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Research Article

Impact of Cooling on Water and Salt Migration of High-Chlorine Saline Soils

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Secondary salinization is a common problem in saline soil projects. In order to grasp the mechanism of water and salt migration of high-chlorine saline soil during the cooling process, the saline soils along the Qarhan-Golmud Highway in the Qinghai-Tibet Plateau were selected as test samples. Firstly, the basic physical parameter test and the soluble salt chemical experiment were carried out and obtained liquid and plastic limits, dry density, etc. Secondly, freezing temperature experiments and water-salt migration experiments under one-way cooling conditions were conducted according to the actual environmental conditions, and after the temperature gradient line of the soil sample was stable, water content and labile salt chemistry experiments were conducted to obtain the distribution of water and salt contents of soil samples. Finally, the effect of crystallization-water phase transition on water and salt migration and the effect of chloride salt on the temperature of crystallization-water phase transition were considered, and a mathematical model applicable to the water and salt migration of highly chlorinated saline soils under the effect of unidirectional cooling was established and solved with COMSOL Multiphysics software, and the correctness of the model was verified by comparing the simulation results with the experimental results. The study found that (1) during the one-way cooling process, both water and salt showed a tendency to migrate to the cold end. The MC (saline soil with medium chlorine content) with an initial water content of 16.9% and Cl^- content of 3.373% was measured to reach a 17.6% water content and 3.76% Cl^- content at the cold (top) end after the experiment. The HC (saline soil with high chlorine content) with an initial water content of 6.6% and Cl^- content of 17.928% was measured to reach a 6.83% water content and 18.8% Cl^- content after the experiment and (2) after the one-way cooling experiment of the MC, the water content at a distance of 1–2 cm from the cold end has abrupt changes, which may be caused by a small amount of crystallization—water phase transition at this location. At the same time, according to the temperature change graph during the cooling process, the phase change temperature was set to $-9°C$ in the numerical simulation process to match the experimental results.

1. Introduction

Qinghai province is located in the northwest inland area of China, which is the gateway of the Qinghai-Tibet Plateau. The region has special climatic and geological conditions, with the largest saltwater lake in China and a large temperature difference between day and night. The type of saline soil distributed in this area is chloride saline soil with a high con-

tent [1]. At the same time, the improvement of saline soil is a difficult and time-consuming work, in which secondary salinization is a very common problem in the process of saline soil improvement. In order to solve these problems, the mechanism of water and salt migration in saline soil is studied.

The presence of salts lowers the freezing point of liquid water and also affects the freezing temperature of the soil.

Bing and Ma [2] conducted a series of freezing temperature tests on saline clay, loess, and sandy soil and found that the freezing temperature generally decreased with the increase of the salt content and increased with the increase of the water content. Watanabe and Mizoguchi [3] studied the influence of different types of salt on the unfrozen water content in different types of frozen soil and found that the unfrozen water content increased with the increase of the salt content, the increase caused by sodium chloride and potassium chloride was roughly the same, and the increase caused by magnesium chloride was the largest. Chen et al. [4] proposed an equation to predict the freezing temperature by considering the water content and the main anion content through a large number of freezing experiments. Nakano et al. [5] carried out frozen soil column experiments under different water contents under isothermal conditions and studied the influence of the ice content on water movement in frozen soil. Xue et al. [6] think that in the unidirectional freezing experiment, the temperature field has an inducing effect on the change of the water field, but the two are not synchronous. When the freezing rate decreases to a certain extent, the water begins to migrate. All the above scholars have studied the freezing process of soils with different water contents and low salinity, but the freezing process of soils with high salinity has not been sufficiently studied. Therefore, in this paper, the freezing process of saline soils with high salinity is studied for the special geological conditions in the inland areas of Northwest China.

Salt comes with water, and salt goes with water is the main law of water and salt migration in saline soil. Bing et al. [7] conducted a one-way freezing experiment on saline soil with an initial water content of 30% and an initial salt content of 0.037%. The three basic elements of water movement during the freezing and thawing process are temperature gradient, unfrozen water content, and water potential. Nassar and Horton [8] derived an equation describing the migration of water and salt and proposed that the main driving forces of salt migration are temperature gradient, water content, and solute concentration. Zou et al. [9] took the cotton field in Dongying city, Shandong province, as an experimental sample and used indoor soil column experiments to study the water and salt migration law of saline soil with a salt content of 0.34 g/kg. Wu et al. [10] prepared silty clays with different salt contents for model tests. The test results showed that water is the medium of salt migration and salt migrates with unfrozen water in the form of ions. The migration rate is related to the suction, and the suction near the freezing edge is the largest and the speed is the fastest. Li et al. [11] found that when the salt content in the soil is large, the soil freezing point will decrease. The soil freezing time will be prolonged, but the soil moisture evaporation will increase. Lin et al. [12] conducted long-term and one-dimensional seepage simulation experiments for loess soils and found that salt transport was influenced by the water content and soil dry density. Liu et al. [13] performed water-salt migration experiments under unidirectional freezing for saline soils with different chloride contents and found that the lower the salt content, the farther the location of the freezing peak was from the cold end. The above scholars

have studied the water-salt migration patterns within saline soils, but they are limited to saline soils with low salinity, and the existing studies are not sufficient for the water-salt migration patterns in saline soils with high salinity.

Numerical simulation of the law of water and salt migration can better help solve engineering problems such as secondary salinization. Kung and Steenhuis [14] established a computer model for simulating soil water and heat movement under freezing conditions. The model is based on the coupled heat and mass migration theory derived from the theory of irreversible thermodynamics. The finite difference scheme is used to solve the spatial coupling flux equation, and a new numerical model for calculating the coupled migration of water and heat in seasonal frozen soil and snow is established. An independent equation describing the flow of unsaturated and saturated soils is proposed. Kelleners [15] combined the infiltration head expression and Clapeyron equation, combined with the V-G (Van Genuchten) model, to study the effect of dissolved ions on the freezing point of soil water. The Thomas algorithm and Picard iterative method are used to solve the hydrothermal coupling equations. Abed and Solowski [16] introduced a thermohydraulic-mechanical framework suitable for simulating the properties of unsaturated soils and deduced the relevant coupled equilibrium equations and carried out relevant experimental verifications. Liu and Li [17] analyzed the characteristics of the dynamic migration of salt in the soil and its influencing factors and used the theory of heat and mass transfer in porous media to establish a mathematical model describing the coupled migration of water, heat, and salt in the soil. Klas et al. [18] proposed a new method for calculating the phase transition in the fully implicit numerical model of coupled heat transfer and variable saturation water flow at temperatures above and below zero. This method is based on a mixed equation of water flow and heat transfer. This method makes numerically stable energy and mass conservative solutions possible. In conclusion, the establishment of mathematical models for soil water-thermal movement has tended to be perfect, but the theoretical models for water-thermal-salt movement have not been sufficiently studied, and at present, no mathematical models for water-salt migration applicable to high salt amounts have been proposed.

