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Meteorological Effect on Temperature Field of Tunnel with High Altitude in Cold Region

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Abstract

To investigate the influence of meteorological conditions on the temperature distribution of the surrounding rock and lining of tunnel in seasonally frozen areas, taking into account phase change, a temperature field model was established based on the principles of continuum mechanics and thermodynamics. The effect of different meteorological conditions on the radial temperature field distribution of the tunnel was explored by varying the annual mean temperature and annual temperature amplitude in the model. Then, the spatio-temporal distribution model of temperature field in the surrounding rock was established. Results show that the latent heat of phase change is not negligible in the modelling process of tunnel in cold region. The annual average temperature has a significant impact on the freezing depth, and the freezing depth of the surrounding rock will gradually increase when the annual average temperature falls below 0°C. The freezing depth of the surrounding rock varies periodically when the average annual temperature is greater than 0°C. The amplitude of the surrounding rock temperature decreases exponentially with the increase of the radial depth of the surrounding rock. After reaching a certain depth, the amplitude of temperature tends to 0, and the average temperature of surrounding rock changes logarithmically. The conclusions provide a significant reference for the frost protection design of tunnel in cold regions.

Keywords: Tunnel in cold region, Temperature field, Numerical simulation, Meteorological condition, Spatio-temporal distribution

1. Introduction

With the implementation of "One Belt, One Road" policy in China, an increasing number of road and railway tunnels are required to build in permafrost regions. The direct excavation in permafrost during the construction process often results in significant disruption to the original water and thermal balance. Additionally, the periodic variation in external low temperature can cause the surrounding rock of the tunnels to experience freeze-thaw cycles during the operation period of the tunnels, which can easily lead to phenomena such as ice hanging, lining cracking, drainage freezing, and road surface icing [1]. The occurrence and progression of these issues pose a severe threat to the safety of the tunnel's structure. The problem of freezing damage to tunnels in cold regions has become a "bottleneck" problem for tunnel construction, maintenance and sustainable development of transportation.

Indeed, effective anti-freezing and thermal insulation measures are crucial for newly constructed tunnels in cold regions of China. Currently, the main anti-freezing and thermal insulation designs for preventing and controlling the tunnel freezing damage include electric heating methods, ground source heat pump methods, thermal insulation doors, and thermal insulation layers [2-5]. The study of temperature fields in cold region tunnels is the basis for conducting research on anti-freezing and thermal insulation design. Only by fully understanding the climate of the tunnel site and the distribution of surrounding rock temperature, can the effective anti-freezing and insulation technology be adopted.

It's true that the surrounding rock temperature field plays an essential role in preventing frost damage in cold region tunnels. Different methods such as field testing, analytical calculation, and numerical simulation are commonly used to study the temperature field in the surrounding rock of cold region tunnels. Field testing is the most direct method for obtaining the distribution of the temperature field and revealing its spatiotemporal evolution, but it has limitations regarding cost and time. Analytical calculation also has limitations regarding complex boundary conditions, while numerical simulation methods are more adaptable.

The issues of frost prevention in cold region tunnels are influenced by various factors, such as climate, surrounding rock conditions, groundwater, and tunnel conditions (size and height difference). However, current engineering designs mostly rely on analogies and general standards, which often result in overly conservative frost prevention designs or insufficient frost prevention lengths, which is a significant concern in China. It's essential to explore the factors affecting the temperature field of cold region tunnels systematically and in-depth, examining meteorological conditions, tunnel conditions, surrounding rock conditions, and groundwater conditions. This study aims to provide a starting point for further research and focuses on the impact of meteorological conditions on the temperature field of cold region tunnels.

2. State of the art

At present, many scholars have carried out research on the issue of tunnel frost damage by using analytical methods, field monitoring and numerical simulations.

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Regarding analytical methods, Bronfenbrener presented an analytical solution for soil temperature field during freezing [6]. Elmer developed a quasi-static analytical solution for this problem [7], whereas Pekeris and Slichte proposed a first-order correct quasi-static analytical solution [8]. Bonaicina et al. obtained a numerical solution for a one-dimensional nonlinear temperature field with phase transition problems [9]. Zhang et al. used the Galerkin method to derive the temperature field control equation considering the phase change, and solved the temperature field of the tunnel enclosure in the cold regions under diverse initial ground temperature and thermal conductivity of the insulation layer [10]. Lai et al. derived a three-dimensional temperature field control equation to analyse the freezing and melting state of the wind-volcanic tunnel surrounding rock of Qinghai-Tibet Railway [11]. Xu established the water-heat coupled mathematical model of Kunlun Mountain tunnel, and carried out the computational analysis of the cold region tunnel [12]. Zhang et al. obtained the theoretical solution of temperature in the radial direction of surrounding rock by using the superposition principle and the theorem of Bessel characteristic function [13]. Zhao et al. derived an analytical solution for the temperature field of circular tunnels in cold regions through theoretical analysis [14].

