Journal of Engineering Science and Technology Review 16 (2) (2023) 91 - 99

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Water Migration and Temperature Field Evolution under Horizontal Freezing Condition

Xianghong He[1], Dahu Rui[1, 2,*], Biao Qin[1] and Jun Zhang[1]

[1] *International Joint Research Laboratory of Henan Province for Underground Space Development and Disaster Prevention, Henan Polytechnic University, Jiaozuo 454003, China*
[2] *State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China*

Received 3 January 2023; Accepted 22 March 2023

Abstract

The application of the hydrothermal relationship under vertical freezing to horizontal freezing is limited, necessitating further study of soil water migration and temperature field law under horizontal freezing conditions. A self-designed transverse freezing equipment was utilized to carry out lateral soil freezing experiments by vertically arranging the freezing plate. The study focused on examining the distribution and evolution of temperature and water fields in the soil during horizontal freezing, as well as determining the migration of freezing fronts. Additionally, the effect of temperature gradient on water migration rate was investigated under an open system. Results show that under the horizontal freezing condition, water on the unfrozen soil side migrates to the freezing front due to the soil water potential gradient induced by the temperature gradient. Moreover, a larger temperature gradient leads to a faster rate of freezing front advancement. The rate of water migration in the soil during freezing is related to the rate of change of the temperature gradient, with a larger rate of change resulting in a higher water migration rate. However, the long water migration path will lead to a decrease of water in the unfrozen area, and the water replenishment rate lags behind the water migration rate. The conclusions provide the theoretical basic for the practical engineering of horizontal freezing.

Keywords: Frost heave, Water migration, Temperature gradient, Horizontal freezing

1. Introduction

Frost heave damage to soil is a common engineering disease in cold regions. Railroads, highways, civil buildings, and water conservancy engineering facilities built in such regions must consider the impact of freezing and thawing on the safety and stability of building structures. Structures located below the freezing depth of the foundation pit experience horizontal freezing due to the exposure of the excavation profile to cold air, which can cause the soil in the support gap to crack or collapse. Tunnel lining concrete can crack or even spall due to horizontal freezing. Under the effect of horizontal frost heave, Retaining structures, such as retaining walls and underground side chambers may produce undesirable sliding displacements. In addition, the use of artificial freezing in the construction of urban underground spaces can generate considerable horizontal freezing forces and deformations, which seriously affect the surrounding soil layers. Water migration is the primary source of soil frost heave [1, 2]. To understand the process and mechanism of frost swelling, it is crucial to first gain a deep understanding of water migration and its specific driving causes and related mechanisms [3].

Frost heave is caused not only by the freezing of in-situ water but also by the migration of water from the unfrozen area to the frozen front. Water migration is the main cause of frost heave. During the freeze-thaw cycle, the hydrothermal state in the soil undergoes complex changes [4, 5]. Therefore, studying the hydrothermal properties of soils during freeze-thaw cycles is essential to study the frost heave property of soils. The study of water migration in frozen soils is now considered as a central issue in the freezing action of soils and has received attention from many countries around the world. When the soil temperature drops below the freezing point, water in the frozen area freezes, and water in the unfrozen area migrates to the frozen area under the action of the matrix, gravity, solute, and temperature potential, forming an ice lens. During this process, various mechanical properties of the soil change. When soil freezes, liquid water is subjected to the action and influence of many forces during the migration process, including gravity, adsorption, capillary force, and seepage force [6]. Different forces have different effects on the migration of liquid water. The migration of water in freezing soil is the result of the combined effect of multiple factors, which is the comprehensive effect of various single factors on water migration [7]. Unlike vertical freezing, horizontal freezing produces different results due to the non-zero angle between matrix forces and gravity. Therefore, studying water migration under horizontal freezing conditions is of great practical significance.

2. State of the art

A large number of experiments on the study of water migration during soil freezing have been carried out. Rui et

*E-mail address: dhrui@hpu.edu.cn
ISSN: 1791-2377
doi:10.25103/jestr.162.12

al. conducted a laboratory experiment that the replenishment water level was flushed with the bottom of the soil column to avoid water migration under the pressure difference of water level [8]. Harlan proposed that the soil water potential gradient serves as the driving force of water migration [9]. Jean and Norbert concluded that the water migration flux is proportional to the temperature gradient through conducting water migration tests under different temperature gradients [10]. Nakano and Tice performed an experimental study on water migration under isothermal conditions and concluded that the water migration flux depends on the gradient of the total water content in the soil [11]. He et al. believed that the driving forces for water migration include matrix potential, solute potential, pore water pressure, and gravity potential [12]. Konrad and Morgensteren suggested that the water migration in frozen soil is affected by the temperature gradient [13]. Tice et al. found that differences in unfrozen water contents between the undisturbed warming and cooling curves depended on the relative degree of saturation and its effect on soil structure. Only slight changes occurred during the warming curves of the remolded soil, indicating minor freezing and thawing consequences on the soil structure [14]. The temperature gradient has been widely accepted as the intuitive driving gradient of water migration.