In summary, most of the existing studies are based on the low salt content and freezing conditions and the study on the freezing temperature and water-salt migration mechanism of high-chlorine salts is not sufficient. Therefore, in order to better understand the law of water and salt migration in high chloride saline soils and to better solve practical engineering geological problems, the following studies were conducted. Take the saline soils along the Qarhan-Golmud Highway in Qinghai province as samples; relevant experiments on physical, chemical, and geotechnical properties were carried out; freezing temperature experiments and water-salt migration experiments under nonfreezing conditions were carried out to obtain the water-salt distribution of different soil samples according to the actual environmental conditions. Based on the law of conservation of mass, Darcy's law, and the convection dispersion equation, the

Figure 1: View of the saline soil sampling points along the Qarhan-Golmud Highway.

water-heat-salt coupling equation of high-chlorine saline soil under the action of temperature is established. This model introduces the relationship between the ice content, water content, and negative soil temperature. The relationship between the ice-water phase change and the retardation of ice on water migration and the influence of salinity on the crystallization temperature of water ice are fully considered. The second development module of the COMSOL Multiphysics finite element software is used to solve the model and finally compare the experimental results.

2. Engineering Background

The Qarhan-Golmud Highway starts in the northwest direction of Qarhan, connects 588.3 kilometers of National Road 215, passes the Qarhan Salt Lake, Garsu Station, Yushui River, crosses the Golmud River, and connects with National Road 109. The total length of the route is 80.052 kilometers. Most of the areas that the highway passes through are saline soil areas. According to the actual engineering geological conditions, a weather station was established at K664+360 of the Qarhan-Golmud Highway to monitor the weather conditions and ground and underground temperature conditions in the Qarhan area; the monitoring situation is shown in Figures 1–3.

According to the temperature data, in Golmud, the month with the highest annual average temperature is July, the temperature is 19°C, the month with the lowest annual average temperature is January, and the annual average temperature is -7°C. Therefore, it can be concluded that the coldest month of the cold season in the Qarhan region is January. The temperature data of 120 days from January to April in different locations are monitored, as shown in Figure 3. The following conclusions can be drawn:

(1) The surface temperature and the temperature change were almost identical. The lowest temperature on the surface in January was about -15°C, and the average temperature was -9.6°C

(2) The temperature at $10\,$cm–$40\,$cm below the ground was most obviously affected by the air temperature. In January, the lowest temperature at $10\,$cm below the ground was -9.4°C and the average temperature
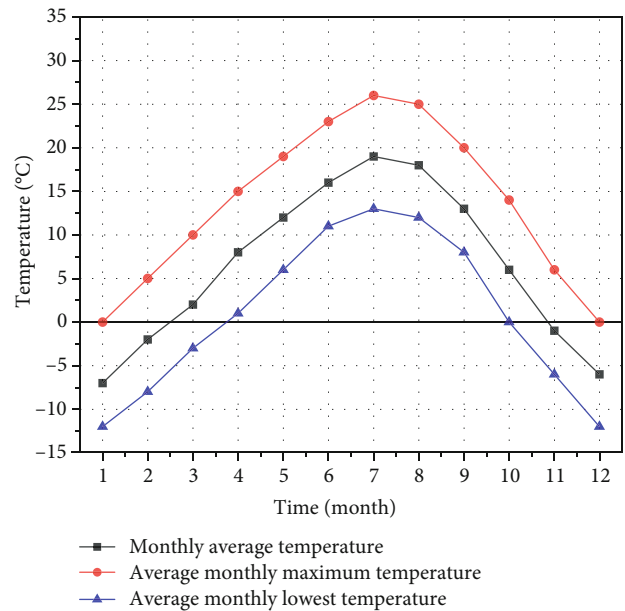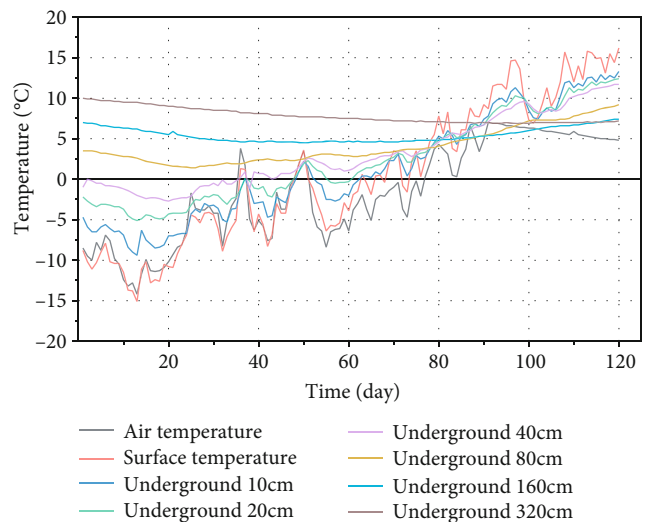

Figure 2: 2017–2020 average monthly temperature map.

Figure 3: Plot of average temperature data at different locations of the test site during 120 days of the cold season from 2017 to 2020.

was −6.3°C, the average temperature at 20 cm below the ground was −3.6°C, and the average temperature at 40 cm below the ground was −1.5°C

(3) The temperature change at 80 cm–320 cm below the ground was not obvious. In Figure 3, the overall temperature trend in 120 days was higher, both at the surface and at 80 cm below the surface, but the temperature change at 160 cm–320 cm below the surface was not significantly related to the air temperature. In addition, the precipitation in this area was small and evaporation was large throughout the year

3. Freezing Temperature Test

3.1. Determination of the Properties of Soil Samples. The saline soil along the Qarhan-Golmud Highway is selected as the experimental sample. According to the weather station data, the precipitation along the road is mainly concentrated in May–September. The average monthly precipitation is less than 7 mm, accounting for more than 80% of the annual precipitation. The average air pressure in January is 7274 Pa, and the average monthly humidity is 43%. The soil samples collected according to the standard have been subjected to basic experiments such as specific gravity, liquid limit and plastic limit water content, maximum dry density and optimal water content, particle analysis, and soluble salt chemical experiments [19]. Figure 4 shows the distribution of the soil particle size. According to the particle size distribution diagram, all types of saline soil collected in the experimental area are fine-grained saline soil. Tables 1 and 2 show the rock and soil mechanical properties and the physical and chemical properties of the soil samples, respectively. Table 3 shows the main salt ion content. Among them, soil sample 1 referred to as LC (saline soil with low chlorine content) is sulfite saline soil; soil samples 2 and 3 are chloride saline soils, referred to as MC and HC.

