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Study on Frost Heave and Thaw Settlement Characteristics of Sanya Estuary Channel Soil Layer

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Abstract: In order to explore the frost heave and thaw settlement characteristics of soil layers in the Sanya Estuary Channel Project, the frost heave rate and thaw settlement coefficient of gravel sand, fine sand, silty clay, and clay are obtained. The most unfavorable soil layers are then compared and analyzed. The variation law of frost heave and thaw settlement performance of the most unfavorable soil layer under different water content is studied. The results are as follows: (1) The freezing stage of the passage through the typical soil layer is divided into four stages: frost shrinkage, rapid frost heave, slow frost heave, and frost heave stability. The melting stage is divided into three stages: slow thaw settlement, rapid thaw settlement, and thaw settlement stability. (2) The most unfavorable soil layer in the typical soil layer of the Sanya Estuary Channel Project is silty clay, with a frost heave rate and thaw settlement coefficient of 4.51% and 5.88% at −28 °C. (3) The frost heave and thaw settlement performance of the most unfavorable soil layer is linearly related to water content. The larger the water content, the greater the frost heave rate and thaw settlement coefficient, and the more prone to damage.

Keywords: frost heave rate; melting settlement coefficient; moisture content; indoor test

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1. Introduction

With the rapid economic development in China and the continuous advancement of urbanization, the demand for urban commuting is increasing, leading to a rise in the number of large underground structures. Currently, the pipe-roof method and artificial freezing method are two widely recognized methods in underground engineering, providing effective solutions for ground displacement and water seepage problems, respectively. Combining these two methods has led to the pipe-roof freezing method. However, pipe-roof freezing construction can cause frost heave and thaw settlement in the soil, which impacts the safety of the construction and the surrounding environment, and in severe cases, can lead to safety accidents, failing to meet the requirements for safe construction. Therefore, an in-depth investigation of the frost heave and thaw settlement characteristics of the soil during pipe-roof freezing construction has become crucial.

Soil frost heave consists of in situ frost heave caused by phase change of water and segregated ice frost heave caused by moisture migration. This phenomenon has been confirmed in the soil freezing experiment results of Taber [1] and Beskow [2], while Everett's first frost heave theory [3,4] and Miller's second frost heave theory [5,6] have provided important theoretical support for better understanding of the mechanism of soil frost heave. When the soil absorbs heat after forming frozen soil, the ice in the soil melts, causing the soil volume to decrease and resulting in thaw settlement. Subsequently, the melted soil undergoes drainage consolidation due to self-weight or external load, leading to compaction settlement. The total settlement displacement of the soil resulting from the combined effects of these two settlements is called the thaw settlement of frozen soil [7,8].

As theoretical research progresses, more scholars are conducting indoor experiments to further study the frost heave and thaw settlement phenomena of soil during freezing construction. Tang et al. [9] investigated the frost heave and thaw settlement around piles in western China through indoor experiments, exploring the relationship between temperature, water content of unfrozen soil, and soil displacement around piles. Mao et al. [10] studied the effects of initial soil moisture content and freezing temperature on soil frost heave characteristics, concluding that significant frost heave deformation occurs during the transitional freezing stage. Lu et al. [11] discovered that the temperature gradient formed within the sample drives internal frost heave in the soil, where an increase in the temperature at the warm end raises both the water supply temperature and soil temperature nearby, thereby inhibiting the development of soil frost heave. Long et al. [12] established a multiple linear regression model using MATLAB to predict the influence of initial moisture content, clay content, compaction, and overburden load on the frost heave rate of clay-improved coarse-grained soil. Ren et al. [13] investigated the moisture migration and frost heave characteristics of clay used as fill material under short-term, high-frequency, shallow freezing conditions. Tang et al. [14] conducted indoor frost heave tests on saturated silty clay in Shanghai to study soil frost heave performance under different freezing temperatures. Zhao et al. [15,16] used a self-made moisture migration test system to study the effects of initial moisture content, dry density, and freezing temperature on moisture migration during freeze-thaw cycles for both undisturbed and remolded soil samples. Wu et al. [17] studied the relationships between frost heave rate, thaw settlement coefficient, fine particle content, initial moisture content, and the number of freeze-thaw cycles through freeze-thaw tests on highway subgrade soil. Numerous scholars [18–20] have demonstrated through experiments that the movement of the freezing front and the formation of ice lenses are major factors affecting soil frost heave and thaw settlement displacement. Frost heave and thaw settlement performance tests can also be combined with actual working conditions or regional characteristics to provide references for inhibiting frost heave and thaw settlement. Wang et al. [21] studied the frost heave rate, thaw settlement coefficient, and moisture field evolution of typical red clay layers in Jiangxi under different freezing temperatures. Wang et al. [22] explored the changes in frost heave and thaw settlement characteristics of silt subgrade soil in western China from the perspective of fiber reinforcement under different moisture contents and fiber parameters. Zhu et al. [23] studied the effects of cement content, curing time, and freezing temperature on the frost heave and thaw settlement performance of cement-improved soil based on typical soil layers crossed by the Fuzhou Metro Line 4 tunnel. Ma et al. [24] studied peat soil in the Dunhua area of Jilin Province, conducting frost heave and thaw settlement investigations on undisturbed soil samples. They analyzed the effects of soil moisture content, dry density, and other factors on frost heave rate and thaw settlement coefficient, and developed a hierarchical evaluation model for the freeze-thaw characteristics of peat soil.