For the field studies, Chen and Zan conducted field test of temperature field in the Denduling tunnel of Qinyu Highway and obtained the variation law of temperature inside and outside the tunnel and surrounding rock with time [15]. Nie investigated the temperature field of Xiluoqi tunnel on the Nenlin Line and obtained the temperature distribution curves inside and outside the tunnel [16]. Zhou et al. studied the temperature field changes during Zilashan Tunnel tunnel operation [17]. Chang et al. monitored the surrounding rock temperature in a cold region tunnel, and found the heat generated by the tunnel traffic was a primary factor contributing to temperature changes in the tunnel [18]. Zhao et al. conducted meteorological monitoring on the air and surrounding rock of Zuomutai Tunnel to reveal that air temperature in the tunnel presented an approximate triangular function periodic change [19]. Liang et al. utilized self-developed intelligent monitoring system to monitor the temperature in the Shiling Tunnel and studied the spatiotemporal distribution of the temperature field inside the tunnel [20]. Lu et al. established a three-dimensional numerical model considering convective heat transfer based on a certain cold region tunnel and validated the numerical model through model experiments and on-site measurement data [21]. Zhao et al. conducted field temperature monitoring in the Xingan Mountains Tunnel and analyzed the sensitivity of freezing depth to different influencing factors [22]. Zhang et al. studied the characteristics of temperature changes caused by construction and boundary temperature changes on the surrounding rock temperature field of permafrost tunnels by the physical model tests [23]. Yu et al. conducted field monitoring on the temperature field of a tunnel on the Qinghai-Tibet Plateau and studied the variation law of the temperature field of surrounding rock at the tunnel entrance by establishing the coupled model of water and heat of the cold region tunnel [24].

For numerical simulation, Neaupane et al. established the control equation of surrounding rock temperature, stress and seepage coupling, considering water phase change for the first time [25]. Guiaice et al. simulated the temperature field of soil during freezing, using the finite element method [26]. Goering investigated the effects of different passive cooling methods on the temperature field of railway roadbeds [27]. Tan et al. divided the surrounding rock into frozen zone, positive frozen zone and unfrozen zone, gave the temperature field control equations of each zone, and solved them by numerical simulation method [28]. Zhang et al. studied the temperature field of Fenghuoshan Tunnel, revealing that the temperature of surrounding rock behind the lining wall of permafrost tunnel changed linearly with time and radius [29]. Lai et al. analyzed the temperature field of Qingshashan Tunnel, showing that the velocity and direction of the air flow in the tunnel significantly affected the temperature rise of the tunnel inlet and outlet sections [30]. Jiang et al. explored the influence of traffic on the temperature fields of spiral and straight tunnels and proposed a new design method for laying the length of insulation layer [31]. Kang and Li established a two-dimensional model of convection-heat conduction coupling and analyzed the variation characteristics of the temperature field with or without insulation layer [32].

The above-mentioned results provide a good understanding of heat transfer in cold region tunnels. However, the influence of meteorological conditions, such as annual average temperature and annual temperature amplitude, on the temperature field of the tunnel is rarely considered. In this study, a heat transfer model of multilayer media considering phase change was established based on porous media and thermodynamic theory. The effect of meteorological conditions on the temperature field in cold tunnels was also studied by using numerical simulation methods.

The rest of this study is organized as follows. Section 3 presents the numerical calculation method and numerical simulation scheme. Section 4 describes the simulation results and analysis, and finally, section 5 summarizes the conclusions.

3. Methodology

3.1 Basic theory of heat transfer

To investigate the impact of meteorological conditions on the radial temperature field within a cold tunnel, a simplified two-dimensional model is utilized. To facilitate the study, the following simplifying assumptions are made: (1) The surrounding rock and lining are homogeneous and isotropic materials. (2) The pore space in the surrounding rock is constant and does not vary with temperature and space. (3) The contact surface between the lining and the surrounding rock is considered to be ideal, resulting in a contact thermal resistance of 0. (4) The rock is considered to be saturated, and the effect of air on the temperature field is not taken into consideration.

