Influence of Freeze-thaw Cycles on Water Content Properties of Silty Clay in Xuchang

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Abstract: Silty clay is the main structural stratum in Xuchang area. Based on the freeze-thaw cycle test, the influence of freeze-thaw on the water content and void ratio of silty clay is analyzed. The test results show that in the case of no recharge water source, the freeze-thaw cycle will cause water migration in the soil body, which will produce local high water content zone on the surface, and cause water loss and water content reduction, which is easy to cause soil loss. Water shrinkage produces cracks. The results show that the higher the initial water content is, the faster the water content will be lost, and the different initial water content will tend to be the same when the freeze-thaw cycle reaches more than 15 times. With the increase of freeze-thaw times (5 times), the void ratio tends to be stable. The change of soil properties caused by water migration under freeze-thaw cycle plays an important role in soil stability control. The research results of this paper are helpful to carry out scientific and reasonable engineering prevention measures and provide basic data.

1. Introduction

Most of the northern areas are the seasonal freeze-thaw zone, about 53.5% of China's total land area. which is the main area of engineering construction, and the seasonal freeze-thaw is one of the main reasons for the damage of the deep foundation pit in winter[1]. In China, the research on frozen soil began in the late 1950s, and the engineering properties research of soil under freeze-thaw cycles began in the 1990s. The practice of prevention and control of frost damage shows that water migration is the main factor of frost damage formation, and water migration has been regarded as a core problem of soil freezing and thawing. Since the 21st century, with the continuous emergence of major project, the cyclic freeze-thaw has caused cracking damage to foundation pits, bridges and culverts, road subgrade construction, slope maintenance, etc. the subgrade, and even uneven settlement occurs. These phenomena further increased the construction cost and maintenance cost, and reduced the service life. These hazards are closely concerned by the majority of engineering and technical personnel. Liu Bing (2008) studied the indoor experiment of water migration in soil during freezing and thawing, it was found that the water migration was slow during freezing and fast during thawing[2]. Zheng Meiyu (2015) studied the structural changes of silty clay before and after freezing and thawing, which showed that the overall distribution trend of pores had no obvious change[3]. He Fei (2016) found that the difference of freezing temperature had the most obvious effect to the freezing depth of samples. The greater the temperature difference, the greater the water migration. When the dry density was smaller, the water migration was more obvious. When the initial moisture content was less than the
liquid limit, the greater the initial moisture content, the greater the water migration[4]. Li Jianhua (2017) thought that the relationship between initial water content and compressibility was approximately linear, but with the increase of pressure, the influence of initial water content on compressibility of soil gradually became smaller[5]. Tang Dongqi (2018) carried out a cyclic freeze-thaw study on silty clay in Zhongyuan area, revealing the influence of freeze-thaw cycles on physical properties of soil[6]; Zheng M Y (2019) studied the phenomenon of frost heaving and thawing settlement of silty clay under seasonal freeze-thaw environment, and found that the frost heaving amount in closed system was less than that open system, while the thawing settlement amount was opposite in systems[7]. Chen Zongfang (2019) used mercury injection method to study the variation of soil pore after freeze-thaw cycles. The results showed that the pore volume of soil samples increased with the increase of freeze-thaw temperature, After 20 freeze-thaw cycles, only the pore structure decreased significantly with the increase of freeze-thaw temperature[8]. Chen Lihao (2020) found that there was a linear relationship under different freezing temperatures between the maximum change of soil resistivity and freezing temperature[9]. Water content plays an important role in soil strength. Under different water content conditions, freeze-thaw cycle resulted in the loss of soil water content, the change of void ratio and strength caused by freeze-thaw cycle play an important role in slope stability. Based on this, this paper studies the change of water content of unsaturated silty clay under freeze-thaw cycle.