This study utilizes closed unidirectional freeze-thaw tests to conduct freeze-thaw experiments on typical soil layers traversed by the Sanya River Estuary Tunnel Project to obtain the frost heave rate and thaw settlement coefficient. Comparative analysis identifies the most unfavorable soil layer for frost heave and thaw settlement. Subsequently, the evolution of frost heave and thaw settlement performance of the most unfavorable soil layer under different moisture contents is explored, revealing the impact of moisture content changes on the frost heave and thaw settlement performance of the soil layer. This study provides a comprehensive analysis of the frost heave and thaw settlement characteristics of typical soil layers traversed by the Sanya River Estuary Tunnel Project, offering references for inhibiting frost heave and thaw settlement in pipe-roof freezing construction for the tunnel project.

2. Experimental Content and Plan

2.1. Experimental Materials

The soil samples for the experiment were taken from typical soil layers traversed by the Sanya River Estuary Tunnel Project. These layers primarily include miscellaneous fill layers, fine sand layers, silty clay layers, gravel sand layers, clay layers, and moderately weathered quartz sandstone layers. For this experiment, four types of soil samples were selected: fine sand, silty clay, gravel sand, and clay.

The soil sample from the fine sand layer is gray, saturated, loose, and has a relatively uniform grain size, with a high quartz content. The depth of this soil layer ranges from −36.89 m to −2.09 m, with an average thickness of 3.90 m. The soil sample from the silty clay layer is gray to dark gray, generally in a soft plastic state, with uniform texture and a smooth cut surface. The depth of this soil layer ranges from −28.95 m to −0.98 m, with an average thickness of 7.25 m. The soil sample from the gravel sand layer is light yellow to light gray-white, primarily consisting of gravel sand and coarse sand, with poor gradation. The depth of this soil layer ranges from −41.89 m to −12.58 m, with an average thickness of 3.57 m. The soil sample from the clay layer is mainly gray to dark gray, with some parts gray-yellow, primarily composed of silt and clay particles, with some medium to fine sand particles or thin layers of fine sand. The depth of this soil layer ranges from −36.33 m to −0.93 m, with an average thickness of 6.29 m. The specific physical parameters of the soil samples used in the experiment are shown in Table 1.

Table 1. Mechanical Parameters of Different Soil Layers.

Soil Layer	Soil Layer Number	Natural Density (g/cm^3)	Natural Moisture Content (%)	Bulk Density (kN/m^3)	Permeability Coefficient (cm/s)
Fine sand layer	4-1	2	17.5	0.0231	2.70×10^{-3}
Silty clay layer	1-2	1.84	30	0.0235	7.99×10^{-6}
Gravel sand layer	6-2	2.21	12.1	0.0243	7.99×10^{-3}
Clay layer	1-3	1.86	34.78	0.0246	4.00×10^{-6}

2.2. Sample Preparation

According to the “Standard for Soil Test Methods” (GB/T 501123-2019 [25]) and the “Code for Frozen Soil Testing” (MT/T 593.2-2011 [26]), the four types of soil were dried in an oven, then crushed and sieved using a 2 mm sieve to remove impurities. The remolded soil samples were then prepared as specified.

The soil samples were subjected to drainage consolidation according to the soil layer depth. Representative samples were taken to measure their moisture content, ensuring that the difference between the sample moisture content and the preparation standard was controlled within ±1%. The soil samples were then cut according to the test dimensions into cylindrical samples with a diameter of 12 cm and a height of 6 cm.

3. Frost Heave and Thaw Settlement Experiment Content and Methods

3.1. Experimental Instruments for Frost Heave and Thaw Settlement

The experimental instruments used in this study were provided by the Department of Underground Architecture and Engineering at Tongji University (Shanghai, China). The primary equipment includes a freezing apparatus, a low-temperature circulation pump, a data acquisition system, and a PC. The experimental system is shown in Figure 1.

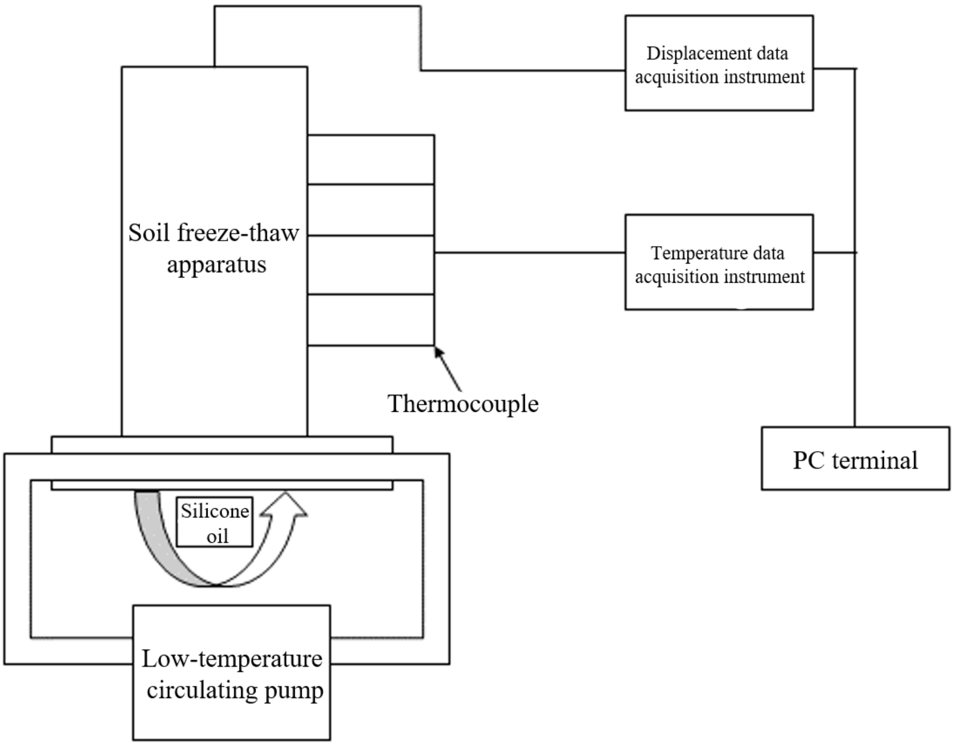


Figure 1. Schematic Diagram of the Experimental System.

