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Effects of Influence Parameters on Freezing Wall Temperature Field in Subway Tunnel

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Abstract: In order to study the influence of different factors on the temperature field of the freezing wall of connecting passage, and to evaluate the effect of different influencing factors, four groups of analyses were carried out through three-dimensional finite element software, including the influence of brine temperature, the influence of freezing pipe diameter, the influence of freezing pipe spacing, and the influence of soil water content. The analysis shows that the finite element method based on the thermodynamics theory can better simulate the freezing temperature field and formation law of the freezing wall of each section. Among the influencing factors, the brine temperature and the freezing pipe spacing have the greatest influence on the temperature field of the freezing wall. The thickness of the freezing wall increases linearly with the increase in the freezing time. At the same time, the thickness of the freezing wall increases with the increase in the diameter of the freezing tube and the decrease in the spacing between the freezing tubes. With the decrease in brine temperature and water content, the difference of freezing wall thickness at different levels becomes larger and larger with the increase in freezing time. The influence of various factors on the freezing wall is in the order of brine temperature, freezing tube spacing, and freezing tube diameter. At present, the saltwater temperature in the freezing project of the metro shield tunnel is generally controlled at -28~-30 °C. Generally, from the perspective of actual engineering, it is better to control the spacing of freezing pipes at 1.0~1.3 m, and the diameter of the freezing pipe of the connecting channel is generally more than 89 mm. By comparing the numerical simulation value with monitoring data, the numerical calculation result is consistent with the monitoring temperature change rule.

Keywords: subway tunnel; freezing method; freezing temperature field; thawing temperature field; deep soil heave and thaw

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1. Introduction

The freezing method is suitable for all types of stratum and is mainly used for the excavation and construction of coal mine shafts. It has also been widely used in subway shield tunnel excavation construction, double-line section tunnel side passage and pump room well construction, pipe jacking in and out of tunnel construction, and underground engineering leakage stoppage rescue construction.

There are more and more large-scale and ultra-large-depth underground spaces, comprehensive transportation hubs, and urban underground complexes in China. These underground projects are often faced with abundant groundwater, weak stratum, and unpredictable deformation. Conventional stratum reinforcement treatment technology sometimes struggles to completely prevent water damage and out-of-control deformation problems, resulting in accidents that cause loss of life and property from time to time. The freezing method has been applied in engineering for nearly 160 years. Since China first adopted the freezing method to construct the air shaft of the Linxi Mine of the Kailuan

Coal Mine in 1955, more than 1000 mine shafts and inclined shafts have been constructed using the freezing method, and this method has been applied in more than 220 subway and municipal engineering constructions.

However, Most subway tunnels are located in prosperous urban areas, and there are many ground buildings and surrounding facilities. The freezing method construction environment of subway tunnels has particularity and complexity, such as frost heaving in the process of freezing and thawing under the influence of unreasonable design or improper construction and other factors. If the amount of thawing settlement is not timely and effectively controlled, it will have a direct adverse impact on the surrounding environment of the project, ranging from extending the project period and increasing the project cost to causing damage to underground pipelines, existing operating subway lines and surface buildings, and roads, endangering construction safety. In serious cases, freezing pipe rupture will occur, which will lead to catastrophic accidents, and different parameters have a greater influence on the freezing law.

The temperature field of frozen soil is the research basis for the formation conditions of frozen soil and the prediction of frost heave and thaw settlement. Research in this field has involved the process of approximate analytical solutions, statistical analysis methods, empirical methods, and numerical analysis methods [1–3]. At the end of the 19th century, Russia established the Permafrost Research Committee. In the middle of the 20th century, the former Soviet Union carried out experimental studies on thermodynamics, thermophysics, engineering building stability, and other aspects related to temperature fields and theoretical calculation studies based on analytical solutions [4]. In the West, Bonacina et al. [5] proposed a numerical method to solve the temperature field of phase change heat conduction. Comin et al. [6] conducted a finite element analysis on the nonlinear problem of the temperature field of phase change heat conduction. Ershov et al. [7,8] studied the influence of the latent heat of phase change on temperature field. In order to study the deformation behavior of fine-grained sandstone subjected to cyclic loading, a series of triaxial cyclic compression tests were performed under different confining pressures in the laboratory [9].

Tan Xianjun et al. [10] established the mathematical model of temperature field in the process of freezing and thawing of rock and soil media, and discussed the influence of the latent heat of phase transformation and the size of the frozen region on the distribution of temperature field in the process of freezing and thawing. Yang Feng et al. [11] analyzed the difference between the three-dimensional temperature field and the two-dimensional temperature field and the development trend of the thickness of the frozen wall with the back-drilled tunnel of the Tianhe passenger station as a background. The temperature field in the frozen area was numerically simulated by ANSYS. Zhang Ting et al. [12] established a finite element temperature field calculation model based on the freezing reinforcement of the shield tunnel of Nanjing Metro Line 2, and studied the development law of the intersection time of the frozen wall and the thickness of the bottom frozen wall. Hou Shuguang et al. [13] carried out the coupling analysis of temperature field and displacement field in the process of soil freezing and thawing through ABAQUS software, and then put forward the coupling numerical calculation method of temperature field and displacement field in the process of soil freezing and thawing. Xia Jiangtao et al. [14] relied on the horizontal freezing reinforcement project of shield tunneling in a metro station and studied the influence of different factors on the temperature field of the cup-shaped frozen soil wall by using the verified model and calculation method, and obtained the influence rule of each factor on the temperature field of the cup-shaped frozen soil wall. Jia Chaojun et al. [15] conducted a series of triaxial compression tests on amygdaloidal basalt under different pore pressures. Based on the experimental results, a micromechanical-based elastoplastic damage model is proposed for such saturated hard rock. Jia, C.J. et al. [16] reports a comprehensive investigation on the deformation characteristics, failure mechanism, and stabilization treatment of the Baitieba slope on the left abutment of the Xiluodu hydropower plant on the downstream reach of the Jinsha River. Li Bo et al. [17] took the freezing method construction of the section connecting channel of Lanzhou Metro Line 2 as the background, and numerically simulated the freezing process of the freezing method of the connecting channel by using ABAQUS software. Lu Xianlong et al. [18] analyzed the characteristics of frozen soil and the physical essence of freezing engineering based on the phase change process and dynamic balance of water in frozen soil. Jia, Chaojun et al [19] took Hunan shale as the background, and the anisotropic properties, including strength, deformation, AE response, and failure pattern of Hunan shale were investigated under various confining pressures. Mei Yuan et al. [20] took a subway connecting passage project in Xi'an as the research object and, based on the measured data and numerical simulation, studied the soil temperature field, stress field, frost heaving, and thawing settlement law of rich water sand layer freezing construction in a collapsible loess area.