Soil freezing is a complex process that involves physical, chemical, and mechanical phenomena, including soil heat transfer and water migration [15]. In hydrothermal systems of frozen soil, water migration affects the thermal characteristic parameters of the soil, leading to the redistribution of heat [16, 17]. Conversely, the soil temperature gradient affects soil water migration and changes in water characteristic parameters [18, 19]. During soil freezing, liquid water inside the soil undergoes a phase change and the freezing front is formed under the effect of temperature below 0°C. The temperature field changes, disrupting the phase equilibrium in the soil, and generating various driving forces that cause water migration. As the freezing process proceeds, the water film on the surface of soil particles becomes asymmetric, and growing ice crystals continuously remove water from the adjacent water film, causing the thinning of the water film. The water molecules in the adjacent thick film are continuously replenished to the film [20]. This sequential transfer creates the migration of water to the frozen surface during freezing**.** However, the soil water potential gradient is difficult to determine because the film on the surface of frozen soil is too small. Therefore, the temperature gradient is the only directly determinable driving gradient[21]. Due to the surface energy of soil particles, some unfrozen film water is always present in the soil. Under the induction of temperature gradient, the film water will migrate from the high temperature to the low temperature and forms ice-segregation in the soil, resulting in frost heave [3]. Through dynamic observations in field experiments, Rui et al. concluded that when the soil temperature gradient changes rapidly and the freezing rate is slow, water has sufficient time to migrate to the freezing front and produce enhanced frost heave [22]. Shang et al. found that the stepwise freezing mode is more likely to produce a larger amount of frost heave compared with the continuous freezing mode through the unidirectional freezing test of silty clay. The mechanism is mainly due to the larger temperature gradient within the frozen fringe of this freezing mode [23].

Most existing studies have focused on the effect of freeze-thaw action on physical and mechanical parameters of soil vertical freezing conditions, from top to bottom [17, 24-29]However, research on water migration in soil under horizontal freezing conditions is limited. In areas rich in natural cold energy, foundation pit engineerings and urban underground spaces are often subject to horizontal freezing. The water migration laws of soil under vertical freezing conditions cannot be fully applied, which highlights the need for a study of temperature gradients and water migration law under horizontal freezing conditions.

The rest of this study is organized as follows. Section 3 gives the soil samples, test setup and test procedure. Section 4 presents the experimental results analysis and discussion, and finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Soil samples

Samples were collected from farmland soil in Jiaozuo, China, at a depth of 0-30 cm. After collecting the soil samples, they were naturally dried and the physical parameters were measured according to the China Standard for Geotechnical Test Methods (GB/T50123-2019). The basic physico-chemical properties are presented in Table 1.

Table 1. Basic properties of test soil samples.

Particle density ρ_s (g·cm^{-3})	Limit moisture content		Compaction test		Particle size (mm)		
	W_L (%)	W_P (%)	Maximum dry density ρ_{dmax} (g·cm^{-3})	Optimum moisture content W_{opt} (%)	≥0.25	0.075-0.25	≤ 0.075
2.67	29.9	16.0	1.70	19.0	24.20%	22.08%	53.72%

3.2 Transverse freezing model test setup

The freezing model test device comprises soil tanks, an artificial freezing system, automatic water replenishment devices, and a data acquisition system, as shown in Fig. 1. The size of the soil tank is 170 cm × 100 cm × 100 cm (length × width × height). The water supply tank with a width of 15 cm is located on both sides of the soil tank. To minimize heat exchange with the external environment, the soil tank is covered with thermal insulation cotton.

The freezing system composes a freezing plate, brine delivery pipes, and a low-temperature brine ($CaCl_2$) tank. The freezing plate, made of stainless steel, has dimensions of 50 cm in length, 40 cm in width, and 8 cm in thickness. The automatic water replenishment equipment consists of mass sensors, micro submersible pumps, water storage buckets, and water level controllers. The amount of water replenishment is automatically recorded and stored by electronic balances.

The arrangement of sensors is illustrated in Fig. 2. The K-type thermocouple is used to measure the temperature in soil, buried at a depth of 25 cm. To measure soil moisture, a TDR moisture sensor is placed along the middle axis of the soil.

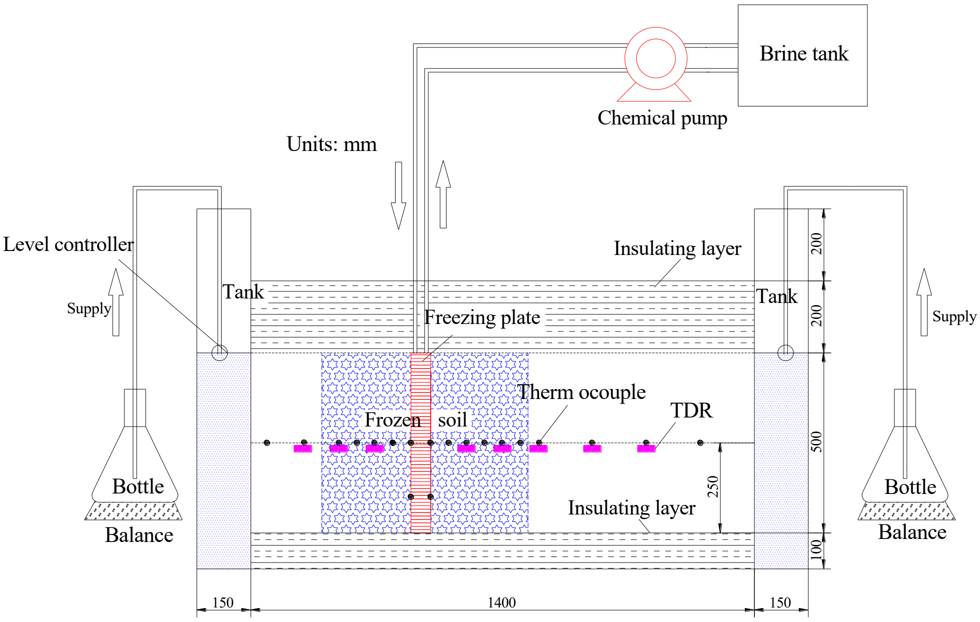


Fig. 1. Transverse freezing model test device.