When the temperature is below 0°C, the water in the rock freezes into ice and releases heat. As the temperature continues to decrease, the freezing depth of the surrounding rock gradually increases. (Since this is a phase change problem, it is necessary to consider the latent heat of phase change. Based on the porous medium and thermodynamic principle [33-37], the governing equation for the heat conduction problem of low-temperature rock is:

$$(\rho C)_{eff}\frac{\partial T}{\partial t}+\rho_l L\frac{\partial \theta_i}{\partial t}=\nabla\left(\lambda_{eff}\nabla T\right) \tag{1}$$

where, $(\rho C)_{eff}$ is the equivalent heat capacity. T is the temperature. ρ is the density. L is the latent heat released per unit mass of water into ice. λ_{eff} is the equivalent heat transfer rate. C is the heat capacity. θ is the volume content. s, l and i are denoted the rock skeleton, water, and ice, respectively.

The equivalent heat capacity $(\rho C)_{eff}$ (J/(m^3·K)) is a measure of the amount of heat energy required to raise the temperature of a material by 1°C per unit volume. For low temperature surrounding rock, the equivalent heat capacity is expressed as a volume-weighted average.

$$(\rho C)_{eff}=\left(\theta_s\rho_s C_s+\theta_l\rho_l C_l+\theta_i\rho_i C_i\right) \tag{2}$$

The equivalent heat transfer rate λ_{eff} (W/(m·K)) can be defined as the amount of heat transferred per unit temperature per unit time through a unit area of media. In this paper, the volume weighted average is used to express the equivalent thermal conductivity:

$$\rho_s C_s\frac{\partial T}{\partial t}-\nabla\left(k_s\nabla T\right)=0 \tag{3}$$

The boundary conditions can be classified into two types: the first type is known as Dirichlet boundary conditions, as shown in Eq. (4), and the second type is known as Neumann boundary conditions, as shown in Eq (5).

$$T=T_0\cdot on\cdot \Gamma_1 \tag{4}$$

Due to the highly nonlinear feature of heat transfer in surrounding rock with phase change, an exact solution cannot be obtained through analytical methods.

$$\lambda\Delta_t\cdot n=q_T\cdot on\cdot \Gamma_2 \tag{5}$$

where, Γ_1 and Γ_2 refer to the boundaries of the computational domain of the model. T is the instantaneous temperature at the boundary Γ_1. T_0 is the known temperature or temperature function on the boundary Γ_1. n is the direction cosine of the normal vector on the surface of the boundary Γ_2. q_T is the known heat flux on that boundary. The boundary conditions described above are determined based on geological prospecting reports and relevant literature [38-40].

The heat transfer of surrounding rock considering phase change is a strong nonlinear problem that cannot be accurately solved using an analytical method. COMSOL Multiphysics is a numerical software based on finite element, and has strong capabilities for solving nonlinear differential equations. In this study, the numerical simulation software will be used to calculate the temperature field containing phase transition. The specific calculation steps of COMSOL simulation are as follows: (1) choosing the porous medium heat transfer and solid heat transfer physical field, (2) establishing a finite element model, (3) adding the basic physical parameters of ice, water, insulation layer and concrete, and assigning them to the finite element model, (4) setting the initial temperature field of the transient analysis by adding boundary conditions, (5) dividing the grid, and (6) setting the calculation time for solving the problem. The flow chart is shown in Fig. 1.

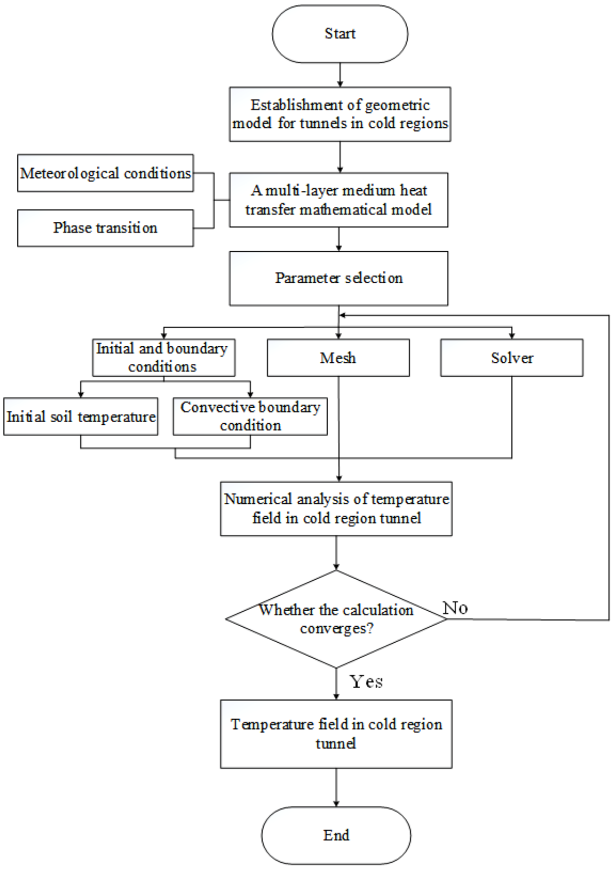


Fig. 1. Finite element calculation flow chart.

