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Research Article

Experimental Study on Frost-Heaving Force Development of Tibetan Clay Subjected to One-Directional Freezing in an Open System

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Frost heave of soils involves complex coupled interactions among moisture, heat, and stress, which can cause serious damage to cold regions engineering. In this paper, a series of one-directional freezing experiments were implemented for the Tibetan clay with rigid restraint in an open system. The varying characteristics of the temperature, frost-heaving force, and water replenishment during the freezing process were analyzed under different freezing temperatures (−5, −7, and − 9°C), dry densities (1.65, 1.7, and 1.75 g cm^{-3}), and initial moisture contents (11, 14, and 17%) of the soil samples. It was concluded that the freezing of soil samples mainly occurred within 10–25 hours from the beginning of the experiment; hereafter, the soil temperatures tended to be stable. The development of frost-heaving force could be divided into three stages as slow increase, quick increase, and relative stable stages. Low freezing temperature, large dry density, and high moisture content were all the contributors to the frost-heaving process of the soil, which could increase the freezing depth, magnitude of the frost-heaving force, and amount of water replenishment. The variations in water replenishment from the open system corresponded to the three stages of the frost-heaving force but had time lags. The moisture contents at different layers of soil samples were measured after the freezing experiment. The results showed that the freeze part of soil samples experienced a significant wetting, while the unfrozen part experienced drying during the experiment. The degrees of wetting and drying were related to the freezing temperature, dry density, and initial moisture content of the soil samples. The experiment results could provide data support for theoretical study on moisture, heat, and stress coupling in freezing soil.

1. Introduction

Frost heave of soils can cause serious damage to various engineering infrastructures built in cold regions [1, 2]. When the temperature of soil decreases to the freezing point, the soil starts to freeze, accompanied by the formation of various types of ice from the pore water, as well as the external water that migrated into the soil. The ice types involve different shapes, such as polycrystals, lens bodies, split ice, and interlayer ice, which all contribute to the increase of soil volume and eventually lead to uneven heave on the ground surface [3, 4]. The frost heave behavior of soils can be illustrated and expressed as two indices, one is the deformation index which means the deformation amount caused by the frost heave, and the other is a mechanical index which is generally known as the frost-heaving force.

In previous researches, one-directional freezing experiments were widely carried out to study the frost heave behavior of soils and its impact factors including the particle-size composition, mineral composition, freezing temperatures, moisture content, density and salinity of soils, and external loads [5]. Tatlor et al. [6] and Li et al. [7] studied the frost-heaving amounts of clay and sand under one-dimensional freezing condition. The results showed that the clay with small particle size had a small frost-heaving amount due to its lower permeability, while the sand with large particle size had a thin unfrozen water film after freezing, which also led to a small frost-heaving amount. Jin et al. [8] used a newly developed temperature-controlled system to conduct frost-heaving experiments and studied the frost-heaving amount of sand under different freezing temperatures. O'Neill et al. [9] established a numerical model to simulate the frost-heaving of saturated granular without air and solute and verified the model through frost-heaving experiments under different loads. Zhou et al. [10] carried out intermittent and continuous frost-heaving experiments on silty clay and found that the frost-heaving amount under the intermittent freezing was less than that under the continuous freezing. Zhang et al. [11] carried out one-directional freezing experiments on sandstone-weathered soil and analyzed the influences of moisture content and dry density on the frost-heaving amount. The amount of frost-heaving amount can also be quantified by the process of water migration and frost-heaving rate [12–17].

Comparing to the deformation amount caused by the frost heave, there are more factors which play a role in the magnitude of the frost-heaving force and make the experiment results unstable because of the limited experiment equipment and technologies. Penner [18] carried out one-dimensional freezing experiments on clay, and the results showed that the frost-heaving force increased with the decreasing freezing temperature. Abzhalimov et al. [19] studied the frost-heaving force under different external loads and obtained the exponential relationship between the external load and frost-heaving force. Ji et al. [20] carried out one-dimensional freezing experiments on the undisturbed silty clay and found that the frost-heaving force decreased with the increasing density of soil sample. Kinosita [21] carried out frost-heaving experiments on sand and clay and found that the frost-heaving force of both clay and sand decreased with the decreasing freezing rate and the calculation formula of frost-heaving force was proposed by treating the frozen and unfrozen soil as viscoelastic bodies. Li et al. [22] analyzed the influences of moisture content, compactness, freezing temperature, and other factors on the frost-heaving force of soil. Tang et al. [23] studied the frost-heaving force of muddy clay under artificial freezing conditions.

In engineering practice, the frost heave of soil is generally restrained by adjacent geostructures. However, up to date, the frost heave behaviors of soil with restraints were not evaluated well. In this paper, the temperature field, frost-heaving force, and water replenishment during freezing process and the distribution characteristics of moisture contents in the soil after the freezing were studied based on a series of one-directional freezing experiments with rigid restraint in an open system. The conclusions are assumed to be data references for theoretical study on moisture, heat, and stress coupling in frost heave process of soils.

2. Experimental Materials and Methods

2.1. Tibetan Clay. The Tibetan clay is the experimental soil used in this research, The soil was collected at the Beiluhe Basin (34.51°N, 92.56°E), the interior of the Qinghai-Tibet Plateau [24], from the depths of 0.5 to 2.5 m. In order to obtain the index properties of the soil, a series of tests for particle screening, boundary moisture content, and compaction were carried out. The results are listed in Table 1 and shown in Figure 1. For the experimental soils, the plasticity and liquid limits are 14.12% and 22.9%, respectively, and the mass percentage of sand with grain size greater than 0.075 mm is 15.88%. Thus, the soil sample was determined as low liquid-limit clay according to the Code for the Design of Railway Subgrade [25].

2.2. Experimental Equipment. The equipment for this frost-heaving experiment in the lab is shown in Figure 2, which is composed of the temperature system, water replenishment system, test system, and other parts.

2.2.1. The Temperature Control System. This equipment can simulate the cycle environment of low temperature and load. The temperatures on the top and bottom cold-bath plates where the soil samples will experience the freeze-thaw cycle are put under control, and the temperatures in the test chamber are controlled by the air-cooling system. The working principle of the air-cooling system is to limit the air discharge per unit of time and then input the cold-source air by using a cold-source pump. By circulating the antifreezing fluid in the top and bottom cold-bath plates, the temperatures for the upper and bottom ends of the soil samples can be controlled separately. The controlled temperatures in the test chamber and those on the top and bottom cold-bath plates are in a range of −60 to 40°C, and the accuracies of the temperature control are ±0.01°C for parts on the bottom and top-plates and ±0.05°C for the test chamber, respectively.

2.2.2. The Test System. The test system integrates the loading and measurement of the force, displacement, and the control of the equipment. The equipment can put load on the top of soil sample, and the loading piston can move up and down freely or can be fixed to achieve displacement limitation. An electric-fluid servosystem controls the movement of the loading piston. The measurement for the load ranges up to 30 kN. The accuracy is ±0.1 N for the load-measurement device and is ±0.01 mm for the displacement-measurement device.

2.2.3. The Water Replenishment System. This part is the Markovian bottle with a measurement of 0–360 mL, made of organic glass. In the freezing process, the water replenishment to the soil will make the water level in the Markov bottle drop down, and the amount of the water replenishment was calculated by the dropping levels.