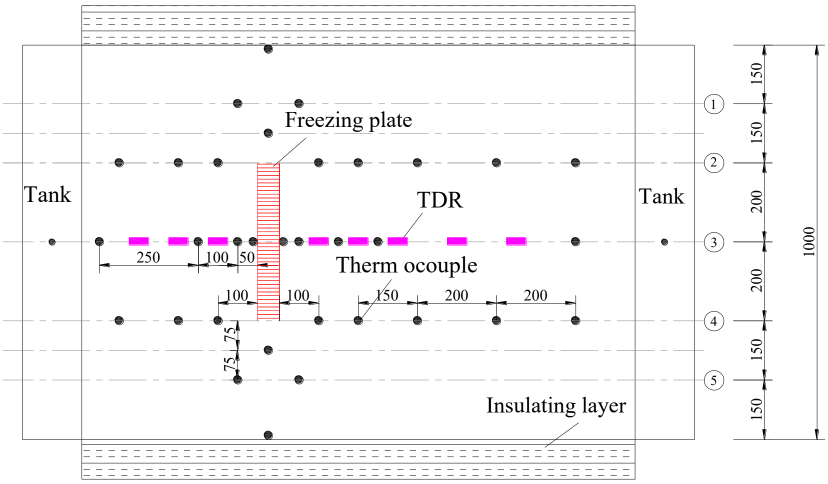


Fig. 2. Layout of measuring point cross section.

3.3 Test Procedure

The air-dried soil sample was prepared with 20% moisture content, and the resulting test soil sample weighed 1200 kg. The prepared soil sample was allowed to stand for 72 h to ensure uniform moisture content in the soil. The soil sample was compacted in layers to produce a sample measuring 1400 mm × 1000 mm × 500 mm(length × width × height) with a density of approximately 1.62 g/cm^3. The permeability coefficient of the soil sample was determined to be 4.29 × 10^{-7} cm·s^{-1} by the variable head permeability test method.

Before freezing, water was supplied to the left and right water tanks, and the water level was adjusted to be flush with the upper end of the soil through the automatic water refill device. When the water level in both tanks remained unchanged, the freezing plate was cooled and the soil was frozen horizontally.

Using a stepwise freezing mode to freeze the soil until the soil no longer absorbs water.

The amount of soil recharge during the freezing process was automatically recorded and stored by electronic balance, and the average rate of soil recharge was calculated.

4. Results analysis and discussion

4.1 Freezing mode

There are two general freezing modes: continuous freezing mode and stepwise freezing mode, which can produce different experimental results. Compared to the continuous freezing mode, the stepwise freezing mode is more likely to cause frost heave and absorb more water. The mechanism behind this phenomenon is that the stepwise freezing mode results in a larger temperature gradient within the freezing fringe. And water migration is positively correlated with the temperature gradient, which promotes the migration of water from the unfrozen area to the frozen area. To increase the amount of water migration during the freezing process and obtain intuitive results, the stepwise cooling mode is employed.

Fig. 3 illustrates the freezing mode of the freezing plate which adopts stepwise freezing mode. The initial temperature of the refrigerant was set at -4℃, and then kept constant after being dropped to -22℃.at a rate of -2℃.d^{-1}. The measured data confirmed that the freezing plate was cooled basically according to the set freezing trend. At the initial stage of freezing, the temperature difference between the brine tank and the freezing plate reached 2.6 °C. After reaching the set temperature, the measured temperature on the surface of the freezing plate was -16.4 °C, which was 5.6 °C higher than the temperature of the brine tank. The reason is related to the energy exchange between the surface of the freezing plate and the surrounding soil, as well as the energy loss during the refrigerant transfer by the brine circulation system.

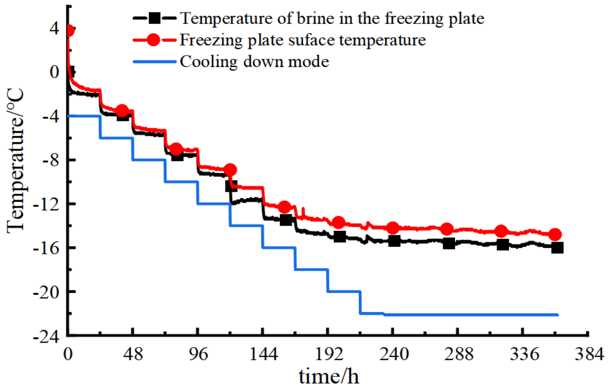
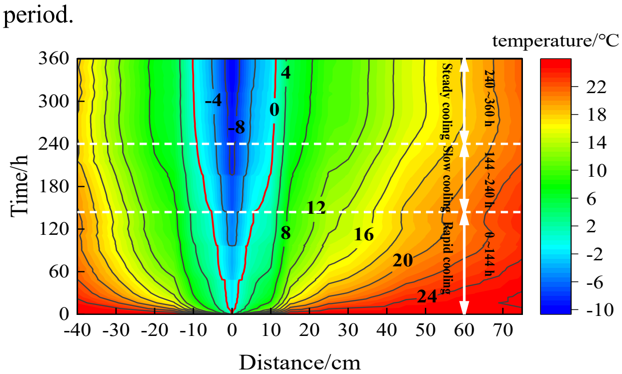


Fig. 3. Temperature control mode and freezing plate surface temperature.

