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Study on Thermal-moisture Migration Patterns of Saturated Clayey Soil during Repeated Segregation Frost Heaving and Thawing

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Abstract

To clarify the phenomenon of repeated segregated ice during the freeze-thaw cycle and improve the theory of soil freezing and thawing, a coupled hydro-thermal model was derived on the premise of previous theories, which described the soil deformation utilizing the Clapeyron equation of thermodynamic equilibrium in the phase change process. Then, the experiments being repeated to separate frost heaving and thawed moisture migration of saturated clayey soil were conducted. Results show that during the freezing period, the temperature change of each measurement point is consistent, and there exists a significant hysteresis with the distance from the cold source. The migration rate of unfrozen water to the freezing front driven by the temperature gradient is related to the freezing rate and has a constant dynamic trend with the frost heave. During the thawing period, there are obvious variations in temperature changes at each measurement point, and therefore the temperature change of the soil layer near the central heating layer is larger. The water supplement rate is comparatively slow, and there exists a trend from gentle to rapid growth. Under the fitted actual experimental boundary conditions, the system of nonlinear differential equations for hydrothermal coupling is solved by COMSOL Multiphysics software. The conclusions obtained in the study provide a reference to freeze-thaw practice.

Keywords: Saturated clayey soil, Temperature distribution, Moisture migration, Heating layer

1. Introduction

The moisture migration experiment is commonly used as an effective method to analyze moisture migration patterns. The phenomenon of moisture migration during soil freezing and thawing was first identified by Taber and Beskow [1, 2]. They found that moisture migration is the main factor inflicting frost heave during the freezing period, and the volume change caused by the ice-water phase change in soil pore water is the visualization of soil deformation (frost heave and thaw settlement). In addition, soil deformation is a typical multi-physics field coupling result, involving heat transfer, moisture migration, ice-water phase change and physical field redistribution [3].

At present, the experimental methods and laws of moisture migration, the heat exchange properties of frozen soil, and the special phenomena caused by moisture migration have gradually become the focus of research [4-5]. One research results show that moisture migration during the freezing period is related to the soil-water potential, which primarily depends on the soil properties, boundary conditions, freezing rate and frost heave rate [6, 7]. However, most of these experimental models equate the soil as a continuous medium, and only the mechanism of moisture migration and segregated ice under unidirectional freezing conditions is studied. Meanwhile, the existing first and second frost heave theories only consider a moisture migration mechanism in capillary water and thin film water, resulting in being tough to fully reveal the moisture migration phenomenon in the freeze-thaw cycle of soil [8].

Moisture migration has been proven an important cause of soil deformation, which seriously damages the stability of buildings and structures on the soil surface. The moisture migration experiment is of great theoretical and sensible significance to research the comprehensive mechanism of continuous freeze-thaw cycles. Therefore, it is necessary to improve the existing theory of freezing and thawing and mitigate frost heave and thaw settlement disasters.

2. State of the art

Moisture migration is littered with numerous factors in frozen soil, being the result of a combination of forces [9-11]. Therefore, the various roles of capillary water, pellicular water, and water vapor should be comprehensively considered in moisture migration when establishing the frost heave model. For this reason, Lai et al. constructed a new mass and energy conservation equation applicable to the transport of unsaturated saline soil media, which effectively describes the moisture-heat-gas-salt interaction process [12]. Zhelnin et al. constructed the constitutive equations related to porosity based on the theory of porosity mechanical [13]. In addition, the constitutive relation of additional mechanical deformation is introduced to describe the volume expansion and creep strain during the freezing period. Sanchez proposed a fully coupled hydrothermal formulation for use in unsaturated soils based on the dual porosity formulation

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[14]. Dumas and Konrad considered the nonlinear relationship between the porosity ratio and the vertical effective stress and established a framework for a finite strain one-dimensional consolidation theory [15, 16]. However, the analysis was based on the constant volume compressibility and hydraulic conductivity of the thawed soil. During the thawing period, they ignored the reduction in porosity due to phase change and excess water drainage.

In view of this, Cheng et al. constructed a capillary-film moisture migration unit model based on the pressure-absorption stress transformation of film water to elucidate the freeze-thaw moisture migration driving force [17]. However, the model was limited to revealing the water migration mechanism of pores/fissures during freezing and failed to account for the influence of interfacial effects on the thawing process. Ming et al. combined the moving boundary technique to ascertain a thawing deformation consolidation theory with the pore ratio as the variable and analyzed the thawing deformation process of permafrost [18]. In contrast to natural thawing, artificially forced thawing occurs not in the thawed area by normal consolidation, but by thermal consolidation. When the thermal expansion of soil particles and water is failed to be negligible, those models are no longer applicable. For this reason, Zhou et al. established a theoretical model and gave an analytical solution to the model for the thawing process of saturated permafrost at high temperatures [19].

