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Model Test Study on Stability Factors of Expansive Soil Slopes with Different Initial Slope Ratios under Freeze-Thaw Conditions

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Abstract: Expansive soil is widely distributed in seasonally frozen areas worldwide. Due to the special expansion and shrinkage characteristics of expansive soil related to water content, there are potential engineering disasters in the subgrade and slope engineering. To investigate the physical and mechanical changes within the expansive soil slope, four freeze-thaw cycles tests were performed on expansive soil slope models in an environmental chamber with slope ratios 1:1.5, 1:1 and 1:0.5. Nuclear magnetic resonance (NMR) technology is used to explain the pore changes in expansive soil during freezing and thawing. Model tests were carried out to monitor the changes in cracks, moisture content, temperature, displacement and soil pressure of the slope model. The results show an increase in the slope ratio may give rise to more intense temperature changes, promote the development of cracks in the model, and increase the temperature gradient and moisture migration rate during freezing and thawing. Following freeze-thaw cycling, the soil structure is destroyed and reassembled, and the soil pressure decreases as the slope ratio increases. Combined with the displacement of slope model and NMR test results, the slope can maintain a stable state after multiple freezing–thawing cycles under a specific moisture content ω_s.

Keywords: expansive soil; slope stability; freeze-thaw cycle; nuclear magnetic resonance; slope ratio; crack

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1. Introduction

The stability of slopes in seasonal frozen areas is affected by freeze-thaw cycles [1–3]. Expansive soil is a special soil that expands and shrinks with changes in moisture content and is widely distributed worldwide [4]. Expansive soil is mainly composed of silicate minerals (montmorillonite, illite and kaolin). According to the proportion of different components, the expansion and shrinkage capacity of expansive soil is different. Suits et al. [5] divided it into five types: negligible, low, moderate, high and very high. X-ray diffraction shows that the higher the content of montmorillonite, the greater the expansion and contraction capacity of expansive soil. There are many expansive soil areas in China's vast frozen soil areas. In these areas, the expansive soil is often affected by climate and subjected to long-term freeze-thaw cycles [6]. Luo et al. [7] introduced the distribution points of expansive soil in Northeast China, among which the railway construction in Yanji area of the Jilin Province was seriously affected by the freeze-thaw disaster of expansive soil.

Many scholars have studied the physical and mechanical properties of expansive soil during freeze-thaw cycles. Lu et al. [8] shows that freeze-thaw cycles will lead to larger and more uniform pores in expansive soils, and freeze-thaw cycles will reduce the shear strength of expansive soils. The lower shear strength means that the bearing capacity of expansive soil slope in frozen soil area decreases, and the stress field in the slope will also change. Tang et al. [9] think that the effective cohesion and internal friction angle of expansive soil will decrease significantly during freeze-thaw cycles. However, the conclusion of the strength changes of expansive soil after freeze-thaw cycles is not uniform. Yang et al. [10] tested the dynamic characteristics of expansive soil slopes during freeze-thaw cycles. It is found that under a certain confining pressure, the freeze-thaw cycle can produce additional deformation in the expansive soil, which means that the expansive soil slope after the freeze-thaw cycle can bear a greater load.

The stability of expansive soil slopes with different slope ratios is very complex. It is generally considered that the expansive soil slope in seasonally frozen areas is affected by periodic ice-water conversion, which causes structural damage to the soil [9], resulting in a significant reduction in the safety factor of the slope [11]. The effect of the freeze-thaw cycle on expansive soil is mainly to change its internal pore structure, resulting in surface cracking and reduced bearing capacity [6]. Hazirbaba et al. [12] monitored that there were severe fluctuations in earth pressure and pore pressure during the freeze-thaw cycle. Moreover, the freeze-thaw cycle caused the water in the soil to collect to the slope surface, increasing the landslide risk [13]. To analyze the changes of physical properties of expansive soil slopes, many scholars have conducted field tests [14,15], centrifuge model tests [16–18] and static model tests [19–21]. Zhang et al. [22] used temperature and displacement sensors to measure the frost heave of soil in seasonal freezing areas, and determined the freeze-thaw stability of coarse saline soil. However, these tests only monitor or simulate the changes of natural moisture environments and do not consider the change in environmental temperature, especially the influence of freeze-thaw cycles on slope stability. Under the freeze-thaw cycling, the expansive soil is in the complex stress state of multifield coupling. In this process, the expansive soil slope has obvious changes in moisture content and soil pressure. After freeze-thaw cycles, expansive soil slopes are characterized by multiple cracks, low resistance and destructive landslides, and large relative displacement at the macro level [23]. Due to the characteristics of expansion and shrinkage of moisture changes, expansive soil easily cracks due to tensile stress in the process of freezing and moisture loss, and the cracks gradually deepen with an increasing number of freeze-thaw cycles [24,25]. The freeze-thaw cracking and moisture migration of expansive soil slope reduces the soil strength, and slope cracks provide conditions for external moisture supply, both of which easily cause soil deformation and landslides [8,26]. Wu et al. [27] used the indoor artificial rainfall system to monitor the impact of cracks on slope landslide and divided slope failure into overall sliding failure, partial sliding failure and flow slide. However, the variation of soil inside physical parameters of expansive soil slopes with different slope ratios during freeze-thaw cycles is not clear.

In this paper, model tests of expansive soil under different slope ratios are carried out. By analyzing the changes in moisture content, soil pressure and displacement in the expansive soil slope model during multiple freeze-thaw cycles, and the crack development mode of the expansive soil slope model, the variation characteristics of the physical parameters of the expansive soil slope model under different slope ratios in freeze-thaw cycles are analyzed. The paper also uses nuclear magnetic resonance (NMR) technology to test the change characteristics of expansive soil pores in the process of freeze-thaw cycling. Combined with the change characteristics of expansive soil pores in the freeze-thaw process, the structural damage to sloped soil caused by freeze-thaw cycles is explained from the microscopic point of view, and an effective way to maintain slope stability during the freeze-thaw process is proposed.

2. Experimental Methodology

2.1. Slope Model Test

2.1.1. Slope Model Preparation

The parameters of the basic physical properties of the soil used in the slope model are shown in Table 1. The remolded expansive soil used in the test is from Meicun Town, Weifang, China. It is located in the seasonal freezing area of China. The slope model test of expansive soil attempts to study the potential problems in road construction of expansive soil in cold areas. Considering that expansive soil is a kind of engineering disastrous weathered soil, this test is only applicable to a single soil to find the dangerous state. The optimal moisture content and maximum dry density of expansive soil were measured according to ASTM D698 [28]. Figure 1 shows the grain-size distribution curves and the optimum moisture content for the expansive soil. Before optimum moisture content (OMC), the water film of soil particles is thin and it is difficult to reach the maximum dry density. For soil exceeding OMC, the water film is thick enough to produce large pore pressure during compaction, which makes it difficult to compact the soil. It is very necessary to evaluate frost susceptibility in frozen soil research. Figure 1a shows that the grain-size of expansive soil used in this test is very small; clay (<2 μm) accounts for about 49% and silt (2–75 μm) accounts for about 36%. Teng [29] believes that clay, due to its low permeability, will not cause frost heave unless freezing is very slow, but silt soil shows frost susceptibility. However, this does not take into account the large volume change during the change in moisture content of expansive soil. Luo [7] also found that expansive clay showed high sensitivity to freeze, and Xu [30] obtained similar results. Therefore, the expansive soil used in this paper can be considered as frost susceptible soil. The free expansion ratio of expansive soil in Table 1 is 1.51, and according to Suits et al. [5], it can be classified as moderate expansive soil. The determination process of free expansion ratio is to place two 10 g dry expansive soil samples in distilled water and kerosene, respectively, and pass them through a 425 mm sieve after they are stable. The volume ratio of the two is the free expansion ratio. Its value represents the water absorption and expansion capacity of expansive soil.

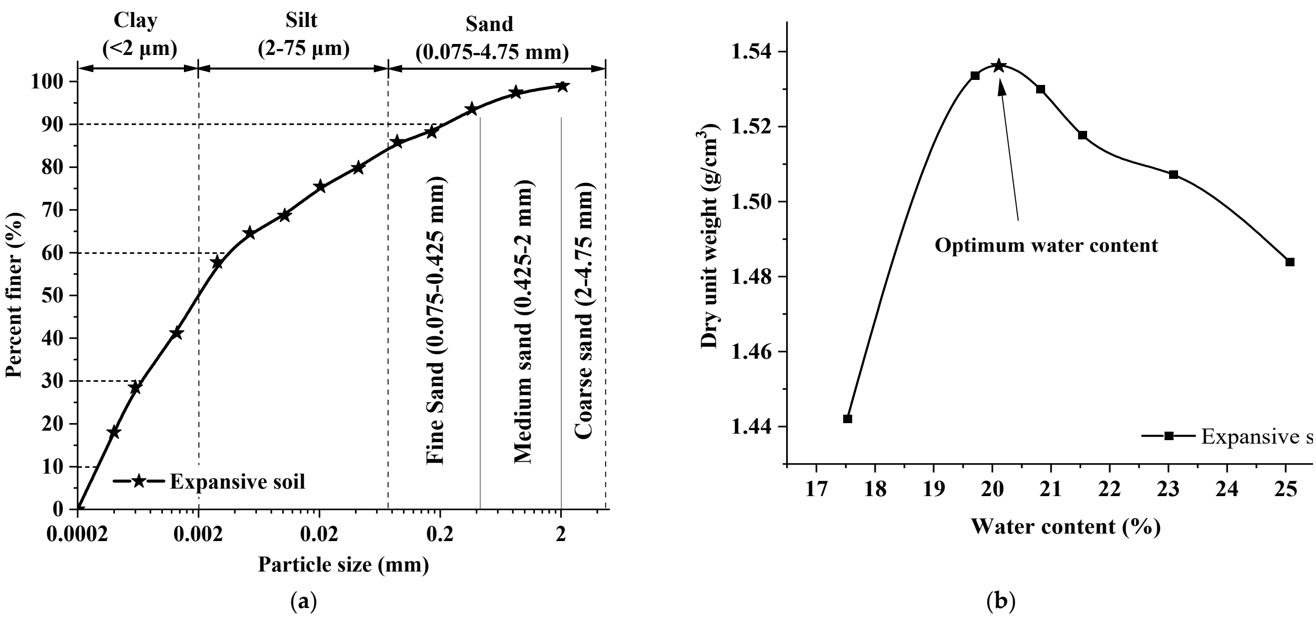


Figure 1. Grain-size distribution curves and compaction test for the soil. (**a**) Ratio and classification of different soil particles; (**b**) compaction curves of the soil.