2. Basic physical properties of soil

![Figure 1. Location of sampling points](image)

The soil sample is taken from a construction site in Chenzhuang street, Weidu District, Xuchang city. From the construction site, it is an ancient river channel sedimentary layer with high water content. From the top to the bottom, the layers are fill, silt, silty clay and silt, and the bottom is the dual structure of silt and silty clay. In this study, silty clay is selected as the research object, and its physical and mechanical properties are shown in Table 1.

| Soil Name | natural density /g/cm³ | layer thickness /m | natural water content /% | liquid limit /% | plastic limit /% | plasticity index | internal friction angle /° | cohesion /kPa |
|-----------|------------------------|-------------------|--------------------------|----------------|----------------|-------------------|--------------------------|--------------|
| Silty clay| 1.95                   | 6.57              | 15.23                    | 41             | 26             | 15                | 20                       | 13           |

3. Soil freeze-thaw cycle test scheme

In order to verify the effect of freeze-thaw cycles under different initial water contents, the samples with water contents of 20%, 25% and 30% were prepared, and then compacted. The samples were obtained by ring knife, with a height of 20 mm and a diameter of 61.8 M. In order to keep moisture,
the soil samples were sealed with plastic film, and then put into the sealed bag, and then put into the freeze-thaw box for cyclic freeze-thaw test.

The winter extreme low temperature in Xuchang area is -17.4°C, partly raining. In this test, the high and low temperature freeze-thaw test chamber is used, and the low temperature is -15°C. According to the existing research results, the thaw temperature has little effect to the physical properties of soil. Therefore, the thaw temperature is +10°C. In this test, the time required to reach -15°C in 720 minutes, the freezing rate is 0.035°C/ min, the temperature is maintained at -15°C (±0.5°C) for 4 hours, and then the temperature is increased to +10°C (± 0.5°C). The time need to reach +10°C is set to 360 minutes, the melting rate is 0.069°C / min, the holding time is 4 hours, and each freeze-thaw cycle time is 24 hours.

4. Analysis of test results

4.1. Surface characteristics of freeze-thaw soil

According to the law of moisture migration in soil during freezing and thawing[10], during freezing, the liquid water is adsorbed in the surface of soil particles first freezes, resulting in the decrease of free water molecules, the increase of matrix suction, and the internal water of soil will move to the surface through the pores between soil particles, thus significantly increasing the solid water content of topsoil. Due to the decrease of internal water content, the soil will lose water and shrinkage, resulting in freezing tension cracks (Fig. 3. The crack expansion gradually increases with the increase of freeze-thaw cycles, which is related to the change of water content. It shows that the change is fast when the water content is high in the early stage, and slow when the water content is low in the later stage, and there is no change when the water content is reduced to a certain extent. This kind of crack, if encountering precipitation, will become a good infiltration channel, which will accelerate the instability and deformation of the slope. In practical engineering, if there are abundant water supply sources, the surface soil will be in the high water content zone and weaken the soil, which is also one of the main reasons for the failure of some winter slopes.

Figure 2. High and low temperature freeze-thaw box

Figure 3 Variation Characteristics of soil surface under different freeze-thaw cycles
4.2. Influence of cyclic freezing-thawing on soil moisture content

During the freeze-thaw cycle, even in a very closed environment, due to the adsorption between the packaging material and the water molecules in the surface layer of the sample, a layer of frozen water film will be attached to the packaging material, resulting in the decrease of the water content of the sample. In order to study the influence of freeze-thaw cycles on the water content loss of silty clay, the water content changes caused by different freeze-thaw times were tested under different initial water content (see Figure 4).

![Figure 4 Variation Law of soil mass under freeze-thaw cycle](image)

![Figure 5 Variation of soil moisture loss under freeze-thaw cycles](image)

According to the curve of freeze-thaw cycle and soil mass, the changing equations are as follows: the initial water content is 20%, and the fitting degree of equation (1) is 0.96, equation (2) with initial water content of 25%, and the fitting degree of equation (1) is 0.97, and equation (3) with initial water content of 30%, and the fitting degree of equation (1) is 0.98, (Fig. 4). With the increase of initial water content, the higher the fitting degree is, it shows that the influence of freeze-thaw cycles on soil is more consistent with the fitting curve with the increase of water content, and the accuracy of prediction of soil moisture content in later stage will be improved.

\[
y = 0.0904x^2 - 2.0627x + 114.78, \quad R^2 = 0.9216 \quad (1)
\]

\[
y = 0.0736x^2 - 1.706x + 112.92, \quad R^2 = 0.9508 \quad (2)
\]

\[
y = 0.0276x^2 - 0.7072x + 107.7, \quad R^2 = 0.974 \quad (3)
\]

Where \(x\) is number of freeze-thaw cycles, \(y\) the mass of soil sample.