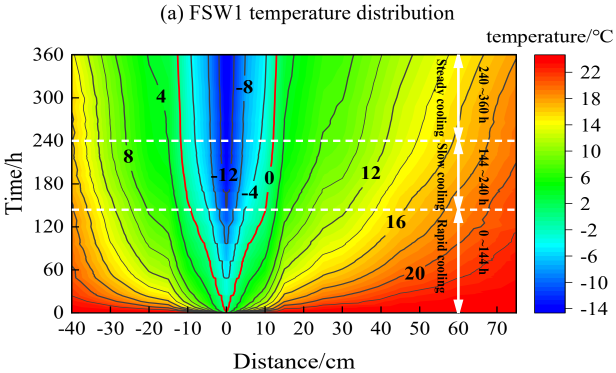
4.2 Temperature field analysis

4.2.1 Soil temperature change

The temperature field changes can directly reflect the effect of freezing and visually demonstrate the progression of the freezing front. Fig. 4. Shows the soil temperature changes at a depth of 25 cm along the main line during the freezing period.



(a) FSW1 temperature distribution



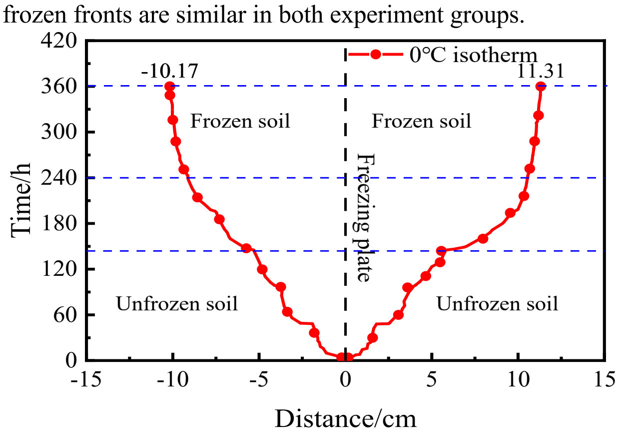
(b) FSW2 temperature distribution

Fig. 4. The temperature change of soil at each distance point on axis 3 during freezing and thawing.

The horizontal axis of 0 cm in the figure is the position of the freezing plate, with the left and right sides indicating soil temperature at different distances and times. As shown in Fig. 4, the temperature of the freezing plate decreased with the increase of freezing time. The cooling capacity was transmitted to both sides, leading to a decrease in temperature at each temperature measuring point. However, the cooling range gradually decreased with the increase in distance from the freezing plate, indicating a trend of gradual decrease. Soil cooling can be roughly divided into three stages: rapid cooling, slow cooling, and steady cooling.

The period of 0-144 h is considered as the rapid cooling stage. During the initial stage of freezing, the water froze in situ due to the soil temperature near the freezing plate suddenly decreasing, leading to a rapid movement of the freezing front. As the freezing time increased, the water in the unfrozen area migrated to the low temperature region under the action of "freezing suction." This migration process releases latent heat, which slows down the advancing speed of the freezing front. The period of 144-240 h is considered as the slow cooling stage, during which the rate of soil temperature decline decreased significantly, and the outward migration rate of frozen soil area slows down. The period of 200-360 h is considered as the stable stage. during which the temperature of the freezing plate remained constant. At this stage, the latent heat released by the freezing of water in the soil and the cooling capacity provided by the freezing plate reach a balance, resulting in a stable soil temperature tended and a dynamic balance of the freezing front.

The red line in Fig.4 illustrates the change in soil temperature at 0 °C isotherm, which indicates the migration of the freezing front. This data was extracted and presented in Fig. 5, which shows that the migration patterns of the frozen fronts are similar in both experiment groups.