3.2. Soil Sample Preparation and Test Plan. According to [19], the optimal water content is selected for the initial water content and the degree of compaction is 96% for soil sample water and salt migration experiments. In the test, a plexiglass cylinder with a diameter of 150 mm and a wall thickness of 10 mm is used. The soil sample is 10 cm high. A thin layer of petroleum jelly is evenly spread on the cylinder wall, and a plastic film with an opening at the bottom is pasted along the cylinder wall, which is used to ensure that external moisture cannot be drawn in during the test. Then, combine the plexiglass cylinder and its matching bottom plate and make the plastic bag close to the top of the board and then press the degree of solidity to calculate the required amount of soil and put it into the plexiglass cylinder in 5 layers and compact it. The control height of the first layer is 20 mm; after the compaction is completed, shave and then compact the next layer. A piece of filter paper is placed on the upper and lower ends of the sample to play a role of water permeability and airtightness. After the sample is prepared, let it stand for hours to make the water in the soil evenly distributed. The sample with a diameter of 40 mm and a height of 90 mm used for the cooling test was trimmed
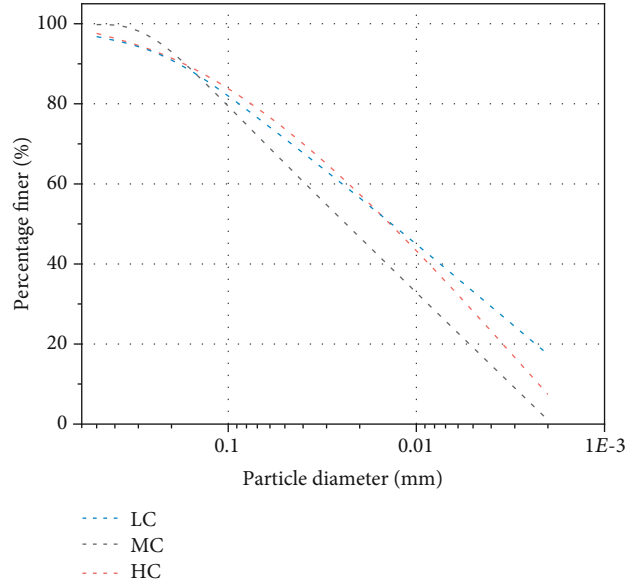

FIGURE 4: Results of the particle analysis test of different soil samples.

from the sample used for the water and salt migration test. Drill a hole at the center of the sample, place a temperature probe, and backfill the hole with soil to ensure complete contact between the temperature probe and the soil.

For the soil freezing experiment, first turn on the low-temperature thermostat and adjust the temperature to 2°C. At this time, the room temperature is higher. In order to reduce the data collection work and achieve the purpose of the experiment, first preset a starting temperature. After the temperature reaches the requirement, put the prepared soil sample into the prepared bag according to the optimal water content, insert the temperature collection probe, seal it, and put it into the cold liquid in the low-temperature thermostat. Then, adjust the low-temperature thermostat again, set the preset temperature to −10°C and −20°C, respectively, start the computer, open the software, and set the temperature collection time interval to 10 s, so that the temperature change inside the sample can be collected on the computer. When the display temperature of the low-temperature thermostat reaches −10°C and −20°C, stop collecting and turn off the instrument; finally, take out the sample, process the data, and draw the graph.

3.3. Test Results. The freezing temperature of free water at standard atmospheric pressure is 0°C, while the pore water in the soil interacts with the surface of the soil particles, causing its freezing temperature to be lower than 0°C. The freezing temperature of soil refers to the temperature at which the pore water freezes stably. It is verified according to the fitting equation of the freezing temperature of saline soil given by Chen et al. [4]

$$-T_d = 2.8752 W^{-1.0509} \left(\mathrm{Cl}^-\right)^{0.8427} \left(\mathrm{SO}_4^{2-}\right)^{0.3575}, \quad (1)$$

where W is the optimal water content, Cl^- is the chloride ion content, and SO_4^{2-} is the sulfate ion content.

TABLE 1: Basic rock and soil mechanical properties of soil samples.

Sampling location	Soil groups	Soil classification	Liquid limit (%)	Plastic limit (%)	Plasticity index	Optimum water content (%)	Max dry density (g/cm³)
K642+200	LC	Silty clay	42.0	27.3	14.7	17.8	1.66
K636+000	MC	Silty clay	38.7	25.4	13.3	16.9	1.96
K603+260	HC	Silty clay	26.3	17.4	8.9	6.6	1.77

TABLE 2: Main salt ion content.

Soil groups	Cl^- content (%)	SO_4^{2-} content (%)	CO_3^{2-} content (%)	HCO_3^- content (%)	Ca^{2+} content (%)	Mg^{2+} content (%)	Total (%)
LC	0.533	0.720	0.000	0.161	0.300	0.244	20.144
MC	3.373	1.488	0.000	0.006	0.700	0.244	5.811
HC	17.928	0.480	0.032	0.129	0.600	0.976	1.958

TABLE 3: Experimental table of physical and chemical properties of soil.

Soil groups	Cl^- content (%)	SO_4^{2-} content (%)	Total salt content (%)	pH	Soil types
LC	0.533	0.720	2.591	7.0	Sulfite saline soil
MC	3.373	1.488	11.879	6.9	Chlorine saline soil
HC	17.928	0.480	36.124	7.0	Chlorine saline soil

According to the content of the main negative ions in the soil sample, it is calculated using equation (1). The theoretical freezing temperature of the LC is −2.8°C, the theoretical freezing temperature of the MC is −23°C, and the theoretical freezing temperature of the HC should be much lower than −23°C.

Perform laboratory tests to confirm the applicability of the equation. Taking into account the in situ soil temperature in winter and the expected low freezing temperature of its higher salt content, the target temperature of the LC is set to −10°C and the target temperature of the MC is −10°C. The target temperature is set to −20°C. The relationship between soil temperature and cooling time of the two samples is shown in Figure 5. The cooling curve of the LC clearly shows the different stages of pore water cooling and freezing, including supercooling before 1.75 hours, freezing of pore-free water from 1.75 hours to 3.5 hours, and bound water or nonfreezing water around the soil particles after 3.5 hours. Freeze the freezing of the water film, as described by Lunardini [20]. For the LC, the freezing temperature is −2.7°C, which is about 4% lower than the value predicted by the equation. However, when the temperature reaches −20°C, the cooling curve of the MC does not show any signs of freezing or latent heat release, which shows that the freezing temperature of MC is at least −20°C lower, which is also consistent with the prediction of the equation. In fact, the field survey data of the highway route shows that its salt con-
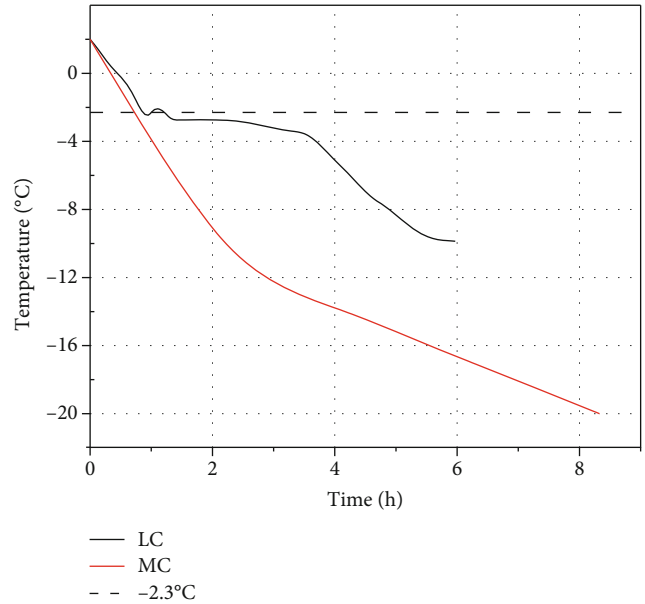