In summary, many studies have been carried out by our predecessors, and the research on the freezing temperature field and the frost heave and thawing deformation has achieved many results, whether in terms of actual measurements, model tests, or numerical simulation research. In the design stage of the metro tunnel freezing project, reasonable methods should be used to predict the possible ground frost heave and thaw settlement effects according to the specific engineering properties, so as to take appropriate freezing implementation plans and corresponding frost heave and thaw settlement prevention measures in the actual construction process, and to minimize the cost and risk of the application of the freezing method.

The temperature field distribution of the freezing wall in the connecting channel of a subway tunnel is complex, and it is affected by the surrounding environment, such as by the air and the freezing wall in the channel. Considering the influence factors, such as the air in the shaft, the frozen wall, and the thickness of the shaft wall, the constitutive model of the frozen wall temperature field is established by improving the adiabatic model and introducing the relevant parameters. The numerical method is used to compare and analyze the influence factors of the frozen wall temperature field. Compared with the field test, this method has high availability, acceptability, and interpretability.

In this paper, through a large number of numerical experiments on the temperature field of artificial frozen wall, the quantitative influence laws of various parameters on the temperature field of frozen wall and the displacement of ground frost heave are obtained, so as to provide certain reference and guidance for design and construction during the artificial freezing of a subway tunnel.

Therefore, the simulation study of soil temperature, freezing wall thickness, and freezing rate in the whole freezing process is carried out based on Suzhou Metro Line 2. The purpose is to obtain rich and credible data through actual measurement and research, so as to provide a strong basis for optimizing the grouting process and solving the problems of prediction and control of post-construction thawing settlement.

2. Freezing Wall Temperature Field

2.1. Formation Process of Frozen Wall

In the numerical simulation, the development process of freezing can be shown in Figure 1. In the process of frozen wall formation, the salt water in the frozen pipe will have a sharp change in heat exchange with the soil around the frozen pipe. With the increase in time, a cylinder-like frozen soil column will be formed around each frozen pipe (Figure 1a). As the heat exchange continues, the frozen soil column range will further develop. When the diameter is expanded to a certain extent, the adjacent frozen soil columns will intersect each other, and a closed frozen wall will be formed between them (Figure 1b). After the intersection of the frozen wall, the inner and outer sides of the frozen wall gradually form the inner frozen front extending into the tunnel, and the outer frozen front extending outwards. After a certain point, the inner and outer frozen front will tend to be smooth, forming a circular frozen wall (Figure 1c) [21]. This calculation simulates the temperature field change in the tunnel excavation in the shadow freezing area.

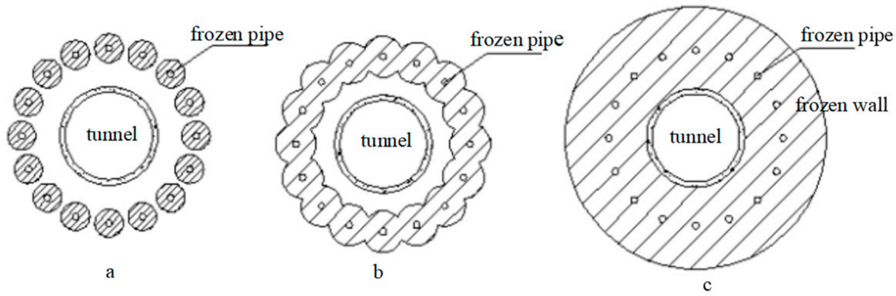

Figure 1. The formation process of a frozen wall. (**a**) frozen soil column, (**b**) soil column intersection, (**c**) frozen wall formation.

After the freezing pipe begins to freeze, the low-temperature brine in the freezing pipe begins to flow. At this time, the brine is kept at a temperature below 0 °C. With the heat exchange between the brine and its surrounding strata, the soil temperature continues to decrease. When the temperature drops to the freezing temperature of the soil, the water in the soil changes from liquid water to ice, and the thawed soil becomes frozen soil. After the thawed soil becomes frozen soil, the frozen soil temperature continues to drop, so that a frozen soil column is formed around each frozen pipe. With the continuous cooling of the frozen pipe, the radius of the frozen soil column increases, and the temperature field in the frozen soil column changes. With the growth of the frozen soil column, the frozen soil columns of adjacent frozen pipes begin to connect, that is, the zero temperature isotherms meet, which is called intersection. Before the freezing cylinder intersects the circle, the freezing expansion speed is faster, the freezing cylinder intersects the circle quickly, the radian of the zero-degree isotherm gradually slows down after the circle intersects, and the expansion speed of the frozen soil wall also gradually slows down. After the adjacent frozen soil columns are connected, a continuous frozen soil wall is formed.

2.2. Freezing Wall Temperature Field

In this study, it is assumed that the freezing pipe is parallel to the axial direction of the tunnel, and multiple sections are divided along the axial direction. The three-dimensional problem is converted into a two-dimensional problem. The heat balance control differential equation considering three-dimensional freezing-thawing temperature field can be expressed as follows [22]:

$$\rho_f c_f \frac{\partial T}{\partial t} - L_w \rho_i \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial x}\left(k_f \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_f \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_f \frac{\partial T}{\partial z}\right) \quad (1)$$

$$\rho_u c_u \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_u \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_u \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_u \frac{\partial T}{\partial z}\right) \quad (2)$$

where T is the soil temperature, t is time, θ_i is ice content per volume, L_w is the water latent heat of phase transformation, c_f and cu are the specific heat of freezing soil and thawing soil (unfreezing soil), respectively, k_f and k_u are the thermal conductivity of freezing soil and thawing soil (unfreezing soil), respectively, and ρ_f, ρu, and ρ_i are the density of freezing soil, thawing soil(unfreezing soil), and ice, respectively.

If the temperature gradient along tunnel axis is assumed to be zero, then the freezing and thawing temperature field can be simplified as a plane problem, and the two-dimensional control differential equation is expressed as follows:

$$C_f \frac{\partial T}{\partial t} - L_w \rho_i \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial x}\left(k_f \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_f \frac{\partial T}{\partial y}\right) \quad (3)$$

$$C_u \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_u \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_u \frac{\partial T}{\partial y}\right) \quad (4)$$

where C_f can be expressed as $C_f = \rho_f c_f$ and C_u can be expressed as $C_u = \rho_u c_u$.