(a) FSW1

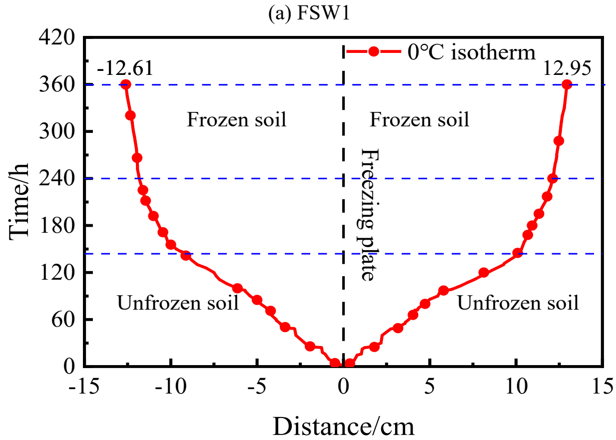
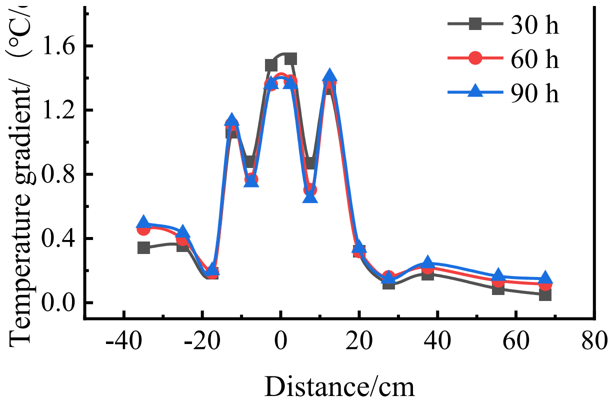


Fig. 5. Dynamic changes of frozen front.

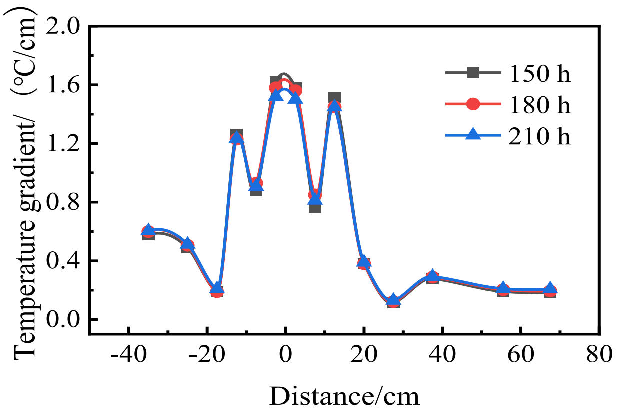
In FSW1, the maximum thickness of frozen soil is 10.17 cm on the left side and 11.29 cm on the right side. While in FSW2, the corresponding values are 12.61 cm and 12.95 cm. The soil in the FSW1 test reaches a negative temperature after 1.67 h of cooling, while the soil of the FSW2 starts freezing after 1.5 h. During the rapid freezing period, the freezing front rapidly pushes forward, and the freezing rate is large. As time passes and the freezing front advances on both sides the freezing rate gradually decreases during the slow freezing period. In the stable freezing period, the freezing front remains almost constant.

4.2.2 Soil temperature gradient changes

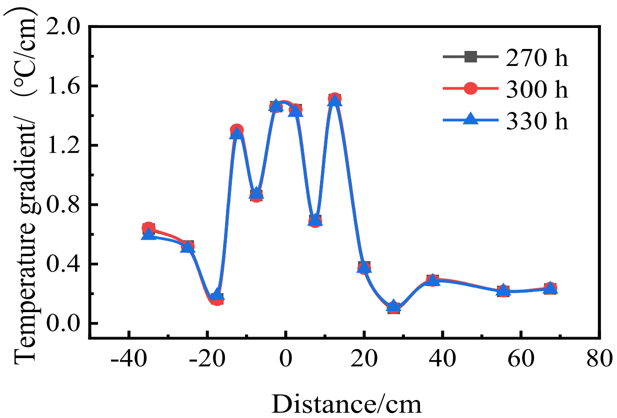
In this experiment, the stepwise cooling mode was selected as a temperature control mode due to its known ability to induce moisture migration [10]. Fig. 6 illustrates the change in temperature gradient during different freezing periods. During the fast freezing period, the temperature of the freezing plate drops abruptly to a negative temperature, causing the freezing front to migrate to both sides. Consequently, the temperature gradient of the soil in the unfrozen area steadily increases.



(a) rapid freezing period (0-144 h)



(b) stable freezing period (144-240 h)



(c) slow freezing period (240-360 h)

Fig. 6. Variation trend of soil temperature gradient during the freezing period.

At the early stage of freezing, the temperature gradient of soil near the freezing plate increases extremely fast because of the sudden decrease in soil temperature near the freezing plate. With the increase of freezing time, the cooling rate of the soil decreases, and the cold energy is transferred to both sides, resulting in a gradual decrease in the temperature gradient of the soil within 15 cm from the freezing plate. Conversely, the temperature gradient of the soil in the non-freezing area shows an increasing trend with a decreasing rate. During the process of stepwise cooling of the soil, the temperature gradient in the frozen area shows an increasing trend after cooling, and at the end of each step of cooling, the temperature gradient again shows a slow decreasing trend.

The changes and fluctuations of temperature gradient near the stable freezing front are more pronounced, with the temperature gradient at the left and right ends of 10 cm being smaller than that at 20 cm. This is due to the closer proximity of this location to the freezing front, resulting in faster water migration from the unfrozen area to the frozen area and a more intense release of latent heat of phase change.

The driving force for water migration in permafrost comes from the unfrozen water potential gradient induced the temperature, and in an open system, the water migration flux in water-saturated positive permafrost is proportional to the temperature gradient in permafrost [11]. As a result, a larger temperature gradient in the frozen area leads to more water absorption by the soil and greater frost heave.