The specific experimental instruments include the following:

(1) Unidirectional Freezing Apparatus

The sample size was selected based on the “Code for Frozen Soil Testing” (MT/T593.2-2011), considering the existing experimental conditions and objectives. Soil samples with a diameter of 12 cm and a height-to-diameter ratio of 0.5 were used for the tests. The size of the test chamber was 40 cm × 40 cm × 80 cm. The general structure of the freezing apparatus is shown in Figure 2.

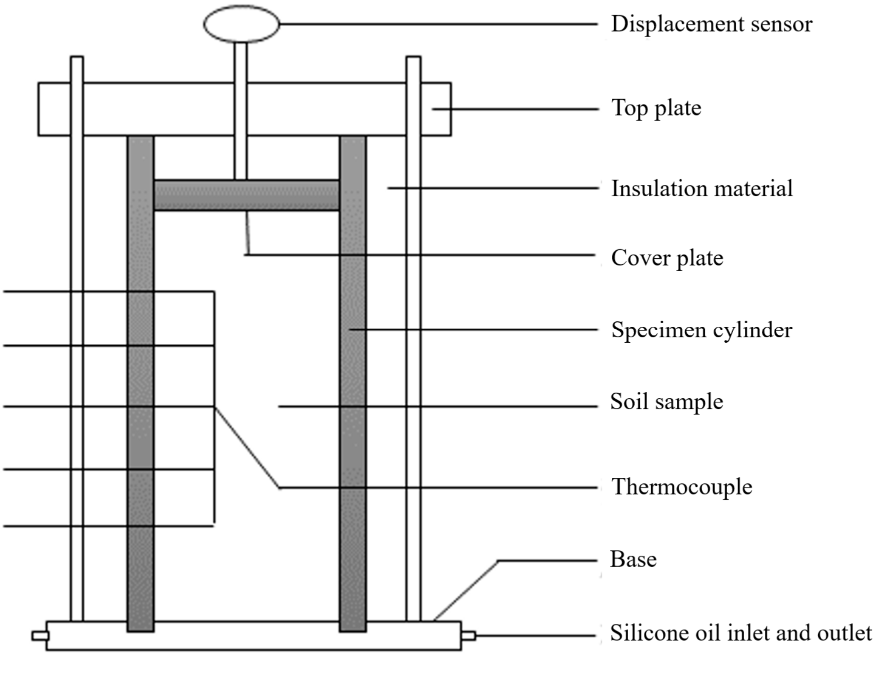


Figure 2. Schematic Diagram of the Freezing Apparatus.

(2) Low-Temperature Cooling Liquid Circulation Pump

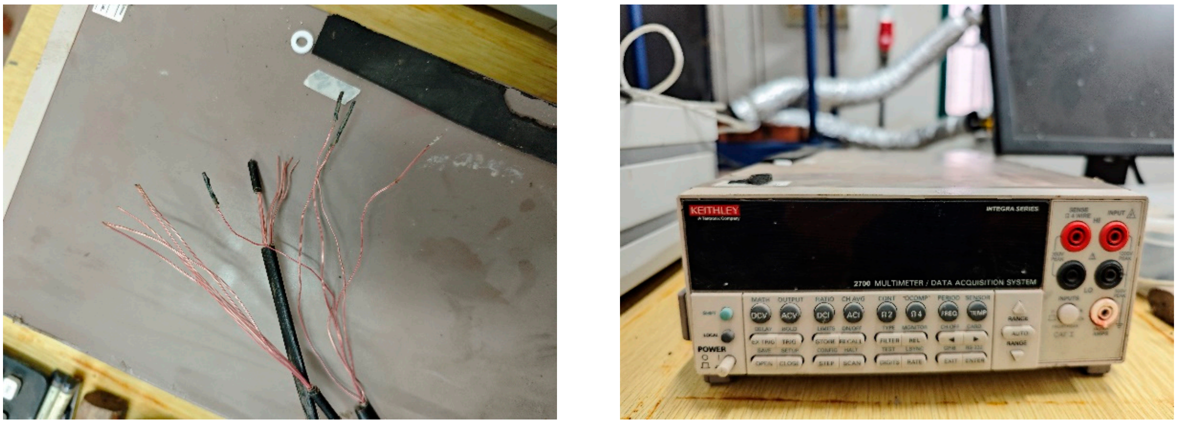
The HRT-100 N low-temperature cooling circulation pump was used in the experiment. This device achieves the freezing effect by mechanically cooling and circulating the low-temperature liquid. In this experiment, silicone oil was used as the cooling medium, which was transported to the bottom of the freezing apparatus to provide continuous low temperatures to the bottom of the sample, achieving the freezing effect. The actual equipment is shown in Figure 3.

(**a**) Circulating pump control panel (**b**) Circulating pump liquid inlet and outlet

Figure 3. Refrigeration and Heating Circulator.

(3) Temperature Sensors and Data Acquisition System

The temperature sensors used in this study are T-type thermocouples (Figure 4a), with a temperature range of −200 °C to 260 °C and an accuracy of 0.1 °C. The Keithley 2700–7700 temperature acquisition instrument was connected and Word software (Microsoft office 2021) was used to collect temperature data, as shown in Figure 4b, to meet the test requirements. During the freeze-thaw tests, thermocouples were placed every 1 cm in the soil sample to measure the temperature changes during the freezing and thawing processes, allowing the study of the temperature field changes in the sample.