2.2.4. Other Parts. The sample-loading device is made of organic glass with a height of 200 mm, an inner diameter of 101 mm, and a wall thickness of 25 mm. The organic-glass device is good at thermal insulation and high strength. There

TABLE 1: Index properties of the experimental soil.

ρ_{dmax} ($g\cdot cm^{-3}$)	ω_{opt} (%)	ω_P (%)	ω_L (%)	PI
1.95	11.08	14.12	22.9	8.78

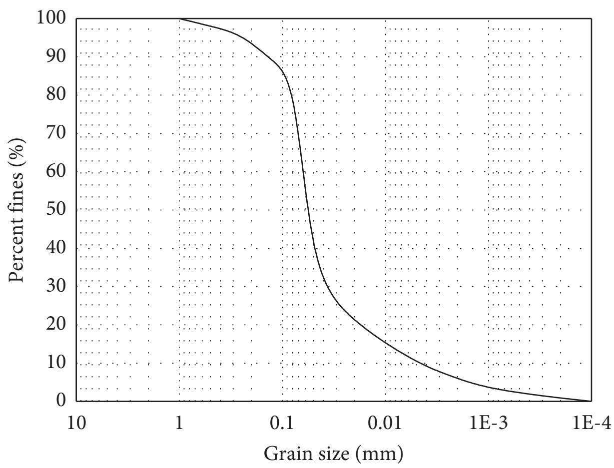

FIGURE 1: Grading curve of the experimental soil.

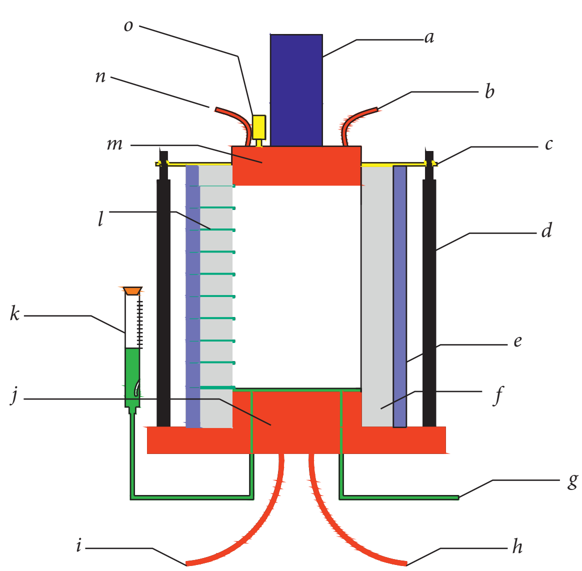

FIGURE 2: Sketch of the experimental equipment. (a) Loading piston; (b) cold-bath outlet; (c) ferrule; (d) fixed rod; (e) insulation layer; (f) sample-loading device; (g) drain hole; (h) cold-bath outlet; (i) cold-bath inlet; (j) bottom cold-bath plate; (k) Markovian bottle; (l) thermistor probe; (m) top cold-bath plate; (n) cold-bath inlet; (o) displacement transducer.

were holes drilled on the side wall to lay the thermistor sensors and monitor the variations in the temperatures inside the soil samples. The interval between the holes, vertically and horizontally, was 1.38 cm. The thermistor sensors had an accuracy of ±0.1°C and a measuring scope of −30 ~+30°C. A total of 10 thermistor sensors were installed from the top to the bottom of the soil sample.

2.3. The Experimental Scheme. This experiment is a one-directional freezing test in an open system, and the freezing time of the soil sample was set up as 72 hours. Before starting the experiment, the soil samples were prepared according to the requirements of the experimental design, mainly the parameters of dry density and moisture content. Firstly, a certain amount of water was added into the soil to make the moisture content of the soil reach the experimental design value. Then, the mixture was placed in an airtight container for 24 h to ensure a homogeneous moisture content within it. Finally, the weighted mixture was put into a plexiglass mold and hammered in layers by a plane hammer until the designed height was obtained. The height of the soil sample was 125 mm, and the diameter was 101 mm. Right after the soil sample was put into the device, the thermistor sensors were inserted into the holes on the side wall of the device, and then adjust the location of the Markovian bottle in the chamber, and put the ferrule and fix the sample device. Before the freezing, both the temperature of the chamber and the top-plate and bottom-plate were set up as +2°C. When the temperatures inside the soil sample reached +2°C, the freezing process was launched.

First, turn the displacement-control program on as a rigid constraint and then manually adjust the temperature of the top cold-bath plate to the designed temperature, while turn the water replenishment system on. The temperatures from the sensors and the water-level data from the Markov bottle were collected during the experiment. When the experiment was over, the variations in the frost-heaving force were collected and stored. The soil sample was taken out of the chamber and sliced into layers with 1 cm in thickness. The moisture content from each layer was measured.

The experimental scheme is listed in Table 2, and three factors including the freezing temperature at the top cold-bath plate, initial moisture, and dry density of samplers were considered in the experiment.

3. Results and Analysis

3.1. The Freezing Process of Soil Samples. Figure 3 indicates the changes of the temperatures in the soil samples during the freezing process of the experiment with different freezing temperature conditions. The freezing temperature of the experimental soil is −0.17°C; thus, the temperature profile inside of the soil samples could be approximately divided into two sections, unfrozen section and frozen section.

There was an obvious relationship between the temperature changes in the soil and the temperatures at the top cold-bath plate. At the beginning of the freezing, there was a slightly overcooling that occurred in the soil when the top-plate temperature was −5°C. When this temperature was −7 to −9°C, there was totally no overcooling that occurred in the soil. The temperature-descending process of the soil could be divided into rapid-freezing, transit-freezing, and stable-freezing stages. When the top-plate temperature was set up as −5°C, the rapid-freezing stage mainly occurred in the first 4 hours; then, the soil temperature went into the transit-freezing stage until the 25 hours. While the top-plate

Table 2: The experimental scheme.

Sample group	Freezing temperature (°C)	Initial moisture content of samples (%)	Dry density of samples (g•cm^{-3})
1	−5		
2	−7	17	1.75
3	−9		
4			1.65
5	−7	17	1.7
6			1.75
7		11	
8	−7	14	1.75
9		17	

temperature was set up as −7°C, the first stage lasted in the first 4 hours and the third stage began at the 16 hours. When the top-plate temperature was set up as −9°C, the total lasting time of the first two stages was only about 10 hours.

Figures 4 and 5 show the changes of the temperatures in the soil samples during the freezing process of the experiment with different dry densities and initial moisture contents. It can be seen that, with the same temperature on the top-plate, the variations in the temperatures of the soils with different dry densities (Figure 4) and initial moisture contents (Figure 5) were pretty similar to each other. The general trend that featured the temperature decreased from top to bottom gradually, and the location of the frozen line was close when the experiments were over. This means that, compared to the top-plate temperature, the influences of dry density and initial moisture content on the freezing process of soil samples were very slight.

3.2. The Freezing Depths of Soil Samples. The frozen depth refers to the distance from the freezing-front to the top of the soil sample. When the freezing-front arrived at its stable spot as the time went on, the freezing depth of the soil reached the maximum which could be regarded as the frozen depth.