The model test includes three expansive soil slope models. For convenience, they are called the S_1, S_2 and S_3 models, respectively. The process of preparing the expansive soil slope model is shown in Figure 2. The expansive soil slope model is prepared with layers, which guarantees the compactness of each layer. To ensure the integrity of the model, a scraping process was conducted at the junction of each layer. When the slope was prepared at the appropriate height, the mold was removed and the slope was manually cut. The four steps are as follows: (a) layered compaction; (b) surface scraping; (c) dismantling mold and (d) slope cutting. In the test, three groups of slope models were placed parallel to each other in a custom-fabricated environmental chamber. Azañón et al. [31] investigated the Riogordo Landslide and found that shallow rotational slides occurred at slope angles of 15–70 °C in seasonal frozen expansive soil area. In order to study the slope stability characteristics under different slope ratio conditions, the optimum moisture content corresponding to the maximum dry density was controlled and different slope ratio tests were set up. Therefore, the moisture content of the slope model was 20% (the optimal moisture content), and the slope ratios were 1:1.5, 1:1 and 1:0.5 (Figure 3). The selection of the slope ratio was to select the common slope angle in the project, which was set from gentle to steep with a certain degree of differentiation. In model tests of freeze-thaw cycles, it is difficult to accurately simulate the external water cycle due to the positive and negative temperature changes in the environment. This includes water evaporation, rainfall (or snow) and groundwater recharge. Therefore, instead of being considered as an open system (where there is water recharge from the outside), this experiment strictly controlled the evaporation of water from a slope as a closed system. After the test started, the surface of the slope model was covered with multilayer preservative film to prevent moisture exchange between the inside and outside of the slope. From the change of soil moisture content in the test, there was no moisture loss in the slope.

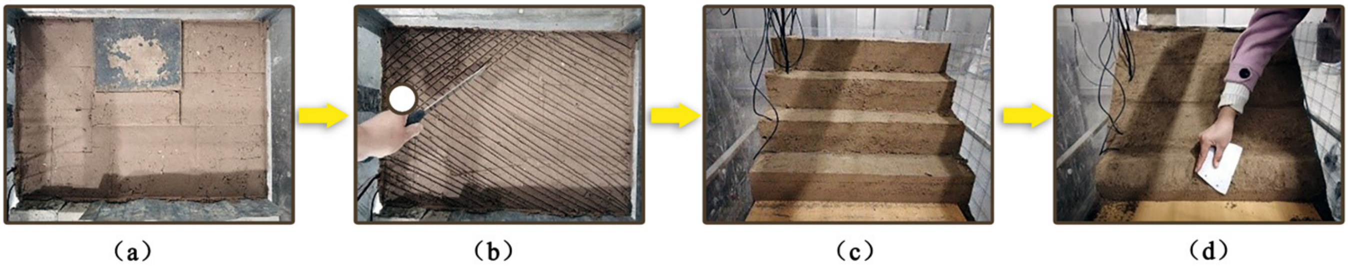


Figure 2. Slope preparation process. ((**a**) layered compaction; (**b**) surface scraping; (**c**) dismantling mold; (**d**) slope cutting).

Table 1. Physical properties of the selected expansive soil.

Properties	Values	Standard Designation
Specific gravity, G_S	2.73	ASTM D854—14 [32]
Natural moisture content (%)	9.14	ASTM D2216—19 [33]
Free expansion ratio	1.51	Suits et al. [5]
Liquid limit, ω_L (%)	45.83	
Plastic limit, ω_P (%)	26.92	ASTM D4318—17e1 [34]
Plasticity index, $I_p = \omega_L - \omega_P$ (%)	18.91	
Optimum water content, ω_{opt} (%)	20.17	ASTM D698—12 [28]
Maximum dry unit weight $\gamma_{d\max}$ (g/cm^3)	1.53	

2.1.2. Sensor Layout

The displacement, soil pressure, temperature and moisture content of the expansive soil slope model during freeze-thaw cycles were recorded. Figure 3 shows the slope model monitoring system used in the test. A HG-C1100 micro laser displacement sensor (160 mm range and 70 μm precision) was used for slope surface displacement monitoring. The displacement sensor was arranged from bottom to top along the slope. Soil pressure was measured by a DMTY resistance strain soil pressure module (range: 0.05–10 MPa), expressed as E1-E3, with a depth of 10 cm, arranged from bottom to top along the slope (Figure 3). The temperature and moisture content were monitored by an integrated sensor, in which the moisture content measurement range was 0–100%, and the temperature measurement range was −40 °C to 80 °C. Five sensor groups were set up for temperature and humidity monitoring of the slope model: W1, W2 and W5 were arranged from bottom to top along the slope surface, while W3, W4 and W5 were arranged at the top of the slope with different depths. In order to detect the cold front intrusion process of slopes at different positions, the sensor was set at 10 cm away from the slope surface. This position was not too deep and difficult to monitor, nor too shallow, resulting in rapid change. At the same time, in order to capture the gradual invasion of the cold front, a group of sensors along the vertical depth were also arranged on the top of the slope with the least impact on the slope stability.

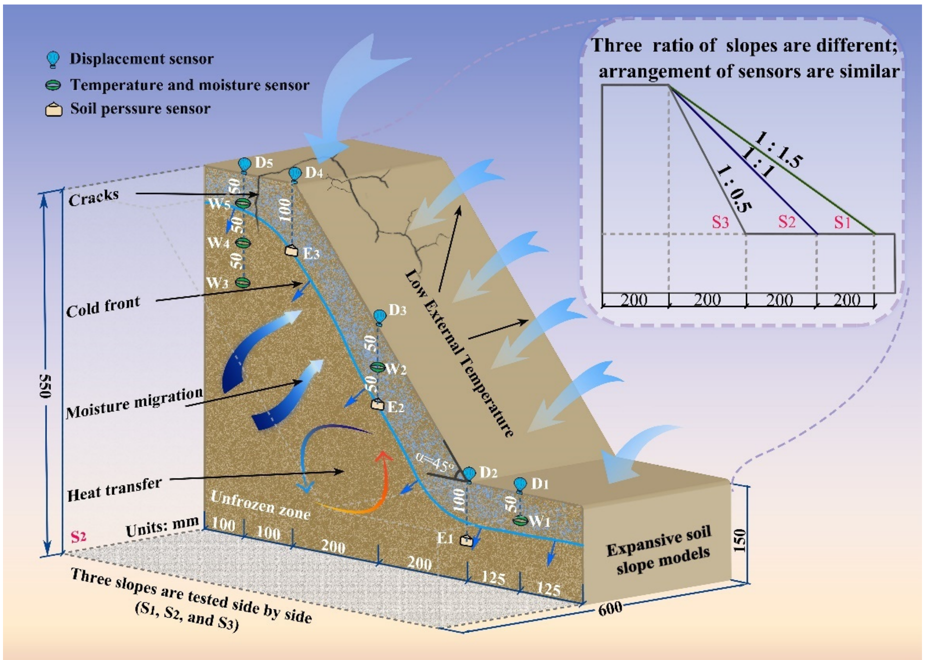


Figure 3. Slope freezing model and freeze-thaw monitoring system.

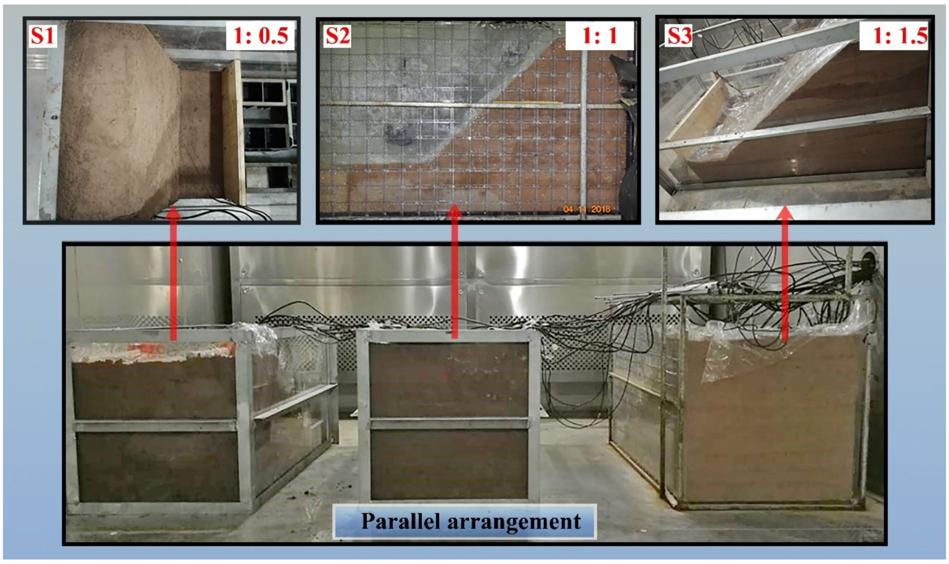
In the test, displacement monitoring used laser measurement which was not in contact with the slope and would not affect the stability of the slope. Along the lateral wall of the model, the temperature and moisture sensors were connected through signal lines to the external signal processing device (Figure 3c). The upper part of the sensor was covered with compact expansive soil, which had no obvious influence on the stability of the slope during the freeze-thaw cycle. During the test, there was no obvious difference between the soil above the sensor and the surrounding soil, and the cracks on the slope surface did not develop along the sensor area. The validity of the test data can be determined by excavating the slope model after the test, and the sensor layout area was consistent with the soil body at the signal line passing through and with other soil bodies.

2.1.3. Experimental Design

In the model test of the expansive soil slope, the freeze-thaw cycle test was carried out using a custom-fabricated environmental chamber (Figure 4). The test temperature range of the equipment was −30 to 80 °C, the temperature change accuracy was ±0.1 °C, the heating rate was 3 °C/min, and the cooling rate was 1 °C/min. Xu et al. [35] showed that the physical properties of expansive soils show dramatic shifts in negative temperatures, and setting the freezing temperature to –10 °C and −20 °C in sequence affects the physical properties of expansive soil the most. Qin et al. [36] showed that a constant positive temperature field of freeze-thaw cycles can reduce the time when the entire slope reaches a stable temperature, and that when the absolute value of the thawing temperature is higher than the absolute value of the freezing temperature, the soil can quickly reach a stable state. There was a large range of expansive soil in the Yanji area of the Jilin province, China. A large amount of expansive soil was found in the process of local railway construction, which brought challenges to the construction of subgrade and roadside slope. To study the freezing and melting stability of the slope, two negative temperature levels were established to simulate the local winter temperature change. In this study, −10 °C and −20 °C were selected as the freezing temperature and 30 °C as the thawing temperature.

