

Research Article

Experimental Study on Moisture Migration of Unsaturated Loess during the Freezing Process

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To reveal the water-heat transfer mechanism of unsaturated loess, the effects of soil dry density (1.30 g/cm³, 1.50 g/cm³, and 1.65 g/cm³), moisture content (13.3%, 16.2%, and 19.4%), cold end temperature (−7°C, −10°C, and −13°C), and freezing mode on moisture migration in unsaturated loess in this paper are studied through indoor tests of moisture migration under the freezing action of large-size unsaturated loess. The results show that the temperature change in soil samples in the freezing process can be divided into three stages: rapid cooling stage, slow cooling stage, and stable stage. The higher the dry density, the closer the freezing front is to the cold end, with the initial moisture content having little effect on the freezing front, while the temperature at the cold end has a significant effect on the location of the freezing front. The total amount of moisture migration decreases with the increase of dry density, increases with the increase of moisture content, and increases with the decrease of cold end temperature. The freezing mode directly affects the distribution of moisture content and total amount of moisture migration in the frozen area.

1. Introduction

China has a vast loess area, most of which is in the seasonally frozen region. The physical and mechanical properties of the topsoil in this region vary greatly as the superficial layer of loess is greatly affected by natural factors. The infiltration of rain in summer and autumn and the freezing of soil layer in winter increase the moisture content of the surface soil, and then the shear strength decreases. As a result, engineering disasters such as slide, slump, and spalling frequently occur to the side slope, roadbed, and bank slope in the Loess Plateau [1–5]. The upward migration of moisture in winter under freezing action causes changes in mechanical properties of topsoil, leading to engineering diseases, which have aroused great attention. Many scholars have studied this phenomenon and discussed the mechanism of diseases [6–10]. However, the mechanism of moisture migration in

unsaturated loess under freezing is still unclear. Considering the importance of this phenomenon to engineering accidents in the unsaturated loess region, it is necessary to study this phenomenon.

At present, some scholars have studied the law of moisture migration in soil samples. Under the action of freezing, the moisture in the unfrozen area of soil moves to the freezing front, which increases the moisture content of the freezing front [11, 12]. Moisture migration under freezing is driven by various forces, including gravity, matric suction, osmotic force, and suction force of the phase transition interface [13–16]. Moisture migration in the soil under freezing also causes salt redistribution, freezing heave, and salt heave of the soil, leading to the occurrence of engineering diseases [17–20]. Mao [21] studied the moisture migration in Aeolian sand in open system under freezing conditions and showed that the moisture migration was

driven by temperature gradient. Zhan et al. [22] analyzed the relationship between side slope diseases and dynamic change of slope body moisture in seasonally frozen soil region by numerical simulation. Konrad and Gilpin et al. [23, 24] studied the law of moisture migration and ice formation mechanism of freezing soil under external load. Reference [25] pointed out that temperature gradient and initial moisture content are two important factors affecting moisture migration during freezing-thawing process. Wang and Nassar et al. [26, 27], through experimental studies, showed that the moisture content of soil samples is related to the initial moisture content, density, and temperature difference under the action of temperature difference. Zhao et al. [28] conducted an experimental study on the effect of freezing-thawing on moisture migration with cohesive soil of Northeast China as an object. The study showed that different freezing temperatures and thawing temperatures had significant effects on moisture migration of samples. Teng et al. [29] found by a series of laboratory experiments that, for a nonfreezing condition, water content gradually decreases from the warmer end to the colder end without any peak value. The results showed that when the soil sample is freezing, the content of liquid water in the frozen zone decreases sharply, which leads to the drop of matric potential and promotes the migration of unfrozen water in the soil along the direction of temperature reduction. Other studies have shown that the water and heat transfer during the freezing process are related to soil pore structure, surface vegetation, snow cover, and other factors [30–32].

A general survey of previous research results shows that existing studies have revealed the characteristics of soil moisture migration toward the freezing front, but lack of systematic study on the effects of factors such as soil density, moisture content, cold end temperature, and freezing mode, on moisture migration in unsaturated loess. In view of this, this paper, through indoor freezing tests of large-size loess, studies the effects of soil dry density (1.30 g/cm^3 , 1.50 g/cm^3 , and 1.65 g/cm^3), moisture content (13.3%, 16.2%, and 19.4%), cold end temperature (-7°C , -10°C , and -13°C), and freezing mode on moisture migration in unsaturated loess, laying a foundation for analysis of the freeze-thaw disease mechanism of loess engineering.

2. Experiment Scheme

2.1. Test Soil Sample. The test soil sample was taken from a foundation pit in Xi'an city, China, which is a seasonally frozen ground region. The soil sample was yellow-brown, with a natural density of 1.56 g/cm^3 , a natural moisture content of 17.2%, a liquid limit of 30.9%, and a plastic limit of 18.1%. The particle composition was as follows: sand grains ($>0.075 \text{ mm}$) accounting for 13%, soil particle ($0.005\text{--}0.075 \text{ mm}$) accounting for 65%, and clay ($<0.005 \text{ mm}$) accounting for 22%.