(**a**) T-type thermocouple (**b**) Temperature data acquisition instrument

Figure 4. Temperature Data Acquisition System.

(4) Displacement Sensors and Data Acquisition System

The displacement sensors used in this study are DH-YWC-20 strain-type displacement sensors (Figure 5a), with measurement coefficients of 279, 286, and 295 με/mm, and a displacement range of 0–20 mm. The displacement data acquisition instrument used was the TST3828E dynamic and static signal testing and analysis system (Figure 5b), with a resolution of 1 με and a range of 0 to ±19,999 με, meeting the experimental requirements.


(**a**) Displacement sensor (**b**) Displacement data acquisition instrument

Figure 5. Displacement Data Acquisition System.

3.2. Design of Frost Heave and Thaw Settlement Experiment

Soil samples were taken from the working shaft of the Hexi port of the Sanya River Estuary Tunnel, from the ground surface to a depth of 39 m. The four types of soil samples included fine sand, silty clay, gravel sand, and clay. For each group of moisture content determinations, two additional sets of parallel experiments were conducted, resulting in a total of three repetitions per group. Specifically, the moisture contents for fine sand were recorded as 17.11%, 17.69%, and 17.71%; for silty clay, they were 29.56%, 30.28%, and 30.15%; for gravel sand, the values were 11.83%, 12.01%, and 12.46%; and for clay, they were 34.61%, 35.19%, and 34.54%. To comply with geotechnical testing standards, the average values of these measurements were adopted as the standard values. The basic physical and mechanical parameters of the soil samples are shown in Table 1.

The water content of the soil is an important parameter that affects the frost heaving and thawing characteristics of the Sanya Estuary Channel Project. Therefore, the main research contents of this chapter are as follows:

(1) Investigate the variation patterns of frost heaving and thawing characteristics of fine sand, silty clay, gravel sand, and clay layers under natural moisture content.
(2) Study the variation patterns of frost heaving and thawing characteristics of the most adverse soil layer under different moisture contents (24%, 27%, 30%, 33%, and 36%).

3.3. Frost Heaving and Thawing Test Data Processing Methods

According to test specifications and the research results of numerous scholars [27–29], the calculation methods for soil frost heaving rate and thawing coefficient are shown in Formulas (1) and (2).

$$\eta = \frac{\Delta h}{H_0} \times 100 \tag{1}$$

where η is the frost heaving rate of the sample, %; Δh is the total frost heaving amount of the sample, mm; and H_0 is the original height of the sample, excluding frost heaving amount, mm.

$$a_0 = \frac{\Delta h_0}{h_0} \times 100 \tag{2}$$

where a_0 is the thawing coefficient of the frozen soil sample, %; Δh_0 is the total thawing amount of the frozen soil sample, mm; and h_0 is the original height of the frozen soil sample, mm.

Based on the data obtained from the tests, the frost heaving rate and thawing coefficient of the soil samples were calculated using the above methods.

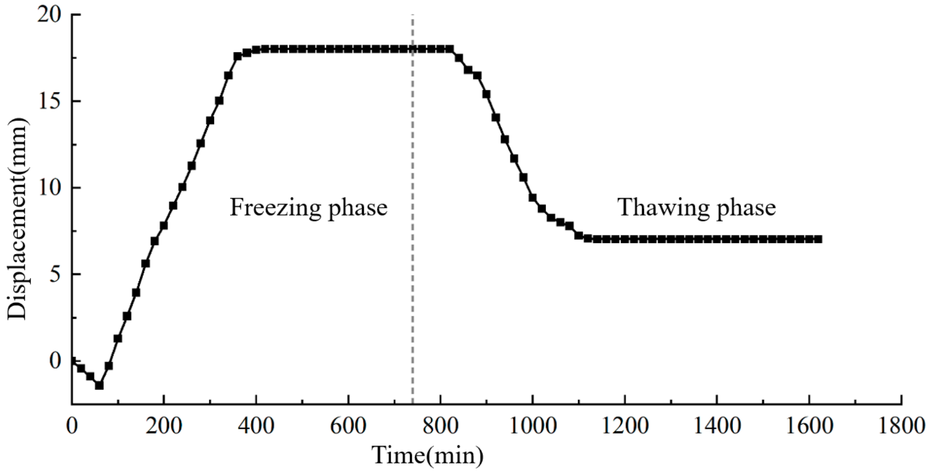
4. Test Results and Analysis

4.1. Analysis of Frost Heaving and Thawing Properties of Different Soil Layers under Natural Moisture Content

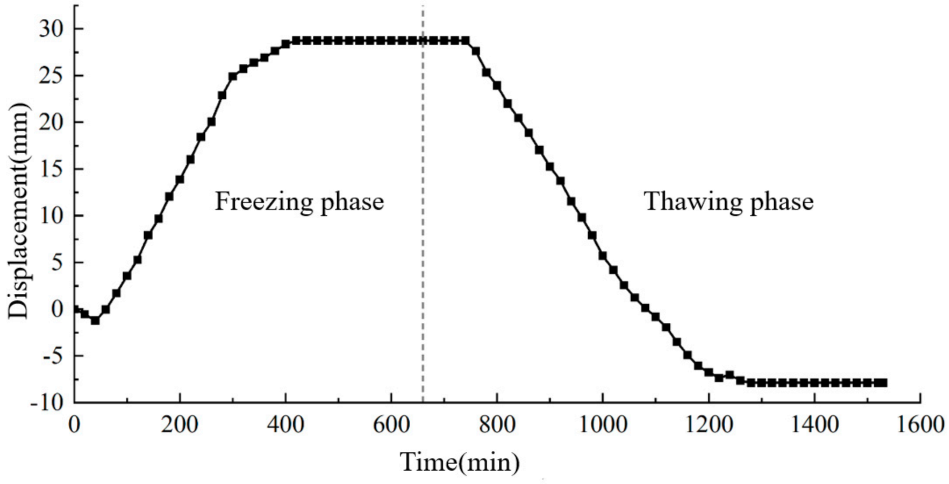
The displacement of the top of the silty clay, clay, fine sand, and gravel sand during the freezing and thawing stages varies with time, as shown in Figure 6.