In Figure 6(a), it can be seen that the freezing depth increased when the temperature on the top-plate decreased. When the top-plate temperature was −9°C, the changing speed of the freezing depth was obviously greater than that when the top-plate temperatures were −5 and −7°C, respectively. Furthermore, the first two periods were a little shorter when the top-plate temperature was −9°C compared to those with the top-plate temperatures of −5 and −7°C. As the experiment kept on going, the soil entered the transit-freezing period. In this period, the scope of the heat transfer enlarged, and the heat transfer gradually fell into the balance status [26]. Along with the developing rate of the freezing-front-edge that decreased, the time that made the front-edge reach the top-plate shortened. When a new balanced condition was obtained, the front-edge stopped moving forward. More heat transfer occurred when the temperature of the soils was lower, accompanied by the greater freezing depth obtained [27]. The frozen depths were 6.3, 9.13, and 9.84 cm when the temperatures on the top-plate were set up as – 5, −7, and −9°C, respectively. Figures 6(b) and 6(c) show the varying curves of freezing depths with time when different dry densities and initial moisture contents of soil samples were used in the experiment. It can be seen that the frozen depth increased as the dry density and initial moisture content increased, but the scope of the increase was not big.

3.3. The Frost-Heaving Force during the Freezing. Figure 7 indicates the changes of the frost-heaving forces during the freezing process of the experiment with different top-plate temperatures, dry densities, and initial moisture contents. The variations in frost-heaving force with time could also be divided into three stages, slow-development stage, the rapid-increase stage, and steady-development stage.

Temperature is one of the most important factors which affects the frost-heaving force of the Tibetan clay soil type, and the variations in the frost-heaving force under different temperature conditions are different, as shown in Figure 7(a). At the beginning of the freezing period, the occurrence of the frost-heaving force originated from the in site frozen-and-heave action because there was no water migration and the corresponding frozen-and-heave action [28]. When the temperature was low, the temperature conduction was faster, which led to a faster freezing. When a large amount of water started to freeze, the free water in the soil which means the water not affected by the attraction of soil particles and the surface tension from the liquid surface, named as capillary force, began to freeze firstly [29]. In this stage, there was less moisture content in the soil, so this stage was related to the freezing rate. The lower the temperature was, the faster the freezing rate was, and the development of the frost-heaving force would be faster in the soils with higher temperature. With the water replenishment condition, the ice content inside the soil increased rapidly as the temperature decreased. When the frost deformation of the soils was restrained, the frost-heaving force is the resistance of the soil to the load above and both of them have the same amount but are in opposite directions. As a result, the frost-heaving increased rapidly at this stage. When the frost-and-heave process finished, the magnitude of the frost-heaving force did not change with time considerably and stayed in a relatively stable status. From Figure 7(a), it can be seen that the lower the temperature was, the faster the frost-heaving force development was. When the temperatures on the top-plate were set up as – 5, −7, and −9°C in the experiments, the amounts of the frost-heaving force obtained correspondingly were 244.3, 284.2, and 313.0 kPa when the experiments were finished.

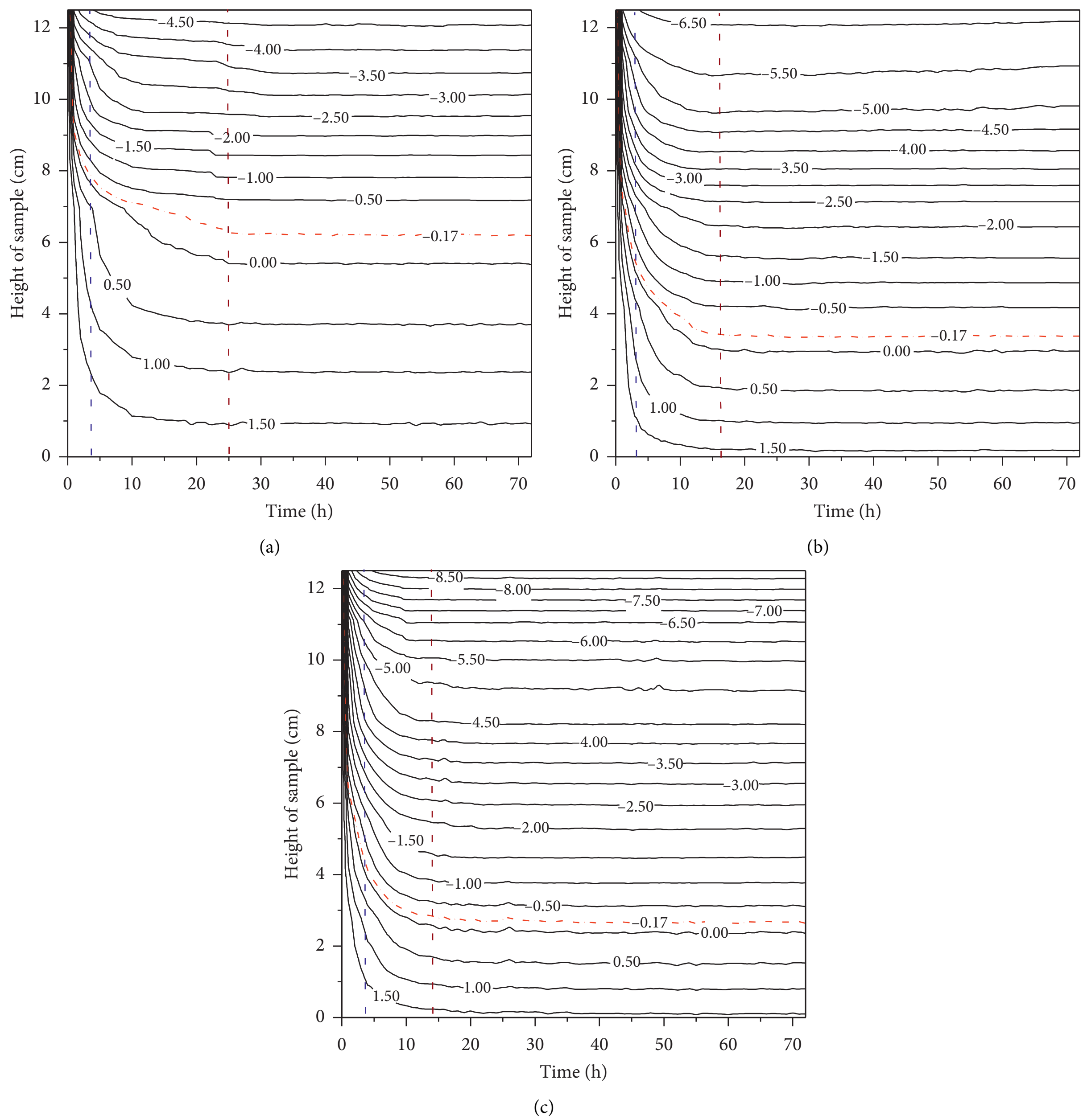

FIGURE 3: The temperature changes in soil samples under different top-plate temperatures. (a) $T_{top} = -5°C$, $\rho_d = 1.75\ g•cm^{-3}$, and $\omega = 17\%$; (b) $T_{top} = -7°C$, $\rho_d = 1.75\ g•cm^{-3}$, and $\omega = 17\%$; (c) $T_{top} = -9°C$, $\rho_d = 1.75\ g•cm^{-3}$, and $\omega = 17\%$.