2.2. Test Equipment. The test equipment is shown in Figure 1. The top end of the sample is placed in the artificial refrigeration chamber, and the bottom end of the sample is

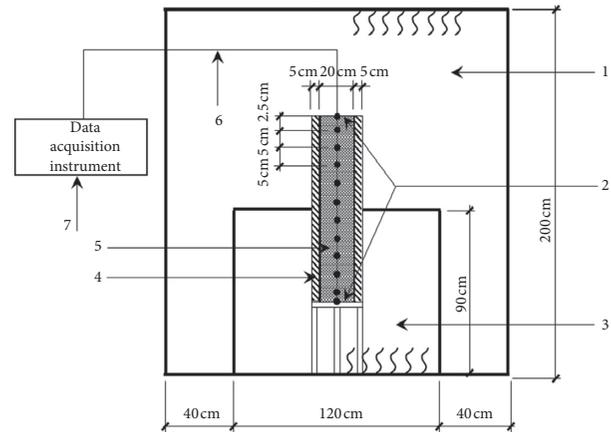


FIGURE 1: Schematic diagram of test equipment. Note: (1) Artificial refrigeration room. (2) Waterproof layer. (3) Thermostatic chamber. (4) Thermal insulation material. (5) Soil sample. (6) Temperature sensor. (7) Data acquisition instrument.

placed in the thermostatic chamber. The artificial refrigeration chamber adopts an air compressor for refrigeration. The temperature of the refrigeration chamber can reach -20°C providing negative temperature for the freezing of soil samples, with an error of $\pm 0.5^\circ\text{C}$. The thermostatic chamber can assure that the bottom of the sample is always applied with positive temperature, with an error of $\pm 0.5^\circ\text{C}$. The test soil sample is packed in a cylindrical PVC pipe with a length of 55 cm and a diameter of 25 cm, surrounded by insulation materials. The thermal conductivity coefficient of the thermal material is $0.028 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, ensuring the unidirectional axial heat conduction of the soil sample. During the test, a thermal resistance temperature sensor is arranged at every 5 cm interval to monitor the temperature change in the sample. The measuring accuracy of the sensor is $\pm 0.1^\circ\text{C}$. The waterproof layer is made of plastic film, which is used to prevent the evaporation of water from the sample, so that the test is carried out in a closed system.

2.3. Test Scheme. To study the law of influence of soil dry density, moisture content, and cold end temperature on the moisture migration in unsaturated loess, 13 groups of soil samples are selected for the test. The temperature of the thermostatic chamber is controlled at 20°C , and the freezing time of samples is 14 d. Other specific test conditions are shown in Table 1.

Test procedure is as follows:

- (1) Sample preparation: The loess sample with a 2 mm sieve was sieved, and soil samples of different moisture contents were then made according to the test requirements. After being moisturized for 2 days, the soil sample was packed into the tube in a layered way with each layer of 5 cm according to the designed dry density, to ensure a consistent dry density of the soil sample. Then the two ends of the soil sample were sealed with plastic film to keep the soil sample in a closed system.

TABLE 1: Test conditions.

Soil sample number	Dry density ρ_d (g/cm^3)	Initial moisture content w (%)	Cold end temperature ($^{\circ}\text{C}$)
N1	1.30	19.4	-13
N2	1.50	19.4	-13
N3	1.65	19.4	-13
N4	1.30	16.2	-13
N5	1.50	16.2	-13
N6	1.65	16.2	-13
N7	1.30	13.3	-13
N8	1.50	13.3	-13
N9	1.65	13.3	-13
N10	1.30	19.4	-7
N11	1.30	19.4	-10
N12	1.30	19.4	Frozen for 5 d at -7°C , 5 d at -10°C , and 4 d at -13°C
N13	1.30	19.4	Frozen for 7 d at -7°C , and 7 d at -13°C

- (2) A hole at every 5 cm from the position 2.5 cm away from the cold end along the length direction on one side of the tube wall was preset. After loading the soil sample, we inserted temperature sensors from the preset holes, buried temperature sensors at both the cold end and the warm end, respectively, and then wrapped thermal insulation materials around the tube.
- (3) The temperature required was applied under the test conditions to record the temperature changes with time during the freezing process.

Each sample was frozen for 14 days according to the test scheme. Once the freezing time is over, the sample was taken out immediately, and the moisture content distribution of soil samples was measured at different locations before thawing. The water content is measured every 1 cm within 3 cm around the phase change interface, the rest of the frozen area is measured every 2 cm, and the rest of the unfrozen area is measured 3 cm. The method of measurement was the drying method according to the Standard for Soil Test Method (GB/T50123-1999). Complete the test of all the soil samples using the above steps.

3. Test Results and Analysis

3.1. Effect of Dry Density on Temperature and Moisture Migration in Soil Samples. According to the test scheme, Figure 2 shows the temperature field test results of soil samples with the same initial moisture content and different dry densities. Figure 2 shows that the temperature field of all soil samples is basically stable and that the temperature change can be roughly divided into three stages, namely, the rapid cooling stage, slow cooling stage, and stable stage. In the rapid cooling stage, mainly between 0 and 48 hours, the closer it is to the cold end, the shorter the cooling time is; the slow cooling stage is mainly between 48 and 240 hours; the stable stage starts from 240 hours to the end of the test. The greater the dry density, the greater the thermal conductivity. However, the higher dry density the soil sample has, the higher moisture content per unit volume is. In the freezing process, the water in the soil sample releases more heat, and

the released heat will prevent the temperature of the whole sample from falling. Therefore, the effect of dry density on the temperature field of the sample still needs to be determined by test. By comparing the three figures in Figures 2(a)–2(c), when frozen for 48 h, the temperature gradient of the soil layer 0–12.5 cm away from the cold end of the soil sample N1 is $0.32^{\circ}\text{C}/\text{cm}$, while the corresponding temperature gradients of soil samples N2 and N3 are $0.224^{\circ}\text{C}/\text{cm}$ and $0.144^{\circ}\text{C}/\text{cm}$, respectively. The temperature gradient decreases with the increase of dry density, which indicates that the change rate of temperature field of soil sample is smaller with the increase of dry density for the same moisture content.