By observing and analyzing, the soil sample displacement can be divided into frost heaving displacement and thawing displacement. The dotted line is the dividing line between the frost heaving displacement stage and the thawing displacement stage. The variation of frost heaving displacement can be roughly divided into four stages as follows:

Stage One: Frost Contraction Stage. During this stage, the volume increase generated by the freezing of water into ice in the soil is not sufficient to offset the volume decrease caused by the low temperature, resulting in a decrease in the volume of the soil sample, leading to negative displacement. When the frost heaving amount exceeds the volume contraction of the soil, displacement starts to increase, marking the end of this stage.

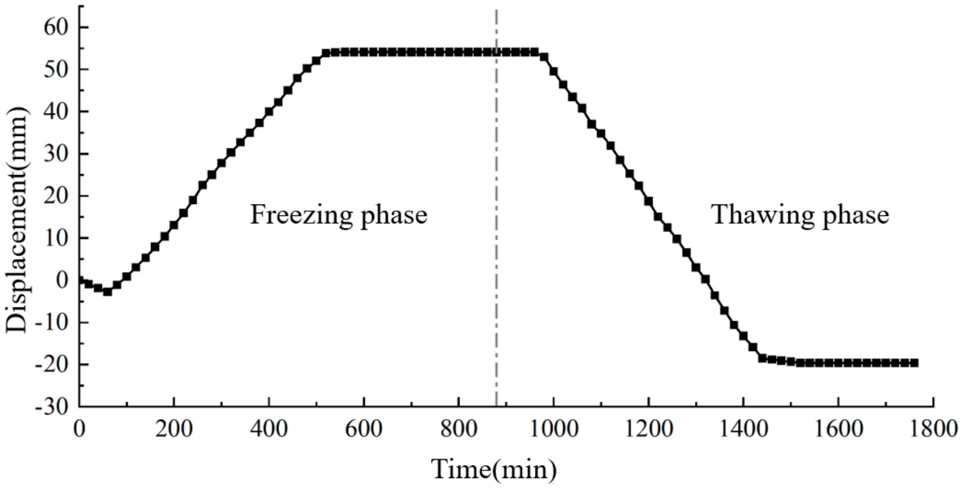


(a) Gravel sand

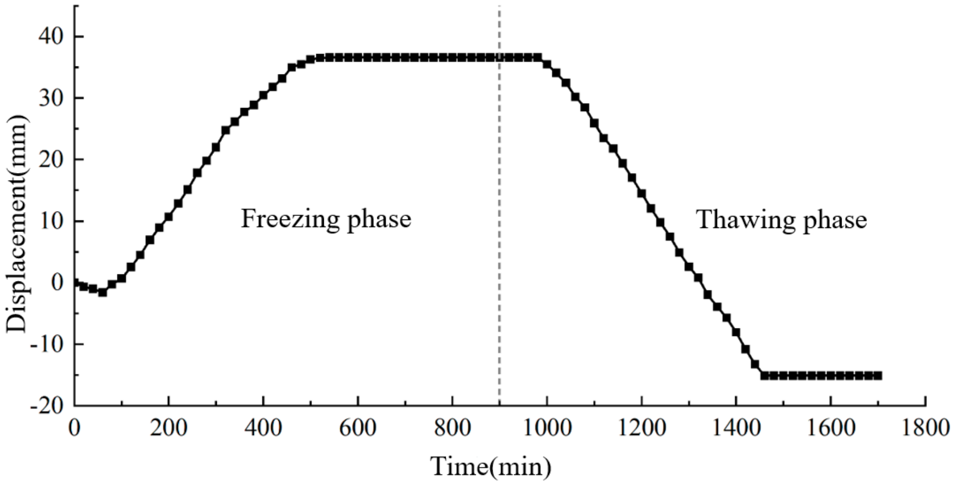


(b) Fine sand

Figure 6. *Cont.*



(**c**) Silty clay



(**d**) Clay

Figure 6. Displacement Variation Curves of Different Soil Layers.

Stage Two: Rapid Frost Heaving Stage. During this stage, water particles near the freezing front in the soil sample quickly freeze into ice and form ice lenses, with a significant ice segregation phenomenon. Therefore, the frost heaving phenomenon in the soil sample is very strong, and the displacement growth rate is fast.

Stage Three: Slow Frost Heaving Stage. During this stage, the ice segregation in the soil sample is fully developed, and the thickness and continuity of the ice lenses slowly increase, resulting in a slow increase in frost heaving displacement.

Stage Four: Frost Heaving Stabilization Stage. During this stage, the freezing front is stable, the ice lenses no longer grow, and the frost heaving displacement slowly increases towards stabilization.

The variation of thawing displacement can be divided into three stages as follows:

Stage One: Slow Thawing Stage. Affected by the freezing temperature, the soil sample does not immediately show thawing displacement after the cold source is removed, resulting in a slow change in thawing displacement.

Stage Two: Rapid Thawing Stage. During this stage, the thawing phenomenon in the soil sample is significant, and the thawing amount continuously increases with time, resulting in a fast change in thawing displacement.

Stage Three: Thawing Stabilization Stage. During this stage, the change in thawing displacement of the soil sample is smooth, eventually stabilizing.