In the phase transition region of frozen soil, the specific heat and thermal conductivity of soil often change dramatically. Therefore, proper treatment should be carried out. Generally, it can be assumed that the transformation only occurs in a temperature range [T_d, T_r], in which T_d is the freezing temperature of the soil and T_r is the melting temperature of the soil. There is no phase change in confidante frozen soil when [$T < T_d$]. Equations (3) and (4) can be decomposed into the thermodynamic control differential equation of frozen soil and normal frozen soil in phase change area, which can be expressed as follows:

$$C_f \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_f \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_f \frac{\partial T}{\partial y}\right) \tag{5}$$

$$C_L \frac{\partial T}{\partial t} - L_w \rho_i \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial x}\left(k_L \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_L \frac{\partial T}{\partial y}\right) \tag{6}$$

where C_L is known volume specific heat of soil in the phase transition zone, k_L is known thermal conductivity of soil in phase transition zone, the volume ice content of the soil in the phase transition area is displayed by the volumetric water content. This being the case, the following Equation (7) can be expressed as follows:

$$-L_w \rho_i \frac{\partial \theta_i}{\partial t} = L_w \rho_w \frac{\partial \theta_w}{\partial t} = L_w \rho_w \frac{\partial \theta_w}{\partial T} \frac{\partial T}{\partial t} \tag{7}$$

where θ_w is the volume of ice content of the soil and ρ_w is the density of water. Equation (8) is as follows:

$$L_w \rho_w \frac{\partial \theta_w}{\partial T} = L_w \rho_w \frac{\rho_d (w_0 - w_u)}{\rho_w (T_r - T_d)} = \frac{L}{T_r - T_d} \tag{8}$$

where ρ_d is the dry density of the soil, w_0 is the initial water content of the soil, w_u is the unfrozen water content in frozen soil, and L is the latent heat of icing per unit volume of soil.

Then, the thermodynamic control differential equation in the phase transition zone can be obtained as follows:

$$\left(C_L + \frac{L}{T_r - T_d}\right) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_L \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_L \frac{\partial T}{\partial y}\right) \tag{9}$$

The volume specific heat C_L and thermal conductivity of the soil in the phase transition area k_L are linearly interpolated according to the temperature, and the equivalent volume specific heat C^* and equivalent thermal conductivity k^* expressed by the control differential equation of the freezing and thawing temperature field can be constructed as follows:

$$C^* = \begin{cases} C_f & T<T_d \\ \frac{C_f + C_u}{2} + \frac{L}{T_r - T_d} & T_d \le T<T \\ C_u & T>T_r \end{cases} \tag{10}$$

$$k^* = \begin{cases} k_f & T<T_d \\ k_f + \frac{k_u - k_f}{T_r - T_d}(T - T_d) & T_d \le T<T \\ k_u & T>T_r \end{cases} \tag{11}$$

By combining this with the Formulas (9)–(11), the two-dimensional control differential equation of the freezing and thawing temperature field can be unified as follows:

$$C^* \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k^* \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k^* \frac{\partial T}{\partial y}\right) \tag{12}$$

2.3. Horizontal Analysis of Temperature Field

According to the oil temperature calculation method of a petroleum pipeline, the connecting passage is divided into multiple sections in the direction of the freezing pipe (Figure 2). The heat loss between each section is calculated to estimate the brine temperature distribution along the direction of the freezing pipe, and the section temperature can be estimated by the following formula [23,24]:

$$T_i = T_{i-1} - \frac{Q_p \Delta x}{(C_0 f)} \tag{13}$$

where T_i is the estimated brine temperature at plane i, T_{i-1} is the known brine temperature at the previous section $i-1$, Qp is the brine heat flux of previous section, Δx is the distance between two sections, C_0 is the volumetric specific heat capacity of brine, and F is the flow rate.

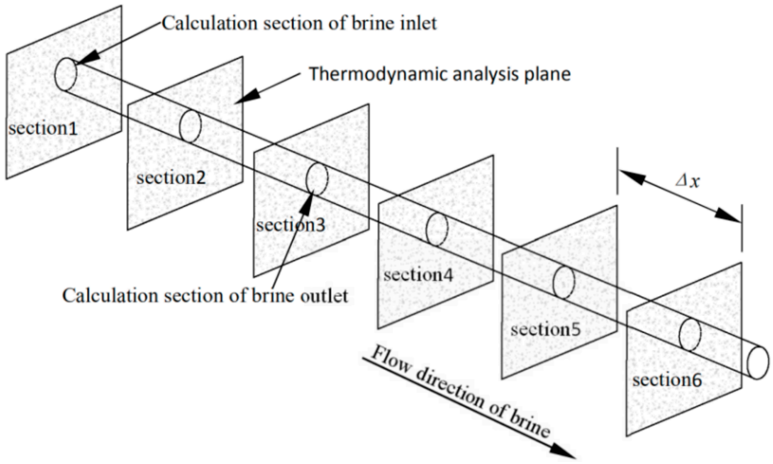

Figure 2. Brine temperature along the direction of the freezing pipe.

3. Computational Model

3.1. Basic Assumptions

This model makes the following basic assumptions:

(1) The stratum is an isotropic elastoplastic body with independent thermal parameters in the freeze-thaw state;
(2) The loss of cooling capacity is perpendicular to the direction of the freezing tube, regardless of the loss along the direction of the freezing tube;
(3) The temperature around the freezing tube is evenly distributed. Considering the temperature loss of low-temperature circulating brine, the temperature of the cold source applied at the location of the freezing tube is 2 °C higher than the actual low-temperature brine temperature;
(4) Considering the heat conduction and ice-water phase transition effect of the cold in the stratum, the convection and heat radiation caused by temperature is ignored, the unfrozen water content is taken as a function of temperature, the latent heat calculated from the unfrozen water content is only in the phase transition temperature range internally generated, and the temperature range of the stratum phase transition is taken from [−1~0] °C;
(5) Regardless of the effect of construction on the stratum freezing, it is assumed that the outer boundary away from the frozen wall area of the geometric model is an adiabatic boundary;
(6) Assuming that the density ρ, the specific heat capacity c, and the thermal conductivity λ are all constant, only the freezing and thawing state of the formation is considered.

3.2. Calculation Model and Parameters

In this study, the temperature field analysis was carried out using the freezing tunnel construction of Suzhou Metro Line 2 as an example (Figure 3).

Figure 3. Photos of the engineering project.

The buried depth of the tunnel center is 16 m, and the excavation section is circular. In order to fully consider the impact of excavation on the surrounding rock of the tunnel, this simulation takes the surrounding rock mass within five times the diameter of the excavation centered on the tunnel axis as the simulation object. At the same time, in order to facilitate calculation and analysis, the problem is treated as a plane strain problem, the unit length is taken in the direction of the tunnel axis, the length and width of the model are 60 m, and the tunnel radius is 3 m. The finite element calculation grid is shown in Figure 4. The length of the frozen engineering section is 60 m. In the calculation, a section is divided every 5 m along the freezing direction, and there are 12 sections in total.