Figure 3 shows the test results of soil samples with different initial moisture contents and dry densities. For each soil sample, after the negative temperature is applied at the cold end for a certain period, the soil sample is divided into two parts: the frozen area and the unfrozen area. At the freezing front, the moisture content increases most. After the negative temperature is applied at the cold end of the soil sample, the freezing front is in an unsteady state and gradually advances from the cold end to the warm end until reaching the steady-state freezing front. The moisture content in the frozen area increases, while that in the unfrozen area decreases. The reason for this phenomenon is that moisture in the unfrozen area migrates toward the freezing front and that there is no water supply in unfrozen area. The moisture content increases locally within about 2 cm at the cold end of the frozen area in each soil sample. As shown in Figure 3(a), the water content in the cold end of three soil samples with an initial moisture content of 19.4% increased from 19.4% to 21.97%, with the average incremental moisture content at the cold end being 2.57%; Figure 3(b) shows that the water content in the cold end of three soil samples with an initial moisture content of 16.2% increased from 16.2% to 17.88% and that the average incremental moisture content at the cold end is 1.68%; Figure 3(c) shows that the water content in the cold of three soil samples with an initial moisture content of 13.3% increased from 13.3% to 13.93% and that the average incremental moisture content at the cold end is 0.63%. The higher the initial moisture content, the higher the moisture content

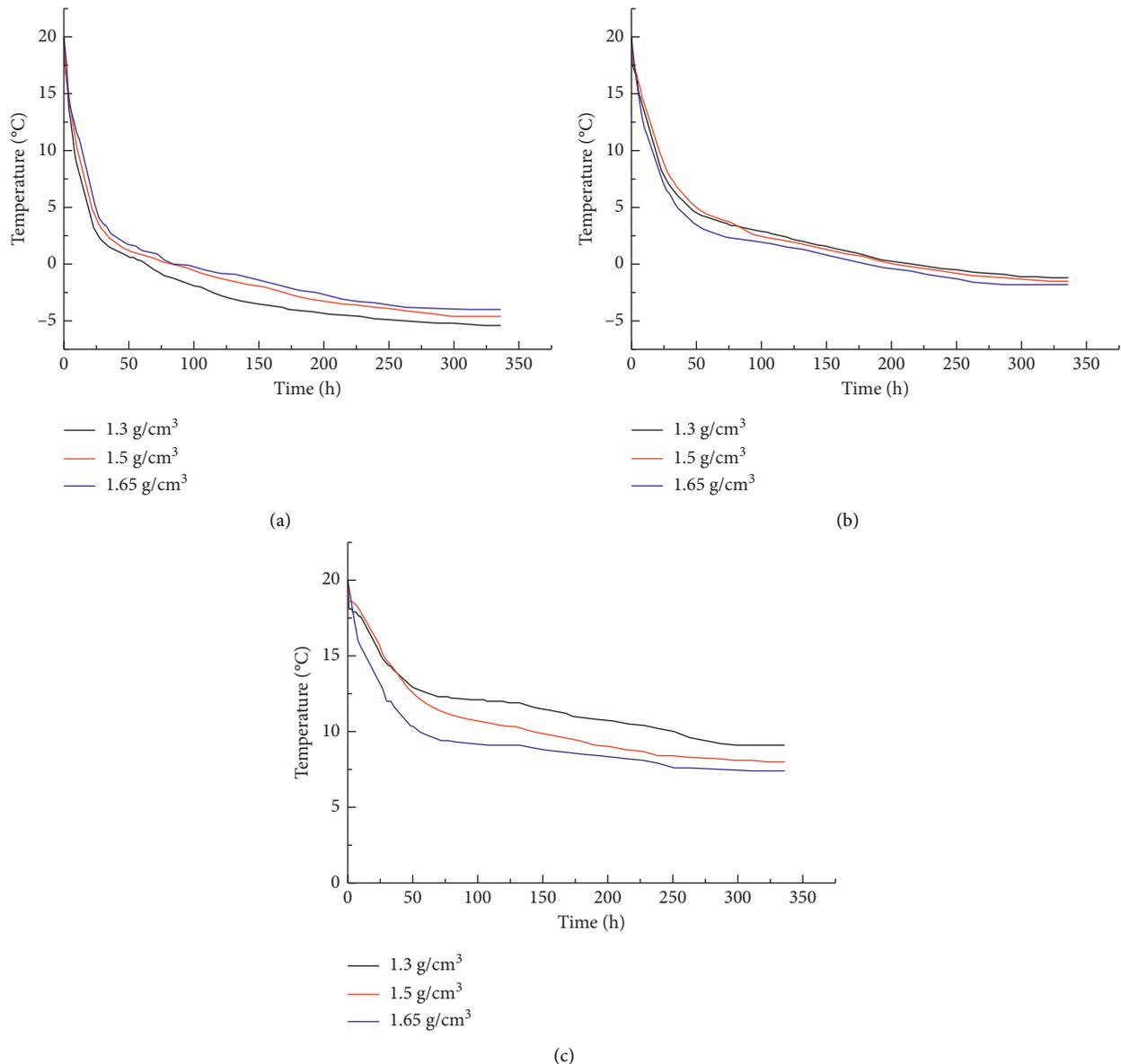


FIGURE 2: Curve of temperature variation of soil samples with different dry densities. (a) 12.5 cm from the cold end. (b) 27.5 cm from the cold end. (c). 52.5 cm from the cold end. Note: (a) corresponding soil sample N1; (b) corresponding soil sample N2; (c) corresponding to soil sample N3.

at the cold end. This is because, as can be seen from the temperature field change in Figure 2, at the beginning of the test, it takes some time for the cold end to cool down from the temperature of soil sample (20°C) before it is frozen to 0°C. The temperature changes dramatically, the water head difference is large, and there is enough water supply, so the local moisture content increases in the cold end.