By comparing and analyzing the displacement variation curves of the four soil samples, it can be observed that:

(1) The time required for the two types of sand to reach the stable displacement stage during freezing and thawing was shorter than that of the two types of clay, indicating that the thermal conductivity of the two types of sand was significantly greater than that of the two types of clay.

(2) Due to the differences in soil properties, the coarse particles of the two types of sand led to lower moisture content during freezing and a less compressible sand skeleton during thawing, resulting in less pronounced frost heaving and thawing characteristics compared to clay.

(3) After the test, all soil samples except gravel sand showed negative displacement, indicating that the frost heaving displacement of all soil samples except gravel sand was greater than their thawing displacement.

The frost heaving rate and thawing coefficient of fine sand, silty clay, gravel sand, and clay were calculated, with the results shown in Table 2.

Table 2. Test Results of Frost Heaving Rate and Thawing Coefficient under Natural Moisture Content.

Serial Number	Soil Type	Frost Heave Rate/%	Thaw Settlement Coefficient/%
1	Gravel sand	1.5	0.9
2	Fine sand	2.41	2.98
3	Silty clay	4.51	5.88
4	clay	3.05	4.18

Comparative analysis shows that the frost heaving rate and thawing coefficient of silty clay in the Sanya Estuary Channel Project were the highest. Based on the principle of the most adverse conditions, silty clay was selected for the analysis of frost heaving and thawing properties under different moisture contents in the next section.

4.2. Analysis of Frost Heaving and Thawing Properties of Silty Clay Under Different Moisture Contents

The displacement of the top of the silty clay during the freezing and thawing stages under different moisture contents (24%, 27%, 30%, 33%, and 36%) varies with time, as shown in Figure 7. The soil samples at the end of the thawing stage are shown in Figure 8.

By comparing and analyzing the displacement variation curves and post-test samples under different moisture contents, the following conclusions can be drawn:

(1) The greater the moisture content in the soil, the greater the volume change of water freezing into ice during freezing. Consequently, the displacement at the stable stages of frost heaving and thawing is larger, and the frost heaving rate and thawing coefficient are higher.

(2) Increasing (decreasing) the moisture content leads to an increase (decrease) in both frost heaving displacement and thawing displacement of silty clay, but the increase (decrease) in frost heaving displacement is smaller than that in thawing displacement.

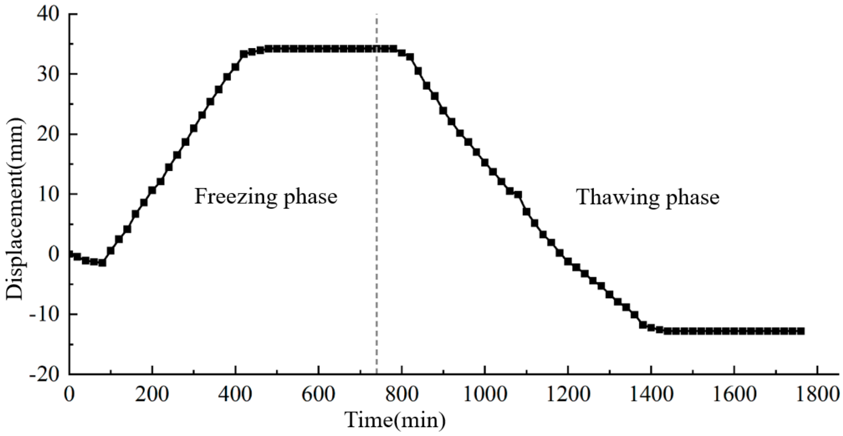
(3) Soil samples with higher moisture content are more likely to show damage after the test, indicating that higher moisture content leads to greater mechanical performance degradation of the soil samples after the test.

The frost heaving rate and thawing coefficient of silty clay under different moisture contents (24%, 27%, 30%, 33%, and 36%) were calculated, with the results shown in Table 3, and the variation curves of frost heaving rate and thawing coefficient under different moisture contents are shown in Figure 9. From the figures and tables, the following conclusions can be reached:

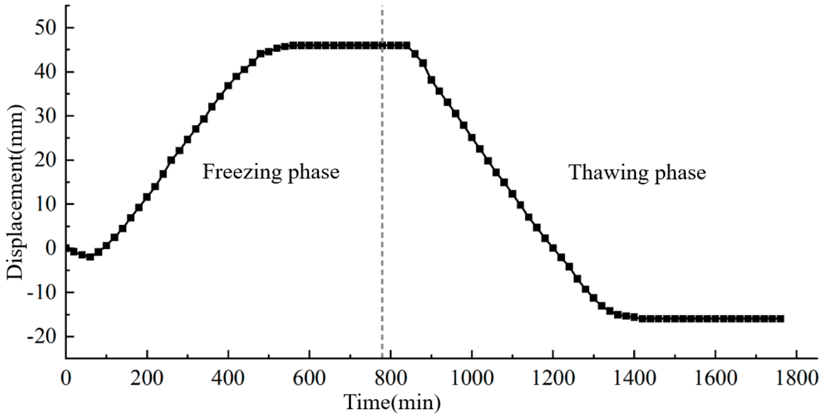
(1) Under the freezing temperature of -28°C, the frost heaving rate of silty clay with 24% moisture content is 2.85%, and when the moisture content increases to 36%, the frost heaving rate increases to 6.84%. Within this range of moisture content change, the frost

heaving rate increases with the increase in moisture content, with the frost heaving rate rising by approximately 0.333% for every 1% increase in moisture content.