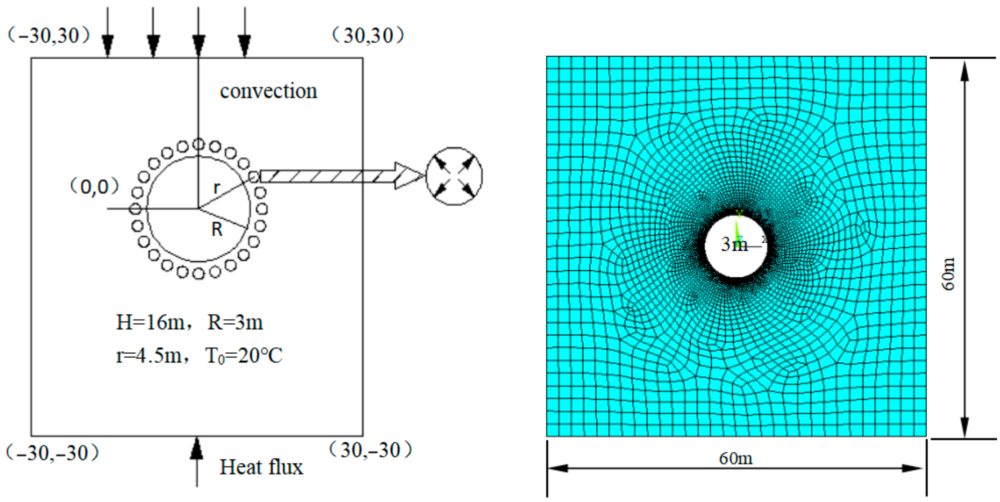

Figure 4. Numerical calculation model.

The range of the numerical analysis model was as follows: in this numerical test, a two-dimensional calculation model is used, and the X direction is taken as −30 to 30 m; The Y direction is taken as −30 to 30 m, and the tunnel axis is at the origin. The model is divided into 1890 nodes and 2658 elements, with triangular and quadrilateral elements. The side and bottom of the model are displacement boundaries. The side restricts the horizontal movement of the model, the bottom restricts the vertical movement, and the upper surface of the model is a free boundary.

The boundary condition treatment was as follows: the two sides of the calculation model in this paper are adiabatic boundaries, the lower boundary has geothermal action, the heat flux is 150 J·h^{-1}·m^{-2}, the upper boundary is connected with the atmosphere, and the heat exchange coefficient between the atmosphere and the surface is 20 W·m^{-2}·°C^{-1}.

In this calculation, the large-scale finite element calculation software ANSYS was used for numerical analysis, and PLANE77 high-order elements were selected. Each node of the element has only one degree of freedom and one temperature. The node element has a consistent temperature shape function, which can be well adapted to models with curvilinear boundaries and is suitable for dimensional steady-state or transient thermal analysis. In order to make the calculation with sufficient accuracy and as few nodes as possible, when dividing the element, the tunnel axis is used as the coordinate origin, triangle elements are used within the radius of 3 m, and quadrilateral elements are used outside [25]. At the top of the model, considering the convective heat transfer boundary conditions between the atmosphere and the soil, the atmospheric temperature is taken as 15 °C.

All soils around the connecting passage are considered as sandy soil, and the parameters adopted refer to similar projects (see Table 1).

Table 1. Soil parameters used in this simulation.

Parameters	Freezing Soil		Unfreezing Soil	
Temperature/°C	−28	−1	0	28
Thermal conductivity/(W·m^{-1}·K^{-1})	1.17	1.17	1.07	1.07
Specific heat/(kJ·kg·°C^{-1})	1.45	1.45	1.69	1.69
Density/(kg·m^3)	1800	1800	1850	1850

According to the geological age, genetic type, lithology, distribution, and burial characteristics of the soil layer, it can be divided into five levels from top to bottom. The distribution of the soil layer is shown in Table 2.

Table 2. List of site soil stratum.

Serial Number	Category (Name)	Thickness h (m)	Weight (kN/m^3)	Water Content w (%)	Plastic Limit w_L	Liquid Limit w_P	Permeability Coefficient k (m/d)	Internal Friction Angle φ_k (°)	Cohesion c_k (KPa)	Compression Modulus E_s (MPa)
①	Miscellaneous fill	1.30	17.8	13.6	1.78	7.08	2.3	16.5	10.5	14.3
②	clay	1.70	18.0	31.5	3.32	26.42	0.004	21.8	8	14.4
③	Silty clay	4.13	19.2	36.7	16.96	29.16	0.08	22.2	12	4.09
④	Silt	4.87	19.0	34.2	4.15	9.75	0.3	24.6	23	10.5
⑤	Silty clay	15.2	18.6	29.7	4.75	22.55	0.06	23.1	34	11.6

It is assumed that the left and right sides are adiabatic boundaries, and only the lower boundary has a heat flow effect. The heat flow density is taken as 150 J·h^{-1}·m^{-2}, the ground surface is taken as the upper boundary, and the heat exchange coefficient between the atmosphere and the ground surface is taken as 20 W·m^{-2}·°C^{-1}. When the brine flows in the freezing pipes, the convective heat transfer boundary is adopted, and the value of the convective heat transfer coefficient is 140 W·m^{-2}·°C^{-1}. The simulation freezing time is 41 days.

According to the actual influencing factors of the connecting passage, four sets of simulations are performed in this paper, including the influence of brine temperature, the influence of freezing pipe diameter, the influence of freezing pipe spacing, and the influence of soil water content.

4. Discussion

4.1. Influence of Brine Temperature

Among all the influencing factors, the brine temperature has the greatest influence on the freezing field. In this study, a fixed section (section 2 in Figure 1) was selected. Assuming that other soil parameters remain the same and that the brine temperature changes, the brine temperatures are set as −20, −22, −24, and −26 °C. The change in soil temperature with time is shown in Figure 5. It can be seen that, with the increase in time, the soil temperature gradually decreases. The soil temperature decreases rapidly in the first

18 days, and then decreases gradually. After reaching the 41st day, the brine temperature tends to a stable state.

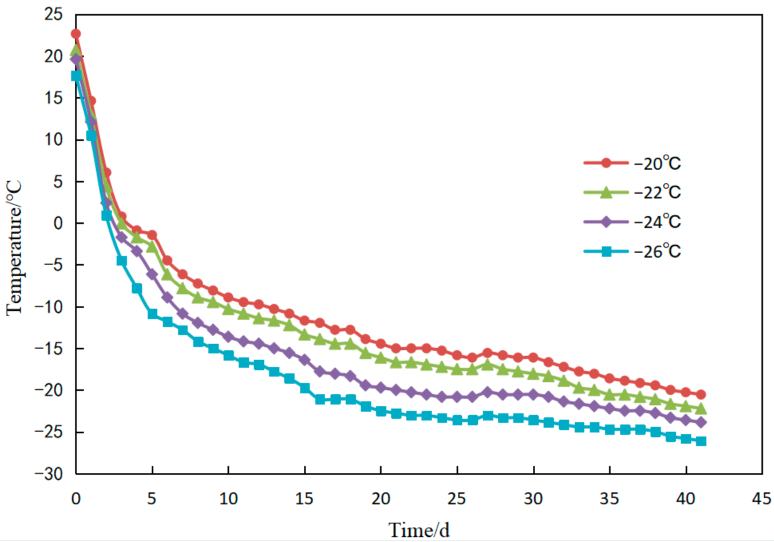

Figure 5. Variation of freezing wall temperature under different brine temperatures.