The above expression can be expressed as a function of the mass of soil sample \(m\) and the number of freeze-thaw cycles \(n\). The expression is as follows:

\[
M = kn^2 + ln + p \quad (4)
\]

In equation (4), \(K\), \(l\) and \(P\) are test parameters, which are related to the initial water content of soil sample.

When the initial water content is high, the loss rate of soil water content is also high at the same number of freeze-thaw cycles, but it gradually tends to be consistent at the later stage. When the number of freeze-thaw cycles reaches 15, the mass difference between different soil samples is very small (Fig. 5). This phenomenon is consistent with the change of water content with freeze-thaw
cycles in references [11] and [12]. With the increase of freeze-thaw cycles, the increment of water content between two adjacent freeze-thaw cycles shows that the change of water content in the first freeze-thaw cycle is more severe, and then gradually flattens. The higher the initial water content is, the larger the mass increment is. When the freeze-thaw frequency reaches more than 15 times, the mass increment of soil sample tends to be consistent (Fig. 5).

After several freeze-thaw cycles, the water content of the soil samples will tend to be the same or close. When the initial water content is high, the freeze-thaw cycle is carried out, and the water content loss of soil is faster. The reason is that the free flowing water molecules in the soil decrease after the surface water is frozen, the increase of the adsorption capacity of soil particles, the adsorption internal water will accelerate the migration to the surface, In the process of migration, a good connecting channel is formed, which provide a way for the subsequent water migration. Therefore, in the early stage of freeze-thaw, the water loss is faster, and gradually decreases in the later stage.

4.3. Influence of freeze-thaw cycle on pore ratio of soil

Due to the freeze-thaw effect, the water in the soil is frozen, resulting in volume expansion of 9% [13]. For unsaturated soil, if there is not enough water supply, the volume change is small, but this small change is enough to destroy the connection between soil particles, and then change the size of soil void ratio, affecting the strength of soil.

In order to test the effect of freeze-thaw cycle on soil void ratio, under the same initial void ratio, different water contents (20%, 25%, 30%) are configured and ring knife samples are taken. The ring knife samples are put into the high and low temperature freeze-thaw box. Due to the control of ring knife, the volume of soil samples can only change in the vertical directions, which also provides convenience for the test. The density of soil is measured by the ring knife method and the density of soil particles are measured by hydrometer method respectively. According to the soil test, the water content after freezing and thawing is measured, and then the void ratio w after freezing and thawing is calculated according to formula (5) [14].

$$e = \frac{\rho_s(1+w)}{\rho} - 1$$

Where:
- \(\rho_s\) - density of soil particle
- \(\rho\) - density of soil
- \(w\) - water content of soil

Figure 6. Relationship between freeze-thaw cycles and void ratio

From the test results of freeze-thaw cycles of soil samples, the relationship between void ratio and freeze-thaw cycles shows that the void ratio increases rapidly with the increase of freeze-thaw cycles in the early stage. At the 5th freeze-thaw cycle, the void ratio reaches the maximum value, then decreases slightly and tends to be stable gradually (Fig. 6). The larger the initial water content is, the more drastic the change of void ratio is. At the later stage, due to the freeze-thaw cycle and the water content accumulation on the soil surface, the void ratio of the soil gradually decreases, it also shows that the void ratio of the soil increases continuously in the early stage of the freeze-thaw cycle (1 ~ 5 times). After reaching the maximum value, continuing the freeze-thaw cycle will destroy the formed soil structure, resulting in the loss of the soil structure. After that, the void ratio and volume of soil decrease gradually.
5. Conclusion
In this paper, it discuss the surface characteristics, water content variation and void ratio of unsaturated silty clay under freeze-thaw cycles, gets the following some understanding:

(1) The freeze-thaw cycle results in the migration of soil moisture, the decrease of local soil moisture content, and the increase of the force between soil particles. In the weak contact zone of particles, it is easy to appear tensile crack.

(2) The effect of freeze-thaw cycles on the water content is that the water content changes sharply during the initial freeze-thaw period. Although the initial water content is different, its change law is basically the same. After 15 freeze-thaw cycles, the change of soil water content tends to be the same. Due to the same structure of soil samples, the final water content tends to be the same.

(3) With the increase of freeze-thaw cycles, the void ratio first increases and then decreases. The higher the initial water content is, the greater the reduction of void ratio is.

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