Although various scholars have improved the moisture migration test model under multi-element influencing factors, there is a lack of being repeated to separate frost heave model [20-24]. Consequently, this paper proposes to carry out an experimental study of moisture migration with different freezing/thawing rates under being RSFH and thawing conditions. Meanwhile, the Clapeyron equation of thermodynamic equilibrium during the phase change process is used to describe the variation of soil deformation. Combined with the calculation results of COMSOL numerical simulation software, we try to reveal the soil temperature distribution and moisture migration characteristics under being repeated to separate frost heaving and thawing.

The rest of this study is organized as follows. Section 3 describes the research methods. Section 4 analyzes the results of moisture migration and verifies the reliability of the numerical model. Finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Numerical modeling

Numerous scholars are more inclined to study permafrost frost heave, whereas comparatively little analysis has been done on moisture migration during the thawing period [25, 26]. This is often a result initially, for the convenience of research, the thaw settlement of frozen soil was tested in periods, i.e., thawing was performed first, and then compression experiments were performed [27]. In distinction, the properties of permafrost are perpetually dynamical with the thawing process, so the thawing and consolidation processes need to be analyzed simultaneously and thereby the mechanism of action needs to be revealed.

3.1.1 Water field constitutive equation

It is assumed that the moisture migration pattern in permafrost is analogous to it in thawed soils, and the moisture migration is mainly caused by the hydraulic and temperature gradients. Referring to the Richards equation characterizing liquid moisture migration and taking the vertical downward as the positive *y*-coordinate axis [28], the constitutive equation of one-dimensional moisture migration in saturated soil is obtained:

$$\frac{\partial \theta_w}{\partial t} + \frac{\rho_i}{\rho_w}\frac{\partial \theta_i}{\partial t} = \nabla\left[K_{lh}\nabla\left(h+y\right) + K_{lT}\nabla T\right] \tag{1}$$

where, θ_w and θ_i are the volume content of unfrozen water and the volume of ice content, respectively. ρ_w and ρ_i are the densities of liquid water and solid water, respectively, kg/m^3. K_{lh} is the infiltration coefficient due to pressure head gradient, m/s [29]. K_{lT} is the infiltration coefficient due to temperature gradient, m/s [30]. *h* is the pressure head, m, given by the V-G model [31]. *y* is the height in vertical coordinates, m. *T* is the temperature, K, and *t* is the time, s.

3.1.2 Temperature field constitutive equation

According to the principle of energy conservation and Fourier's law, treating the latent heat of phase change as an internal heat source [32], the one-dimensional differential equation of heat conduction for the transient temperature field of saturated soil:

$$C_p\frac{\partial T}{\partial t} - L_f\rho_i\frac{\partial \theta_i}{\partial t} = \nabla\left[\lambda\left(\theta\right)\nabla T\right] - C_w q_w \nabla T \tag{2}$$

where, C_p and C_w are the specific heat of soil and water, kJ/(kg·K), respectively. λ_θ is the thermal conductivity of soil, W/(m·K) [33]. L_f is the latent heat of crystallization or thawing of water, kJ/kg. θ_i is the volumetric ice content, %. q_w is the liquid water flux, m/s.

3.1.3 Contact equation

The moisture migration Eq. (1) and the heat transfer Eq. (2) contain three variables: temperature, *T*; unfrozen water content θ_w, and volumetric ice content θ_i. Therefore, the connection between *T*, θ_w, and θ_i should be found, i.e., a linkage equation should be introduced to resolve the coupled water-heat model. In this study, the dynamic equilibrium relationship between unfrozen water content and temperature is determined as follows.

$$\theta_w = a\left|T\right|^{-b} \tag{3}$$

where, *a* and *b* are the parameters related to soil quality.

3.2 Moisture migration modeling

3.2.1 Experiment equipment

As shown in Fig. 1, the indoor experiment device is principally composed of a freeze-thaw experiment device, a water supplement device, and a data acquisition system.

The moisture migration experiment device on the condition of freeze-thaw cycles includes a specimen cylinder, a refrigeration device, and a heating layer. The specimen cylinder is 50 cm high, 20 mm inner diameter, and has a 1.5 cm wall thickness. The outer side of the cylinder wall is jacked with a PT100 temperature probe in a 2 cm horizontal direction and 1cm vertical direction, so the holes spiral up equally in the height direction. Besides the outside of the cylinder wall is insulated to prevent heat loss. The cooling device consists of two low-temperature constant temperature cold baths. The central part of the soil sample is organized with a homemade resistance wire heating layer, which may provide the temperature required for the thawing period through the temperature controller, and conjointly plays the role of monitoring the temperature of the central soil sample.

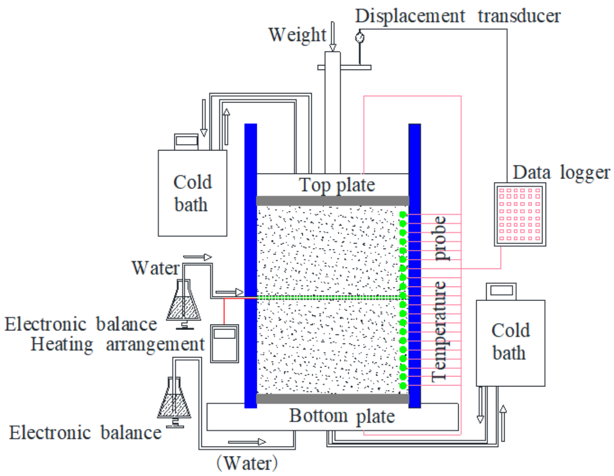

Fig. 1. Schematic diagram of the experiment device.