FIGURE 5: Cooling time history curve of the soil sample LC and MC.

tent is generally greater than 10%, which means that most of the saline soil along the route will not freeze in winter.

4. Mathematical Model

4.1. Basic Assumption. Saline soil is composed of three phases of solid, liquid, and gas, and it is a multiphase continuous porous medium [21]. When the soil is saturated, only the interaction between the solid phase and the liquid phase is considered and the influence of the gas phase is ignored. According to the determination of the physical and chemical properties of the collected samples, the area is dominated by chloride salts and the content is high, so only one salt, namely, sodium chloride, is considered for migration. Assume that the liquid phase is an ideal solution consisting of unfrozen water and dissolved salt. In addition, other assumptions of the theoretical model are

(1) The soil is homogeneous and isotropic, and the soil particles are incompressible

(2) The water migration in the frozen zone and nonfrozen zone is carried out in liquid form, without considering the migration of ice crystals

(3) Ignore convective heat transfer and solute heat transfer

(4) Ignore the crystallization of sodium chloride solution

(5) It is assumed that temperature changes will not cause changes in soil particles

4.2. Temperature Field Control Differential Equation. For the water-heat-salt coupling problem, according to the law of conservation of energy, the ice-water phase transition process in the saline soil is considered and the temperature field equation is set as

$$\rho_d C(\theta) \frac{\partial T}{\partial t} = \nabla(\lambda(\theta)\nabla T) + L_i \rho_i \frac{\partial \theta_i}{\partial t}, \quad (2)$$

where ρ_d is the density of the soil, ρ_i is the density of the ice, the unit is g/cm^3, $C(\theta)$ is the volumetric heat capacity of the soil, $\lambda(\theta)$ is the thermal conductivity of the soil, L_i is the latent heat of phase change, with a value of 334.5 J/g, θ_i is the ice content of the soil, ∇ is the Hamiltonian, and the $\lambda(\theta)$ and $C(\theta)$ of the soil are functions of the change with the water content. For the value, please refer to Bai [22].

4.3. Differential Equation of Water Field Control. The water migration in the soil conforms to the law of conservation of mass, that is, the total water content is equal to the sum of the liquid water content and the ice content, namely,

$$\theta = \theta_u + \frac{\rho_i}{\rho_w} \theta_i. \quad (3)$$

The conversion equation of the mass water content and volume water content is

$$\theta_u = \frac{\rho_d}{\rho_w} \cdot w_u, \quad (4)$$

where w_u is the mass water content, θ_u is the volumetric water content of soil liquid water, and ρ_w is the density of water.

Water migration follows Darcy's law. According to Richard's equation, considering the retarding effect of water crystallization into ice on the migration of liquid water, the governing equation of the water field is as follows:

$$\frac{\partial \theta_u}{\partial t} + \frac{\rho_i}{\rho_w} \frac{\partial \theta_i}{\partial t} = \nabla(D(\theta_u)\nabla\theta_u + K_g(\theta_u)). \quad (5)$$

In the equation, $D(\theta_u)$ is the diffusion coefficient of liquid water in the soil and $K_g(\theta_u)$ is the permeability coefficient of the unsaturated soil in the direction of gravitational acceleration. The calculation equation is

$$D(\theta_u) = \frac{K(\theta_u)}{C(\theta_u)} \cdot I(\theta_i),$$

$$K(S) = k_0 \cdot S^l \left(1 - \left(1 - S^{1/m}\right)^m\right)^2,$$

$$C(S) = \frac{a_0 \cdot m}{1 - m} \cdot S^{1/m} \left(1 - S^{1/m}\right)^m, \quad (6)$$

$$S = \frac{\theta_u - \theta_r}{\theta_s - \theta_r},$$

$$I(\theta_i) = 10^{-10 \cdot \theta_i}.$$

$K(S)$ is the soil water permeability coefficient, $C(S)$ is the specific water density, $I(\theta_i)$ is the impedance factor, S is the relative saturation of the soil, θ_s is the saturated water content of the soil, and θ_r is the residual water content of the soil. The rate, a_0, m, and l are the constitutive parameters of the soil.

4.4. Differential Equation of Salt Field Control. According to the related properties of sodium chloride, the solubility of sodium chloride is 36 g/100 g at 20°C. Assuming the sufficient Na$^+$ content in the soil, the equation for calculating the chloride salt concentration in saline soil is

$$m_{Cl^-} = \rho_d \cdot w_{Cl^-},$$

$$m_{NaCl} = \frac{\rho_d \cdot w_{Cl^-}}{M_{Cl^-}} \cdot M_{NaCl}, \quad (7)$$

$$C_{NaCl} = \frac{\rho_d \cdot w_{Cl^-} \cdot M_{NaCl}}{\rho_d \cdot w_u \cdot M_{Cl^-}}.$$

In the equation, m_{Cl^-} refers to the salt content per unit volume of the soil, w_{Cl^-} is the salt content of the chloride ion mass in the soil, measured by experiments, M_{Cl^-} refers to the relative molecular mass of chloride ion, M_{NaCl} refers to the relative molecule of sodium chloride mass, the value is 58.44, m_{NaCl} refers to the mass of sodium chloride in a unit volume, w_u is the soil mass water content, and C_{NaCl} refers to the concentration of soil sodium chloride in a unit volume.

For high-chlorine saline soil, if the salt content of the soil is higher than the maximum value of soluble salt, the solute concentration in the soil will reach saturation and there will be excess salt undissolved. This part of the salt does not participate in solute migration. Regarding the inherent properties of chlorinated saline soil, ignoring the physical and chemical reactions of the solute in the soil and the physical and chemical changes of the solute itself, the law of solute migration follows the convective dispersion equation, so the salinity field governing equation is

$$\theta_u \frac{\partial C}{\partial t} = \nabla(D_{sh}(v, \theta_u)\nabla C + q\nabla C, \quad (8)$$

where $D_{sh}(v, \theta_u)$ is the diffusion coefficient of salt in water, C is the concentration of salt in the soil, and v is the Darcy flow rat.