When the deformation rate of the expansive soil slope was less than 0.01 mm within 2 h, the test was complete. Define *n* times complete freeze-thaw cycles as FTn. A single freeze-thaw test was divided into three stages: freezing at −10 °C, freezing at −20 °C and thawing at 30 °C. The samples were basically stable at the end of six days (144 h) at −10 °C, and then the temperature of the model box dropped to −20 °C for three days (72 h). Subsequently, the thawing temperature was maintained at 30 °C for two days (48 h). In 11 days (264 h), a freeze-thaw cycle of the slope model was completed, and four freeze-thaw cycles were tested totally (FT1 to FT4). This is because the slope displacement is small after four freeze-thaw cycles, and the test is terminated.

(**a**)



(**b**)

Figure 4. Custom-fabricated environmental chamber. (**a**) freeze-thaw environmental chamber, test temperature range: −30 to 80 °C, temperature change accuracy: ±0.1 °C, heating rate is 3 °C/min, cooling rate is 1 °C/min; (**b**) slopes are arranged parallel in the test, and the ratio of three groups of slopes is different.

2.2. Expansive Soil Nuclear Magnetic Resonance (NMR) Test

The soil samples used in the NMR test under freeze-thaw cycling were taken from the slope model test. The size of the sample used in the nuclear magnetic resonance test was small (Figure 4), and it could be stabilized quickly in the process of freezing or thawing. The physical properties of soil hardly change after freezing and thawing. Therefore, the single freezing and thawing time was analyzed to be 24 h, and a total of six freeze-thaw cycles were carried out. The samples were vacuumed and saturated for 48 h, and then frozen in −25 °C low temperature chamber (TSM9015) for 8 h. After freezing, the T2 spectra were tested. Then, the samples were thawed in a 25 °C low temperature box for 12 h, and the T2 spectra were measured after thawing. These previous steps were repeated six times. The experimental NMR instrument was a medium-sized imaging analyzer (MesoMR12-60H-I), produced by Suzhou Niumag Analytical Instruments Co., Ltd. (No. 98, Qinghua Road, Suzhou, China) The magnet used was a permanent magnet with a main frequency of approximately 12 MHz (1 H), and the inner diameter of the hydrogen test probe was 25 mm. Figure 5 shows the equipment used in this test. On the left side is the test equipment, and the right side is the testing and control system.

Figure 5. Nuclear magnetic resonance analysis instrument and test samples.

3. Results

3.1. Cracks and Pore Volume of Expansive Soil Development

After four freeze-thaw cycles, the development of cracks at the top of the S_1, S_2 and S_3 slope models is shown in Figure 6. The maximum width of cracks on the S_1 slope top was 4 mm, that of the S_2 slope was 5 mm, and that of the S_3 slope was 6 mm. Lu et al. [24] divided the development of cracks in expansive soil into three stages: crack initiation, crack propagation and crack stabilization, and attributed the formation of cracks to moisture evaporation and ice sublimation. However, in this test, the slope was in a closed system, and there was no moisture exchange with the outside. Figure 7 shows that there was obvious moisture migration to the slope surface during the freeze-thaw cycle. For a closed system, moisture migration to the surface of the slope model means that the moisture content in the slope decreases, and the expansive soil particles shrink rapidly due to moisture loss. This will lead to an increase in pores in the slope model and will produce fine cracks, which will affect the structure and stability of the slope.

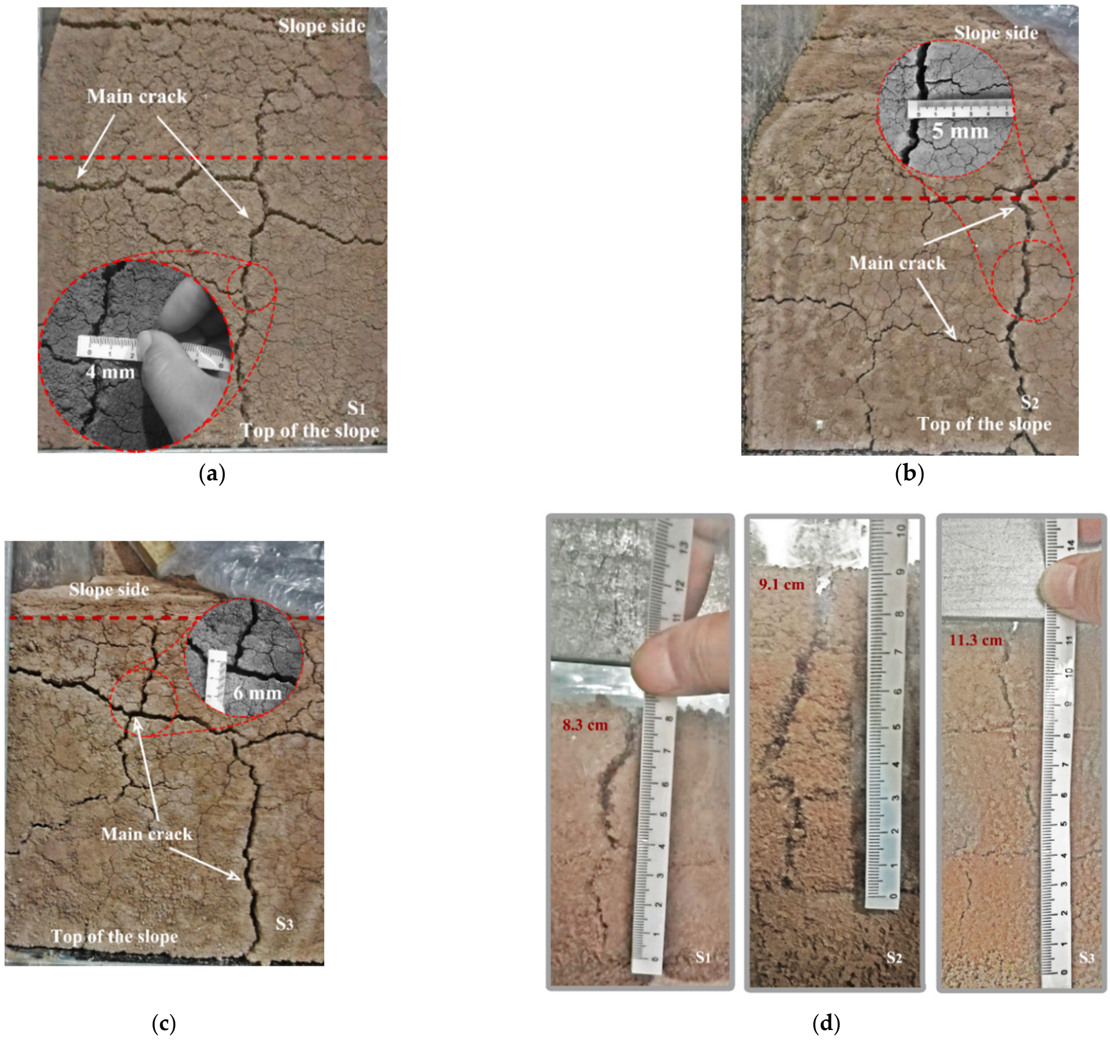


Figure 6. Crack development of the slope model after four freeze-thaw cycles (**a**) S_1(**b**) S_2 (**c**) S_3 (**d**) Vertical cracks.

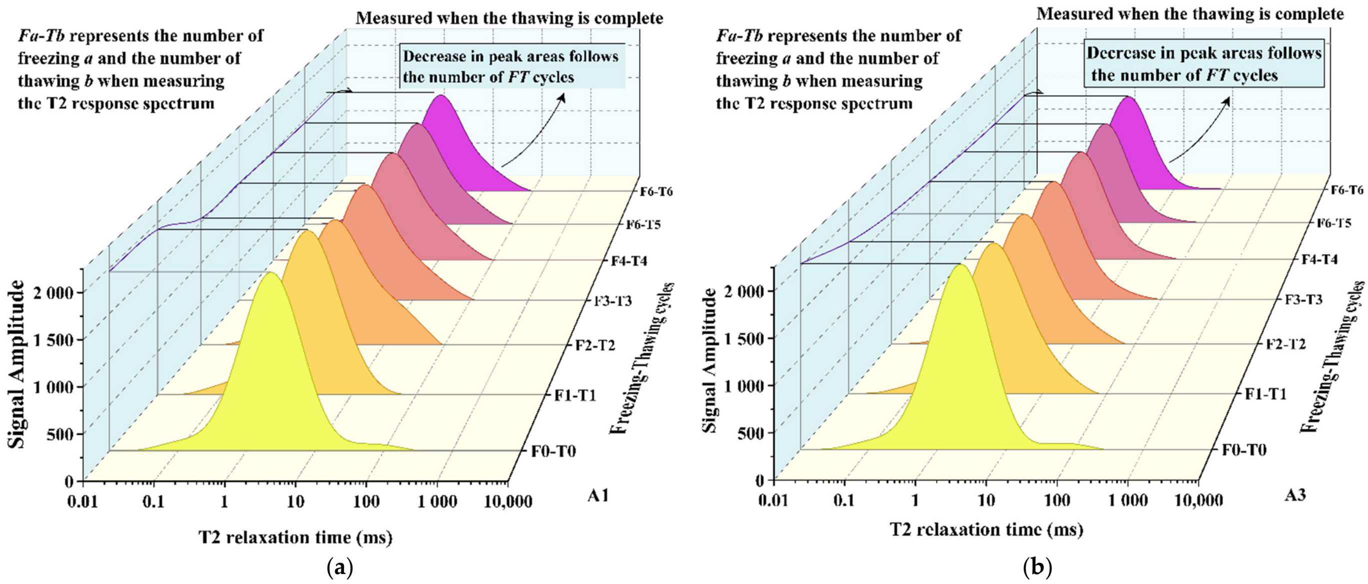


Figure 7. T2 distribution of the expansive soil after six freeze-thaw cycles. (**a**) A1 sample test results; (**b**) A3 sample test results.