3.2 The computational model

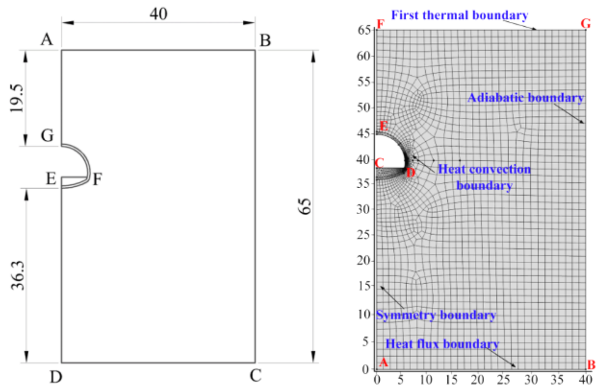
The modelling study took the Duolong Tunnel, located in Qinghai Province, as an example. The tunnel is situated in the eastern portion of the Qilian Mountains in the northeastern part of the Tibetan Plateau, within the mid-latitude westerly zone, which is characterized by a continental climate. During the winter, the area is affected by a dry and cold Siberian climate, resulting in relatively chilly and arid conditions. The multi-year average temperature is 0.8°C with extreme maximum and minimum temperatures of 27.9°C and -25.8°C, respectively. The daily temperature fluctuation ranges from 11.6-17.5 °C.

The entrance section of Duolong Tunnel, precisely the K41+780 section, was selected for analysis. The inner wall clearance width of the tunnel is about 11.77 m, and the clearance height is about 6.80 m. The tunnel lining, measuring 50 cm in thickness, and road surface are constructed using concrete materials. The model considered the actual tunnel size, which includes the insulating layer, secondary lining, lining, surrounding rock and concrete pavement. In this study, the temperature field simulation and calculation of surrounding rock was simplified into a two-dimensional transient model. The boundary conditions of the temperature field calculation were based on the temperature data from a measured geological survey report. The computational model is shown in Fig. 2.

The initial value of the surrounding rock is 2°C. The thermodynamic boundary condition is as follows: The AG and ED in the model are taken as symmetric boundaries. BC is the thermal insulation boundary. DC is the flow boundary and $\vec{q}$ =3.33 W/m^2. AB and GFE take convective boundary, and convective heat transfer coefficient between air and surrounding rock and lining is h=15 W/(m^2·K) [41]. The atmospheric temperature of the region where Duolong Tunnel is situated conforms to a sinusoidal function, delineated based on the data extracted from local meteorological records.

$$T = T_a + A\sin(\omega t + \varphi) \tag{6}$$

where, T is the atmospheric temperature (°C). T_a is the annual average temperature of the atmosphere (°C), 0.8°C. A is the atmospheric temperature amplitude (°C), 26.85°C. ω is the temperature change period, generally take 1 a for a period. φ is the initial phase, decide the starting moment.



(a) Size of model (b) Subdivision of grid

Fig. 2. Numerical calculation model.

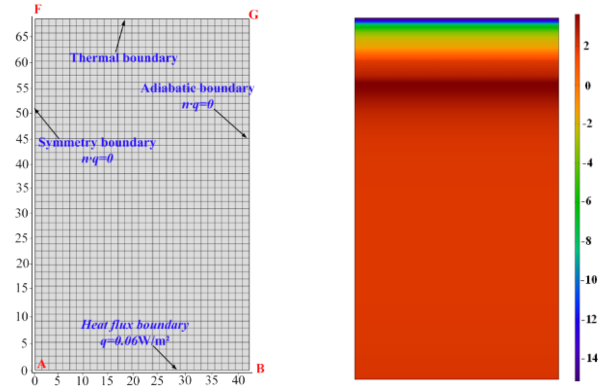
According to the address survey report, the main calculated physical parameters are taken as shown in Table 1. The analysis of temperature field distribution in cold regions includes the impact of meteorological conditions. The effect of annual average temperature and annual temperature amplitude on the freezing depth of the tunnel and the temperature at different depths was analyzed by using the single factor cycle method, without considering the initial temperature of the surrounding rock. The design table of working conditions of single-factor cyclic method is shown in Table 1.