The freezing wall thickness is also greatly influenced by the temperature, as shown in Figure 6. At the same freezing time, the freezing wall thickness increases with the decrease in brine temperature. Similarly, the lower the temperature is, the shorter the time it takes to reach the same thickness. However, it is undesirable for the freezing temperature to be as low as possible, as a too-low brine temperature often leads to an increase in engineering costs. Considering various factors, if the project allows, the higher brine temperature shall be selected to reduce the refrigeration cost. The brine temperature in the connecting passage is generally controlled between −25 °C and −30 °C [26].

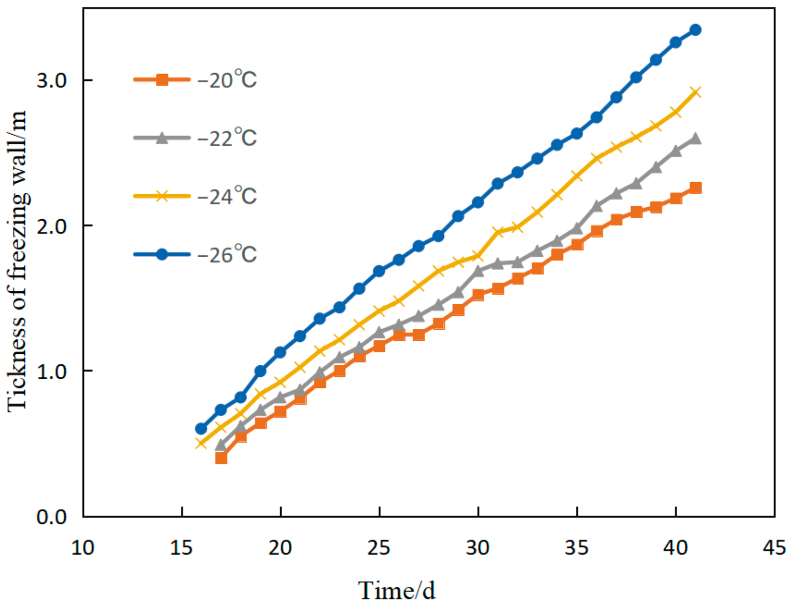

Figure 6. Variation of freezing wall thickness under different brine temperatures.

The brine temperature also has a great influence on the freezing rate. According to the analysis at the beginning of crossing cycle, it can be seen from Figure 7 that the maximum freezing rate reaches 95 mm/d (−26 °C), while the minimum freezing rate is only 50 mm/d (−20 °C). As the brine temperature decreases, the freezing rate becomes higher and higher. After about 41 days, the freezing rates tend to be stable.

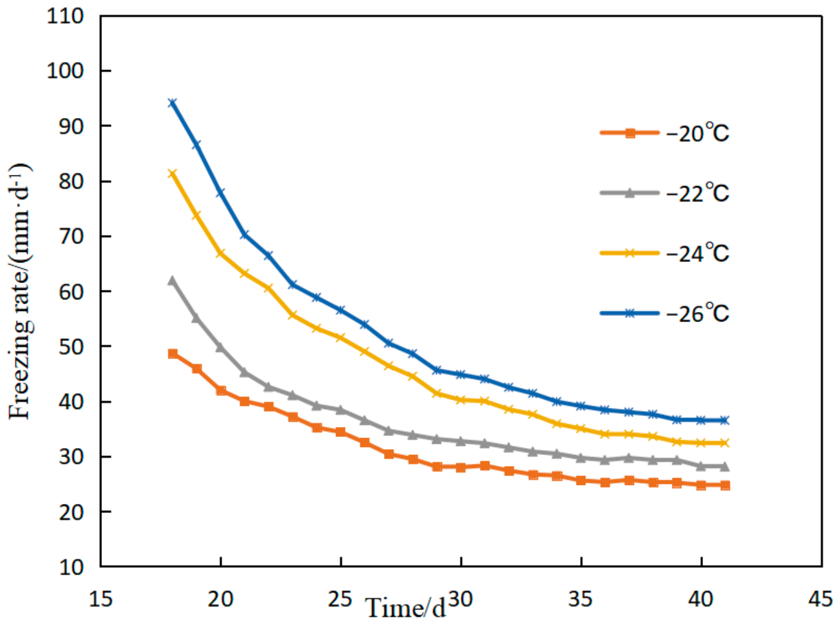

Figure 7. Variation of freezing rate of freezing wall under different brine temperatures.

4.2. Influence of Freezing Pipe Diameter

In this case, assuming that the other parameters remain unchanged, the influence of the change in the freezing pipe diameters on temperature field is studied. The freezing pipe diameters are set as 80 mm, 100 mm, 120 mm, 140 mm, and 160 mm, respectively. Figure 8 shows the variation rule of soil temperature with time at section 2. It can be seen that, the larger the freezing pipe diameter is, the faster the soil temperature will drop. In the first 18 days, the soil temperature will decrease rapidly, and then the temperature will decrease gradually. On the 41st day, the soil temperature will tend to be stable.

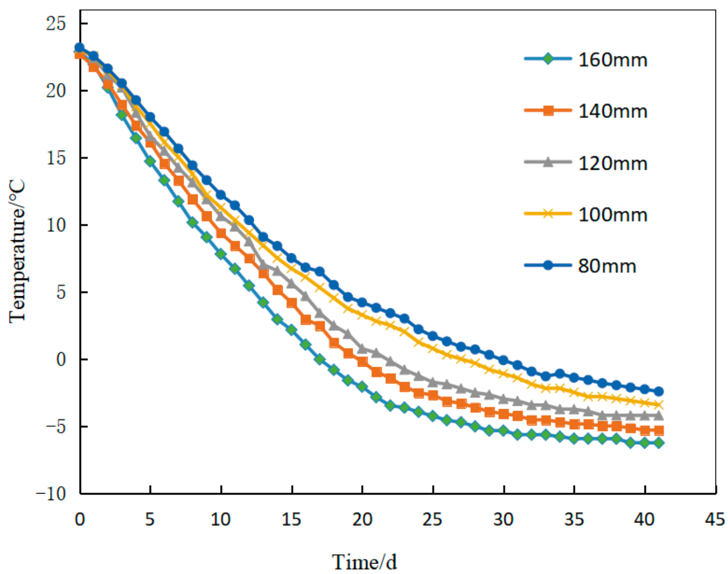

Figure 8. Variation of freezing wall temperature under different freezing pipe diameters.

The freezing pipe diameter also has an influence on the freezing wall thickness. As can be seen from Figure 9, the freezing wall thickness at each diameter is approximately linear with time. When the freezing time is the same, the freezing wall is thicker with a larger freezing pipe diameter, but the gap is not very large. When only considering the freezing construction period, the larger the diameter, the better. However, the increase in diameter leads to higher material costs. Therefore, various factors need to be considered, and a reasonable freezing pipe diameter should be taken. At present, the freezing pipe diameter in the connecting passage construction is generally 89 mm.