The data acquisition system consists of mass, temperature, and displacement acquisition systems. Two water supplement devices are installed in the middle and bottom plates, and the water source in the supplement bottle is replenished to the interior of the soil through a conduit. The supplement bottle is placed on a mass sensor with an accuracy of 0.1 g, and the mass of the water supplement can be calculated by reading the distinction of the corresponding mass at different moments. The temperature acquisition instrument is the JM3813 static strain experimenting and analysis system. This instrument will measure and collect temperature records in real-time on the computer. The displacement acquisition system records the displacement change of the sample top plate through the displacement sensor of the top plate and stores it in the computer. To ensure the accuracy of the data, the displacement electrical device is fixed on the counterforce frame throughout the experiment and the telescopic rod of the displacement electrical device is formed parallel to the guide bar.

3.2.2 Experiment design

The experiment soil sample was taken from local farmland in Jiaozuo City. After natural air drying, the soil sample was crushed and passed through a 2 mm square sieve, and the basic parameters of the soil sample were determined according to the Chinese Standard for Geotechnical Experiment Methods (GB/T50123-2019) [34], as detailed in Table 1. The plasticity index of the soil sample was calculated to be I_p=13.3, thus the soil sample was pulverized clay.

Table 1. Basic physical properties of soil samples.

Soli properties	Value
Particle density ρ_s (g·cm^{-3})	2.67
Limit of liquidity W_L (%)	29.9
Limit of plasticity W_P (%)	16.0
Maximum dry density ρ_{dmax} /(g·cm^{-3})	1.70
Optimum moisture content W_{opt} (%)	19.0
Particle size (≥ 0.25 mm)	24.2
Particle size (0.075 mm-0.25 mm)	22.08
Particle size (≤ 0.075 mm)	56.63

The experiment soil samples were prepared by the method of drainage consolidation. Therefore, the saturated specimens will exclude the interference of the gas phase in the soil and simplify the complexity of the analysis of the experiment results. The density of the prepared soil sample was 2.07 g/cm^3 and the water content was 21.79%. The selection of the cooling rate with the adoption of different experimental conditions is listed in Table 2.

Table 2. The experimental conditions.

Group	Cooling/warming rate (℃/h)	Top plate temperature (℃)	Bottom plate temperature (℃)	Central water supplement	Bottom water supplement	Loading (kPa)	Central heating temperature (℃)
RCW-1	0.2	25 to -20 -20 to 0	4 -20 to 0	Yes Yes	Yes No	10 0	No 4.5 to 5.5
RCW-2	0.3	25 to -20 -20 to 0	4 -20 to 0	Yes Yes	Yes No	10 0	No 4.5 to 5.5
RCW-3	0.4	25 to -20 -20 to 0	4 -20 to 0	Yes Yes	Yes No	10 0	No 4.5 to 5.5
RCW-4	0.5	25 to -20 -20 to 0	4 -20 to 0	Yes Yes	Yes No	10 0	No 4.5 to 5.5

4. Results Analysis and Discussion

4.1 Temperature field analysis

The experiment was conducted in a unidirectional freezing mode, and the soil samples were frozen sequentially from top to bottom. Due to the length of the paper, only the results of the RCW-1 experiment are illustrated in this paper. The boundary temperature conditions of the RCW-1 experiment are shown in Fig. 2.

4.1.1 Freezing period

The temperature variation curves with time at different locations of the soil sample from the top plate are shown in Fig. 3. Relative to the upper soil temperature change, there is an obvious time lag in the lower layer temperature. Because the cold energy transfer from the low-temperature region to the high-temperature region in addition to the energy consumption also desires a certain time, this time is the lag time.

During the quick freezing period, owing to the points area and the top plate cold source temperature difference being large, each layer of soil is rapidly exothermic. Quick freezing lasts for 80 h, step into the slow freezing period. The temperature difference between the temperature of each point area and the warm end of the bottom plate becomes larger, and the rate of absorbing the heat transferred upward from the bottom plate gradually increases, leading to a decrease in the overall cooling rate of the soil sample. To highlight the role of the heating layer in the middle of the thawing period, weaken the lag of temperature transfer, and ensure that the soil column is in the same physical state, thus the two-way freezing mode is adopted in the late freezing period. When the two-way freezing period ends, the soil column is fully frozen.