In the process of freeze-thaw cycles, the evolution mode of cracks in expansive soil slopes gradually changes from irregular straight lines to polygonal cracks. Chernyshov [37] called this kind of quasi-vertical slope crack network a systematic crack network. The development pattern of surface cracks in the slope is related to its initial moisture content. The surface of the slope with a higher moisture content tends to generate irregular cracks during freeze-thaw cycling. In Figure 6 the cracks of S_1, S_2 and S_3 at the top and slope surface are mainly systematic cracks, and the maximum width of cracks also increased with the gradual increase in the slope ratio, which indicates that steep slopes, such as S_3, are more likely to generate large cracks during freeze-thaw cycles. This leads to moisture penetration along the cracks, and eventually reduces the stability of the expansive soil slopes. Figure 6d shows the development of the vertical fissure depth of the S_1, S_2 and S_3 slope models after freeze-thaw cycling. The vertical cracks depth of the S_1 slope was 8.3 cm, that of the S_2 slope was 9.1 cm, and that of the S_3 slope was 11.3 cm. The fissure width and fissure depth were directly proportional to the slope ratio; the larger the slope ratio, the greater the fissure width and depth. The freeze-thaw cycles weathered the shallow slope of the expansive soil slope. The larger the slope ratio, the greater the weathering depth of the slope model surface, and the greater the impact on the stability of the expansive soil slope.

Compared with the T2 response spectrum of freezing and thawing process, it can be seen that the signal amplitude in the thawing stage was significantly greater than that in the freezing stage. The reasons for this are mainly as follows: a. During the freezing process, the pores between expansive soil particles decrease, that is, they experience freeze shrinkage; b. part of the free moisture in the soil becomes solid ice, which further reduces the pores between soil particles. In the thawing state, the peak value of the NMR spectra decreases with increasing thawing times (Figure 7a,b), and tends to stabilize. However, in the freezing state, the peak value of T2 decreased sharply after the first freezing, and then increased slowly with increasing freezing times. The peak value of the T2 response spectrum measured at thawing was significantly greater than that measured at freezing. The area of the T2 response spectrum measured in the frozen state first decreased and then increased because a large amount of free moisture in the soil was frozen during the first freezing. The content of residual free moisture in soil pores was measured by nuclear magnetic resonance (NMR) and represented the amount of pore in frozen soil at this time. In the process of freezing, the expansive soil particles shrink and the volume of ice generated by moisture increases. The combined action of these two factors causes the pore volume of expansive soil shrink to the minimum when the first freezing is completed. In the later thawing stage, the consolidation of expansive soil causes the pore structure to become more compact. In each subsequent freeze-thaw cycle, the framework of expansive soil is broken and the structure is loose due to the frost heaving of moisture, which leads to an increase in the porosity of expansive soil in frozen state. The above-mentioned NMR tests indirectly verified the failure mode of soil skeleton during freeze-thaw cycles. The test was only conducted for six cycles, because the area change of T2 response spectrum in the last two times was very small, and the test stopped at this time.

3.2. Moisture Content in the Slope during Freeze-Thaw Cycling

Figure 8 shows the change in the moisture content of the slope model during four freeze-thaw cycles. It can be found that with the increase in freeze-thaw cycles, the moisture content at the sensor had different degrees of cyclic rise, which indicated that moisture migration had occurred in the slope. During the four times freezing process, the moisture in the slope moved towards the freezing front, while the upper expansive soil held the moisture transferred from the slope, which led to a decrease in the internal moisture content in the closed expansive soil slope model and an increase in the surface moisture content of the slope. In the single freezing process, there was an obvious peak value of moisture content in the 23–30 h stage. It can be seen from Figure 9 that the soil temperature was approximately 0 °C during this period, which indicates that the phase transformation of moisture in the slope model released much latent heat. This slowed down the speed of the decreasing slope temperature and led to a steady change in the moisture content. According to the test results, the time when the slope reaches 0 °C can be analyzed by monitoring the change in the peak moisture content value.

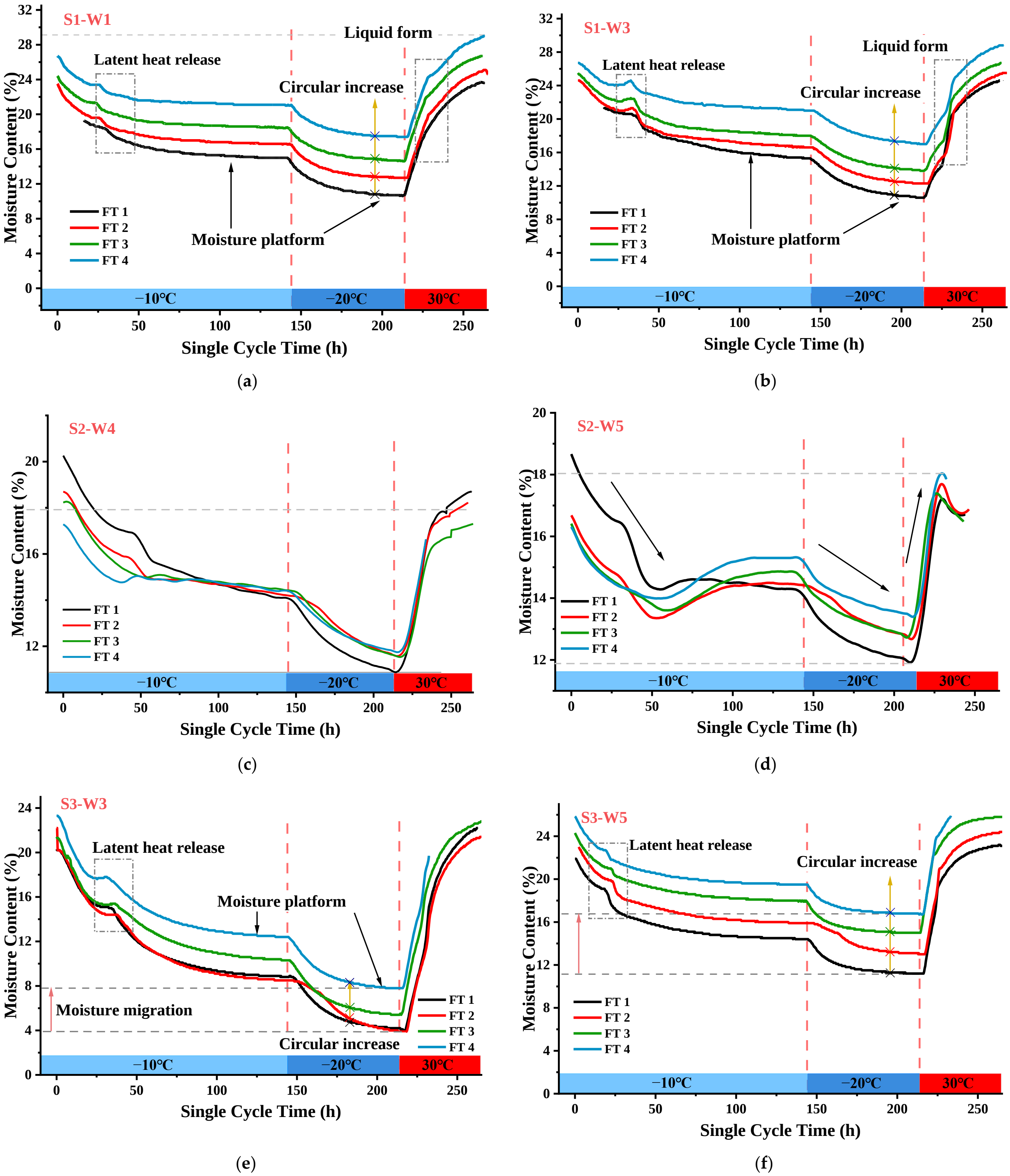


Figure 8. Moisture content of the slope model after four freeze-thaw cycles. (**a**) S1-W1; (**b**) S1-W3; (**c**) S2-W4; (**d**) S2-W5; (**e**) S3-W3; (**f**) S3-W5.

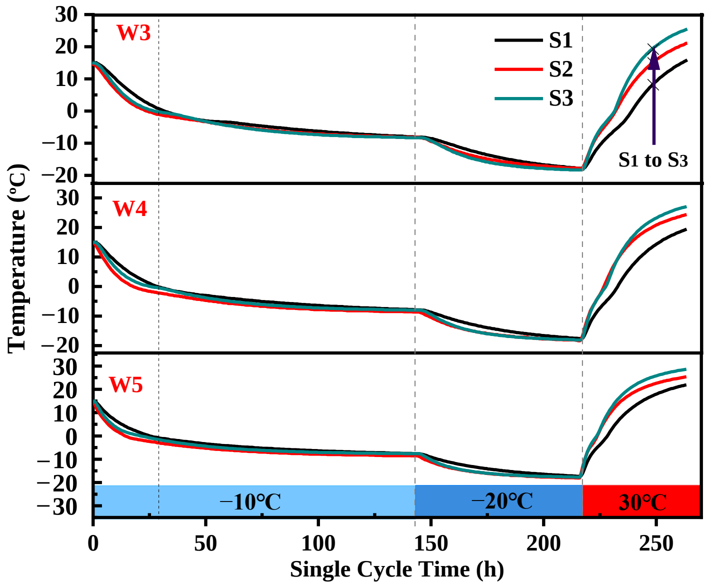


Figure 9. Temperature of slope model in one freeze-thaw cycle.

The migration of moisture is related to the freezing speed. When the freezing is slow, the freezing front invades the slope slowly (Figure 3) and maintains the same position for a long time. At this time, a large amount of liquid moisture will migrate to the freezing front, and ice lenses of different sizes will be formed behind the freezing front. A frost-free zone between the ice lenses and the freezing front is called the freezing edge [38]. Konrad and Morgenstern [39] proposed the concept of segregation potential (SP), which is defined as the ratio of the moisture transfer rate to the temperature gradient at the freezing edge of frozen soil. The empirical relationship between moisture migration and the temperature gradient is as follows:

$$V(t) = SP(t)gradT(t) \quad (1)$$

$V(t)$, $SP(t)$ and $gradT(t)$ in the formula are the moisture migration, segregation potential and temperature gradient, respectively. The formula shows that the greater the temperature gradient is, the greater the moisture migration. Therefore, the rapid cooling of the slope will produce more moisture migration than slow cooling, which will further reduce the slope stability. Figure 7 shows the temperature change of the slope during the freezing and thawing process. The moisture content changed rapidly at the initial stage of freezing under negative temperature, which also corresponded to the rapid rate of change of the moisture content reduction and moisture migration. In combination with the above formulas, it can be found that with the increase in slope ratio, the moisture migration rate of the slope increases during the thawing process, which results in the further development of freeze-thaw cracks on the upper part of the dangerous surface and increases the overturning moment.