TABLE 4: Numerical simulation parameter and boundary conditions.

Soil type	Constitutive parameters			Residual water content θ_r	Saturated water content θ_s	Permeability coefficient k_0 ($m^2 \cdot s^{-1}$)	Constant B	Boundary temperature (°C)	
	a_0	m	l					Top	Bottom
Silty clay	2.65	0.25	0.5	0	0.42	10^{-7}	0.47	−10	5

$$D_{sh}(v, \theta_u) = D_s(\theta_u) + D_h(v),$$

$$D_s(\theta_u) = D_0 \cdot ae^{b\theta_u}, \qquad (9)$$

$$D_h(v) = \lambda \cdot \left| \frac{q(x)}{\theta_u(x)} \right|,$$

where $D_s(\theta_u)$ is the mechanical dispersion coefficient of the solute, $D_h(v)$ is the hydrodynamic dispersion coefficient of the solute, and D_0, a, and b are constitutive parameters.

4.5. Coupling Relationship. In equations (2), (5), and (7), the hydrothermal-salt coupling equation of saline soil contains four unknown quantities: temperature T, volume ice content θ_i, liquid water content θ_u, and concentration C, but there are only three differential equations. According to [23, 24], the concept of the solid-liquid ratio is introduced, that is, the relationship between the unfrozen water content and temperature:

$$\frac{w_0}{w_u} = \left(\frac{T}{T_f} \right)^B, \quad T \le T_f.$$

$$B_i = \frac{\theta_i}{\theta_u} = \begin{cases} 1.1 \left[\left(\frac{T}{T_f} \right)^B - 1 \right], & T \le T, \\ 0, & \text{else}. \end{cases} \qquad (10)$$

In the equation, T_f is the crystallization temperature of liquid water in the soil and also the ice-water phase transition temperature of the salt solution. According to the inhibitory effect of NaCl on the ice-water phase transition temperature in solution, the effect of NaCl on the freezing temperature of the soil is more significant [25]. The freezing temperature of NaCl saline soil deviates from the freezing temperature in general solution under the effect of surface energy, and the deviation between them gradually increases with increasing concentration and reaches the maximum at the concentration of 23.08%. Thereafter, the deviation of freezing temperature remained almost constant with the increase of concentration. The equation for the freezing point in solutions with different concentrations of NaCl is [22]

$$-T_f = 1.86 \times 2C_{MNaCl}. \qquad (11)$$

Among them, C_{MNaCl} is the molar mass concentration of sodium chloride and the unit is mol/kg.
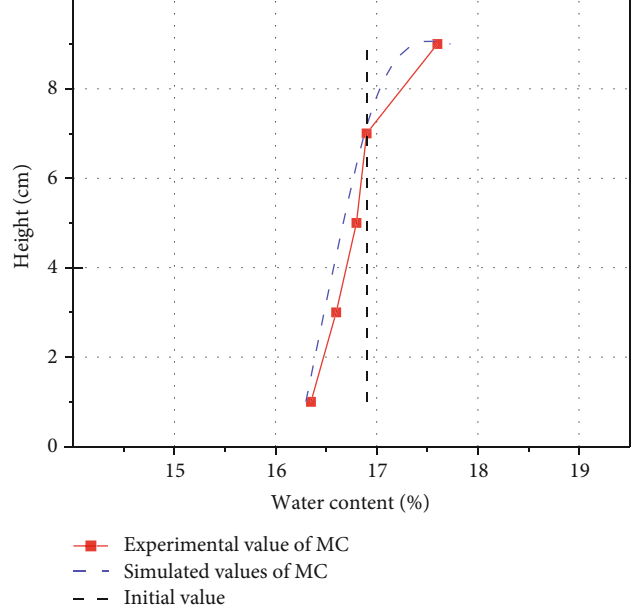

Experimental value of MC
Simulated values of MC
Initial value

FIGURE 6: Comparison diagram of MC water content experiment simulation of soil samples.

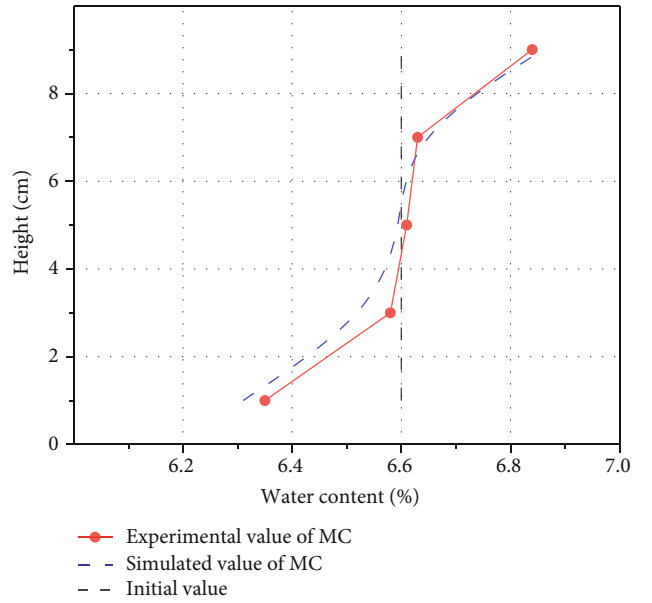Experimental value of MC
Simulated value of MC
Initial value

FIGURE 7: Comparison of experimental and simulated values of the HC water content of soil samples.
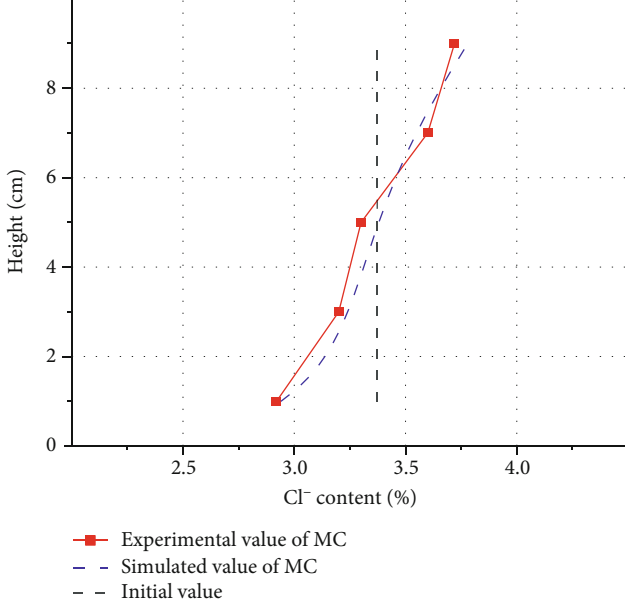
FIGURE 8: Comparative analysis of experimental and simulated values of the MC Cl$^-$ content in soil samples.
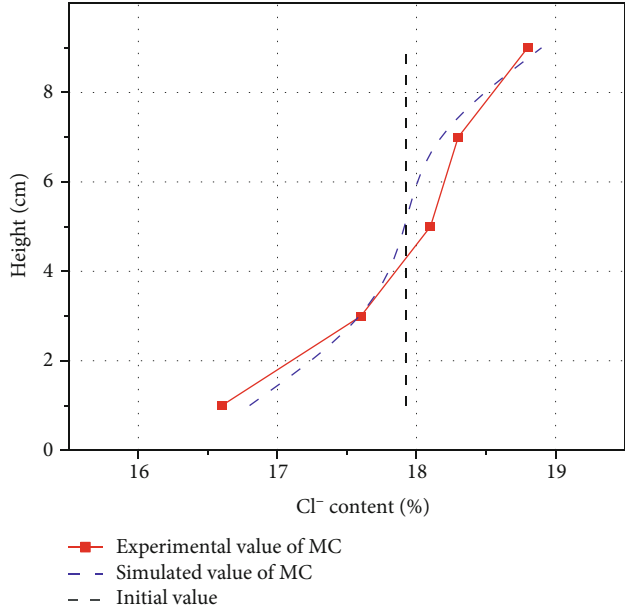