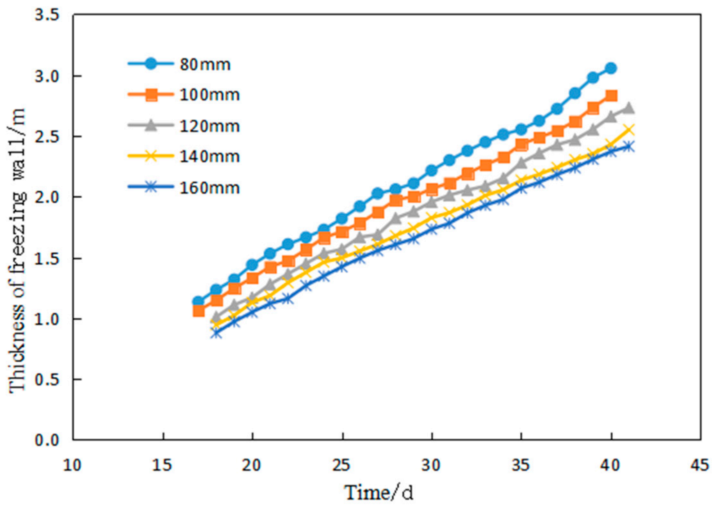

Figure 9. Variation of freezing wall thickness under different freezing pipe diameters.

The freezing pipe diameter also has a great influence on the freezing rate. According to the analysis at the time of intersection, the maximum freezing rate reaches 98 mm/d (diameter = 160 mm), while the minimum freezing rate is only 53 mm/d (diameter = 80 mm) (Figure 10). With the decrease in the freezing pipe diameter, the freezing rate becomes smaller and smaller, and each freezing rate tends to be stable after 41 days.

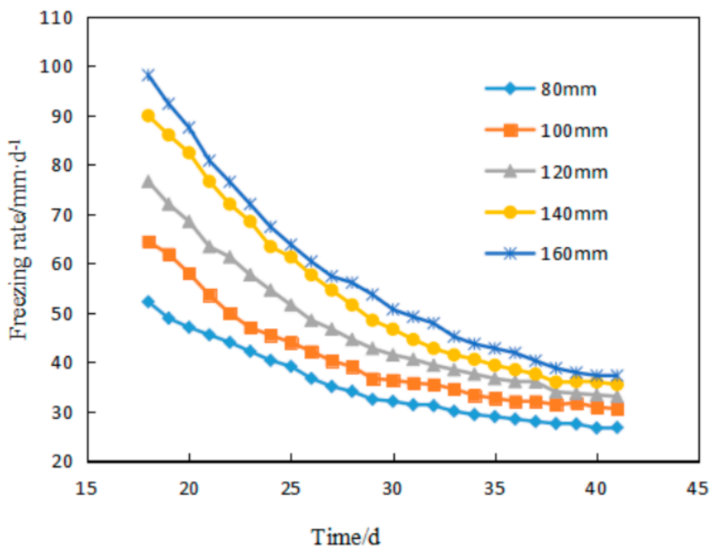

Figure 10. Variation of freezing rate under different freezing pipe diameters.

4.3. Influence of Freezing Pipe Spacing

In order to study the influence of freezing pipe spacing on the temperature field, the numerical test is mainly carried out by changing the freezing pipe spacing. The spacings are set as 0.5 m, 0.7 m, 0.9 m and 1.1 m, respectively, and the other parameters remain unchanged. Figure 11 is the temperature curve of different freezing pipe spacing at section 2. It can be seen that the smaller the freezing pipe spacing is, the faster the soil temperature will drop. In the initial stage of freezing, the increase in the freezing pipe spacing will have a greater influence, the soil temperature will drop significantly, and then the temperature drops gradually to a stable level.

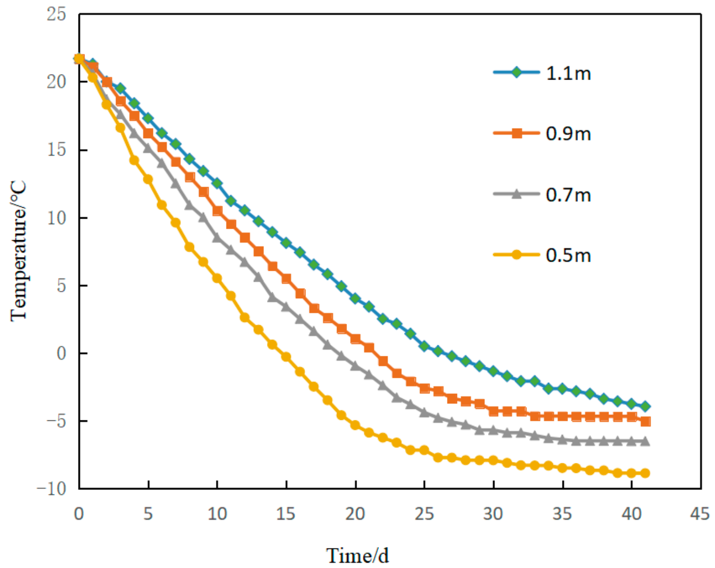

Figure 11. Variation of freezing wall temperature under of different freezing pipe spacing.

The development of freezing wall thickness under different freezing pipe spacing is shown in Figure 12. It can be seen that the freezing wall thickness is basically linear with time. When the freezing time is the same, the larger the freezing pipes' spacing is, the thicker the freezing wall is. When the freezing time reaches 41 days, the freezing wall thickness with the spacing of 1.1 m is 2.13 m, and the freezing wall thickness with the spacing of 0.5 m is 2.93 m. According to the existing engineering experience, the spacing of freezing pipes in a connecting passage is generally from 0.8 m to 1.2 m.

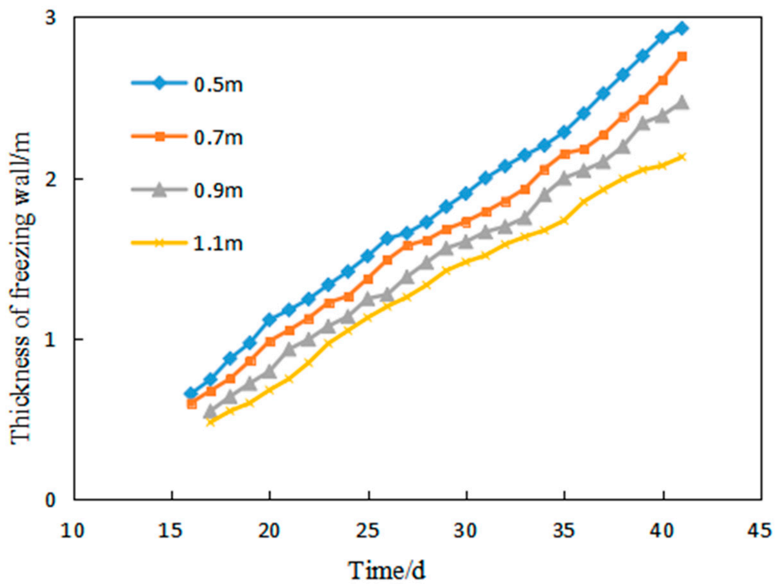

Figure 12. Variation of freezing wall thickness under different freezing pipe spacing.