It can be seen from Figure 8 that the moisture content of the slope in a single freeze-thaw cycle decreased rapidly at first, then gradually decreased more slowly and finally tended to be stable. When the freezing temperature was severe, the moisture content of the slope decreased rapidly again and tended to be stable. It can be inferred that for a constant low temperature, the slope tends to be stable. When the external temperature changes, the slope tends to reach another stable state. This is because the lower negative temperature can lead to further phase transformation of residual free moisture in soil [22]. It can also be seen from Figure 8 that with the continuous improvement of the slope gradient, the amplitude of the moisture content changed in the process of a single freeze-thaw cycle. At the same time, Figure 9 shows that the temperature change of S_3 is faster than that of S_1 and S_2 in each temperature stage. This is because with an increase in the slope ratio, the freezing front invaded the slope more quickly along the vertical direction. The slope can be regarded as transient two-dimensional freezing (slope top and slope surface), which can reach the external freezing temperature in a shorter time. After freezing, there was less free moisture in the slope, and the change in amplitude of the moisture content was larger.

3.3. Soil Pressure in the Slopes during Freeze-Thaw Cycling

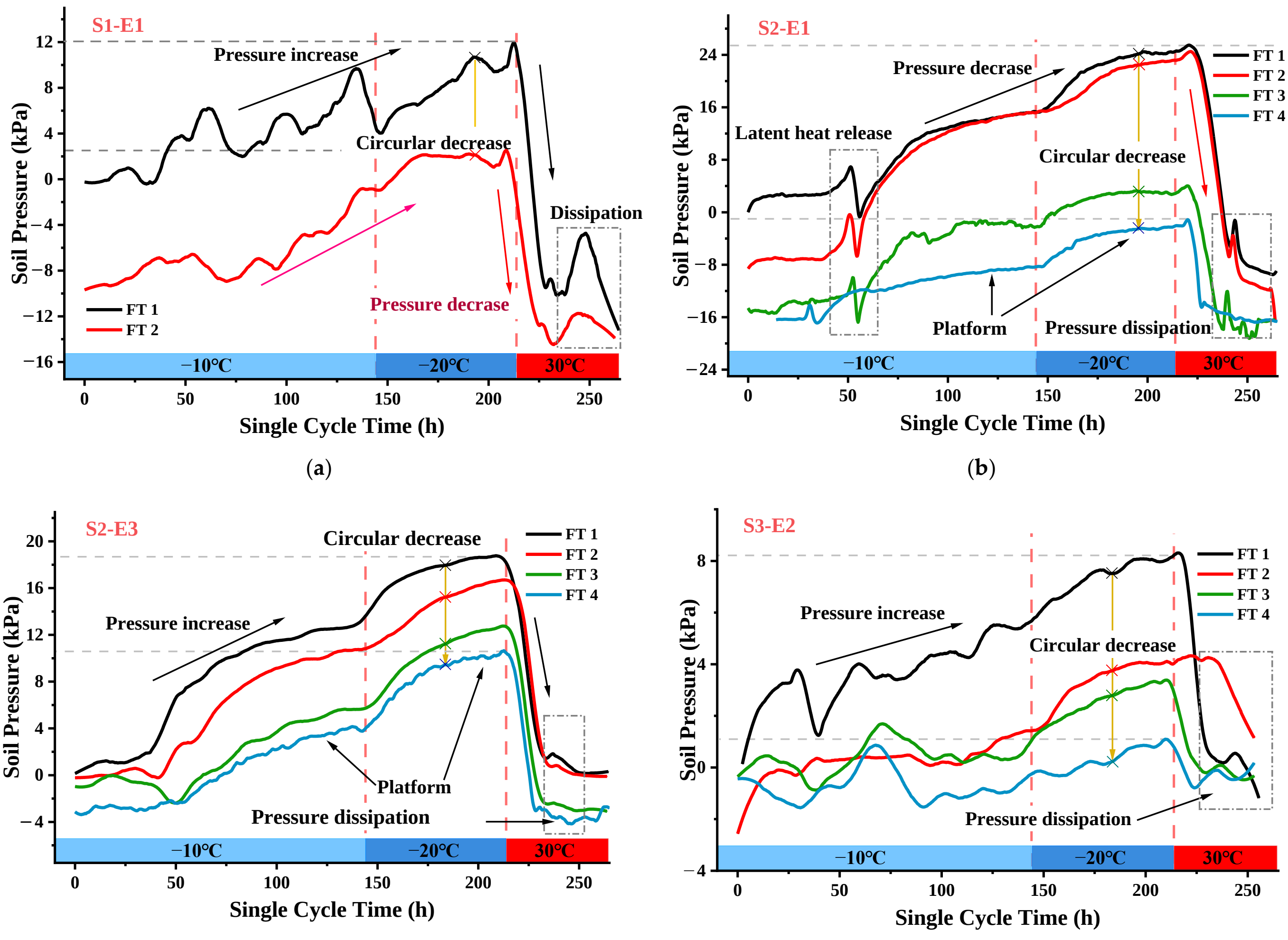
Figure 10 shows the change in soil pressure of the three groups of expansive soil slope models in four freeze-thaw cycles. The soil pressure increased in the freezing process and decreases in the thawing process during a single freeze-thaw cycle, and the soil pressure at the top of the S_1, S_2 and S_3 slope models decreased gradually. This is because during the freezing process, the free moisture in the soil gradually changes into ice crystals, and the volume increases. This causes the frost heaving force in the soil, and the frost heaving stress is transmitted to the soil skeleton, which eventually leads to the rise in soil pressure [40]. In the process of a single freeze-thaw cycle, a peak appears at the beginning of freezing, which is the stage of releasing latent heat from ice-moisture conversion in the soil. With the stability of the freezing temperature, the soil tends to be frozen stable, and the positive temperature stage of the external environment will lead to another thawing stability of the slope. This phenomenon can also be analyzed from the perspective of pore pressure change. Wang et al. [41] monitored the pore pressure change process of silty clay during the freeze-thaw cycle. It was found that the pore pressure decreased continuously during freezing and increased continuously during melting. In Figure 10, the rising soil pressure during freezing corresponds to the dissipation of pore pressure, while the decreasing soil pressure during melting corresponds to the gradual increase in pore pressure. This is because the absorbed water freezes gradually during the low temperature process, resulting in changes in unfrozen water thickness and adsorption potential in soil samples. During the melting process, the radius of curvature of the ice-water interface increases, changing the adsorption potential, resulting in an increase in pore pressure.

The overall effect of multiple freeze-thaw cycles on the soil pressure can be seen in Figure 10. The results of the soil pressure sensors of all slope models were consistent, and the soil pressure decreased with the increase in the number of freeze-thaw cycles. This is because the freeze-thaw cycles can destroy the skeleton of expansive soil and make the structure looser [42]. The weathering cracks on the slope surface can also reduce the soil pressure at E1-E3, but the decrease in measured soil pressure caused by the increase in slope pore cannot indicate that the slope is safer, because the increase in slope pore leads to the decrease in the area of soil pressure box contacting the soil, thus reducing the measured value of soil pressure. It can be seen from Section 3.2 that the freeze-thaw cycles bring moisture migration to the slope surface in the expansive soil slope model, which will cause an increase in the soil bulk density γ. The formula for soil self-weight stress is as follows.

$$\sigma_z = \gamma\, z \tag{2}$$

where σ_z, γ and z are the self-weight stress of the soil, the bulk density of the soil and the depth, respectively.

Moisture migration in the closed system will lead to an increase in the soil pressure on the surface of the slope and a decrease in the internal soil pressure. The slope increases the gravity above the sliding surface of the slope and reduces the slope stability. It can be seen from Figure 10a that there is a peak soil pressure in the thawing stage, because the ice in the soil melts into a large amount of free moisture in the high temperature thawing stage, which brings excess pore moisture pressure. According to the principle of effective stress, the dissipation of excess pore moisture pressure causes an increase in soil skeleton stress, and finally leads to the peak value of soil pressure.



(c) (d)

Figure 10. Soil pressure of the slope model in four freeze-thaw cycles. (**a**) S1-E1; (**b**) S2-E1; (**c**) S2-E3; (**d**) S3-E2.

3.4. Displacement Changes in the Slope during Freeze-Thaw Cycling

Figure 11 shows the change in slope displacement during freeze-thaw cycles. Under one freeze-thaw cycle, the displacement of the S_1, S_2 and S_3 slope models decreased with temperature in the freezing process and increased with temperature in the thawing process, which is called "freeze shrinkage and thaw expansion". The overall trend of the slope was towards the free face and tended to be stable after the second freeze-thaw cycle. After the displacement attained stability, the maximum changes in the slope top displacement of the S_1, S_2 and S_3 slope models were 12.66, 12.24 and 6.73 mm, respectively. The vertical displacement of the slope decreased with increasing slope ratio.

According to the research of Hamilton [43] and Xu et al. [35], the soil shrinks during freezing. This phenomenon depends on the amount of moisture content in the expansive soil and the difference between pore volume and expansion of moisture freezing. When the moisture content is less than 70% of the saturated moisture content, freezing shrinkage occurs, and frost heaving plays a leading role when the moisture content is high. In the test, the main reasons for freezing shrinkage of slope displacement were as follows. In the process of liquid moisture changing into solid ice, the volume expansion occupied the pores, and the gas in the pores was driven out, which led to the destruction of the soil skeleton and the rearrangement of soil particles. This eventually led to volume reduction and drying shrinkage of expansive soil particles due to moisture loss.