FIGURE 9: Comparative analysis of experimental and simulated values of the HC Cl$^-$ content in soil samples.

In summary, the hydrothermal salt migration equation of chloride saline soil is

$$\rho_d C(\theta) \frac{\partial T}{\partial t} - \nabla(\lambda(\theta)\nabla T) = L_i \rho_i \frac{\partial \theta_i}{\partial t},$$

$$\frac{\partial \theta_u}{\partial t} + \frac{\rho_i}{\rho_w}\frac{\partial \theta_i}{\partial t} - \nabla\left(D(\theta_u)\nabla\theta_u + K_g(\theta_u)\right) = 0, \qquad (12)$$

$$\theta_u \frac{\partial C}{\partial t} - \nabla(D_{sh}(v,\theta_u)\nabla C - q\nabla C) = 0.$$
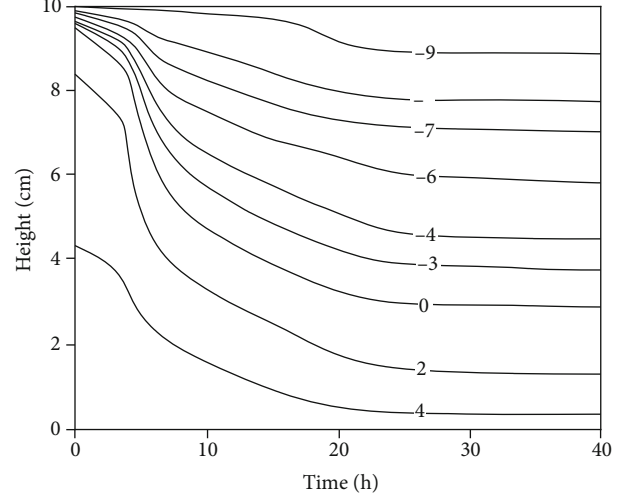

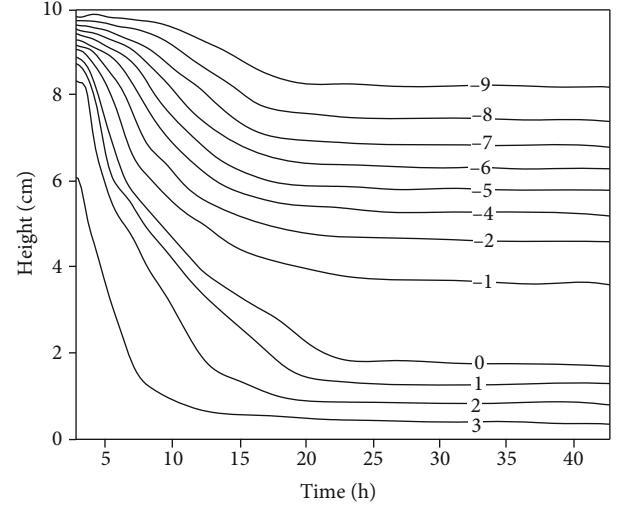FIGURE 10: Temperature change process of soil MC.


FIGURE 11: Temperature change process of soil HC.

Numerical simulation parameters and boundary conditions are shown in Table 4.

## 5. Numerical Simulation Verification of Experimental Results

COMSOL Multiphysics is a very powerful multiphysics finite element simulation software that can use its internal PDE module to establish mathematical models of the three fields of saline soil, water, heat, and salt.

The expression of coefficient-shaped partial differential equations and boundary conditions in the software is

$$e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla(-c\nabla u - au + r) + \beta \cdot \nabla u + \alpha u = f, \quad \text{in } \Omega,$$

