climate. The silty clay layer is mainly distributed in northeast China. It is a kind of fine grained soil with strong water absorption and water permeability, and it is sensitive to frost heave. Silty clay's mineral composition is mainly quartz, feldspar, montmorillonite and illite. In the case of low water content, silty clay not belong to the weak strata, is an ideal subgrade soil.

Other countries had earlier studied the mechanical properties of remolded soil under freeze-thaw cycle. Viklander, P conducted triaxial drainage shearing on remolded silt samples with different cycle times of freeze-thaw. It was concluded that the cohesion of remolded silt increases compared with that of non-freeze-thaw group after freeze-thaw cycle[1]. Janoo, v., Shoop, S. grouped undisturbed fine grained soil and remoulded them into saturated remolded soil samples of different degrees, and measured the effects of water content and confining pressure on the mechanical properties of fine grained remolded soil by applying different confining pressures on them[2].

In recent years, China has introduced new research on remolded silty clay. Jia Wang compared the remolded silty clay with the undisturbed soil and concluded that the strength of the remolded sample was lower than the undisturbed soil mainly because the cementing material in the soil structure was destroyed[3]. Nan Xue applied different freezing temperatures and cycle times of freeze-thaw to prepared soil samples, and obtained that the cohesion was proportional to the cycle times of freeze-thaw and had little relation with freezing temperature[4].

Yong Feng adopted orthogonal test to analyze the influence of soluble salt content, clay content and other factors on the shear strength of fine grained soil in freeze-thaw cycle[5]. Zhiqin Wu established multiple linear regression model to explore the change rule of shear strength index of silty clay[6].
This article reference in Rock And Soil Engineering[7] analysis method for silty clay, and in strict accordance with the Geotechnical Test Method Standard[8] to test the soil sample. Testing the soil sample density, water content, particle composition, the basic parameters such as liquid limit and plastic limit is important. Through the analysing of Grey Theory, this article finally analyse the shearing strength of the silty clay change rule, provide the reference to the following seasonal frozen area subgrade problems to lay the foundation.

2. Physical properties and particle composition of samples

The silty clay used in this paper was taken from the construction site of Changchun, and the indoor geotechnical test was carried out on it. The physical properties are determined as shown in Table 1.

| Natural density (g cm⁻³) | Natural water content (%) | Liquid limit (%) | Plastic limit (%) | Plastic index | Specific gravity (g cm⁻³) |
|-------------------------|--------------------------|-----------------|-----------------| -------------|-------------------------|
| 1.98                    | 26.13                    | 37.35           | 23.41           | 13.94        | 2.70                    |

The soil used in this test is fine grained soil. Firstly, boil the soil mixture into soil liquid, then grind it, repeat until all suspended liquid through the sieve of 0.075mm. Dry and weigh the sand particles on the sieve. Then the density meter method was used to determine the content of particles smaller than 0.075mm and calculate particle size less than a certain value particle percentage content, the specific results are shown in Table 2.

| Particle size (mm) | Percentage of each grain group(%) | Soil name |
|-------------------|----------------------------------|-----------|
| 2-0.075mm         | 8.11%                            | Silty clay|
| 0.075-0.005mm     | 76.89%                           |           |
| 0.005-0.002mm     | 6.67%                            |           |
| <0.002mm          | 8.33%                            |           |

3. Freeze-thaw cycle test and determination of shear strength

After sampling at the construction site, the silty clay samples are distributed with water according to the corresponding proportion. Remold it into three types of remolded samples with water content of 26%, 30% and 37%, and control the mass to keep compactness constant, and respectively do 5, 10, 15 times of freeze-thaw cycle in the freezing temperature of -5°C, -10°C, -15°C. The melting temperature is 20°C. Freezing for 12h and melting for 12h is a freeze-thaw cycle. At the same time, a group of unfrozen-thawing soil samples were set as the control group. Shearing uses the quick shearing method of the straight shearing method. Keep the shear rate in line with the requirements of geotechnical test standards. According to the Coulomb's law: \( \tau_f = \sigma \tan \phi + C \), with the parameters of cohesion C and the internal friction angle \( \phi \) as the index of shear strength, the cohesion and the internal friction angle of silty clay are measured. Drawing through the Origin software to analyse the change rule of cohesion and internal friction angle.