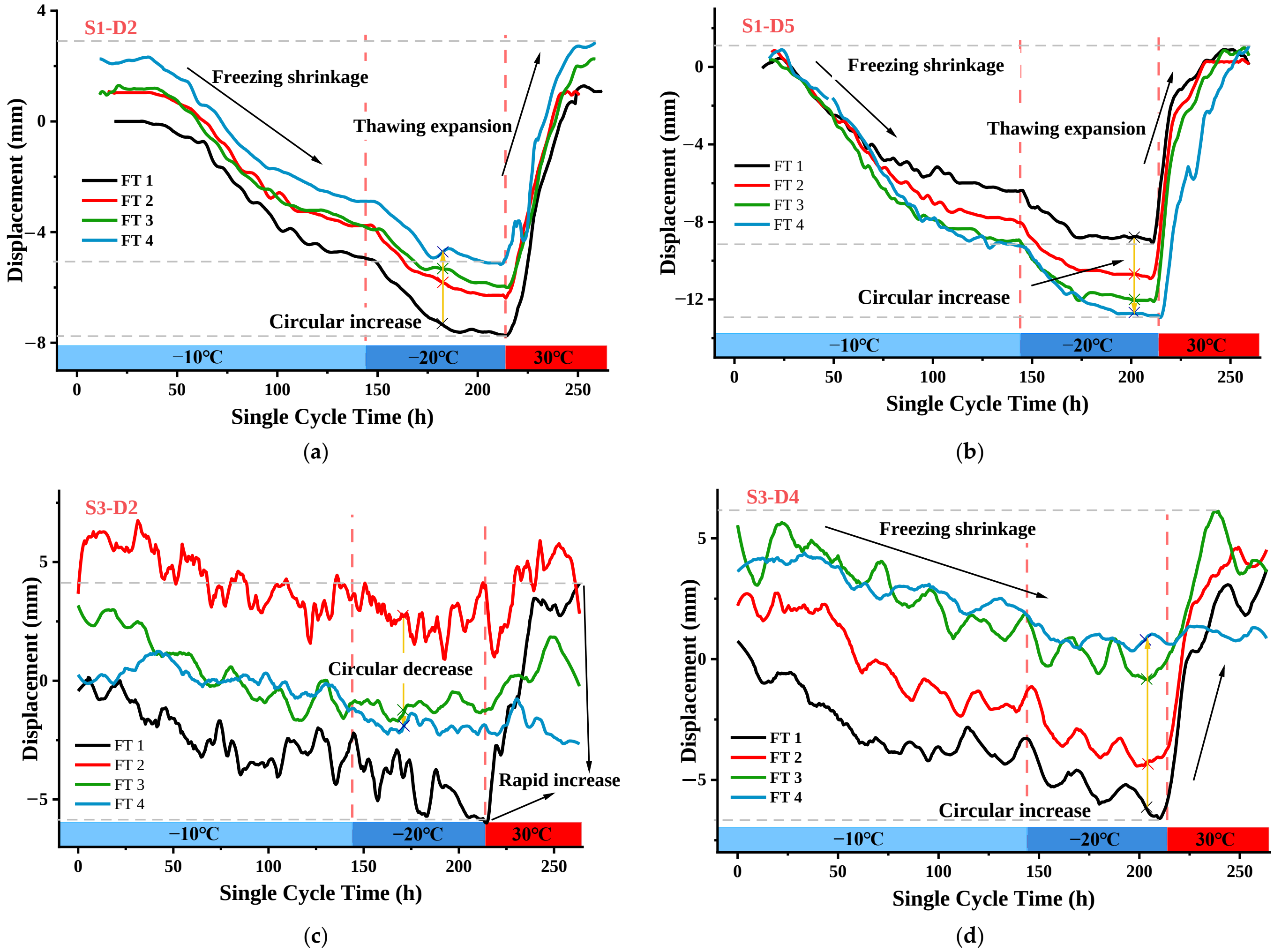


Figure 11. Displacement of the expansive soil slope model in four freeze-thaw cycles. (**a**) S1-D2; (**b**) S2-D5; (**c**) S3-D2; (**d**) S3-D4.

Fleureau [44] and Amarasiri [45] found that ice crystals appear in larger pores during freezing, forcing moisture from small pores to migrate to these crystals. However, due to the low porosity and permeability of cohesive soil, large negative pore pressure is formed, resulting in the drying and shrinkage of the soil skeleton. The pore size change of the initial structure promotes soil shrinkage under freezing conditions. For two reasons, the soil had enough shrinkage space, and the phenomenon of "freezing shrinkage" appeared in the test soil. There are two reasons for the phenomenon of "swelling". (1) During the freezing process, the moisture absorption expansion of dry shrinkage soil particles occupied the pores between soil particles expanded by solid ice. The moisture absorption and expansion of soil particles and the homogenization the effect of frost heaving force on the size of soil particles caused the soil particles to break, the soil structure to rearrange, and the pores to become larger; (2) solid ice becomes liquid moisture, and its volume becomes smaller. These two reasons led to the phenomenon of soil "swelling". Based on the freezing and thawing characteristics of expansive soil, we guess whether there is a certain moisture content to ensure that the expansion volume of water phase change in the freezing and thawing process can be roughly consistent with the water loss shrinkage volume of expansive soil, and the reduced volume of water melting in the melting stage can be roughly the same as the water absorption expansion volume of expansive soil. Combined with this possible method, it may have better engineering effect to use traditional admixtures such as cement, lime and fly ash to improve expansive soil.

4. Discussion

4.1. Analysis of Cracks during Freeze-Thaw Cycles

Expansive soil is a kind of plastic material. Fissure is the physical characteristic of expansive soil itself. When tensile stress is produced in the soil, the corresponding strain is produced by internal cohesion. When the tensile strain exceeds the limit, cracks will occur [46]. During the freezing process, the moisture content of expansive soil slope decreases rapidly, the free water in the expansive soil forms ice crystals, and the thickness of the moisture film on the surface of particles decreases, which leads to the shrinkage of expansive soil particles and tensile stress. Figure 12a is a schematic diagram of freeze-thaw cracks. During freezing, the temperature and moisture content of expansive soil at different depths are different, which leads to uneven stress between the upper and lower soils. When the stress difference between the upper and lower strata is greater than the tensile stress of expansive soil, cracks will occur. Lu et al. [24] studied the development process of cracks in expansive soil during the freeze-thaw cycle and proposed that the repeated formation of ice lens led to the generation of cracks. This was not observed in this test, which may be because Lu et al. [24] used expansive soil with a high moisture content (liquid limit), so ice lens was easy to produce during the freeze-thaw cycle. Li et al. [47] used CT to scan the development of cracks in the soil during the freeze-thaw cycle and found that cracks appeared in the soil when the cold front passed, which was consistent with the description in Figure 12a.

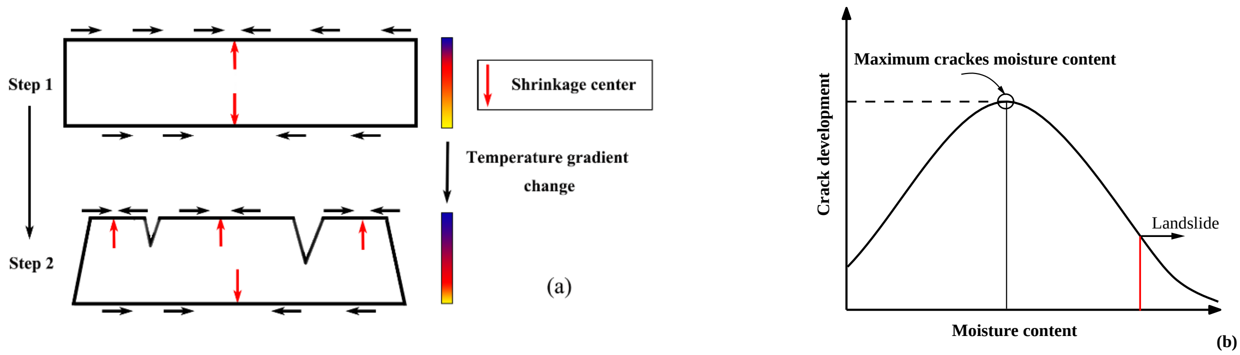


Figure 12. Crack development of the slope during freezing and thawing (**a**) formation process of freeze-thaw cracks; (**b**) relationship between cracks and moisture content in the freeze-thaw process.

When the expansive soil is frozen, the free moisture forms ice and its volume increases. Therefore, without considering moisture evaporation and ice sublimation, the development depth of cracks in expansive soil is related to its own expansibility and moisture content. The larger the free expansion rate of expansive soil is, the greater the moisture loss and shrinkage of soil particles in the freezing process, the greater the tensile stress in the slope and the greater the development speed of cracks. Figure 12b shows that cracks will not obviously develop during freezing and thawing when the moisture content of expansive soil is small. With an increase in moisture content, the moisture loss of soil particles in freezing is greater than the increase in ice volume, and cracks develop to a significant degree. When the moisture content of expansive soil is large enough, the cracks of the slope decrease gradually because the shrinkage of expansive soil particles is less than the volume increment of ice.

Compared with the fractures of three different slope ratios after freeze-thaw cycles (in Figure 6), the fracture development depth and width of S_1, S_2 and S_3 increased continuously. After freeze-thaw cycles, the fracture depth of S_2 was 1.1 times of S_1, and the width was 1.25 times that of S_1. The fracture depth of S_3 was 1.36 times that of S_1, and the width was 1.5 times of S_1. This is because: (1) during the freeze-thaw cycle, the angle between the slope and the top of the slope is small for the slope with large slope ratio, which easily forms a cold front invasion in both directions of the slope and the top of the slope. This causes the temperature gradient of the slope to increase, resulting in an increase in moisture migration. At the same time, it also leads to a significant difference between the surface and internal shrinkage of the slope, thus forming large cracks; (2) when cracks are formed, the component force of the soil gravity under the cracks in the slope surface direction is greater for slopes with larger slope ratios. The stress is transferred to the crack tip, which leads to a more obvious stress concentration, thus promoting the fracture to develop wider and deeper.

4.2. Displacement of the Slope Model in Freeze-Thaw Cycles and Its Microscopic Interpretation

From Figure 13, we can see that the displacement variation characteristics of the expansive soil slope during freeze-thaw cycling were as follows: (1) freezing shrinkage and thawing expansion occurred during freezing; (2) after freezing many times, the top of the slope dropped and the bottom of the slope rose, which indicates that there was a slow creep of the slope during the freezing process; that is, the soil particles shrank and slid downward. All displacements in this paper refer to vertical displacements. However, the slope surface and the top of the slope moved towards the free surface (displacement was positive) after several freeze-thaw cycles, which indicates that the pore structure in the slope was larger and the soil skeleton structure was looser. It can be seen from Figure 13 that with an increase in the slope ratio, the vertical displacement variation of the slope after several freeze-thaw cycles also increased, which indicates that the larger the slope ratio is, the greater the displacement of the slope in the freeze-thaw cycle is, and the worse the stability is.