4.3 Moisture distribution in soil

Taking the FSW2 experiment as an example, Fig. 8 shows the variation of volumetric water content at different positions of the soil with a depth of 25 cm along axis 3 with freezing temperature, while Fig. 9 presents the variation of volumetric water content with times. The changes in volumetric water content can reflect the processes of water absorption.

According to Fig. 8, the temperature trends of the soil on both sides of the frozen plate are approximately the same. Comparing the volumetric water content of the soil at the same distance between the left and right sides of the freezing slab, it can be observed that the volumetric water content of the soil at 10 cm depth decreased significantly with the freezing, while the soil at 20 cm and 30 cm depth did not freeze, but the migration of water to 10 cm under the action of "freezing suction" shows a decreasing trend. The decrease in volumetric water content of the soil at 20 cm and 30 cm on the left side is less than that on the right side, which is because the left side is closer to the replenishment tank, and water replenishment is faster, while the right side is farther away from the replenishment tank and there is a lag in replenishment. Under the condition of unidirectional freezing in a closed system, the water on the unfrozen side migrates to the surface of the freezing front, resulting in a decrease of its water content. However, under open condition, the volumetric water content on the unfrozen side does not change significantly, indicating that under a certain temperature gradient, the water in the recharge tank flows through the soil particles toward the freezing front.

Combined with Figs. 8 and Figs 9, during the initital stage of freezing, the temperature of the soil around the freezing plate decreases, causing water in the unfrozen area to migrate towards the freezing front and resulting in a decrease in the water content in the unfrozen area. Meanwhile, water from the supply tank infiltrates the soil to compensate for the water migrated from the unfrozen area.

Before the start of freezing, the soil temperature was uniformly distributed. After 1.5 h of freezing, the soil reached negative temperature and the volumetric water content at the freezing slab decreased. During the 24 h to 168 h of freezing, the soil temperature within 10 cm of the freezing plate continued to decrease, leading to a continuous decrease in the volumetric water content. At 168 h of freezing, the temperature of the soil at 10 cm was negative, resulting in a significant drop in soil water content. At 216 h of freezing, the freezing slab was cooled to its final temperture, which was maintained until 360 h.

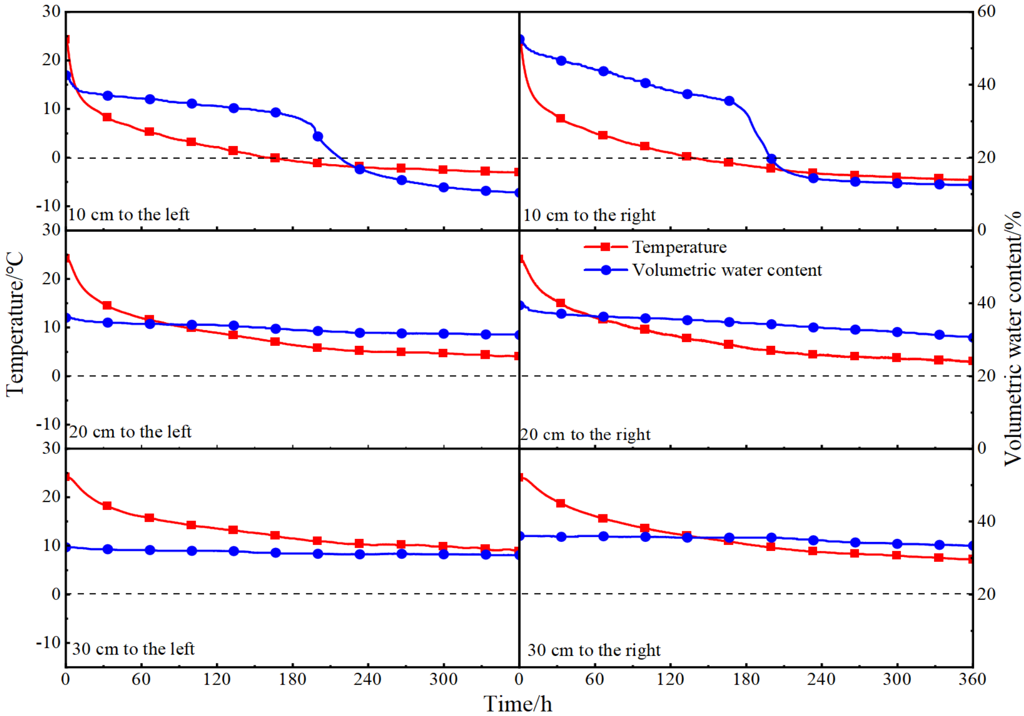


Fig. 8. Changes of soil volume water content at different positions.