3.1. The change rule of cohesion

Based on certain freezing temperature, different water content is linear variable, to observe the relationship between the cycle time of freeze-thaw and the cohesion of soil sample. The results show that cohesion under -5°C with the increase of cycle time of freeze-thaw, firstly decreases and then increases. 26%, 30%, 37% water content groups compared to unfrozen-thawing group increasing amplitude are 55.8%, 42.1%, 109.8%. Cohesion under -10°C with the increase of cycle time of freeze-thaw, it increases in a straight line. 26%, 30%, 37% water content groups increasing amplitude are 86.2%, 80.5%, 124.5%. Cohesion under -15°C with the increase of cycle time of freeze-thaw decreases. 37% water content group increases, increasing amplitude is 52.4%, 26%, 30% water content groups decreasing amplitude are 56.3%, 5.9%. The specific situation is shown in Figure 1.

Based on certain cycle time of freeze-thaw, different water content is linear variable to observe the relationship between the freezing temperature and the cohesion of soil sample. The results show that cohesion under 5, 10, 15 times freeze-thaw with the dropping of freezing temperature, the deepening
of freezing, firstly increases and then decreases. -10℃ could be the characteristic value of freezing temperature. The specific situation is shown in Figure 2.

Analysing the relationship between water content and soil sample cohesion is vital to explore the change characteristics of cohesion. The results show that within the range from plastic limit to liquid limit, the relationship between water content and cohesion is linear. With the increase of water content, the cohesion of soil sample decreases, and there is a critical value. At the situation of 15 times freeze-thaw cycle in the freezing temperature of -10℃, the cohesion of soil samples with water content of 26%, 30% and 37% reaches the maximum value. In the interval of positive correlation between cohesion and cycle time of freeze-thaw, -10℃ group cohesion as freeze-thaw cycles increases the growth rate of slightly less than -5℃ freeze-thaw cycle group. 15 times freeze-thaw cycle in the freezing temperature of -15℃ get the lowest cohesion for 26% water content group. 5 times freeze-thaw cycle in the freezing temperature of -15℃ get the lowest cohesion for 30% and 37% water content groups. For the 37% water content group, in the interval of positive correlation between cohesion and cycle time of freeze-thaw, the increase rate of cohesion increases with the dropping of freezing temperature. The specific situation is shown in Figure 3.

Figure 1. -5℃ Freezing temperature - Cohesion - Cycle time of freeze-thaw
Figure 2. 5 Times freeze-thaw cycle - Cohesion - Freezing temperature
Figure 3. Cohesion - Freezing temperature - Cycle time of freeze-thaw
X-axis - Freezing temperature
Y-axis - Cycle time of freeze-thaw
Z-axis - Cohesion
Linear variable - Water content
3.2. The change rule of internal friction angle

Based on certain freezing temperature, different water content is linear variable, to observe the relationship between the cycle time of freeze-thaw and the internal friction angle of soil sample. The results show that 26%, 37% groups internal friction angle under -5℃ with the increase of cycle time of freeze-thaw decreases, decreasing amplitude are 35.6%, 22.3%, 30%, water content groups compared to unfrozen-thawing group increasing amplitude is 5.2%. Internal friction angle under -10℃ with the increase of cycle time of freeze-thaw, it decreases in a straight line. 26%, 30%, 37% water content groups decreasing amplitude are 35.6%, 6.6%, 41.2%. Internal friction angle under -15℃ with the increase of cycle time of freeze-thaw decreases. 26%, 30%, 37% water content groups decreasing amplitude are 28.0%, 39.9%, 45.5%. The specific situation is shown in Figure 4.

Based on certain cycle time of freeze-thaw, different water content is linear variable to observe the relationship between the freezing temperature and the internal friction angle of soil sample. The results show that internal friction angle under 5, 10, 15 times freeze-thaw with the dropping of freezing temperature, the deepening of freezing, 26% group decreases, 30% group increases, 37% group changes little. The specific situation is shown in Figure 5.