Figure 7(b) shows the development process of the frost-heaving force in the experiment under different dry density conditions. The bigger the dry density was, the more the amount of soil particles was and the less the space between the soil particles was and then the stronger the soil-water potential would be. Accordingly, there is less unfrozen water which participates in the frost-heaving force development. It can be seen from Figure 7(b) that the frost-heaving force increased with the increase of the dry density of the soil. The amounts of the frost-heaving force were 142.9, 199.3, and 284.2 kPa, respectively, when the experiments were finished, corresponding to the dry densities of 1.65, 1.7, and 1.75 $g\,cm^{-3}$ used in the experiments. Although the development of the frost-heaving force was in the steady stage when the dry density was 1.65 and 1.7 $g\,cm^{-3}$, respectively, at the end of the experiment, the increase of the frost heave force in this stage was very slow. Meanwhile, the soil samples with greater dry density reached the rapid-increase development stage of the frost heave force firstly and tended to be stable earlier.

Figure 7(c) shows the development process of the frost-heaving force in the experiments with different moisture contents in the soils. It can be seen that the initial moisture contents in the soil also had a remarkable impact on the development of the frost-heaving force provided all the other conditions were the same. Within an open system, the

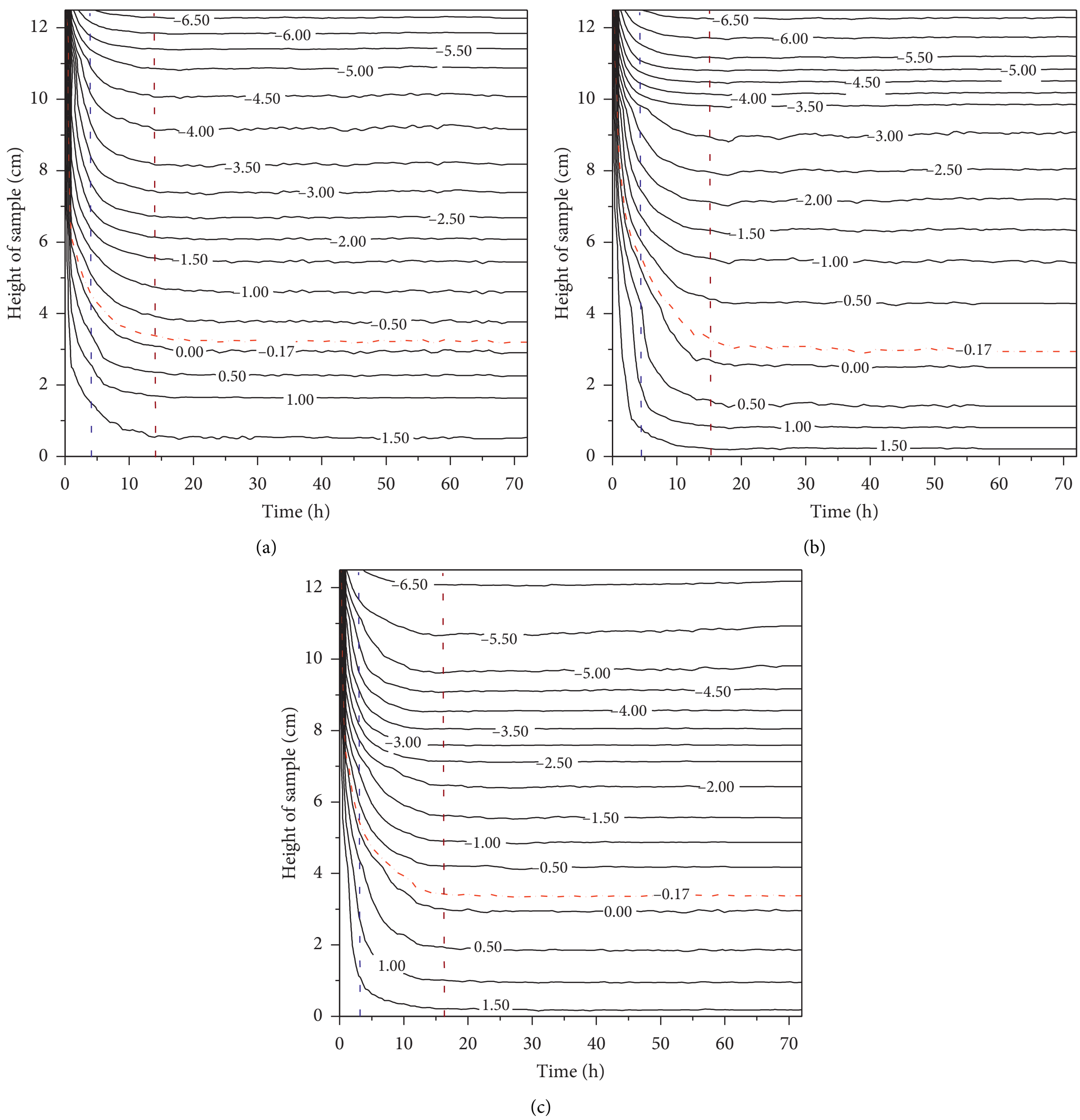

Figure 4: The temperature changes in soil samples with different dry densities. (a) $\rho_d = 1.65$ g•cm^{-3}, $T_{top} = -7$°C, and $\omega = 17\%$; (b) $\rho_d = 1.70$ g•cm^{-3}, $T_{top} = -7$°C, and $\omega = 17\%$; (c) $\rho_d = 1.75$ g•cm^{-3}, $T_{top} = -7$°C, and $\omega = 17\%$.

magnitude of the frost-heaving force obtained from the experiment by taking the soil sample with an initial moisture content of 17% was obviously greater than the soil samples with the initial moisture content of 14 and 1%. Furthermore, during the two stages of the slow-development and the rapid-increase development of the frost-heaving force, the soil sample with the initial moisture content of 17% produced a greater rate of the increasing force than the other two initial moisture contents. This can be explained as the in site freezing heave was the main type of the frost-heaving in the soil at the beginning period of the freezing, and the soil samples with higher moisture content will produce more frost-heaving force. In the period of rapid-increase development of the frost-heaving force, with the water replenishment condition, the lower the moisture content was, the weaker the frost-heaving force from the replenished water in the soil would be. When the experiments finished, the magnitude of the frost-heaving force produced in the experiments with the initial moisture content of 17, 11, and 14% was 189.4, 231.8, and 284.2 kPa, respectively.