As shown in Figure 3(a), the freezing front of soil samples with an initial moisture content of 19.4% and a dry density of 1.3 g/cm³ is located at 30 cm from the cold end, while the freezing front of soil samples with a dry density of 1.5 g/cm³ and 1.65 g/cm³ is located at 28 cm and 27 cm from the cold end, respectively. This indicates that the higher the dry density is, the closer the freezing front is to the cold end. The reason of this phenomenon is mainly related to the

difference of soil moisture distribution in the frozen area. When the dry density is large, the increases of moisture content in the frozen area are small, and the increase of the thermal conductivity is small, hindering the advance of the freezing front. Conversely, when dry density is small, the thermal conductivity of the frozen area increases greatly, which is beneficial to the advance of the freezing front. This rule is consistent with the effect of dry density on soil samples with different initial moisture contents in Figures 3(b) and 3(c).

Figure 3(a) also shows that the freezing front of soil samples with an initial moisture content of 19.4% and a dry density of 1.3 g/cm³ has a 7.72% increase in moisture content compared with the initial moisture content, while the moisture content at the freezing front of soil samples with

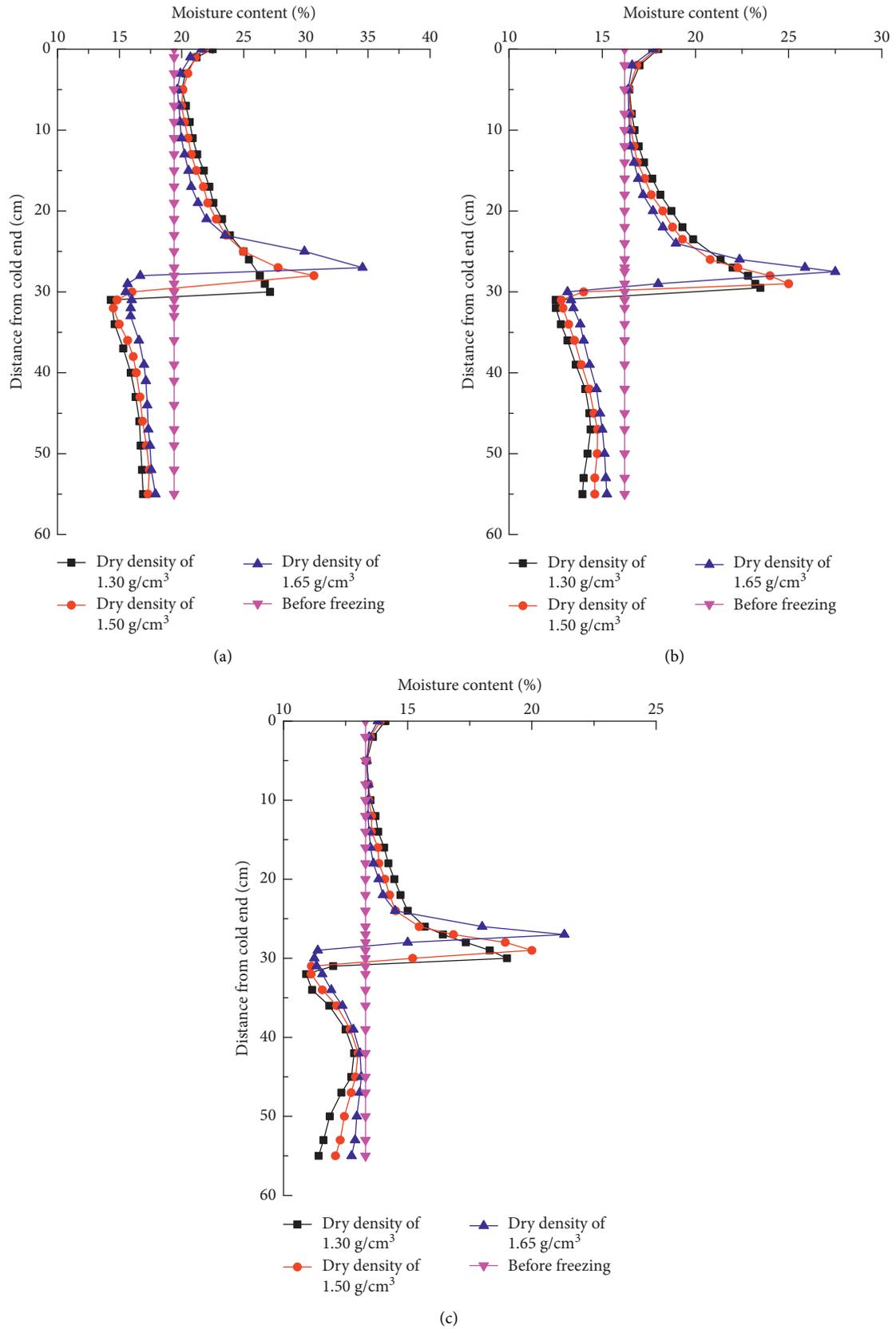


FIGURE 3: Moisture migration in soil samples with different dry densities and different initial moisture contents at -13°C . (a) $W = 19.4\%$. (b) $W = 16.2\%$. (c) $W = 13.3\%$.