Analysing the relationship between water content and soil sample internal friction angle is vital to explore the change characteristics of internal friction angle. The results show that within the range from plastic limit to liquid limit, the relationship between water content and internal friction angle is linear. With the increase of water content, the internal friction angle of soil sample decreases. With the increase of cycle time of freeze-thaw and rising of freezing temperature, 26% group internal friction angle decreases, 30% group increases, 37% changes little. The specific situation is shown in Figure 6.
4. Correlation analysis based on grey theory

Gray associate analysis method is one of the basic methods of Grey System Theory. It can analyze and determine the degree of influence between various factors or the contribution of several subfactors (reference series) to the main factors (comparison series). It is an analysis method to measure the degree of correlation between factors through quantitative analysis[9].

Water content, freezing temperature and cycle time of freeze-thaw for subsequence X, are selected in the corresponding sequence components under the condition of cohesion and internal friction angle as mother sequence Y1, Y2, and selection of cohesion and internal friction angle when the data is the basic condition for the water content is 26%, freezing temperature is -5℃, cycle time of freeze-thaw for five times, the matrix can be expressed as:

\[
X = \begin{bmatrix}
X_1 \\
X_2 \\
X_3
\end{bmatrix} = \begin{bmatrix}
x_{11} & x_{12} & x_{13} \\
x_{21} & x_{22} & x_{23} \\
x_{31} & x_{32} & x_{33}
\end{bmatrix} = \begin{bmatrix}
\text{water content} \\
\text{freezing temperature} \\
\text{cycle time of freeze-thaw}
\end{bmatrix} = \begin{bmatrix}
0.26 & 0.30 & 0.37 \\
-5 & -10 & -15 \\
5 & 10 & 15
\end{bmatrix}
\]

(1)

\[
Y_1 = \begin{bmatrix}
Y_1 \\
Y_2 \\
Y_3
\end{bmatrix} = \begin{bmatrix}
y_{11} & y_{12} & y_{13} \\
y_{21} & y_{22} & y_{23} \\
y_{31} & y_{32} & y_{33}
\end{bmatrix} = \begin{bmatrix}
0.00765 & 0.00550 & 0.00380 \\
0.00765 & 0.01410 & 0.00640 \\
0.00765 & 0.01160 & 0.01540
\end{bmatrix}
\]

(2)

\[
Y_2 = \begin{bmatrix}
Y_1 \\
Y_2 \\
Y_3
\end{bmatrix} = \begin{bmatrix}
y_{11} & y_{12} & y_{13} \\
y_{21} & y_{22} & y_{23} \\
y_{31} & y_{32} & y_{33}
\end{bmatrix} = \begin{bmatrix}
0.1794 & 0.1056 & 0.0551 \\
0.1794 & 0.1916 & 0.1955 \\
0.1794 & 0.1583 & 0.1422
\end{bmatrix}
\]

(3)

Due to its various factors dimension is not the same, some numerical difference is bigger, need to deal with data to eliminate the dimension influence on the result, this paper adopts the method of the range processing made on the test data, for the (1), (2), (3) transform processing, get the corresponding difference sequence matrix, then take resolution coefficient δ is 0.5, get the corresponding relational coefficient matrix, which average in each row is the correlation degree.

Correlation degree is a value between 0 and 1 describing the degree of influence of various influence factors on a certain value. The closer to 1, the more sensitive the influence is, and the closer to 0, the less sensitive the influence is.

The final cohesive correlation degree G1 and internal friction angle correlation degree G2 are respectively

\[
G_1 = [0.97, 0.48, 0.48]^T \quad G_2 = [0.96, 0.46, 0.48]^T
\]

(4)

To prove the validity of the results, with the water content is 30%, freezing temperature is -10℃, cycle time of freeze-thaw is 10 times as the basic conditions of grey relational analysis again, obtained cohesion of correlation degree G1 and internal friction angle of correlation degree G2 is respectively

\[
G_1 = [0.96, 0.48, 0.46]^T \quad G_2 = [0.98, 0.46, 0.47]^T
\]

(5)