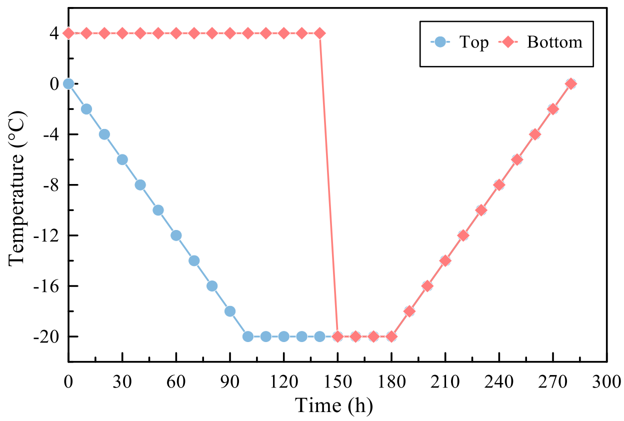

Fig. 2. The curves of boundary temperature vs. time in RCW-1.

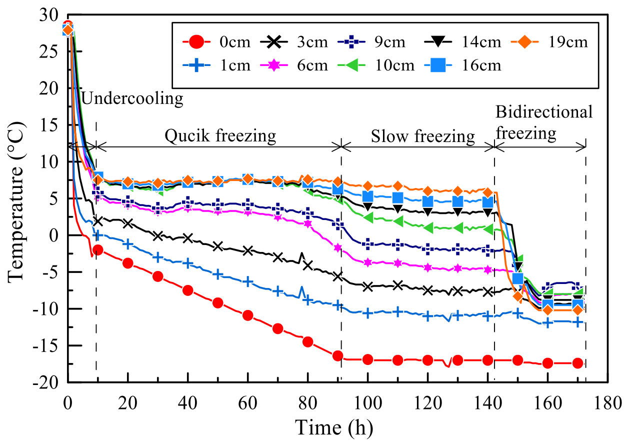

Fig. 3. The curves of temperature vs. time during the freezing period.

Besides, because the heat transfer process in permafrost is influenced by numerous factors, the various rate of temperature decrease in Fig. 3 indicates the distinction in heat transfer between the permafrost and normal solid materials. The water phase in the soil pores becomes ice, leading to increased heat transfer and loss of heat flux due to latent heat. It also indicates that permafrost has different thermophysical properties compared to ordinary solid materials.

It has been proven that the freezing point of the soil sample is -0.5°C by the experiment standardization. Therefore, this paper considers that the soil starts to freeze when the temperature in the soil reaches the freezing point, that is, the location at the temperature of -0.5°C is where the freezing front is located. According to the research of Wang, indicating the soil temperature is linearly associated with the distance after the temperature field of the soil subject to unidirectional freezing is stabilized [35]. Consequently, the temperature at each point of the longitudinal direction is taken to be -0.5°C as the freezing temperature.

The variation curve of the freezing front with time is obtained in Fig. 4. Due to the soil being the first to freeze in situ, the freezing front failed to move for 8.7 h before freezing. After 8.7 h, the external water recharge promoted the soil to provide sub-condensation and the freezing front slowly pushed downward. The freezing rate during the cooling process is susceptible to changes because of the combined effects of ambient temperature, latent heat of phase change, and thermal convection of unfrozen water. Under the condition of constant negative boundary temperature, the freezing rate shows a trend of increasing in the early period and decreasing in the later period. This is often a result of the freezing front moving, the water of unfrozen areas migrating to the freezing front. Leading to the unfrozen water content in the soil decreasing, the thermal conductivity of the soil gradually increasing with the increase of ice content, and the freezing rate accelerating. When the negative temperature lasts for a certain period, the influence of the boundary temperature on the internal temperature distribution of the soil gradually weakens. Resulting in the latent heat released by the water phase into ice gradually hinders the downward transfer of cold energy, and the freezing rate rapidly decreases. Taking time as the independent variable and depth as the dependent variable, the fitting curve expression of the freezing depth with time is y=-0.5616x^2+20.148x-30.347. Moreover, the R^2 of the fitting curve is 0.9534, and the change law of the freezing front position shows a better quadratic function form.

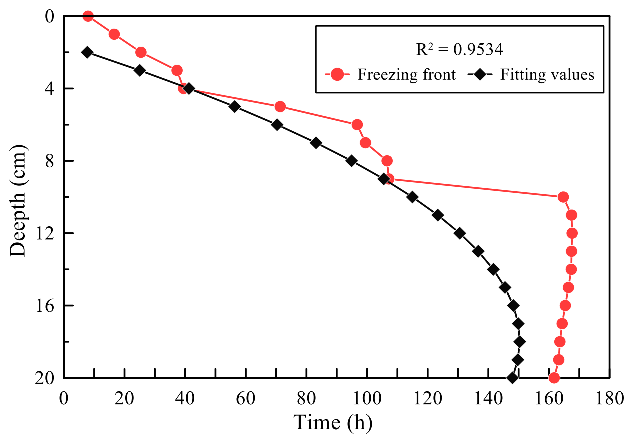

Fig. 4. The curves of freezing front vs. time.