dry densities of 1.5 g/cm^3 and 1.65 g/cm^3 increases by 11.25% and 15.16%, respectively. This indicates that the higher the dry density, the greater the increase of moisture content at the freezing front. The total amount of moisture migrated in soil samples with an initial moisture content of 19.4% and a dry density of 1.3 g/cm^3 is 574 g, and the amount of moisture migrated in soil samples with dry densities of 1.5 g/cm^3 and 1.65 g/cm^3 is 565 g and 500 g, respectively. This indicates that the higher the dry density, the smaller the total moisture migration in the frozen area. This is because the higher the dry density is, the less the time it takes for the freezing front to reach the steady-state position. When the temperature is stable, the longer the freezing front stays at the steady-state position, the more the moisture accumulates in the freezing front. For the frozen area, in the advancing process of the freezing front, since the permeability coefficient of soil samples with a high dry density is small and the freezing front advances quickly, the time for the stable position is less, and the moisture migrated is low. The above effects of dry density on the process of moisture migration are shown in the test results of soil samples with different initial moisture contents. In the unfrozen area, due to the large suction of the freezing front, the water quickly migrates to the freezing front, resulting in the smaller water content near the freezing front. The unfrozen area far away from the freezing front accelerates the supply under the action of temperature gradient and matrix suction gradient and migrates to the freezing front. For the same initial moisture content soil sample, the smaller the dry density, the greater the permeability coefficient, the faster the replenishment, and the greater the amount of water migration in the unfrozen area.

3.2. Effect of Moisture Content on Temperature and Moisture Migration in Soil Samples. Figure 4 shows the test results of temperature field of soil samples with the same dry density and different moisture contents. It can be seen from Figure 4 that the temperature change can be roughly divided into three stages: rapid cooling stage, slow cooling stage, and stable stage. This is consistent with the law of temperature change in Figure 2.

When the dry density is the same, the greater the moisture content is, the greater the thermal conductivity is and the greater the heat released in the freezing process will be. As the heat released prevents the temperature of the whole sample from falling, the influence of moisture content on the temperature field of the sample still needs to be determined by test. By comparing Figures 2 and 4, when it is frozen for 48 h, the temperature gradient in the soil layer thickness 0–12.5 cm from the cold end of soil sample N1 is 0.32°C/cm . The temperature gradients at the corresponding locations of soil samples N2 and N3 are 0.264°C/cm and 0.288°C/cm , respectively. The difference of temperature gradient is not significant, which indicates that the change rate of the temperature field of soil samples with the same dry density and different moisture contents has a little difference.

Figure 5 shows the freezing test results of soil samples with a dry density of 1.3 g/cm^3 and different initial moisture

contents at -13°C . As can be seen from the figure, the initial moisture content has a significant impact on the moisture migration of the frozen soil sample, but little impact on the location of the freezing front. This is mainly because the higher the moisture content, the higher the thermal conductivity, but, at the same time, the greater the heat release when freezing. According to the test results, the effects of the two almost mutually offset each other.

The total amount of moisture migrated in soil samples with an initial moisture content of 13.3% is 219 g, while the total amounts of moisture migrated in soil samples with initial moisture contents of 16.2% and 19.4% are 410 g and 574 g. This indicates that the total amount of moisture migrated increases with the increase of the initial moisture content under the condition that the initial dry density remains unchanged. The moisture content of the freezing front of soil samples with an initial moisture content of 13.3% increases by 5.70%, while the moisture contents of the freezing front of soil samples with initial moisture contents of 16.2% and 19.4% increase by 7.28% and 7.72%, respectively. This indicates that the increment of moisture content in the stable freezing front increases with the increase of initial moisture content. According to the analysis of the results, the reason for this is that, in the freezing process, with the advance of the freezing front, the higher the initial moisture content in soil samples, the higher the permeability coefficient, the faster the moisture migration rate to the freezing front, and the higher the total amount of moisture migrated and the moisture content increment in the freezing front.

Figure 5 shows in the unfrozen area, from the adjacent freezing front to the warm end, the moisture content first increases and then decreases, and the smaller the initial moisture content is, the more obvious this phenomenon is. The reason for this phenomenon is that the freezing front produces a suction force on the unfrozen area, and there is a temperature gradient in the unfrozen area. The temperature gradient causes a difference in matric suction in the unfrozen area, leading to the migration of moisture from the warm end of the high temperature area to the low temperature area and the increase of moisture content in the low temperature area. However, in the unfrozen area immediately adjacent to the freezing front, due to the large suction force of the freezing front, moisture quickly migrates to the freezing front, leading to a phenomenon that the moisture content decreases as the location is closer to the freezing front. Under the action of the suction force of the freezing front, the moisture in the unfrozen area adjacent to the freezing front migrates to the freezing front, and the unfrozen area further away from the freezing front accelerates replenishment under the action of temperature gradient and large moisture difference. The higher the moisture content is, the higher the permeability coefficient is and the faster the replenishment is, while the temperature gradient effect of moisture content distribution in the unfrozen area is not obvious. Conversely, the smaller the soil moisture content is, the smaller the permeability coefficient is and the slower the replenishment is, while the temperature gradient effect of moisture content distribution in the unfrozen area becomes obvious. This