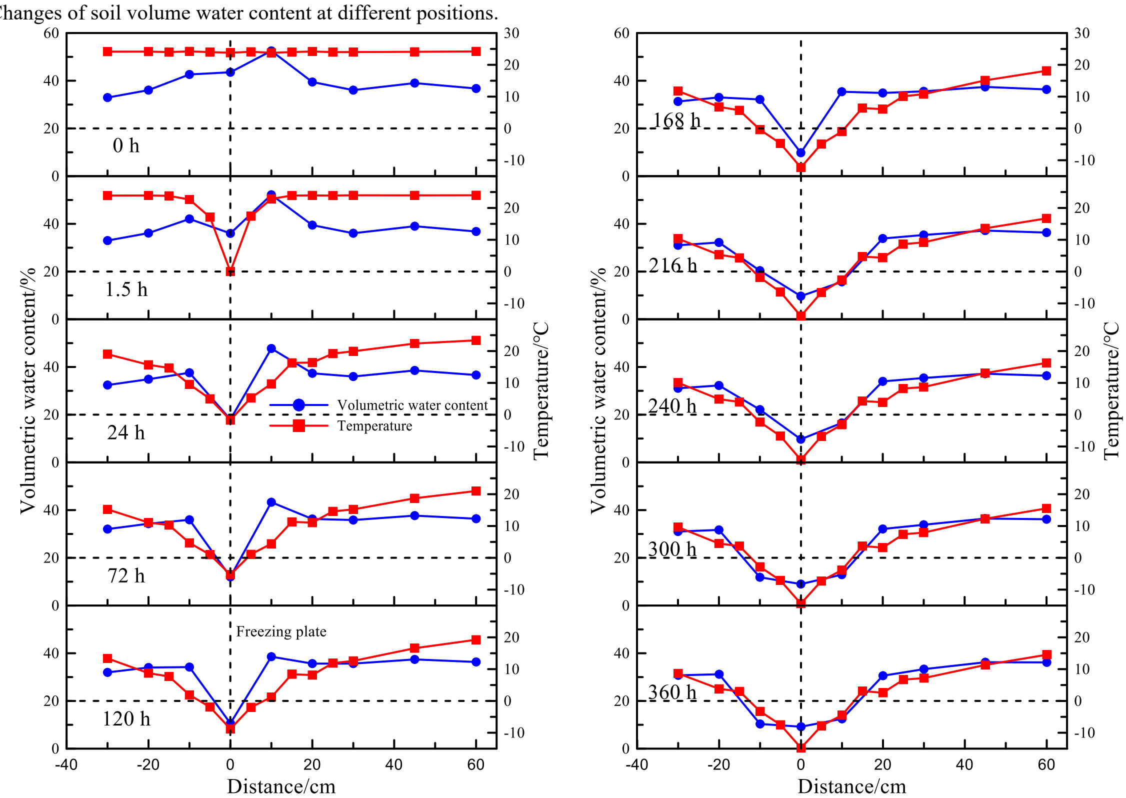


Fig. 9. Changes of soil volume water content at different times.

At 300 h of freezing, the volumetric water content of the soil located 10 cm away from the freezing plate decreased significantly due to the majority of the free water in the soil freezing into ice. The volumetric water content at distances of 10 cm, 20 cm, and 30 cm from the left side of the freezing plate decreased by 76.1%, 13.5%, and 6.7%, respectively. On the other hand, the volumetric water content at distances of 10 cm, 20 cm, and 30 cm from the right side of the frozen slab decreased by 76.4%, 23.1%, and 7.6%, respectively. The reason is that when the temperature of the soil is lower than the freezing temperature, the liquid water phase in the soil pore becomes ice crystals which are bonded with the soil particles. However, the liquid water on the surface of the soil particles does not become ice. and a small amount of unfrozen water remains wrapped around the surface of the soil particles As a result, the free energy of the unfrozen water is significantly reduced. and based on the energy balance, water migrates from the unfrozen area to the frozen area to compensate for the water loss caused by the phase change in the frozen area. Therefore, a segregation ice lens is formed along the water lateral migration path. Simultaneously, water on both sides of the water tank migrates to the unfrozen area, with the migration path on the left side being shorter, leading to a faster replenishment of water, Consequently, the reduction in volumetric water content at different locations is smaller on the left side than the right side.

4.4 Frozen rehydration volume and rehydration rate

Fig. 10 shows the amount of soil recharge from the left and right sides during the entire freezing process for FSW2.

The replenishment volume of water was 10.684 kg on the left side and 17.250 kg on the right side, totaling 27.834 kg. During the rapid freezing period, the amount of water replenishment increased rapidly, and during the slow freezing period, the rate of water replenishment decreased. During the stable freezing period, the water replenishment rate further decreased. Fig.11 shows the specific water replenishment rate with time.

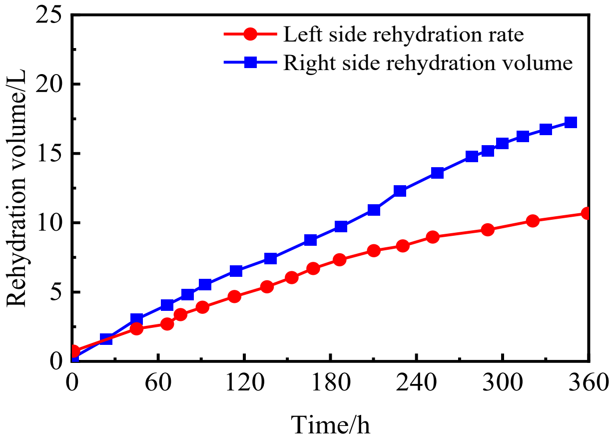


Fig. 10. Water replenishment volume on both sides.