4.1.2 Thawing period

The temperature variation curves of the thawing period with time are shown in Fig. 5. Except for the points near the heating layer, the temperature variation rate of the upper soil layer gradually decreases with the location from the cold source, and the temperature variation rate of the lower soil layer gradually increases with the increase of the distance from the heating layer. The temperature of the stable phase is between 0 and -1°C, with slight differences among soil layers. This is because the latent heat of phase change of the ice-water phase change absorbs heat, which makes the temperature remain stable in this period, i.e. the stable temperature is the freezing point of water in this experiment. The difference is that the temperature of the heated layer increases sharply adjacent to its top and bottom. Because the actual temperature of the central soil fluctuates repeatedly between the set heating area, the temperature distribution curve at 11 cm and 12 cm shows mechanical oscillation. Besides the temperature at these two locations tends to decrease, unlike the temperature change pattern at other locations.

In addition, based on the density of the curve distribution, it had been inferred that the curve distribution became dense after the phase change latent heat phase (i.e., after the experiment proceeded to 256 h), indicating that the phase changes latent heat played a role in reducing the temperature difference between the layers of the soil. In the bidirectional thawing mode, the last soil layers to complete thawing are those at a position in the middle of 0 cm to 10 cm and 11 cm to 20 cm, and this phenomenon plays an important role in the redistribution of water after soil thawing. Since ice prevents moisture migration, unfrozen water in the soil accumulates near the frozen front, that is the reason why the final melted soil layer usually has higher water content.

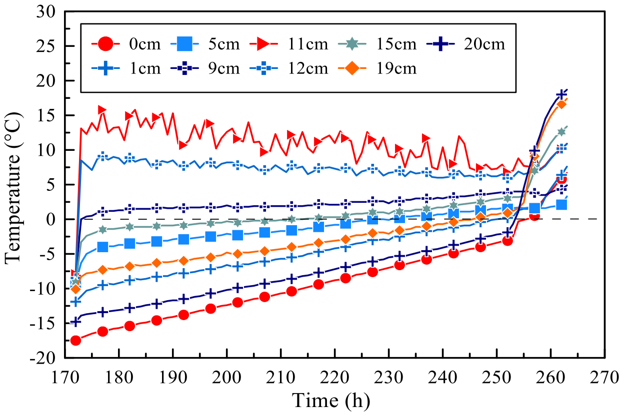

Fig. 5. The curves of temperature vs time during the thawing period.

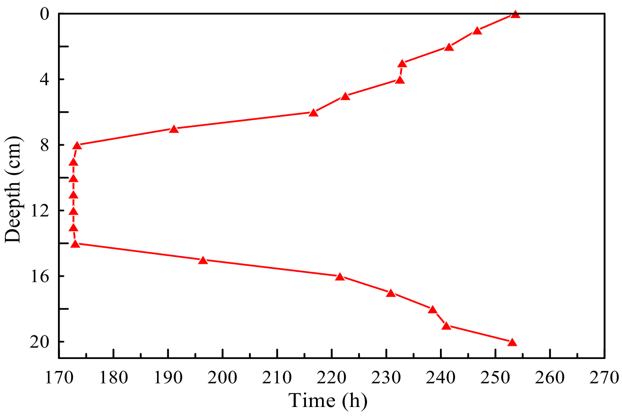

Fig. 6. The curves of thawing front vs. time.

By analogy with the definition of the freezing front, the thawing front is the position wherever the thawing temperature -0.5°C is located when the ice phase changes to water. As seen from Fig. 6, the change curve of the thawing interface with time is symmetrically distributed on both sides with the symmetry axis at 11 cm. Due to the continuity of the experiment, at the end of the freezing phase, the whole soil was in a frozen state. With the beginning of the thawing period, the temperature of the top and bottom plates is increased from negative temperature to positive temperature linearly and gradually, with a longer temperature increase time. While the central heating layer is directly given a positive temperature of 5°C, making the soil layer near the middle the first to produce a thawing area. The top and bottom soils are going to slowly thaw oppositely at the same time. Additionally, the heat energy is gradually consumed in the transfer process, creating the 6 cm and 16 cm soils relatively less affected and the thawing rate relatively slow.

4.2 Water field analysis

4.2.1 Freezing period

The variation curves of the water supplement in the central and bottom parts with the amount of freezing and thawing with time are listed in Fig. 7. As seen from the change curve of the water supplement, in the early period of freezing, the water supplement nearly tends to zero, and then gradually increases. Because the process of fractionated ice formation will produce a larger suction force within the frozen edge below the ice lens body. Especially for saturated soils, the matrix suction force is small, and the moisture migration is mainly caused by the freezing suction force, which makes unfrozen water migrate from the unfrozen area to the frozen front. Moreover, the soil recharge gradually increases with freezing time, leading to the rate of water supplement suddenly decreasing and gradually stabilizing at 100 h of the freezing period.