The first displacement trend of the expansive soil slope was the same as the pore change trend of the slope model in the freeze-thaw cycles described in Section 3.1. That is, in the process of thawing, the porosity of expansive soil gradually decreased, and the slope displacement decreased; in the freezing process, it decreased first and then increased. However, during the remaining freeze-thaw cycle, the change trend of the two was opposite. This is because the moisture content of the two was different. In the nuclear magnetic resonance (NMR) test, the expansive soil samples must be in the saturated state, which leads to the phenomenon that the expansive soil particles shrink and the pores increase during the freezing process, while the expansive soil particles increase in the thawing process, but the consolidation settlement occurs. Differently from the saturated soil sample, for the expansive soil slope with low moisture content, the slope displacement fluctuates greatly during the freeze-thaw cycle, which eventually leads to the overall displacement to the free surface in the thawing stage, and the increase in slope ratio increases the displacement amplitude.

Therefore, for expansive soil slopes with high moisture content, the freeze-thaw cycling leads to the reorganization of the soil particle skeleton and a reduction in porosity, which is manifested as a decrease in the overall displacement. However, the expansive soil slope with low moisture content tends to free face (displacement is positive) after several freeze-thaw cycles, that is, the slope moves upward and the structure is looser. It can be speculated that between these two moisture contents, for a certain kind of expansive soil, there is a constant moisture content ω_s that causes the overall displacement of the slope to remain basically unchanged after several freeze-thaw cycles; that is, it reaches a stable state. It is suitable to maintain this saturation when the method of maintaining the moisture content is used to treat expansive soil in cold regions. For different kinds of expansive soil, displacement tests of freeze-thaw cycles under a moisture content gradient are needed to analyze ω_s. In practical engineering, controlling ω_s should have a good constraint effect on cracks.

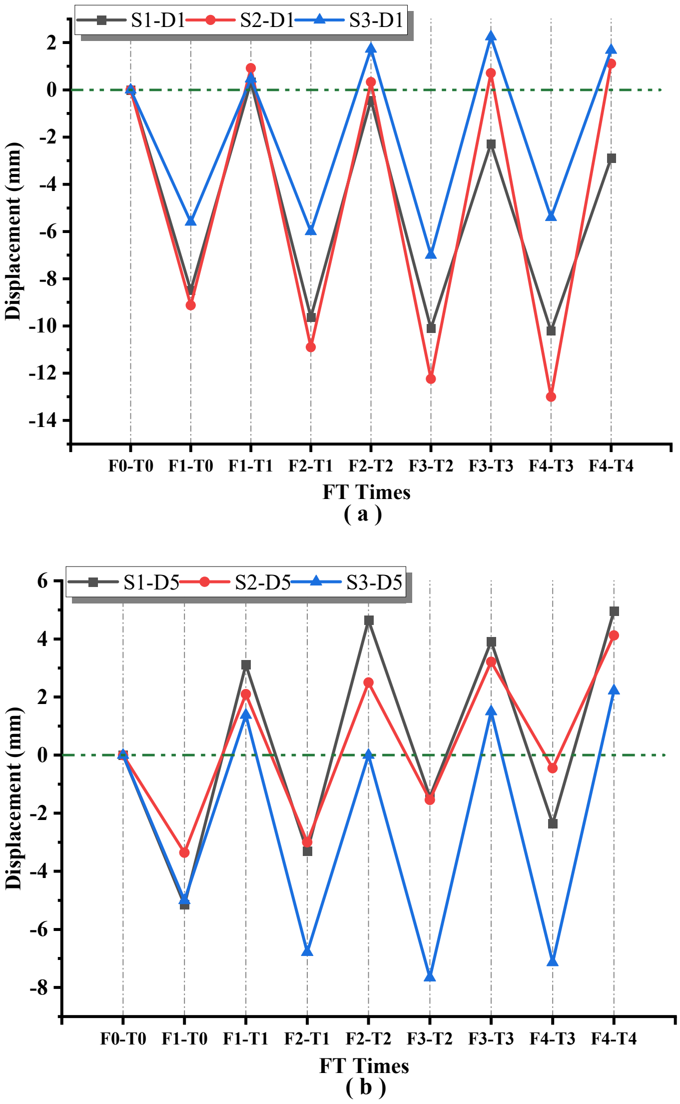


Figure 13. Slope displacement variation after freezing and thawing. (**a**) Slope bottom displacement; (**b**) slope top displacement.

4.3. Engineering Suggestions on Expansive Soil Slope in Seasonal Freezing Area

When using a finite element method to analyze expansive soil slopes in seasonal frozen zones or to deal with actual projects in this area, attention should be paid to the influence of slope ratio on slope stability, which is not only different from the calculation of the slope safety factor in the traditional sense. Due to the crack characteristics of expansive soils, the width and depth of cracks on slopes with larger slope ratios are larger, which is particularly important in finite element analysis because the path of external moisture entering the slope is increased. At the same time, it can be found that compared with the small slope ratio, the large slope is more temperature sensitive in the expansive soil slope, and the moisture content and temperature inside the slope change more dramatically. Therefore, in both modeling and practical engineering, additional safety factors should be added to the slope ratio. The absence of these changes may cause the calculation of slope support structure to be smaller. Finally, there is potential displacement creep for expansive soil slope in the freeze-thaw cycle, and there is a downward trend for expansive soil slope at all slope ratios.

The freeze-thaw cycle process of the slope is the freezing process, the cold front gradually invades the soil, and then gradually leaves the slope in the melting stage. The physical and mechanical properties of expansive soil in the area where the cold front is active have changed greatly, but there will be no significant change in the area where the cold front is not invaded. The intrusion of a cold front will lead to a loose slope structure and creep to the lower part of the slope, increase the risk of landslide and reduce the bearing capacity of the slope. Under the actual engineering conditions, there is replenishment and evaporation of external water sources in different seasons. Due to the uncertainty of rainfall and evaporation by air humidity and wind speed, the change of expansive soil slope in a freeze-thaw cycle under an open system should be more complex. However, as a freeze-thaw cycle, the sensors required for in situ tests are complex, and the cycle time takes one year. Many unpredictable risks are easy to occur in such a long-time dimension. Combining this test with the field expansive soil engineering, it is necessary to gradually increase the volume and internal stress of the slope, and the external complex environment should also be controlled, and a single variable should be discussed step by step. It is necessary to use some finite element simulations for the problem of expansive soil slopes in seasonally frozen areas and continue to study the indoor model test.

5. Conclusions

The stability of the expansive soil slope model is affected by surface cracks, displacement, internal moisture content and soil pressure changes during freeze-thaw cycles. With the increase in slope ratio, under the influence of frozen soil cycle, there is a risk that large slope ratio expansive soil slope is easily neglected in crack development and cold front intrusion speed, etc., as described below:

(1) Under freeze-thaw cycling, the slope surface of the expansive soil slope model will be weathered and a large number of cracks will be generated. The main cracks are formed and developed around the slope. The increase in slope ratio will lead to the further development of crack width and depth. The above phenomenon would cause external moisture to enter the inner conditions of the slope, resulting in the risk of landslide;

(2) In the process of freezing and thawing, the moisture in the slope will clearly move upward. During the freezing process, the moisture in the slope moves to the cold source and is fixed by the upper unsaturated expansive soil during the thawing process to increase migration, which eventually leads to the increase in the upper moisture content of the slope model after the freeze-thaw cycle. The slope ratio will affect the rate of heat transfer. The larger the slope ratio is, the faster the temperature transfer rate is, and the greater the value of the change in moisture content in the freeze-thaw cycle of the slope. The change in moisture content increases with the influence of segregation potential;

(3) In the process of freeze-thaw cycling, the skeleton of expansive soil is destroyed, which makes the slope structure looser, and finally leads to a decrease in the contact area of the soil pressure box and a decrease in soil pressure. However, combined with the increase in slope surface gravity caused by moisture migration, it is found that the weight of soil above the most dangerous sliding surface increases and the overturning moment increases. At the same time, the larger the slope ratio is, the greater the increase in the overturning moment of the most dangerous sliding surface;

(4) In the freeze-thaw cycle, the slope tends to develop towards the free face. In the freezing stage, downward creep of the slope occurs with the top falling and the bottom rising, and the increase in slope ratio will affect the variation in displacement. The results of nuclear magnetic resonance (NMR) results that the porosity of the saturated expansive soil decreases gradually in the thawing stage, increases first and then decreases in the freezing stage. The comparison of the above two results shows that the displacement of expansive soil can maintain a certain value after freeze-thaw cycling under the specific saturation ω_s of expansive soil.