3.4. The Amount of Water Replenishment during the Freezing. The water level in the Markovian bottle kept moving down when the tested soil was in the freezing process, which meant that the water migrated from the Markov bottle to the soil samples. Similar to the varying process of the development of the frost-heaving force, the process of the water

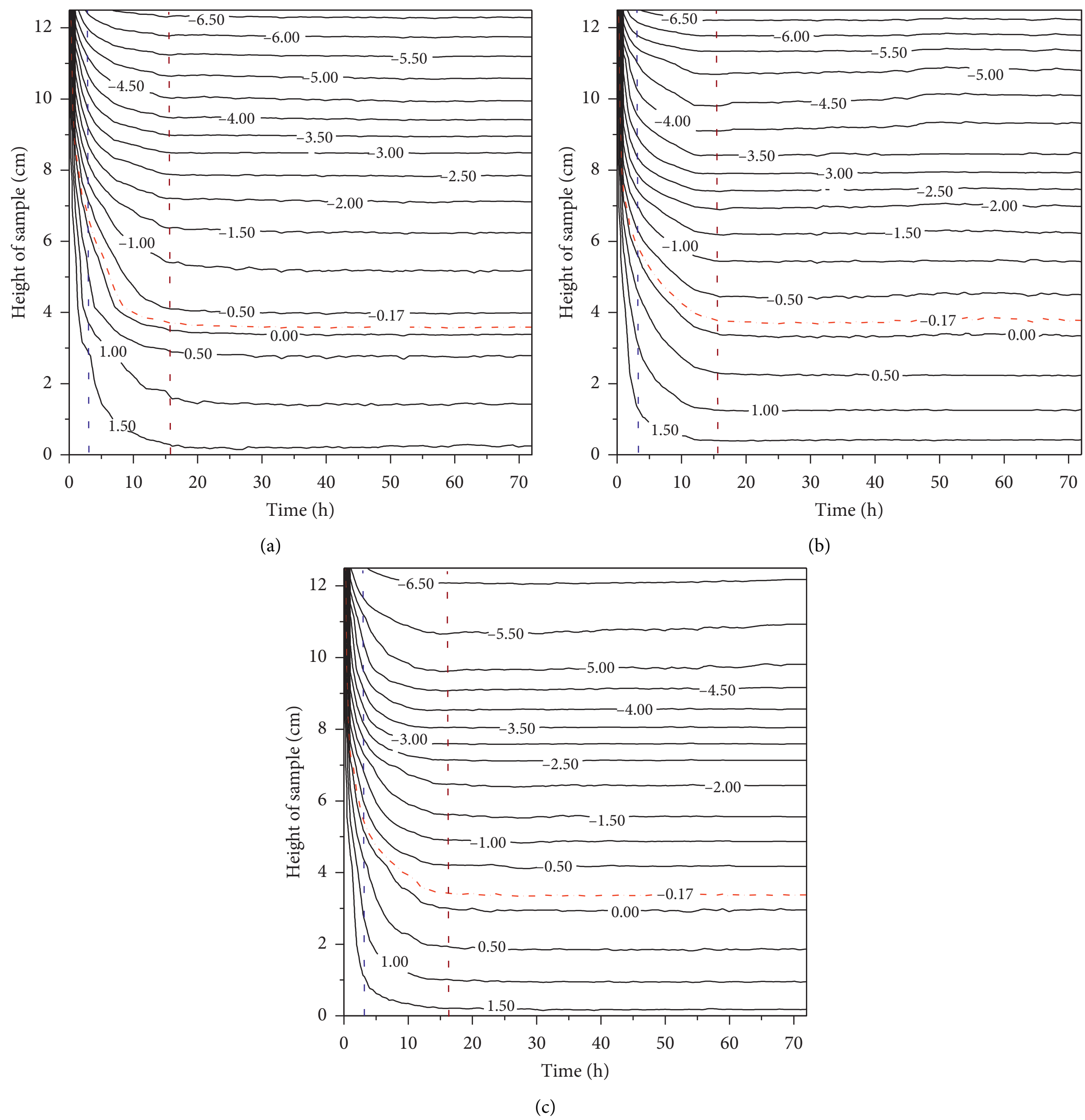

Figure 5: The temperature changes in soil samples with different initial moisture contents. (a) $\omega = 11\%$, $T_{top} = -7^{\circ}C$, and $\rho_d = 1.75\ g \bullet cm^{-3}$; (b) $\omega = 14\%$, $T_{top} = -7^{\circ}C$, and $\rho_d = 1.75\ g \bullet cm^{-3}$; (c) $\omega = 17\%$, $T_{top} = -7^{\circ}C$, and $\rho_d = 1.75\ g \bullet cm^{-3}$.

replenishment in the soils during the freezing could be divided into three stages (Figure 8).

Figure 8(a) showed the variations in the water replenishment when different temperatures on the top-plate were set up in the experiment. At the beginning of the freezing period, the water replenishment was very small. Controlled by the low temperature at the top-plate, the upper part of the tested soil sample started to freeze firstly, and then the freezing-front moved rapidly downwards [30]. Although there was temperature gradient existing in the soil, the long penetrating path combined with the freezing-front kept moving down which determined that there was no obvious water replenishment happening. As the freezing-front gradually changed to be steady, the water replenishment increased and the amount of replenished water increased rapidly as time was moving on. The lower the temperature on the top-plate was, the greater the temperature gradient in the soils would be, and the earlier the freezing-front tending to be stable would be, and the earlier the time that the water replenishment happened to increase would be. The ending time of the rapid-increase of the water replenishment was the 27 hours when the top-plate temperature of the tested soil was set up as −9°C. Afterwards, the changes in the amount of water replenishment reduced, and the total amount of the replenished water in this experiment was 29.6 mL. When the temperature on the top-plate of the chamber was set up as −7°C, the ending time of the rapid-increase stage was the 34 hours, and the amount of the