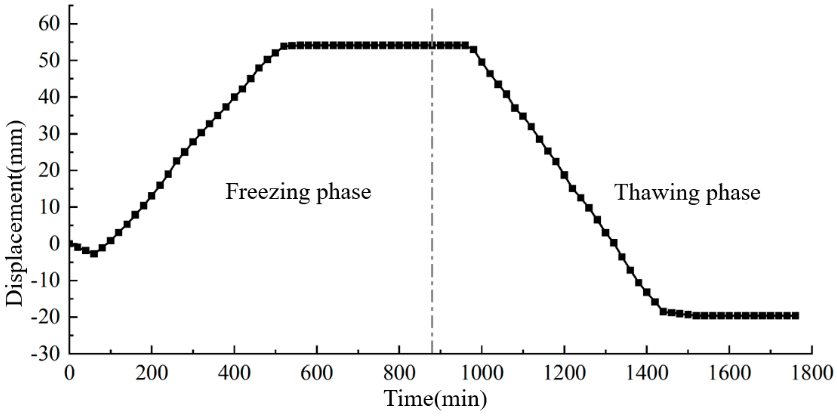
(2) Under the freezing temperature of −28°C, the thawing coefficient of silty clay with 24% moisture content is 3.81%, and when the moisture content increases to 36%, the thawing coefficient increases to 8.43%. Within this range of moisture content change, the thawing coefficient increases with the increase in moisture content, with the thawing coefficient rising by approximately 0.385% for every 1% increase in moisture content.



(**a**) 24% moisture content

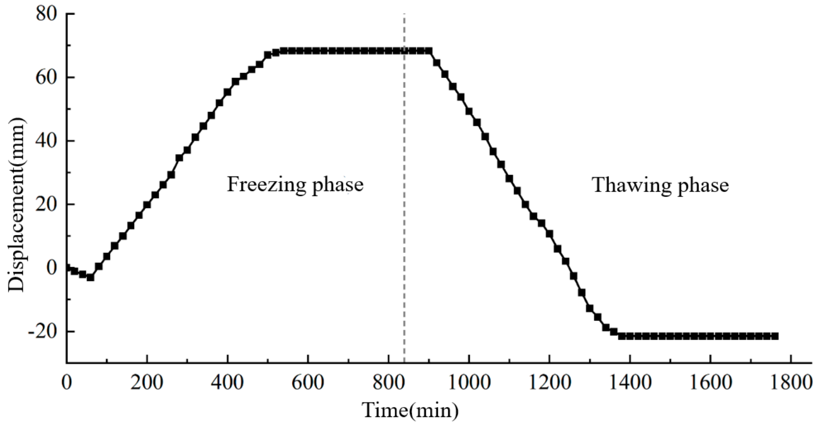


(**b**) 27% moisture content

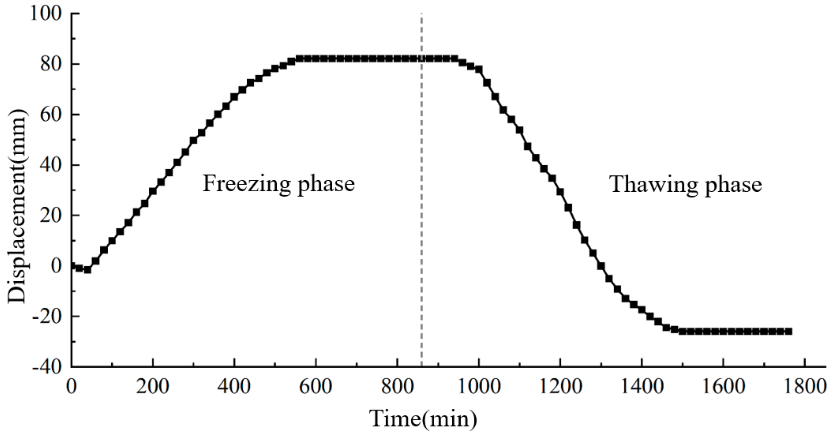


(**c**) 30% moisture content

Figure 7. *Cont.*



(**d**) 33% moisture content

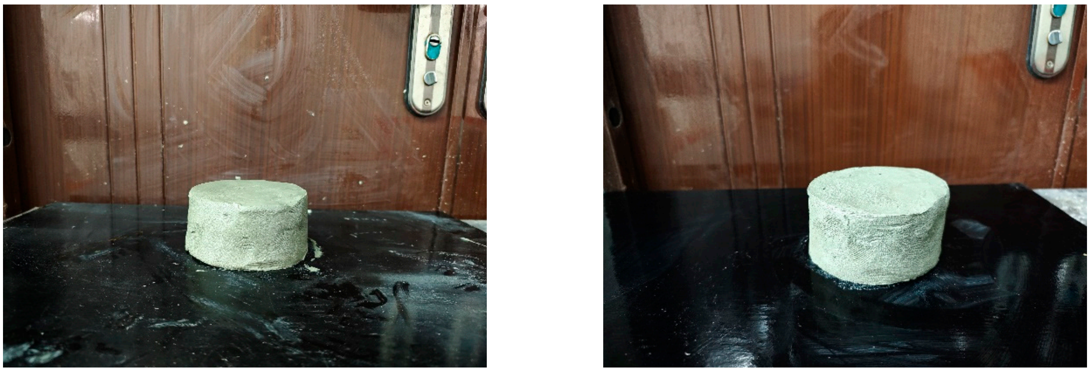


(**e**) 36% moisture content

Figure 7. Displacement variation curves of silty clay under different moisture contents.

Table 3. Test Results of Frost Heaving Rate and Thawing Coefficient of Silty Clay under Different Moisture Contents.