The freezing pipes' spacing also has a great influence on the freezing rate, as shown in Figure 13. The maximum freezing rate reaches 82 mm/d (freezing pipes' spacing = 0.5 m), while the minimum freezing rate is only 38 mm/d (freezing pipes' spacing = 1.1 m). With the decrease in the freezing pipes' spacing, the freezing rate becomes larger and larger, and the freezing rates tend to be stable at about 41 days.

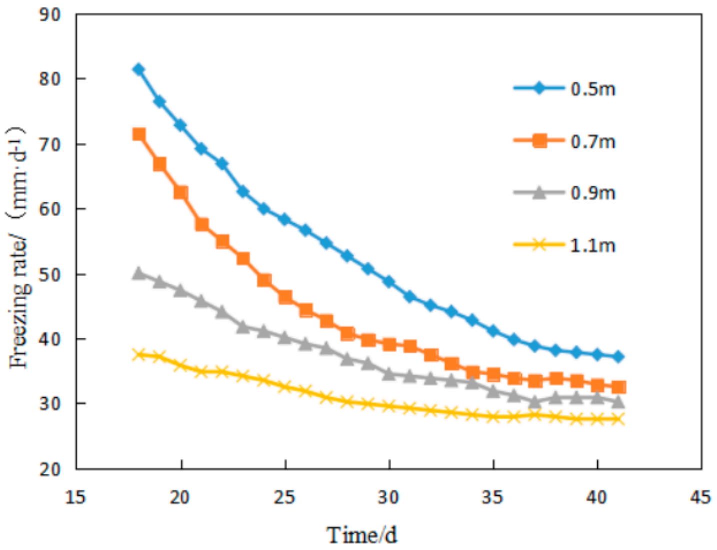

Figure 13. Variation of freezing rate under different spacing of freezing pipes.

4.4. Influence of Soil Water Content

In order to study the influence of soil water content on the freezing rule, the soil water content is set as 30%, 40%, 50%, and 70%. Figure 14 is the freezing wall temperature under different water content at section 2.

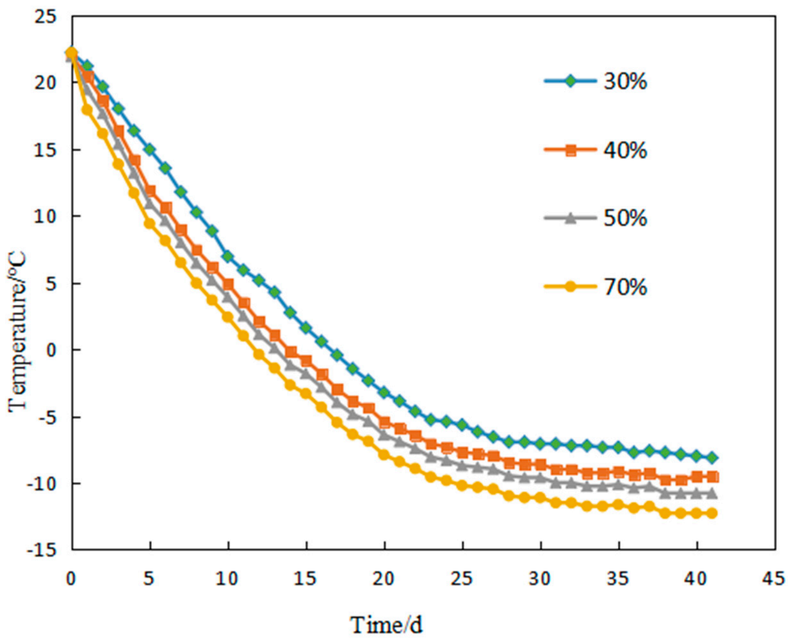

Figure 14. Variation of freezing wall temperature under different water content.

It can be seen that, the higher the water content is, the faster the soil temperature decreases. The lower the water content is, the slower the soil temperature decreases. At the initial stage of freezing, the soil temperature with different water contents has a relatively obvious decrease, and then the temperature drops gradually to a stable level.

The development of freezing wall thickness under different water content is shown in Figure 15. It can be seen that, the greater the water content is, the smaller the freezing wall thickness is. For example, on the 40th day, when the water content is 70%, the freezing wall thickness is 1.45 m, and when the water content is 30%, the freezing wall thickness is 2.69 m. The difference is obvious and, thus, the water content has a great influence on the development of the freezing wall thickness.

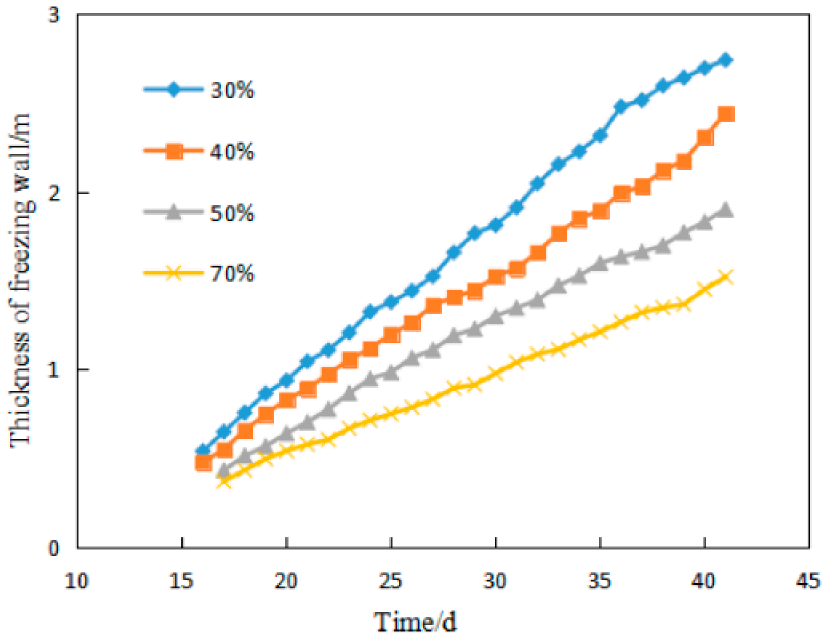

Figure 15. Variation of freezing wall thickness under different water content.

Figure 16 shows the development of the freezing rate of the freezing wall with time under different water content. It can be seen that the maximum freezing rate is 79 mm/d (water content = 30%), while the minimum freezing rate is only 31 mm/d (water content = 70%). The smaller the water content is, the greater the freezing rate is, and the freezing rates tend to be stable at around the 41 days.