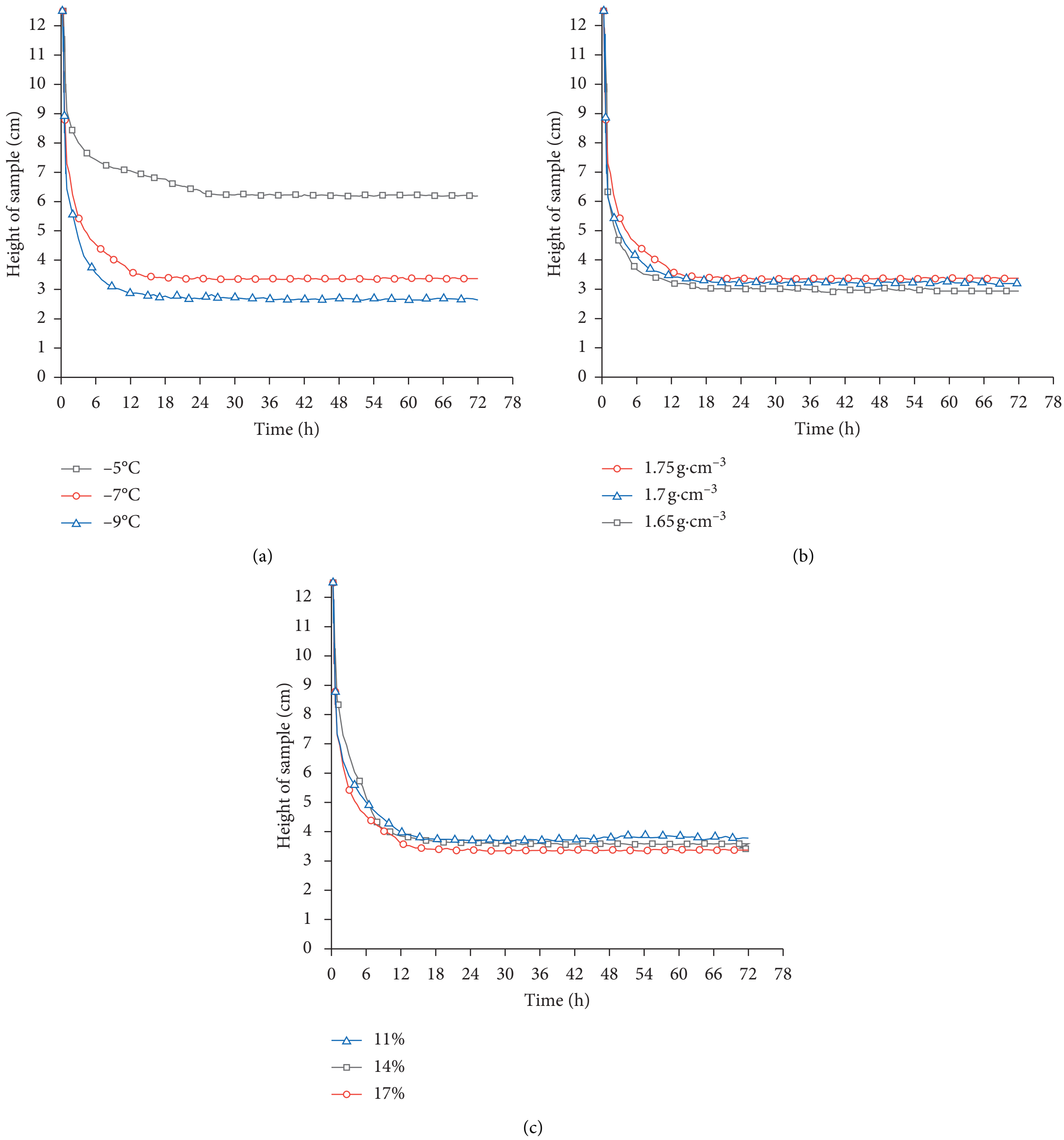

Figure 6: Freezing depths of soil samples under (a) different top-plate temperatures, (b) dry densities, and (c) initial moisture contents.

replenished water was 21.1 mL. When the temperature on the top-plate was −5°C, the two experimented numbers were the 45 hours and 16.3 mL, respectively.

Figures 8(b) and 8(c) show the variations in the amount of the replenished water in the experiment by using different soil samples with different dry densities and initial moisture contents. In Figure 8(a), the biggest influence period which affected the amount of the replenished water was the rapid-increase stage. The greater the dry density was, the smaller the pores in the soil were, and the stronger the constraint from the soil particles to the water was, which led to a strong water-soil potential and a faster water migration in the soil. Accordingly, the soil produced a channel of water replenishment connecting its bottom to the outside of the experiment system, which ensured that the external water can keep migrating into the frozen soil area through the unfrozen area. Therefore, the soil samples with greater dry density would have more water replenishment. It can be seen from the figure that the lasting time of the rapid-increase stage of the water replenishment was 18 hours for the soil sample with a dry density of 1.75 $g\,cm^{-3}$ and the total amount of the replenished water in the experiment was 21.14 mL. The lasting hours increased to 29 hours when the soil sample had a dry density of 1.7 $g\,cm^{-3}$, and the total

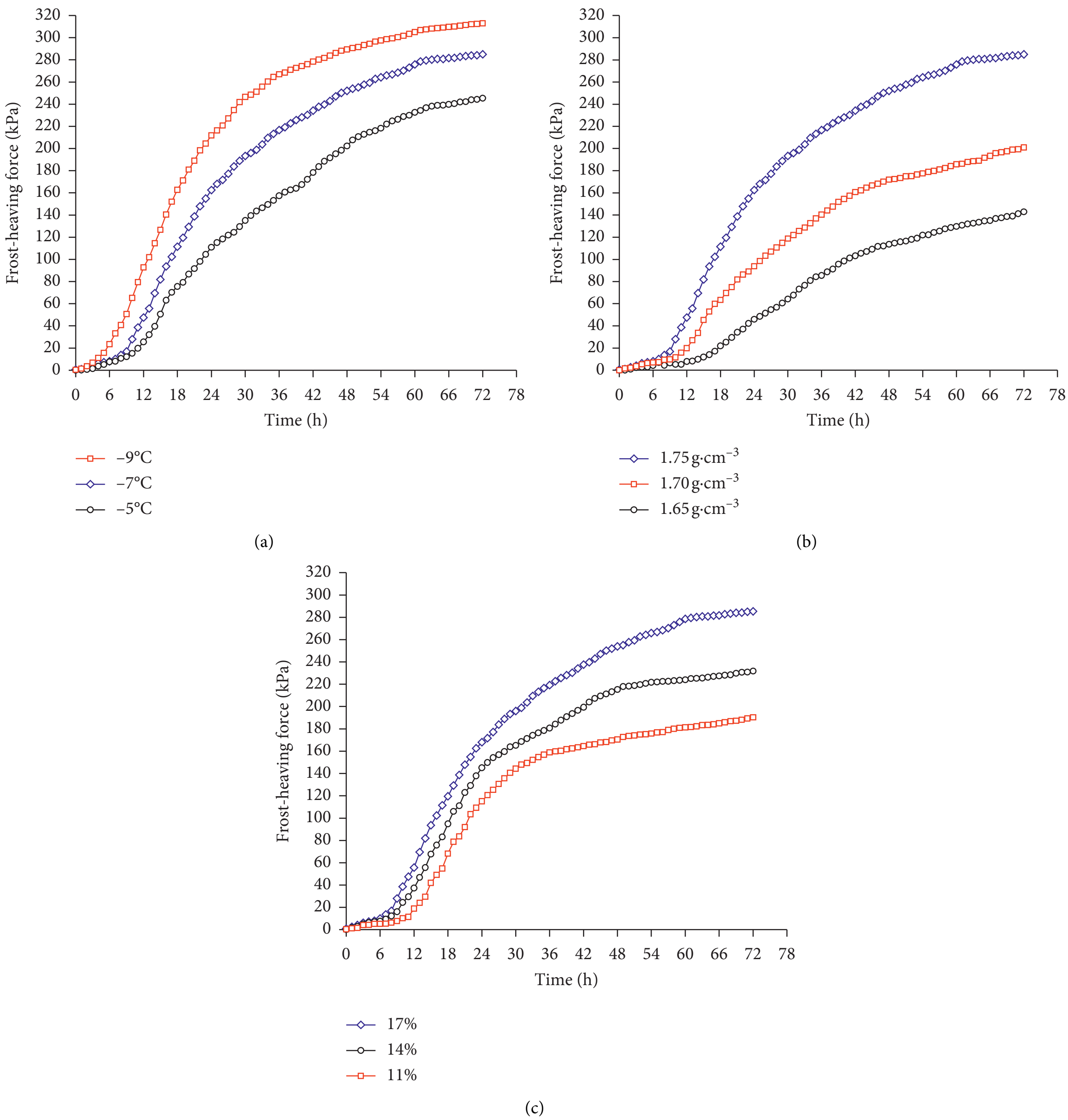

Figure 7: Frost heave forces under (a) different top-plate temperatures, (b) dry densities, and (c) initial moisture contents.

water replenishment was 18.60 mL. For the soil sample with the dry density of 1.65 g cm$^{-3,}$ the two numbers obtained from the experiment were 36 hours and 13.6 mL, respectively. For soil samples with different initial moisture contents, there was almost the same amount of the water replenishment in the beginning of the freezing. As the experiment moved on, the soil samples with higher moisture content produced a larger amount of water replenishment in the experiment, and there is no close relationship between the ending time of the rapid-increase stage of water replenishment in the experiment and the moisture content of the soils. For all the three soil samples with the initial moisture contents of 11, 14, and 17%, the period of rapid-increase stage of the water replenishment was 36 hours, and the amounts of the replenished water in the experiments were 9.5, 14.3, and 21.1 mL, respectively.