So by gray associate analysis method shows that for the silty clay, sensitivity of various factors affect the size of cohesion of the sort order for water content>freezing temperature>cycle time of freeze-thaw, the sensitivity factors which influence the internal friction angle of the size of the various sort of water content>freezing temperature>cycle time of freeze-thaw. That is to say, among the three main factors selected, the change of water content has the greatest influence on the cohesion and internal friction angle of silty clay, and the correlation degree>0.80. The changes of freezing temperature and cycle time of freeze-thaw have little effect on the cohesion and internal friction angle of silty clay. Therefore, the biggest contribution degree of cohesion and internal friction angle of silty clay is water content, followed by freezing temperature and cycle time of freeze-thaw, and the contribution degree of freezing temperature and cycle time of freeze-thaw is general.
5. Experiment results and discussion
The freezing-thawing cycle is a unique form of temperature change that can be studied using a unique form of strong weathering[10]. Shen Jiang used undisturbed silty clay samples for different times freeze-thaw cycle and measured the shear strength, found that freeze-thaw cycle significantly reduced the shear strength of undisturbed soil[11]. However, for remolded soil, its shear strength increased. Studies have shown that the freeze-thaw cycle increases the porosity ratio of the dense soils, but decreases the porosity ratio of the loose soils. After freeze-thaw cycle, the index of porosity ratio tends to a steady value -- residual porosity ratio[12]. For under consolidated soil with little prophase consolidation pressure and the remolded soil with normal consolidation, the soil samples are compacted during the freeze-thaw cycle, so that their structure is strengthened.

- Soil is a three-phase material composed of soil particles, water and gas. During the freeze-thaw cycle, owing to the temperature changing constantly between negative temperature and room temperature 20℃, water in the soil changes from liquid to solid ice crystals, which then liquefy to form water. At constant mass, the volume of water converted to ice increases and vice versa, so during the freezing process ice crystals formed by water will squeeze the nearby soil particles, damaging the soil structure, changing the pore space in the soil and rearranging the internal soil particles. At the same time, the soil particles have the ability to absorb water in the soil through surface charge adsorption, Van Der Waals force and hydrogen bond, etc. Due to the continuous water-ice transformation during the freeze-thaw cycle, the soil particles will absorb new unfrozen water and lead to water flow in the soil, which is the main reason for water migration. In conclusion, the influence of cycle time of freeze-thaw is essentially the remodeling of soil structure and water migration. There is space for the deformation of soil particles in the loose remolded soil, when the force generated in the process of ice crystal formation destroys the weak cementing force in the remolded soil and compacts the soil particles instead of damaging them. Due to the water migration, the soil particles at all positions in the soil sample will be squeezed evenly, so that the soil can be fully compacted. Repeated freeze-thaw increases the degree of compaction of the soil sample, increases the content of fine particles in a certain volume, and makes the adsorption force on the surface of the soil particles stronger. The cementing connection between particles was broken, and the continuous migration of water resulted in the soil sample being fully lubricated and the soil sample's friction decreased. Therefore, with the increase of cycle time of freeze-thaw, the cohesion of soil sample increases and the internal friction angle decreases.

- The dynamic ratio of ice to unfrozen water in soil samples in freeze-thaw cycle changes with different freezing temperatures. When the cycle time of freeze-thaw of soil samples is controlled to be constant value, the lower the freezing temperature is, then the deeper the freezing degree is and the larger the proportion of ice is. The cohesion of the soil sample during freeze-thaw cycle reaches maximum value when freezing temperature is -10℃ in this experiment. At this time, the ratio of ice to unfrozen water is the optimal state for water-ice transformation, and the remolded soil structure and water migration generated in the transformation are the largest, so there is a critical temperature at which the cohesion of frozen soil samples reaches the maximum. Due to the mutual restriction of increasing water lubrication and ice proportion, the soil cementation connection is strengthened, and the change of internal friction angle is not obvious. It shows a decreasing trend in the 26% water content group and an increasing trend in the 37% water content group.

- The change of water content has a linear relationship with the change of cohesion and internal friction angle. With the increase of water content, both cohesion and internal friction angle decrease significantly. Based on Grey Theory analysis, water content has the greatest influence on cohesion and Angle of internal friction. Hong Liu believes that the influence of water content on soil can be divided into two aspects: On the one hand, it affects the original cohesion of soil. On the other hand, it affects the solidification strength of soil, which cannot be recovered after damage[13]. With the increase of water content, the Hydration generated by clay mineral and water increases, which destroys the cementation connection formed by chemical components in soil, reduces the original cohesion and solidification strength. And at the same time, the lubrication action caused by the increase of water
content significantly reduces the friction of soil. Therefore, with the increase of water content, the cohesion and internal friction angle of soil sample decreased obviously.