Serial Number	Moisture Content	Frost Heave Rate/%	Thaw Settlement Coefficient/%
1	24	2.85	3.81
2	27	3.83	4.97
3	30	4.51	5.88
4	33	5.69	7.08
5	36	6.84	8.43

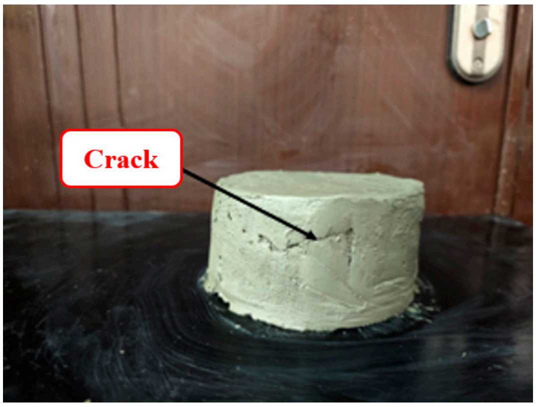


(**a**) 24% moisture content

(**b**) 27% moisture content

Figure 8. *Cont.*

(**c**) 30% moisture content (**d**) 33% moisture content



(**e**) 36% moisture content

Figure 8. Samples of Silty Clay after Freezing and Thawing under Different Moisture Contents.

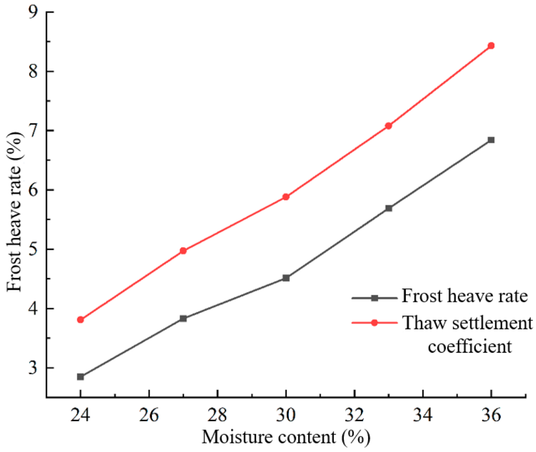


Figure 9. Frost Heave Rate and Thaw Settlement Coefficient of Silty Clay as a Function of Moisture Content.

Additionally, the displacement rate changes during the freezing phase for gravel sand, fine sand, silty clay, and clay are 0.064 mm/min, 0.083 mm/min, 0.128 mm/min, and 0.093 mm/min, respectively. During the thawing phase, the displacement rate changes are −0.046 mm/min, −0.080 mm/min, −0.158 mm/min, and −0.114 mm/min, respectively. At moisture contents of 24%, 27%, 30%, 33%, and 36%, the displacement rate changes for silty clay during the freezing phase are 0.102 mm/min, 0.112 mm/min, 0.128 mm/min, 0.163 mm/min, and 0.171 mm/min, respectively. During the thawing phase, the rates are −0.080 mm/min, −0.123 mm/min, −0.158 mm/min, −0.201 mm/min, and −0.329 mm/min, respectively. Based on the data, it can be concluded that higher frost heave ratios and thaw settlement coefficients correlate with greater displacement rate changes. Silty clay exhibits the fastest rate of change, while gravel sand shows the slowest. Furthermore, higher moisture content accelerates the rate of displacement change due to frost heave and thaw settlement.

5. Discussion

This study conducted a comprehensive analysis of the frost heave and thaw settlement characteristics of typical soil layers in the Sanya River Estuary Tunnel Project, with a focus on the impact of different moisture contents on the frost heave and thaw settlement performance. Through systematic freeze-thaw experiments on soil layers such as fine sand, silty clay, gravel sand, and clay, it was found that the frost heave rate and thaw settlement coefficient of silty clay exhibited a significant linear relationship under varying moisture contents. Particularly at higher moisture contents, both the frost heave rate and thaw settlement coefficient increased, posing greater threats to the structural safety.

This finding has important implications for the safe construction of tunnel projects. The pipe curtain freezing method employed in tunnel construction may trigger serious frost heave and thaw settlement issues, especially in soil layers with high moisture content. Therefore, by controlling the moisture content of the soil, the risks associated with frost heave and thaw settlement can be effectively reduced, thus ensuring the safety and stability of the construction.

Moreover, given that silty clay exhibits the most adverse frost heave and thaw settlement characteristics in the Sanya River Estuary Tunnel Project, this paper suggests that future research could consider soil improvement techniques, such as the use of additives like cement for soil stabilization. This measure could not only enhance the engineering properties of the soil but also further reduce the structural risks caused by frost heave and thaw settlement.

6. Conclusions

This paper provides a detailed account of the frost heaving and thaw settlement tests of typical soil layers in the Sanya Estuary Channel Project, monitoring the displacement evolution during freezing and thawing processes, and calculating the frost heaving rate and thaw settlement coefficient. The main findings are as follows:

(1) During the freezing test, the displacement changes in the soil layers can be divided into four stages: frost shrinkage stage, rapid frost heaving stage, slow frost heaving stage, and stable frost heaving stage. The displacement changes mainly occur in the rapid frost heaving stage and the slow frost heaving stage.

(2) During the thawing test, the displacement changes in the soil layers can be divided into three stages: slow thaw settlement stage, rapid thaw settlement stage, and stable thaw settlement stage. The displacement changes mainly occur in the rapid thaw settlement stage.

(3) Among the fine sand, silty clay, gravel sand, and clay at natural water content, the silty clay exhibited the highest frost heaving rate and thaw settlement coefficient. At a freezing temperature of -28°C, the frost heaving rate and thaw settlement coefficient of the silty clay were 4.51% and 5.88%, respectively, making it the most unfavorable soil layer.

(4) The frost heaving rate and thaw settlement coefficient of the silty clay increase (decrease) with increasing (decreasing) water content. Additionally, soil samples with higher water content experience greater mechanical performance degradation and are more prone to damage after testing.

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