3.5. Moisture Redistribution within the Soil Samples after the Freezing. The moisture migration in the soil contributed to the changes of the soil-moisture in the distribution spatially. A slice-layer technique was used to analyze the redistribution of moisture in the soil samples after the experiment.

Figure 9(a) shows the variations in the moisture content of the soil samples with the heights of soil samples under

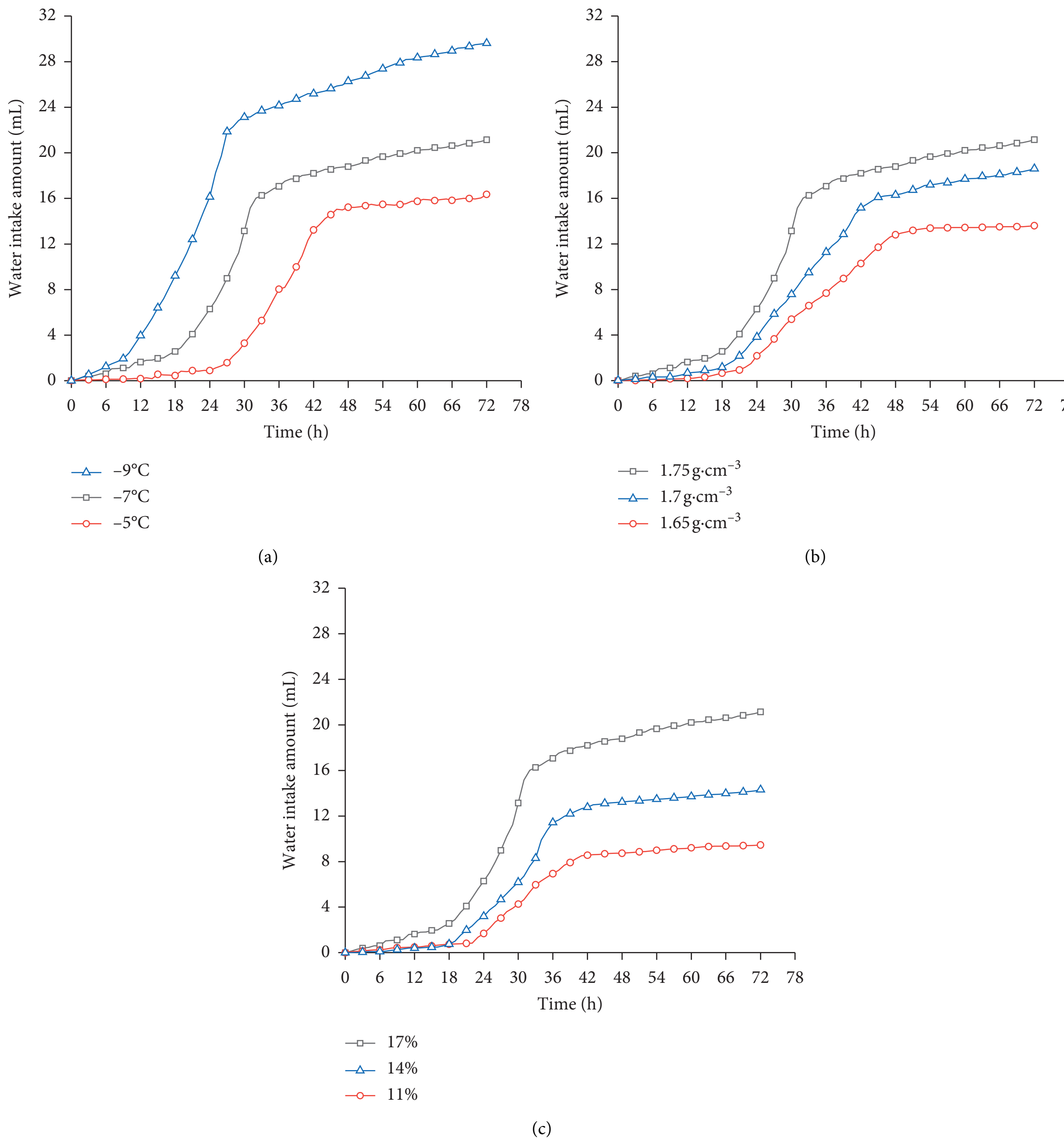

Figure 8: Water intake amounts under (a) different top-plate temperatures, (b) dry densities, and (c) initial moisture contents.

different temperature conditions. The locations, where the freezing-front stabilizing was different when different temperature gradients on the two ends were put, can be seen. The larger the temperature gradients were at the two-ends, the further the distance of the steady freezing-front away from the top-plate would be. When the temperature at the top-plate was −9°C, there was a greater frozen depth in the tested soil compared to that with the temperatures of −5 and −7°C on the top-plate, which had been discussed before in this paper. The moisture contents at the same depth varied in different soil samples with different temperature gradients. In the beginning of the freezing period, there was no enough time for the moisture to migrate but get frozen in site as the result of the temperature gradients. As the freezing-front moved toward to the warm end, the moisture content in the soil decreased accompanied by the temperature potential that increased. The smaller the increase in the moisture content was, the faster the temperature field becoming stable was. When the freezing-front stabilized at a location in the soil, there was enough time for the water from the unfrozen area to migrate, which leads to the decrease of the moisture content in the soil. In order to contribute the system to be a balance situation, the moisture from the unfrozen area would keep migrating to the freezing-front of the soils,