$$n(c\nabla u + au + r) + qu = g - h^T \mu, \quad \text{on } \Gamma,$$

$$u = r, \quad \text{on } \Gamma,$$

$$(13)$$
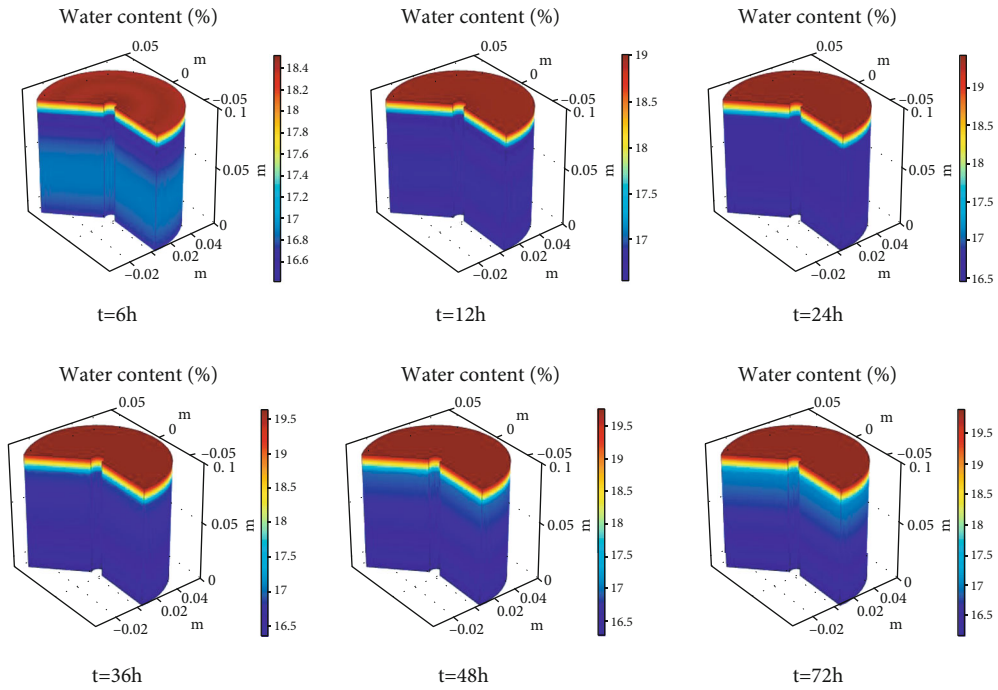
(a) Cloud map of water content distribution of MC at different times
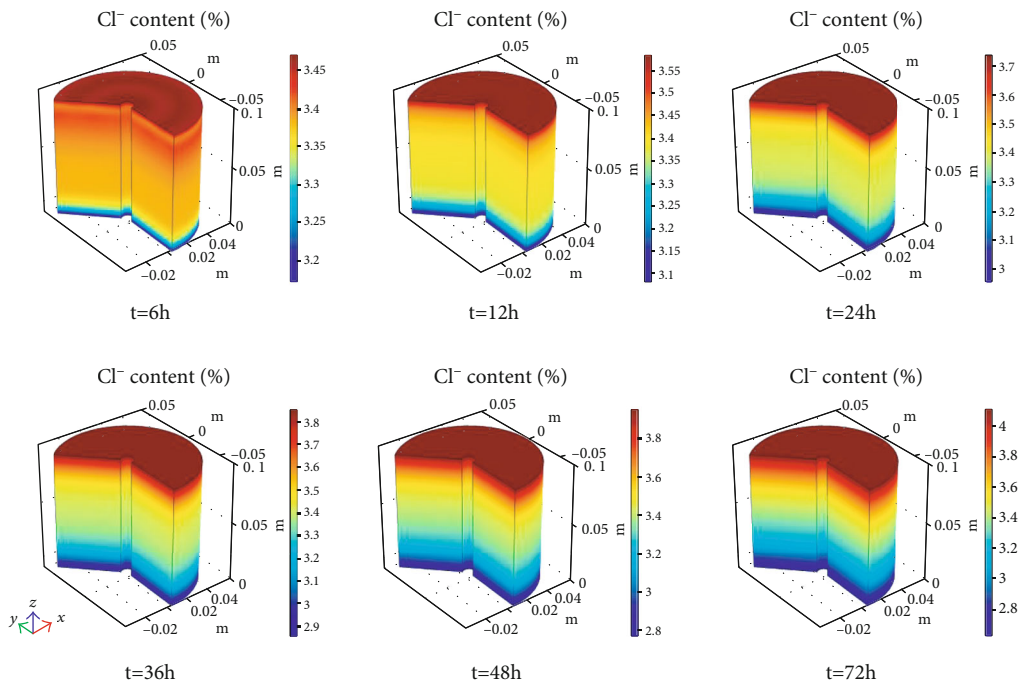
(b) Cloud map of the salt content distribution of MC at different times
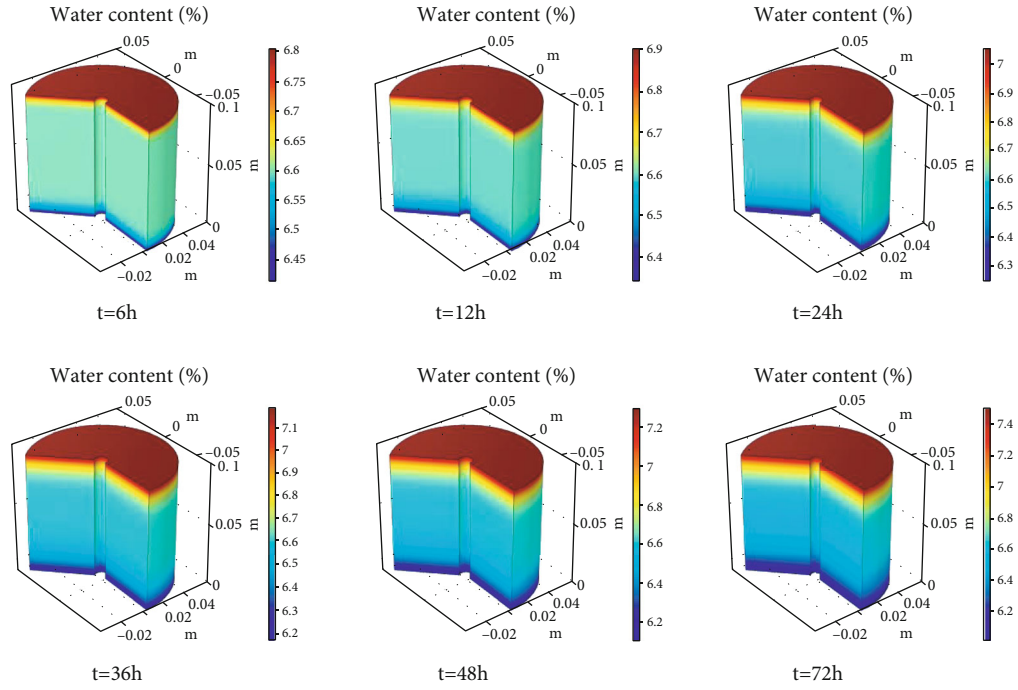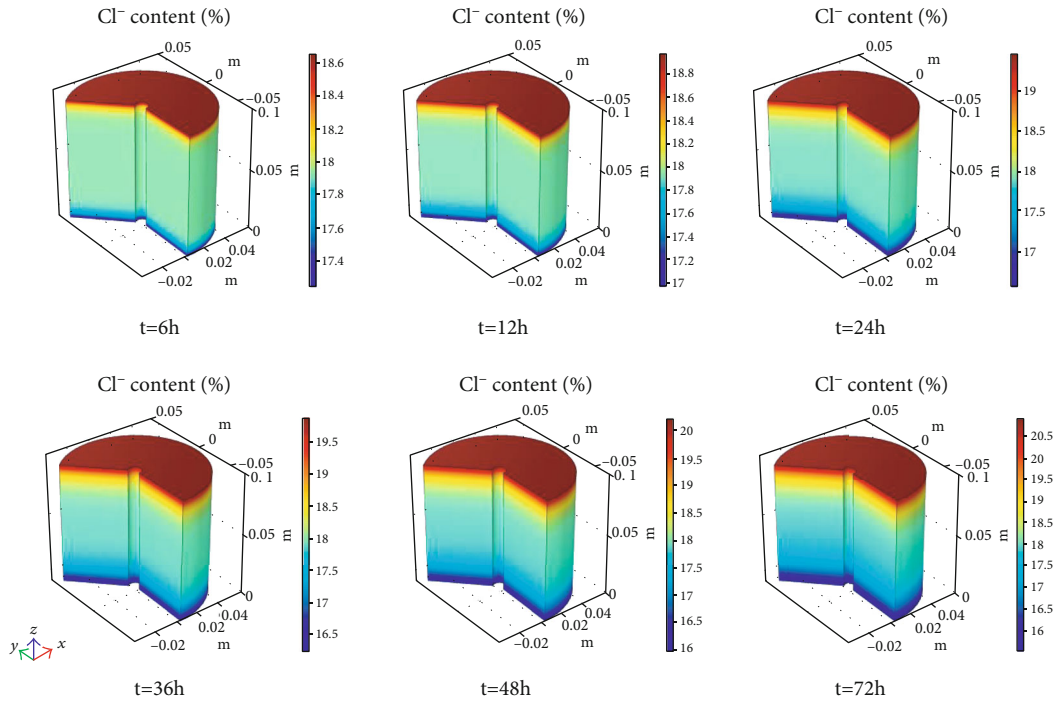
FIGURE 12: Continued.