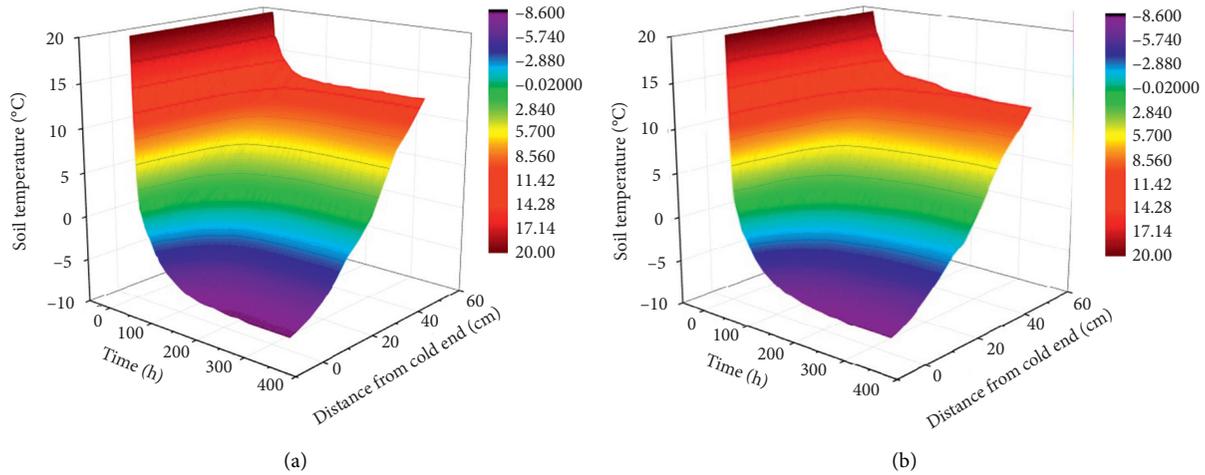


FIGURE 4: Surface of temperature variation of soil samples with different moisture contents. (a) Corresponding soil sample N7. (b) Corresponding soil sample N4.

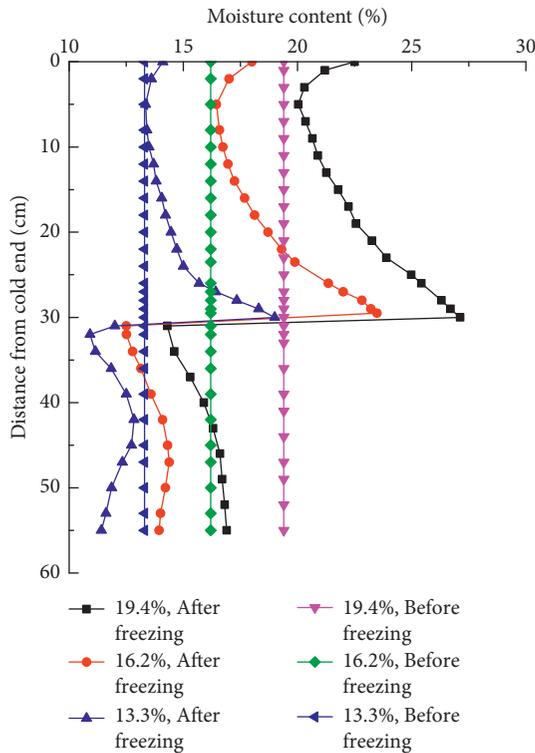


FIGURE 5: Moisture migration in soil samples with different initial moisture contents at -13°C .

leads to the phenomenon that the moisture content in the unfrozen area from the adjacent freezing front to the warm end first increases and then decreases. The smaller the initial moisture content, the more obvious this phenomenon is.

3.3. Effect of Cold End Temperature on Temperature and Moisture Migration in Soil Samples. Figures 6(a) and 6(b) show the test data of soil temperature field change at the cold end temperature of -7°C and -10°C , respectively. It can be seen from Figures 6(a) and 6(b) that the temperature change

is still roughly divided into three stages: rapid cooling stage, slow cooling stage, and stable stage. This is consistent with the aforementioned law of temperature change. By comparing Figures 2, 6(a), and 6(b), when it is frozen for 48 h, the temperature gradient in the soil layer thickness 0–12.5 cm from the cold end of soil sample N1 is $0.32^{\circ}\text{C}/\text{cm}$. The temperature gradients at the corresponding locations of soil samples N10 and N11 are $0.16^{\circ}\text{C}/\text{cm}$ and $0.26^{\circ}\text{C}/\text{cm}$, respectively. The temperature gradient increases with the decrease of the cold end temperature and the freezing front of soil samples advances faster.

Figure 7 shows the freezing test results of the cold end of the soil sample at different cold end temperatures. As can be seen from the figure, the cold end temperatures have a significant impact on the location of the freezing front. The lower the temperature at the cold end is, the farther the steady-state freezing front is away from the cold end and the larger the frozen area is. However, cold end temperatures have little impact on the increase of moisture content of the freezing front. The lower the temperature at the cold end, the higher the temperature gradient in the soil sample, the higher the freezing rate, and the faster the freezing speed of the soil sample from the cold end forward. As a result, the freezing front stays for a short time at the early stage of freezing, and the amount of moisture migration is small, so that the increase of moisture content is small in the area near the cold end. In Figure 7, the total amount of moisture migration of soil samples corresponding to the cold end temperatures of -13°C is 574 g, and the total amounts of moisture migrated in soil samples corresponding to the freezing temperature of -10°C and -7°C are 545 g and 441 g, respectively, indicating that the lower the cold end temperature is, the greater the total amount of moisture migration is.