6. Peroration
Northeast China has a vast territory and low development level, which is an important development area for highway engineering in the future. The shear strength of subgrade soil is an important factor affecting the stability of highway. Silty clay seasonal frozen area is widely distributed in northeastern China. In this paper, the remolded soil made from the undisturbed soil at the construction site are taken as the test objects to carry out experimental research on the cohesion and internal friction angle change rules under different water content, freezing temperature and cycle time of freeze-thaw. The conclusions are as follows:

- There is a linear relationship between water content and cohesion or internal friction angle. Within the range from plastic limit to liquid limit, the internal friction angle and cohesion decrease with the increase of water content.
- Freezing temperature has a critical value, in the test the experimental groups which freezing temperature is -10℃ compared with other experimental groups under negative temperature, soil sample's cohesion is the largest, meanwhile, the maximum cohesion of each water content group is obtained after 15 times freeze-thaw cycle, but internal friction angle does not change significantly with temperature.
- There is a linear relationship between the cycle time of freeze-thaw and cohesion. With the increase of cycle time of freeze-thaw, the soil sample's cohesion generally increases, but when freezing temperature is -15℃, the experimental groups' cohesion which water content is 26% declined slightly.
- Grey Theory analysis shows that the grey correlation degree of water content, freezing temperature and cycle time of freeze-thaw to cohesion are 0.97, 0.47 and 0.47, and to internal friction angle are 0.95, 0.45 and 0.47. The effect of water content on cohesion and internal friction angle is the greatest, but the effect of freezing temperature and cycle time of freeze-thaw is general and roughly equal.
- To build a highway, it is necessary to excavate the subgrade, destroy the original structure and re-compaction it. In the construction of silty clay seasonal frozen area, attention should be paid to the reasonable arrangement of construction period, the influence of cycle time of freeze-thaw, freezing temperature and water content on subgrade soil, so as to ensure the excellent shear strength index of subgrade soil.

Acknowledgements
This study was financially supported by National Natural Science Foundation of People's Republic of China (Grant No. 41502272).

References
[1] Viklander, P. (1995) Influence of cycles of freezing and thawing on the permeability in soils, a literature investigation. Lulea University of Technology.
[2] Janoo, V., Shoop, S. (2004) Influence of spring thaw on pavement rutting. UNBAR6 Pavements Unbound. Nottingham. pp. 115-124.
[3] Wang, J. (2015) Simulation test on strength growth of changchun silty clay. Jilin University
[4] Xue, N. (2017) Experimental study on mechanical properties of seasonal frozen soil in jilin region. Northeast Dianli University.
[5] Feng, Y., He, J.X. (2008) Experimental study on shear strength characteristics of fine soil under freeze-thaw cycle. Glacial Permafrost. 30(06). pp .1013-1017.
[6] Wu, Z.Q. (2012) Effect of freeze-thaw cycle on shear strength of silty clay. Heilongjiang University.
[7] Tang, D.X. (1999) Rock And Soil Engineering. Beijing: geological press.
[8] GB/T 50123-1999 Geotechnical Test Method Standard.
[9] Deng, J.L. (2002) Standard for geotechnical test methods. Wuhan: huazhong university press
[10] Deng, X. (2015) Mechanism and quantitative research method of freeze-thaw cycle on soil structure. Glacial Permafrost. 37(01). pp.132-137.
[11] Jiang, S. (2017) Effect of freeze-thaw cycle on shear strength of silty clay subgrade. Hunan transportation technology. 43(02). pp.59-62.
[12] Viklander, P. (1998) Permeability and volume changes in till due to cyclic freeze-thaw. Canadian Geotechnical Journal. 35(3). pp.471-477.
[13] Liu, H. (2006) The influence of water content of clay soil on its mechanical properties. Northeast China water conservancy and hydropower. (11). pp.55-56.