(c) Cloud map of water content distribution of HC at different times

(d) Cloud map of the salt content distribution of HC at different times

FIGURE 12: Spatial distribution map of the water content and salt content of different soil samples at different times.

where u is the variable in the equation, e_a is the mass coefficient, d_a is the damping coefficient, c is the diffusion coefficient, a is the absorption coefficient, f is the source term, α is the conservative flux convection coefficient, γ is the conservative flux source term, q is the absorption coefficient on the boundary, g is the source term on the boundary, μ is the Lagrangian multiplier, h and r are the coefficients of the equation, and Ω is the solution domain.

5.1. Comparison of Experimental and Numerical Simulation Results. The experimental and numerical simulation results are shown in the following figures, where Figures 6 and 7

show the comparison of numerical simulation and experimental results of the water content, Figures 8 and 9 show the comparison of numerical simulation and experimental results of the Cl⁻ content, Figures 10 and 11 show the time course of the temperature change of MC and HC during the one-way cooling process, and Figure 12 shows the clouds of water content and salt content distribution of HC and MC at different times during the numerical simulation.

Based on the experimental and model results, it can be concluded that water and salt in the soil show a tendency to migrate to the cold end under the effect of top plate cooling, just because the initial content of water and salt are different, resulting in different amounts of specific migration changes.

Based on the analysis of water migration, for MC, its initial water content was 16.9% and the temperature gradient line of the soil sample was basically stable after the cooling effect of −10°C at the top for 72 h and the water content reached about 17.6% at the 9 cm height of the soil sample and the change rate of the water content at the top was 4.14% and the water content at the bottom was about 16.3% and its rate of change was −3.55%; for HC, its initial water content was 6.6% and the temperature gradient line of the soil sample had also stabilized after the cooling effect of −10°C at the top for 72 h. After the experiment, the water content at the top reached 6.83%, with a rate of change of 3.48%, and the water content at the bottom was about 6.25%, with a rate of change of −5.3%.

Based on the analysis of salt migration, for MC, the initial Cl⁻ content was 3.373%, and after the test, the apical Cl⁻ content reached about 3.8%, with a rate of change of 12.66%, the bottom Cl⁻ content was about 2.8%, and the change rate of its bottom Cl⁻ content was −16.98%; for HC, the initial Cl⁻ content was 17.928%, and after the test, the apical Cl⁻ content was 18.8%, with a rate of change that was 4.86% for the top end, 16.5% for the bottom Cl⁻ content, and −7.97% for the bottom end.

6. Discussions

After the test, when the water content of MC was measured, it was found that the water content at 1–2 cm from the top changed significantly and the water content here reached 17.6% from 16.9%, which implies that a small amount of crystallization-water phase transition may have occurred here, producing a phase change zone that led to a large amount of water accumulation at the top part; at the same time, during the simulation, the phase change temperature was set to −9°C; according to Figure 10, the numerical simulation curve and the actual measurement curve are in good agreement.

As can be seen in Figure 8, there is an error between the simulated value and the experimental value of the Cl⁻ content of MC at 4–6 cm. This may be due to the high content of SO_4^{2-} in MC. In the one-way cooling experiment, SO_4^{2-} can combine with 10 H_2O molecules to form Glauber's salt crystals, which may block the migration of water and salt in the soil sample, resulting in the simulated value of the

Cl− content in the MC at 4–6 cm higher than the experimental value.

The change rate of the Cl⁻ content of HC is much smaller than that of MC, which may be caused by its high salinity and low water content; when the soil is saturated with salt solution and has a large amount of undissolved salt, the water in the soil sample is not crystallized, so that the chloride ions involved in the migration are much less than the actual chloride ions, resulting in a lower rate of change compared to MC. Also, as can be seen in Figure 9 that the Cl⁻ content of MC at 4–6 cm, the simulated value is smaller than the experimental value, which may be the result of the high salt content of HC. In the unidirectional cooling experiment, although the temperature potential is the main driving force for water-salt migration, the solute potential of the high-salinity soil samples cannot be neglected.

7. Conclusions

In this paper, three samples of saline soils with different Cl⁻ contents (LC, MC, and HC) were selected as the research object along the Qarhan-Golmud Highway in Qinghai province and the soil freezing temperature experiment and water-salt migration experiment were carried out. In addition, a three-field mathematical coupling model of water-thermal-salt in chloride saline soils under the effect of cooling was established and solved by COMSOL Multiphysics and the simulation results were compared and analyzed with the experimental results and the following conclusions were drawn.

(1) In water-salt migration experiments of nonfreezing saline soils for MC, the temperature gradient line of the soil sample reached stability after 72 hours of action at −10°C for the top plate and 5°C for the bottom plate; then, the change rate of the water content at the top of MC was 4.14% and the change rate of the Cl− content was 12.66% and the change rate of water at the bottom was −3.55% and the change rate of the Cl⁻ content was −16.98%

(2) For HC, the salt content was high, the initial Cl⁻ content reached 17.928%, and the initial water content was only 6.6%. After 72 hours of action at −10°C for the top plate and 5°C for the bottom plate, the change rates of the Cl⁻ content at the top and bottom were 4.86% and −7.97%, respectively. The reason for this high salinity and low change rate may be that the salt solution was initially oversaturated in HC, resulting in the proportion of actual chlorine salts involved in water-salt migration to total chlorine salts being smaller than MC

(3) The reasons for the large change in the water content of MC at 1–2 cm from the top were analyzed, which may be due to a small amount of crystallization-water phase change in this region, resulting in a higher water content at the top. In the numerical simulation, the phase transition temperature was

set to −9°C, which was in good agreement with the experimental results

(4) The presence of sulfate ions will have an effect on the migration of water and salts in soil samples. During the cooling process, sulfate ions will form Glauber's salt $(Na_2SO_4 \bullet 10H_2O)$ which will have a blocking effect on the migration of water and salts. Therefore, the solute potential plays a discordant and neglected role, in addition to the leading role of the temperature potential from the water-salt migration experiment and numerical simulation of saline soils with high salinity

Data Availability

The [DATA TYPE] data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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