3.4. Effect of Freezing Mode on Temperature and Moisture Migration in Soil Samples. It can be seen from Figure 8 that the temperature change curve of soil samples after the cold

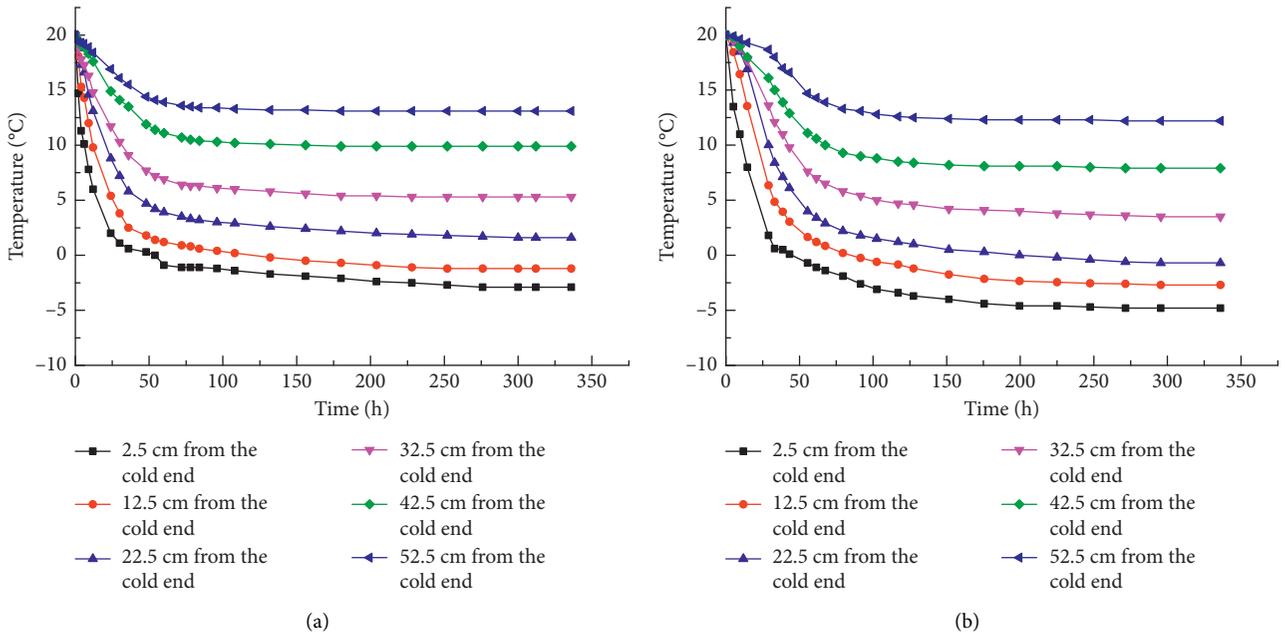


FIGURE 6: Curve of temperature variation of soil sample with time at different cold end temperature. (a) -7°C . (b) -10°C .

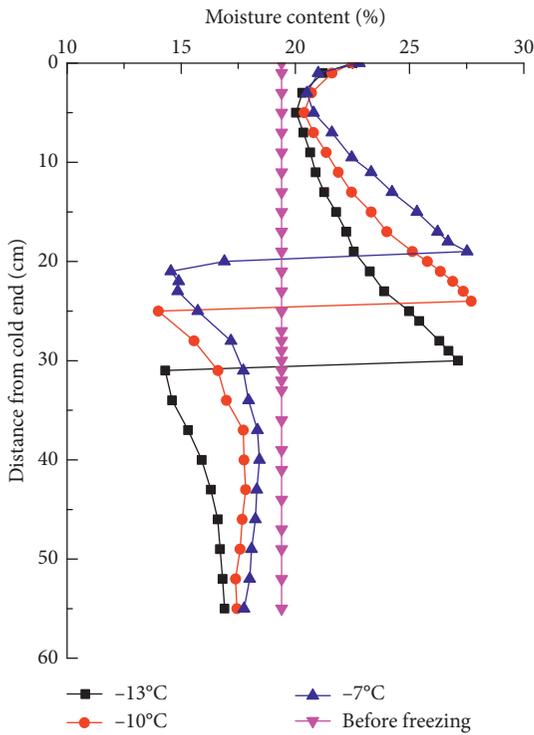


FIGURE 7: Moisture migration in soil samples in soil samples at different temperatures.

end temperature adjustment has a short period of sudden drop, and the closer to the cold end, the more obvious the change. This is mainly because the soil sample releases a great deal of heat in a short time after the cold end temperature drops, which leads to the sudden drop in temperature in a short time.

Figure 9 shows the moisture migration test results of soil samples with different freezing modes. The three soil samples undergo different freezing processes, and the final cold end temperature is the same. In the same freezing time, the soil sample 1 freezes with the cold end maintaining the same temperature, the soil sample N12 freezes with the cold end undergoing two temperature changes, and the soil sample N13 freezes with the cold end undergoing one temperature change. The figure shows that the moisture content in the frozen area generally shows a monotonically increasing distribution from the cold end to the freezing front after the cold end is frozen at a negative temperature and reaches a steady state. However, in the case of variable temperature freezing at the cold end, the moisture content distribution in the frozen area shows a waveform distribution with valley and peak connected, and the number of wave peaks corresponds to the number of temperature changes. This is mainly because each temperature change has a short and rapid cooling process, which allows the freezing front to advance rapidly, and the rapid advance of the freezing front leads to small moisture migration to the freezing front, so the valley-peak connected waveforms appear. It can be seen from Figure 8 that there is an obvious rapid drop process in the temperature curve after temperature change, and, at this location, the freezing front advances rapidly. When the final cold end temperature is the same, different freezing modes also change the total amount of moisture migration. The amount of moisture migration in the soil sample N1 is 574 g, and the total amounts of moisture migration in the soil samples N12 and N13 are 464 g and 543 g. This indicates that the total amount of moisture migration in the soil sample N1 is the largest in different freezing modes. Therefore, the freezing mode directly affects the distribution of moisture content and total amount of moisture migration in the frozen area.