In the process of the freezing front gradually pushing from the top to the bottom plates, the temperature gradient in the soil gradually stabilizes, and the position and thickness of the freezing edge failed to change significantly. Moreover, it is known from the theory of partial condensation potential that when the last ice lens body is formed, the partial condensation potential is constant and the suction force is constant. Therefore, the water can continue to migrate to the freezing area, the recharge rate is gradually stabilized, and the recharge volume gradually increases with time.

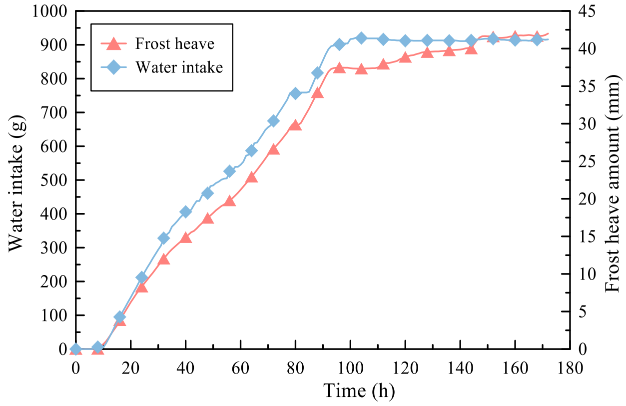

Fig. 7. The curve of water supply and frost heave vs. time during the freezing period.

The change curve of soil deformation has the same change trend as the change curve of water supplement in the center with time. Throughout the experiment, the freezing point of water is lowered due to the adsorption force and curvature on the surface of soil particles, which makes the soil sample not freeze at the starting period of freezing. Although the temperature near the top plate of the soil sample is lower than 0°C, i.e., the amount of freezing expansion is still zero. When the soil temperature is lower than the freezing temperature, the external water source is continuously taken in, and the unfrozen water phase in the soil becomes ice, and the amount of freezing expansion grows faster. In addition, with the growth of freezing time, the rate of freezing expansion gradually decreases and gradually converges to a non-zero constant, making the amount of freezing and thawing gradually reach a stable state.

4.2.2 Thawing period

To ensure the continuity of the experiment, the initial values of water supplement and top displacement in the thawing period were established after the end of the freezing period. Fig. 8 shows the variation curves of water supplement in the central of the thawing period and top displacement with time. During the thawing period, the ice phase in the pores of the soil near the heated layer changes to water due to the positive temperature of 5°C provided in the middle, which reduces the volume by 9%. Leading to the water being sucked into the vacuum area under the vacuum suction, which then freezes this sucked water into ice.

Corresponding to the top displacement change curve is the curve fails to show a trend of increasing or decreasing but fluctuates up and down at a certain value. As the thawing time increases, the thawing area of the soil column increases, causing a gradual increase in the positive and negative temperature gradients in the upper and lower soil layers. The reason for the increase of recharge water in the late thawing period may be that the ice in the soil gradually phases into the water, leading to the porosity increase. Meanwhile, there will generate a greater vacuum negative pore pressure inside the soil column. Under the combined effect of suction and temperature gradient, the central recharge water increases, which is by the "vacuum infiltration mechanism".

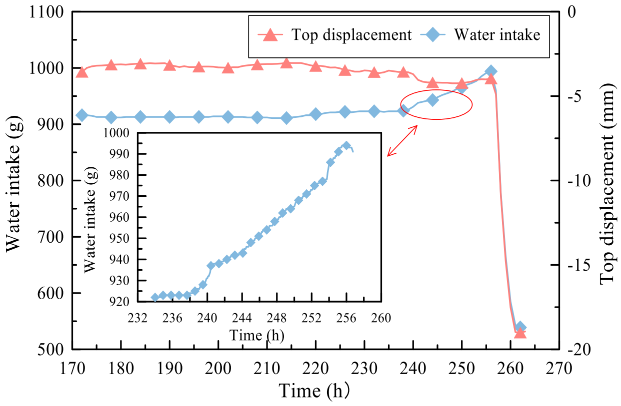

Fig. 8. The curve of water supply and top displacement vs. time during the thawing period.

By comparing the recharge water in the freezing and thawing periods, it will be found that the recharge rate in the thawing period is only 40% of the recharge rate in the freezing period. The reason for this distinction is that the driving force of water recharge in the freezing period is the temperature gradient. Whereas the temperature gradient in the thawing period is thanks to the interference of the central heating layer, which makes the upper and bottom soil layers produce positive and negative temperature gradients, respectively. Because the two cancel each other, the effect of the temperature gradient is weakened. Additionally, the main driving force of water recharge is the pumping force generated by the negative pore pressure.

4.3 Model validation and analysis

Due to the limited space of the article, using RCW-1 freezing and thawing temperature fields to verify the reliability of the established numerical model in simulating water and heat migration laws.

4.3.1 Temperature field during freezing period

The measured temperature of each soil layer at 10 h, 30 h, 60 h, and 110 h of the freezing experiment and the simulated calculated temperature value are shown in Fig. 9.