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References

1. Jia, Z.G.; Li, F.R.; Li, K. Instability and Failure Mechanism of Slope in the Condition of Extreme Snow Hazard. *Appl. Mech. Mater.* **2013**, *353–356*, 208–212. [CrossRef]
2. Korshunov, A.; Doroshenko, S.P.; Nevzorov, A.L. The Impact of Freezing-thawing Process on Slope Stability of Earth Structure in Cold Climate. *Procedia Eng.* **2016**, *143*, 682–688. [CrossRef]
3. Subramanian, S.S.; Ishikawa, T.; Tokoro, T. Stability assessment approach for soil slopes in seasonal cold regions. *Eng. Geol.* **2017**, *221*, 154–169. [CrossRef]
4. Jones, L.D.; Jefferson, I. *Expansive Soils*; ICE Publishing: London, UK, 2012; pp. 413–441.
5. Suits, L.D.; Sheahan, T.; Prakash, K.; Sridharan, A. Free Swell Ratio and Clay Mineralogy of Fine-Grained Soils. *Geotech. Test. J.* **2004**, *27*, 220–225. [CrossRef]
6. Li, T.; Kong, L.; Liu, B. The California Bearing Ratio and Pore Structure Characteristics of Weakly Expansive Soil in Frozen Areas. *Appl. Sci.* **2020**, *10*, 7576. [CrossRef]
7. Luo, J.; Tang, L.; Ling, X.; Geng, L. Experimental and analytical investigation on frost heave characteristics of an unsaturated moderately expansive clay. *Cold Reg. Sci. Technol.* **2018**, *155*, 343–353. [CrossRef]
8. Lu, Y.; Liu, S.; Alonso, E.; Wang, L.; Xu, L.; Li, Z. Volume changes and mechanical degradation of a compacted expansive soil under freeze-thaw cycles. *Cold Reg. Sci. Technol.* **2019**, *157*, 206–214. [CrossRef]
9. Tang, L.; Cong, S.; Geng, L.; Ling, X.; Gan, F. The effect of freeze-thaw cycling on the mechanical properties of expansive soils. *Cold Reg. Sci. Technol.* **2018**, *145*, 197–207. [CrossRef]
10. Yang, Z.; Zhang, L.; Ling, X.; Li, G.; Tu, Z.; Shi, W. Experimental study on the dynamic behavior of expansive soil in slopes under freeze-thaw cycles. *Cold Reg. Sci. Technol.* **2019**, *163*, 27–33. [CrossRef]
11. Guo, Y.; Shan, W. Monitoring and Experiment on the Effect of Freeze-Thaw on Soil Cutting Slope Stability. *Procedia Environ. Sci.* **2011**, *10*, 1115–1121. [CrossRef]
12. Hazirbaba, K.; Zhang, Y.; Hulsey, J.L. Evaluation of temperature and freeze-thaw effects on excess pore pressure generation of fine-grained soils. *Soil Dyn. Earthq. Eng.* **2011**, *31*, 372–384. [CrossRef]
13. Wang, T.; Li, P.; Li, Z.; Hou, J.; Xiao, L.; Ren, Z.; Xu, G.; Yu, K.; Su, Y. The effects of freeze-thaw process on soil water migration in dam and slope farmland on the Loess Plateau, China. *Sci. Total Environ.* **2019**, *666*, 721–730. [CrossRef] [PubMed]
14. Ng, C.W.W.; Zhan, L.T.; Bao, C.G.; Fredlund, D.G.; Gong, B.W. Performance of an unsaturated expansive soil slope subjected to artificial rainfall infiltration. *Géotechnique* **2003**, *53*, 143–157. [CrossRef]
15. Khan, M.S.; Hossain, S.; Ahmed, A.; Faysal, M. Investigation of a shallow slope failure on expansive clay in Texas. *Eng. Geol.* **2017**, *219*, 118–129. [CrossRef]
16. Chen, T.-L.; Zhou, C.; Wang, G.-L.; Liu, E.-L.; Dai, F. Centrifuge Model Test on Unsaturated Expansive Soil Slopes with Cyclic Wetting–Drying and Inundation at the Slope Toe. *Int. J. Civ. Eng.* **2018**, *16*, 1341–1360. [CrossRef]
17. Zhang, C.; Cai, Z.-Y.; Huang, Y.-H.; Chen, H. Laboratory and Centrifuge Model Tests on Influence of Swelling Rock with Drying-Wetting Cycles on Stability of Canal Slope. *Adv. Civ. Eng.* **2018**, *2018*, 4785960. [CrossRef]
18. Silvani, C.; Lucena, L.; Guimarães Tenorio, E.; Filho, H.C.S.; Consoli, N.C. Key Parameter for Swelling Control of Compacted Expansive Fine-Grained Soil-Lime Blends. *J. Geotech. Geoenviron. Eng.* **2020**, *146*, 06020012. [CrossRef]
19. Nowamooz, H.; Masrouri, F. Hydromechanical behaviour of an expansive bentonite/silt mixture in cyclic suction-controlled drying and wetting tests. *Eng. Geol.* **2008**, *101*, 154–164. [CrossRef]
20. Wang, N.; Zhang, W.; Gu, X.; Zeng, Y. Model Test on Inundation Swelling Deformation of Expansive Soil Foundation. *J. Highw. Transp. Res. Dev. (Engl. Ed.)* **2008**, *3*, 72–76. [CrossRef]

21. Cheng, Z.L.; Ding, J.H.; Rao, X.B.; Cheng, Y.; Xu, H. *Physical Model Tests of Expansive Soil Slope*; Geo-Congress: San Diego, CA, USA, 2013. [CrossRef]
22. Zhang, M.; Zhang, X.; Lu, J.; Pei, W.; Wang, C. Analysis of volumetric unfrozen water contents in freezing soils. *Exp. Heat Transf.* **2018**, *32*, 426–438. [CrossRef]
23. Khattab, S.A.; Al-Mukhtar, M.; Fleureau, J.-M. Long-Term Stability Characteristics of a Lime-Treated Plastic Soil. *J. Mater. Civ. Eng.* **2007**, *19*, 358–366. [CrossRef]
24. Lu, Y.; Liu, S.; Weng, L.; Wang, L.; Li, Z.; Xu, L. Fractal analysis of cracking in a clayey soil under freeze-thaw cycles. *Eng. Geol.* **2016**, *208*, 93–99. [CrossRef]
25. Wang, Y.-X.; Guo, P.; Ren, W.-X.; Yuan, B.-X.; Yuan, H.-P.; Zhao, Y.; Shan, S.-B.; Cao, P. Laboratory Investigation on Strength Characteristics of Expansive Soil Treated with Jute Fiber Reinforcement. *Int. J. Géoméch.* **2017**, *17*, 04017101. [CrossRef]
26. Li, Y.-X.; Yang, X.-L. Stability analysis of crack slope considering nonlinearity and water pressure. *KSCE J. Civ. Eng.* **2015**, *20*, 2289–2296. [CrossRef]
27. Wu, L.; Huang, R.; Xu, Q.; Zhang, L.; Li, H.L. Analysis of physical testing of rainfall-induced soil slope failures. *Environ. Earth Sci.* **2015**, *73*, 8519–8531. [CrossRef]
28. ASTM D698-12e2. *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft–lbf/ft3 (600 kN–m/m3))*; ASTM International: West Conshohocken, PA, USA, 2012. [CrossRef]
29. Teng, J.; Shan, F.; He, Z.; Zhang, S.; Zhao, G.; Sheng, D. Experimental study of ice accumulation in unsaturated clean sand. *Géotechnique* **2019**, *69*, 1–32. [CrossRef]
30. Xu, X.; Wang, B.; Fan, C.; Zhang, W. Strength and deformation characteristics of silty clay under frozen and unfrozen states. *Cold Reg. Sci. Technol.* **2020**, *172*, 102982. [CrossRef]
31. Azañón, J.M.; Azor, A.; Yesares, J.; Tsige, M.; Mateos, R.M.; Nieto, F.; Delgado, J.; Chicano, M.L.; Martín, W.; Rodríguez-Fernández, J. Regional-scale high-plasticity clay-bearing formation as controlling factor on landslides in Southeast Spain. *Geomorphology* **2010**, *120*, 26–37. [CrossRef]
32. ASTM D854-14. *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer*; ASTM International: West Conshohocken, PA, USA, 2014. [CrossRef]
33. ASTM D2216-19. *Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*; ASTM International: West Conshohocken, PA, USA, 2019. [CrossRef]
34. ASTM D4318-17e1. *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*; ASTM International: West Conshohocken, PA, USA, 2017. [CrossRef]
35. Xu, L.; Xue, Y.; Lu, Y.; Song, Y.J.; Zhang, Y.Z.; Kong, W.Y. Test of freeze- thaw cycle of expansive soil under condition of different freezing temperatures. *J. Water Resour. Water Eng.* **2016**, *27*, 189–1939. (In Chinese) [CrossRef]
36. Qin, Z.; Lai, Y.; Tian, Y.; Zhang, M. Stability behavior of a reservoir soil bank slope under freeze-thaw cycles in cold regions. *Cold Reg. Sci. Technol.* **2021**, *181*, 103181. [CrossRef]
37. Chernyshov, C.H. *Water Movement in Fracture Network*; Geological Publishing House: Beijing, China, 1987. (In Chinese)
38. Miller, R.D. Freezing and heaving of saturated and unsaturated soils. *Highw. Res. Rec.* **1972**, *393*, 1–11. Available online: https://trid.trb.org/view/126419 (accessed on 15 July 2021).
39. Konrad, J.-M.; Morgenstern, N.R. A mechanistic theory of ice lens formation in fine-grained soils. *Can. Geotech. J.* **1980**, *17*, 473–486. [CrossRef]
40. Takashi, T.; Ohrai, T.; Yamamoto, H.; Okamoto, J. Upper Limit of Heaving Pressure Derived by Pore-Water Pressure Measurements of Partially Frozen Soil. *Fundam. Discret. Elem. Methods Rock Eng.—Theory Appl.* **1982**, *28*, 245–257. [CrossRef]
41. Wang, D.; Yang, C.; Cheng, G.; Ma, W.; Zhang, L. Experimental Study on Pore Water Pressure and Microstructures of Silty Clay Under Freeze-Thaw Cycles. *Lect. Notes Civ. Eng.* **2020**, *2*, 239–254. [CrossRef]
42. Tang, L.Y.; Yang, D.; Liu, L.; Jin, L.; Yang, L.; Li, G. Effect mechanism of unfrozen water on the frozen soil-structure interface during the freezing-thawing process. *Geomech. Geoeng.* **2020**, *22*, 245–254. [CrossRef]
43. Hamilton, A.B. Freezing Shrinkage in Compacted Clays. *Can. Geotech. J.* **1966**, *3*, 1–17. [CrossRef]
44. Fleureau, J.-M.; Kheirbek-Saoud, S.; Soemitro, R.; Taibi, S. Behavior of clayey soils on drying–wetting paths. *Can. Geotech. J.* **1993**, *30*, 287–296. [CrossRef]
45. Amarasiri, A.L.; Kodikara, J.K.; Costa, S. Numerical modelling of desiccation cracking. *Int. J. Numer. Anal. Methods Géoméch.* **2011**, *35*, 82–96. [CrossRef]
46. Shi, B.-X.; Chen, S.-S.; Han, H.-Q.; Zheng, C.-F. Expansive Soil Crack Depth under Cumulative Damage. *Sci. World J.* **2014**, *2014*, 498437. [CrossRef]
47. Li, J.; Wang, F.; Yi, F.; Wu, F.; Liu, J.; Lin, Z. Effect of Freeze-Thaw Cycles on Triaxial Strength Property Damage to Cement Improved Aeolian Sand (CIAS). *Materials* **2019**, *12*, 2801. [CrossRef]