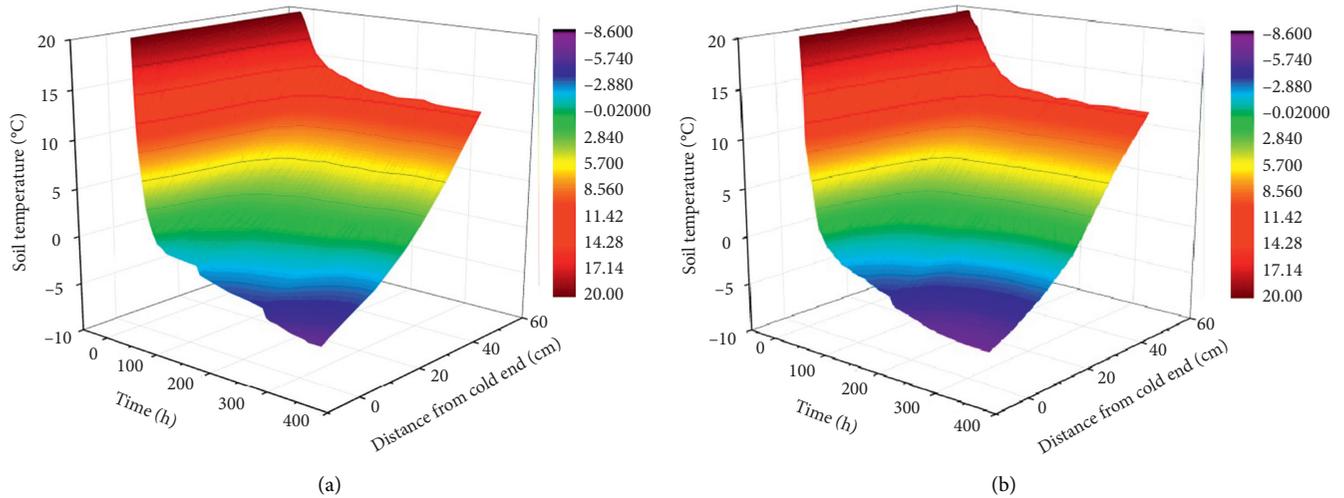


FIGURE 8: Curve of soil temperature with time with different freezing modes. (a) Corresponding to soil sample N12. (b) Corresponding to soil sample N13.

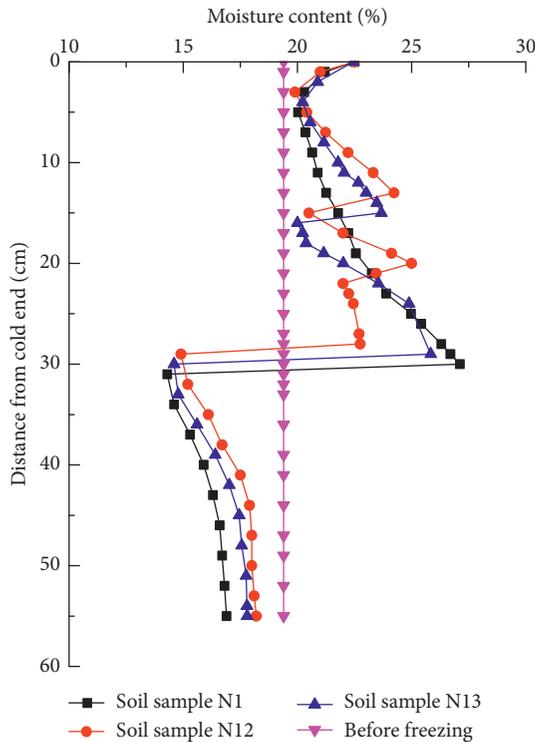


FIGURE 9: Moisture migration in soil samples with different freezing modes.

4. Conclusions

- (1) It is found in the test that the soil dry density (1.30 g/cm^3 , 1.50 g/cm^3 , and 1.65 g/cm^3), moisture content (13.3%, 16.2%, and 19.4%), cold end temperature (-7°C , -10°C , and -13°C), and freezing mode have a great influence on the moisture migration in unsaturated loess.
- (2) The temperature change in soil samples in the freezing process is divided into three stages: the rapid cooling

- stage, from 0 to 48 hours; the slow cooling stage, from 48 to 240 hours; and the stable stage, after 240 hours.
- (3) At a specific time point, the temperature gradient decreases with the increase of dry density but changes a little with the increase of moisture content. The thickness of frozen area decreases with the increase of dry density, changes a little with the increase of moisture content, and increases with the decrease of cold end temperature.
- (4) Under the freezing action, soil moisture migrates from the unfrozen area to the freezing front, which is the result of the combined effects of temperature gradient and matric suction gradient. The lower the cold end temperature is, the higher the temperature gradient is and the faster the advancement of the freezing front of soil samples is. The higher the dry density is, the closer the freezing front is to the cold end and the higher the increase of moisture content at the freezing front is, but the smaller the total amount of moisture migrated is. The higher the initial moisture content in the soil sample is, the higher the total amount of moisture migrated is and the larger the increment of moisture content at the freezing front is. The cold end temperature has a significant influence on the location of the freezing front. The lower the temperature at the cold end of the soil sample is, the farther the steady-state freezing front is away from the cold end. However, the temperature at the cold end has a little influence on the increase of moisture content at the freezing front. The lower the temperature at the cold end, the greater the total amount of moisture migrated. The freezing mode directly affects the distribution of moisture content and total amount of moisture migration in the frozen area.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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