The variation of temperature with distance at different moments in the soil sample will intuitively reflect the spatial variation of temperature during the freezing process of the soil sample. The trend of temperature variation with distance is the same at all time points. And the decreasing trend of temperature with distance changes from fast to slow and finally stabilizes. With the increase of freezing depth, the cold energy is consumed by latent heat and convection in the process of transfer. The temperature gradient decreases continuously, eventually leading to a slow decrease in temperature and a decrease in the rate of downward movement of the freezing front.

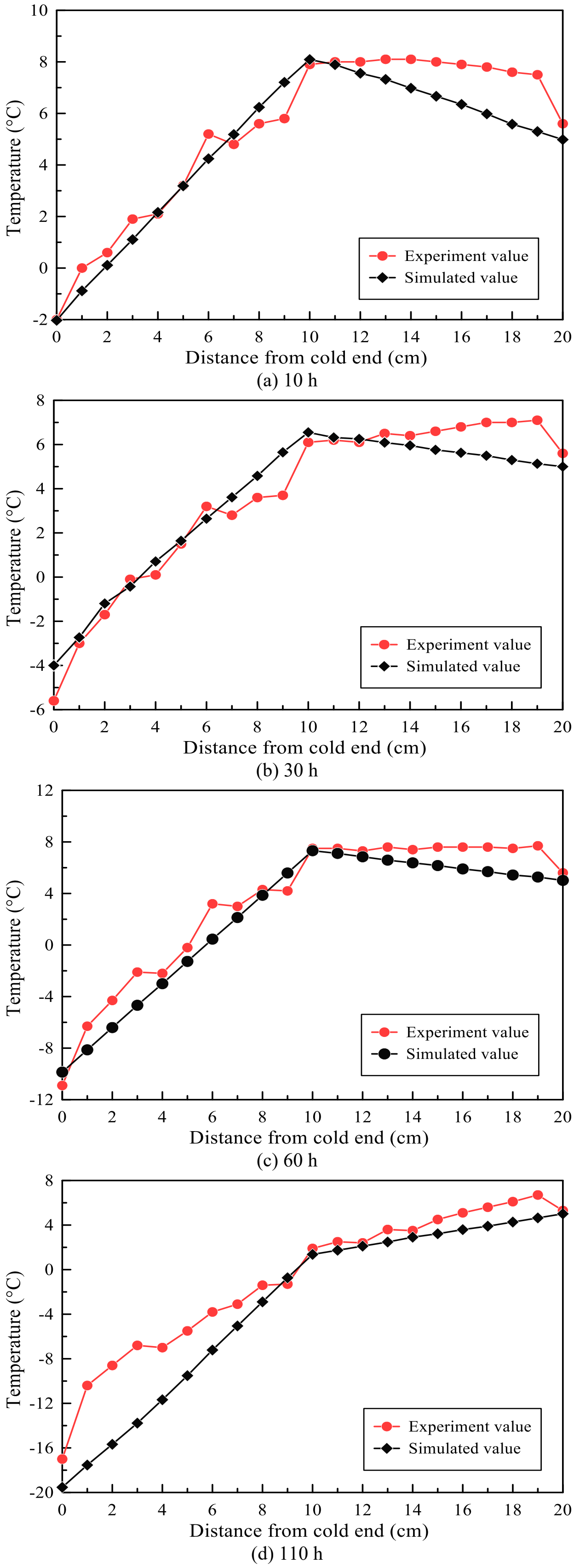

Fig. 9. The variation curves of simulated and experiment temperatures at 10, 30, 60, and 110 h during the freezing period.

Comparing the changes in experiment values and temperature values during freezing, the degree of temperature change in the upper soil layer is more drastic than that in the lower soil layer. During the early period of freezing, the limited cold provided by the cold bath failed to eliminate the latent heat of water phase change in the saturated soil. Resulting in the cold being gradually consumed in the process of downward transfer, especially at the position of the lower soil layer close to the lower plate. The cold coming from the top part will neutralize each other with the heat transferred upward from the bottom plate. Therefore, with the beginning of the freezing phase, the calculated results of the temperature of the upper soil layer are in strong agreement with the experimental values.

However, the results fitted for the lower soil layer are somewhat different from the actual ones, and the variability increases with the distance from the cold source. The inflection point of the curve at 10 cm is because the heating layer is made of stainless steel plate, which has a large difference with the heat exchange coefficient of the soil and failed to consider when establishing the model. On the other hand, a large amount of liquid water will accumulate near the central recharge layer. When the freezing front failed to be pushed to the heating layer, unfrozen water will also consume the cold amount coming from the top part. Because in the late freezing period, the freezing front has already crossed the heating layer, the effect of the central recharge device is lost, and the cold energy transfer downward is less affected by the migration of unfrozen water. Leading to the fitted data of the lower soil layer being closer to the experiment values in the late freezing period.

4.3.2 Temperature field during thawing period

The simulated temperature of each soil layer at different moments of the thawing period compared with the measured temperature is shown in Fig. 10. It can be seen that the curve is convex in the middle and symmetrically distributed on both sides. This is because, during the thawing period, the middle heating layer provides a forced constant positive temperature. While the heat energy from the top and bottom plates is blocked in the process of transferring to the central, which makes the temperature in the middle of the soil change abruptly.