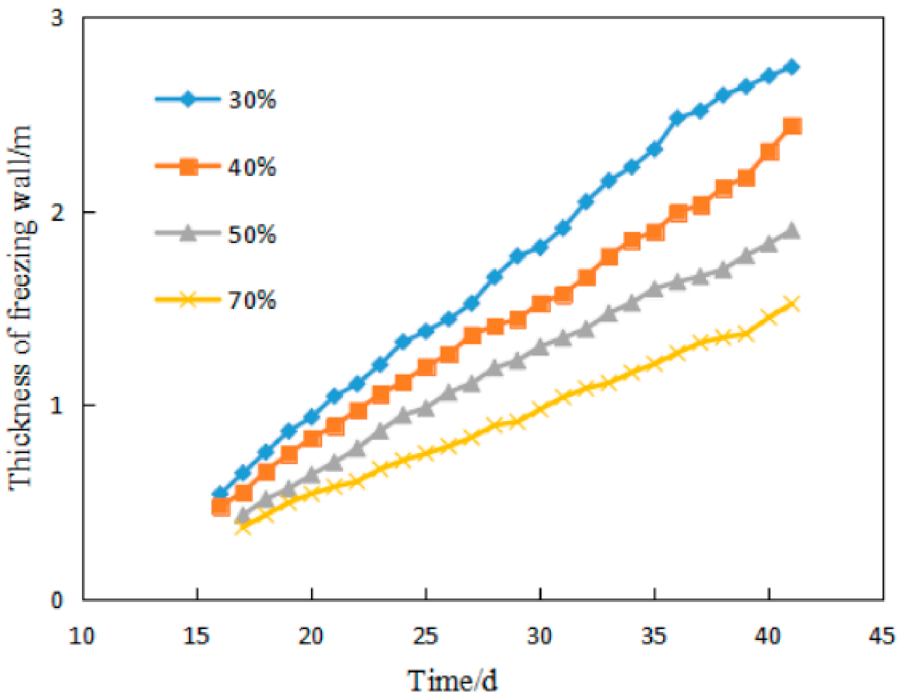

Figure 16. Variation of freezing rate under different water content.

4.5. Comparison of Numerical Simulation and Field Monitoring Data

In order to verify the correctness of the calculation results in this paper, the difference between the numerical simulation value and monitoring value in a temperature measuring hole is compared.

This comparison takes the freezing method construction of Changzhou Metro Line 1 in Jiangsu Province as an example. Figure 17 shows the comparison between the temperature change in the monitoring hole C9 on the freezing wall and the calculated value.

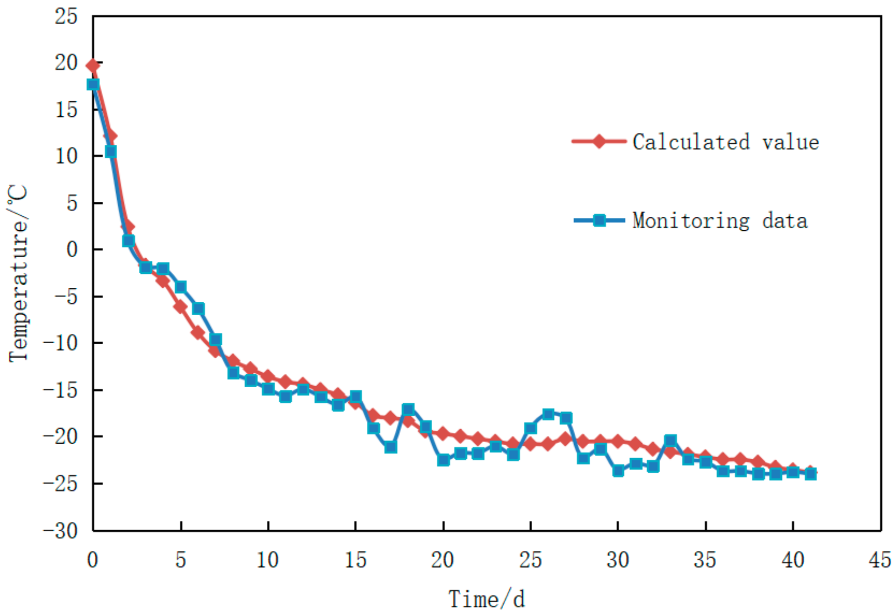

Figure 17. Comparison between monitoring value and calculated value.

It can be seen from the comparison that the changes in the two data are very consistent during active freezing, which shows that the finite element model has good reliability and can provide effective guidance for construction [27–29].

4.6. Engineering Suggestions

Our engineering suggestions are as follows:

Considering the freezing time alone, the lower the temperature of brine in the freezing pipe, the better. However, the lower the brine temperature, the greater the cooling demand and the higher the cooling cost. Under the condition of meeting the construction conditions of the project, the higher brine temperature shall be selected to reduce the refrigeration cost. At present, the saltwater temperature in the freezing project of a metro shield tunnel is generally controlled at −28~−30 °C;

The smaller the spacing of the freezing pipes, the less time it takes to freeze a certain thickness of soil. However, the smaller the spacing of freezing pipes, the more freezing pipes are needed and, thus, the construction cost will be increased. The influence of freezing tube spacing on freezing is mainly manifested in the speed of the intersection time of adjacent freezing tubes in the first stage, which further affects the freezing time required for the whole freezing wall to reach the design thickness. Generally, from the perspective of actual engineering, it is better to control the spacing of freezing pipes at 1.0~1.3 m;

The larger the diameter of the freezing pipe, the less time it takes to freeze a certain thickness of soil. However, the larger the freezing pipe, the higher the construction cost and construction risk. At present, the diameter of the freezing pipe of the connecting channel is generally more than 89 mm.

5. Conclusions

Based on the mathematical model of soil freezing and thawing temperature field, the evolution characteristics of freezing wall temperature field of a subway connecting passage are analyzed, and the following conclusions are drawn.

The temperature field of the freezing wall is influenced by various factors. The finite element method based on the thermodynamics theory can simulate the freezing temperature field and the formation law of the freezing wall of each section.

Among the influencing factors, the brine temperature and the freezing pipes' spacing have the greatest influence on the temperature field of a freezing wall. The thickness of the freezing wall increases linearly with the increase in the freezing time. At the same time, the thickness of the freezing wall increases with the increase in the diameter of the freezing tube and the decrease in the spacing between the freezing tubes. With the decrease in brine temperature and water content, the difference in the freezing wall thickness at different levels becomes larger and larger with the increase in freezing time. The influence of various factors on the freezing wall is in the order of brine temperature, freezing tube spacing, and freezing tube diameter.

At present, the saltwater temperature in the freezing project of a metro shield tunnel is generally controlled at −28~−30 °C. Generally, from the perspective of actual engineering, it is better to control the spacing of freezing pipes at 1.0~1.3 m, and the diameter of the freezing pipe of the connecting channel is generally more than 89 mm. By comparing the numerical simulation value with monitoring data, the numerical calculation result is consistent with the monitoring temperature change rule.

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