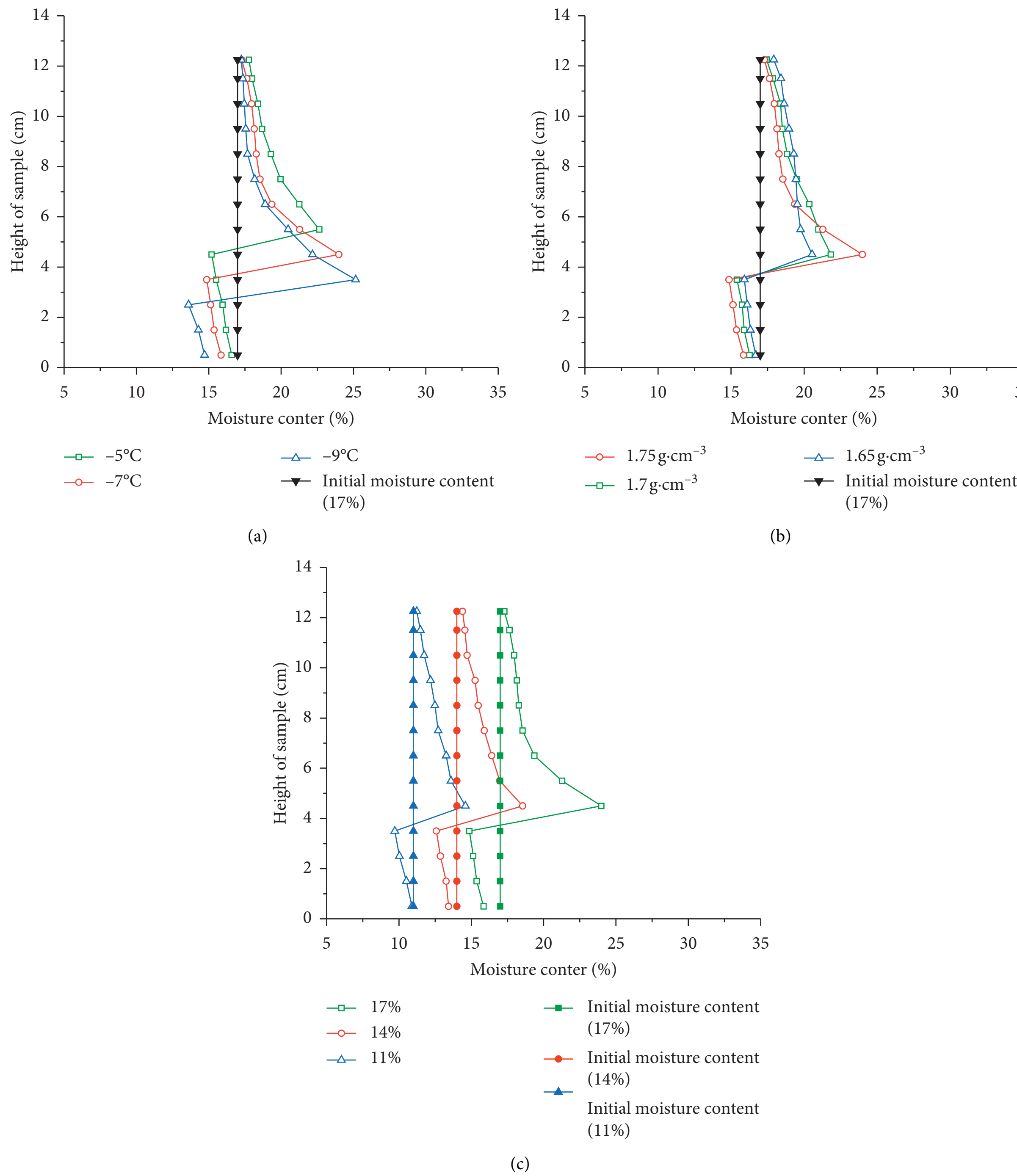

FIGURE 9: Variation of moisture content in soil samples under (a) different top-plate temperatures, (b) dry densities, and (c) initial moisture contents after the freezing experiments.

which caused a higher moisture content in the frozen part of the tested soil compared to the unfrozen part. The greater the temperature gradient was, the higher the moisture content in the freezing-front would be, and the lower the moisture content in the unfrozen area would be. The moisture contents in the soil samples were 22.6, 24 and 25.2% when the tested soil reached its balance situation when the temperatures on the top-plate were set up as −5, −7, and −9°C, respectively.

Figure 9(b) shows the variations in the moisture contents with the change of the heights of the soil samples in the experiment when different dry-density parameters were used. It can be seen that the locations of the freezing-front varied slightly when the tested soils with different dry density reached their balance situations. Because of the rapid advance of the freezing-front in the soil at the beginning of freezing period, there was no time for the moisture to migrate. Accordingly, a lower moisture content was obtained in the frozen area of the soil with a higher dry density. As the experiment went on, the freezing-front tended to be stabilized, and the moisture from the unfrozen area of the soil samples migrated to the freezing-front and the water replenishing into the soil made up the loss from the water migration. For the soil with higher dry density and small pores, it has a large capillary force which will produce a strong effect on the water and a large amount of water replenishment. Therefore, the moisture content in the unfrozen area was low, while it was generally high at the freezing-front. The experimental moisture contents of 20.5, 21.8, and 24.0% were obtained when the soil samples with dry density of 1.65, 1.7, and 1.75 g cm^{-3} reached their balance situation in the experiment.

Figure 9(c) shows the distribution of the moisture content at different depths of the soil after it was frozen, in which the soils had different initial moisture content conditions. The freezing-front for the soil samples with initial moisture content of 11, 14, and 17% was almost the same when they were stabilized, which meant that moisture content was not the main factor which will influence the location of the freezing-front in the soil. The variations in the moisture content, with different initial moisture content conditions, with the heights of the soils did not change a lot. For the soil samples with higher moisture content, they will have stronger capillary force and will produce larger amount of water migration, and the increase scope of the moisture content at the freezing-front would be bigger. From Figure 9(c), it was obtained that the increase of the balanced moisture content for the soil samples with their initial moisture content of 11, 14, and 17% was 32.6, 32.9, and 41.1%, respectively.

4. Conclusions

In order to study the influences of dry density, moisture content, and freezing temperature on the development process of frost-heaving force, a series of one-directional freezing experiments were implemented for the Tibetan clay with rigid restraint in an open system. The following conclusions are drawn from the analysis of the test results:

(1) The temperature-descending process of soil can be divided into three stages, including the rapid temperature-descending stage, slowly temperature-descending stage, and relative stability stage in the one-dimensional freezing experiment. Freezing temperature, dry density, and moisture content have certain influence on the development process of the three stages; among them, freezing temperature has more significant effect on freezing process and freezing depth than dry density and moisture content. Under the experimental conditions, the freezing time from the beginning to relatively stable stage is 25, 16, and 14 hours; the freezing depth is 6.3, 9.1 and 9.8 cm, when the freezing temperature is −5, −7, and −9°C, respectively.

(2) Under the rigid restraint conditions, the frost-heaving force produced in the process of soil freezing corresponds to the freezing process; it can also be divided into three stages, including slow increase, quick increase, and relative stable stages. Freezing temperature, dry density, and moisture content all have a significant impact on the development process of frost-heaving force, with the low freezing temperature, large dry density, and high moisture content; the development process of frost-heaving force is faster and the magnitude is larger. Under the experimental conditions, the frost-heaving force at the relatively stable stage increases to 28.1% when the freezing temperature fell from −5 to −9°C. And the value of frost-heaving force with dry density of 1.75 g cm^{-3} is about twice that of 1.65 g cm^{-3}. And the value increased by 50% when the initial moisture content increased from 11 to 17%.

(3) The amount of water replenishment is significant, and the process can also be divided into three stages, but there is an obvious time lag to the freezing process and the development of frost-heaving force. Similarly, with the low freezing temperature, large dry density, and high moisture content, the amount of water replenishment is greater. How much is it related to the pore structure, temperature gradient, soil-water potential, and other factors? Under the experimental conditions, the water replenishment amount increases from 16.3 to 29.6 mL when the freezing temperature fell from −5 to −9°C and increases from 13.6 to 21.1 mL when the dry density increased from 1.65 to 1.75 g cm^{-3} and increases from 9.5 to 21.1 mL when initial moisture content increased from 11 to 17%.

(4) At the end of the freezing experiments, there is an obvious phenomenon of redistribution, and obvious wetting phenomenon has appeared in the frozen area, especially in the freezing cover position when the moisture content increases significantly. However, in the melting zone, drying phenomenon appeared. The degrees of wetting and drying are related to the freezing temperature, dry density, and moisture content. Under the experimental conditions, the maximum increase of moisture content can reach 48.2% compared with the initial moisture content at the freezing-front position, while the maximum decrease range of moisture content in the unfrozen area can reach 23.5%.

Data Availability

The data are available upon request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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