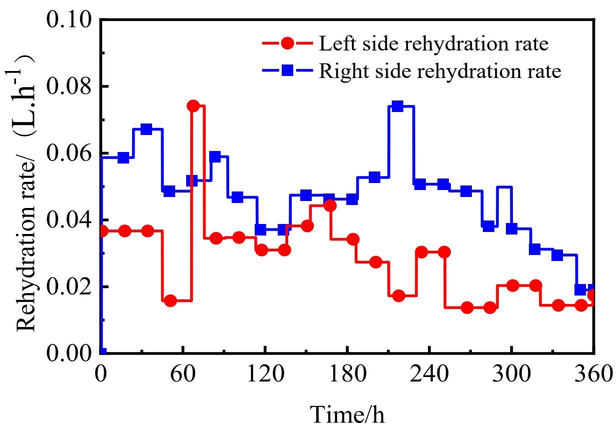


Fig. 11. Water replenishment rate on both sides.

During the rapid freezing period, the average water replenishment rate of the left side reached 0.0367 $L.h^{-1}$ and the average water replenishment rate of the right side reached 0.0587 $L.h^{-1}$. Due to the sudden decrease of the freezing plate temperature, the nearby soil freezes in situ and the water migrates, and the left side is closer to the water tank, which allows for more water replenishment. However, the right side is farther away from the water tank, and the water migration path is longer, resulting in a relatively stable recharge rate.

During the stable freezing period, the migration rate of the freezing front decreases. The water replenishment rate on the left side showed a downward trend, while the water replenishment rate on the right side remained relatively stable. This is due to the long water replenishment path on the right side, and the water replenishment rate was calculated based on the reduction of water in the two water tanks. Therefore, the right side lags behind the left side in terms of recharge rate.

During the slow freezing period, the freezing front is in a state of dynamic equilibrium. The average water replenishment rate on the left side decreases to 0.0204 $L.h^{-1}$ and remains stable, while the right side shows a decreasing trend because of the lag and the final recharge rate reaches 0.0191 $L.h^{-1}$. Among them, compared with the changing trend of soil temperature gradient at different positions in Fig.10, it can be found that the water replenishment rate is positively correlated with the change rate of temperature gradient in frozen soil area.

5. Discussion

During horizontal freezing of the soil, the structure is subjected to horizontal forces that increase the horizontal displacement due to the growth of the ice lens. This phenomenon commonly occurs in tunnels, mines, foundation pits and other facilities built in seasonally frozen soils and can lead to the risk of structural instability or damage. Frost heave damage is directly related to water migration in the soil. In this study, the temperature field and water migration during horizontal freezing of soils under open systems are investigated. To provide a reference for the theoretical research and engineering practice related to water migration laws under horizontal freezing conditions in future projects.

The self-designed horizontal freezing equipment is used to vertically arrange the freezing plate to freeze the soil horizontally. The distribution and evolution of the temperature field and water field in the soil during the freezing process are studied. During the freezing process of the soil, the water in the unfrozen area migrates to the low temperature end under the action of the soil water potential gradient. The migrated water releases latent heat during the freezing process, which slows down the pushing speed of the freezing front. The rate at which the freezing front advances increases with a larger temperature gradient. The rate of water migration in the soil during freezing is related to the rate of change of the temperature gradient, and the greater the rate of change, the greater the amount of water migration.

The water migration rate in the freezing process is approximated by the rehydration rate. The left side of the freezing plate (short side) exhibits more consistency, while the right side of the freezing plate (long side) experiences a lag phenomenon. This is due to the long water replenishment path on the right side, where more latent heat is released during water migration and water replenishment time is delayed. In practical applications, a suitable water replenishment path can be chosen to achieve the intended effect.

The experiment investigates the transverse water migration law of saturated soil without the use of a displacement sensor to calculate frost heave. The following study will further investigate the relationship between the hydrothermal effect and the amount of frost heave during transverse freezing process of unsaturated soil.

6. Conclusions

In this study, the temperature field, water field and water migration in the process of soil freezing were analyzed through the test of vertical freezing plate and transverse freezing soil in the model groove soil. The main conclusions are obtained as following:

(1) The cooling of the soil can be divided into three stages: rapid cooling, slow cooling, and stable stage. The speed of the freezing front decreases with the freezing time. When the latent heat released by the freezing of water in the soil and the cooling provided by the freezing plate reaches a dynamic equilibrium, the soil temperature stabilizes and the freezing front reaches a steady state. The phase change of water near the freezing front releases intense latent heat, which lends to a greater temperature gradient.

(2) The use of stepwise cooling mode leads to a larger temperature gradient in the frozen area, causing the soil to absorb more water and produce a larger amount of frost heave. In the actual project, the corresponding cooling mode can be selected to achieve the desired effect.

(3) The driving force of water migration in permafrost comes from the unfrozen water potential gradient induced by the temperature gradient, and the water migration rate in water-saturated positive permafrost under an open system is positively correlated with the temperature gradient change rate. In the horizontal freezing process, a too long recharge path will lead to the "lag" phenomenon of water migration, where the water cannot be replenished to the unfrozen area in time, and thus the water content will decrease. Reasonable planning of the water replenishment distance can help in horizontal soil freezing.

Based on the experimental research results, the next step is to carry out the field transverse freezing test to facilitate the engineering application.

Acknowledgements
The study was financially supported by the State Key Laboratory of Frozen Soil Engineering (SKLFSE201917) and the Technological Project of Henan Province Office of Education (14B170007), China.

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