As the central heating layer heats up and the temperature of the top and bottom plates rises, it causes the temperature change curve of the upper and lower parts of the soil column to gradually converge to a straight line from a fold. Because the top, middle, and bottom parts of the soil column are thawing at the same time, creating a certain thickness of thawed area. The heating device will stop when the temperature of the heating layer reaches the predetermined temperature range. While the unthawed soil at both ends of the column and the middle thaw area form a certain temperature gradient, which makes the migrated unfrozen water freeze again at the freeze-thaw interface. The process is formed repeatedly at the freeze-thaw interface, i.e., the formation of a “repeated segregated ice” phenomenon [36].

As the thawing continues, the temperature of each soil layer gradually tends to stabilize, thus the phenomenon of sub-condensation into ice no longer occurs and the curve becomes a smooth straight line. Comparing the experimental and simulated data, it will be found that the two have a similar trend of change and the degree of fit is more consistent. However, there is a sudden increase in the experiment results at the soil layer of 10-12 cm. In the thawing period, there is a positive temperature gradient in the upper soil layer and a negative temperature gradient in the lower soil layer, which is a more complicated situation. Under the induction of a positive temperature gradient, the water migrates from the heating layer to the upper freezing area, and most of the moisture migration occurs in the non-vigorous phase transition area. Under the induction of a negative temperature gradient, the water migrates from the heating layer to the lower freezing area, and moisture migration occurs in the vigorous phase transition area. Consequently, the moisture migrating downward is inevitably more than the moisture migrating upward, which is shown in the image as a sudden increase in the curve. However, as the thawing time continues, the experimental values gradually agree with the simulated values.

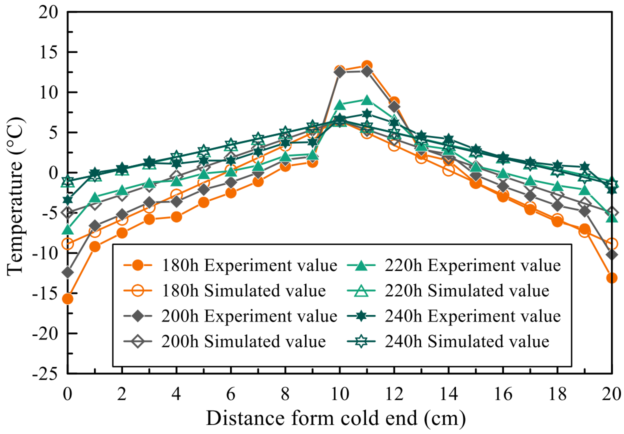

Fig. 10. The variation curves of simulated and experiment temperatures at different moments during the thawing period.

5. Conclusions

In this study, the indoor repeated freezing and thawing experiments with different cooling and warming rates were carried out to measure and plot the variation curves of temperature, top displacement, and middle recharge in different soil layers with time. The following conclusions were drawn.

(1) The temperature of each measurement point in the freezing period has similarity and hysteresis with the position of the distance from the top plate (cold end), and the temperature no longer changes after a certain position from the top plate. The temperature of each measurement point in the thawing period has variability with time, especially the closer to the central heating layer, a lot of drastic temperature change, the last location where the soil melted is 6 cm and 16 cm.

(2) The driving force of water supplement in the freezing period is the temperature gradient, and the difference in soil temperature distribution during freezing makes the water supplement more. The driving force of water supplement in the thawing period is the suction force generated by the vacuum negative pore pressure, which is weaker in driving water compared with the temperature gradient, making the supplement rate during the thawing period only 40% of the supplement rate during the freezing period.

(3) Repeated sub-condensation into ice phenomenon is achieved by regulating the temperature of the heating layer. Combining with COMSOL Multiphysics for numerical calculation, the calculation results are in good conformity with the experiment results, which can make up for the shortcomings of the experiment and provide theoretical reference for the normal conduct of the subsequent experiment. However, the existence of the heating layer is the main reason for the discrepancy between the numerical simulation and the experimental results, which is a problem should be considered for future numerical calculations.

Based on the theory of the formation of thick layered ground ice, this study reveals the temperature and moisture migration characteristics under the condition of being repeated to separate frost heaving and thawing through experiments and numerical simulations. However, there exist some shortcomings in the study, which need to be further optimized.

Firstly, for the establishment of one-dimensional partial differential equations. The unfrozen water content in the frozen area is taken as a constant, thereby the effect of unfrozen moisture migration in frozen soil area is failed to consider. Due to the one-dimensional numerical model being established, only the change of heat and moisture in the vertical is considered, leading to the variation pattern on the horizontal pattern failure to be known. Secondly, for the moisture migration experiment of repeated segregated frost heaving and thawing. Since the phenomenon of repeated segregated ice is mainly manifested in the early period of thawing, a reasonable control of thawing temperature needs to be developed.

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