Table 1. Physical parameters of the model.

Materials	λ (W/(m·K))	*C* (J/(kg·K))	*P* (kg/m³)	*θ* (°)
Ice	2.14	2100	917	0.3
Water	0.56	4180	1000	
Surrounding rock	3.00	850	2530	
Concrete	1.74	970	2400	

3.3 Initial surface temperature

As there was a lack of measured ground temperature data of Duolong tunnel, this study conducted a numerical simulation to calculate the surface temperature of the tunnel for 100 years, in order to obtain the initial temperature field and enhance the accuracy of calculation results. The numerical model was established with dimensions of 40 m wide and 65 m high. AF boundary conditions were symmetric, and FG, AB and BG boundary conditions were the same, as shown in Fig. 3. The thermal and physical parameters of surrounding rock are listed in Table 1. The phase transition latent heat of the surrounding rock was found to be 23.22 kJ/kg, while that of ice water was 333 kJ/kg. The surface temperature field calculated by the model for 100 years is shown in the Fig. 3. As seen from Fig. 3, the heat near the surface decreases rapidly, while the magnitude of attenuation becomes weaker with increasing depth. At this point, the ground temperature remains relatively constant and can be considered a stable temperature field. For this study, the temperature field was used as the initial ground temperature to calculate the Duolong Tunnel model.



(a) Initial temperature model (b) Temperature distribution

Fig. 3. Initial temperature field model and distribution.

3.4 Probe measuring points setting

The probe function in COMSOL software was used to study the temperature field distribution of surrounding rock at different radial depths. Six temperature monitoring points were designated at various radial depths: 0 m, 0.27 m, 1.5 m, 2.5 m, 4.6 m and 10.5 m from the lining surface, respectively. The location of these monitoring points is depicted in Fig. 4 and Table 2.

The influence of meteorological conditions on the distribution of temperature fields was analyzed in cold regions. The effect of annual average temperature and annual temperature amplitude on the freezing depth of the tunnel and the temperature at different depths was analyzed using the single factor cycle method, without considering the initial temperature of the surrounding rock. The design table of working conditions of single-factor cyclic method is shown in Table 3.

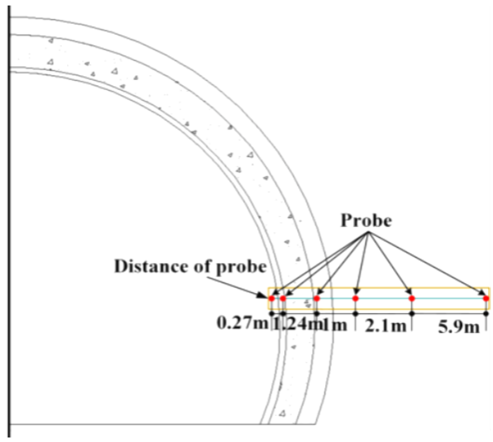


Fig. 4. Probe monitoring chart.

Table 2. Probe monitoring position.

Distance from lining surface (m)	0	0.27	1.50	2.50	4.60	10.50
Prob	1	2	3	4	5	6

Table 3. Single-factor cycle condition design table.

Work conditions	T_a (°C)	*A* (°C)
1	-4, -2, 0, 2, 4	26.85
2	0.80	10, 15, 20, 25, 30

4. Results analysis and discussion

4.1 Distribution characteristics of radial temperature field of tunnel in cold region

4.1.1 Effect of ice-water phase transition

The proposed numerical calculation method of radial temperature field was used to solve the temperature distribution of the lining and surrounding rock of K41+780 section of the tunnel. As the ice-water phase transition is a critical factor in the study of temperature field in cold regions, the temperature field of surrounding rock and lining was calculated with and without phase transition, respectively. The temperature probe data were extracted as shown in Figs. 5 and 6.

As seen from Fig. 5, the temperature of probes 1 and 2 exhibits a consistent variation. This is due to the fact that probes 1 and 2 are situated in the liner, consisting of concrete, without considering the ice-water phase transition. From Fig. 5(a), it can be concluded that for the model considering ice-water phase change, the temperature at different depths in the surrounding rock (Probe 3, 4, and 5) exhibits differing degrees of change near 0°C, and the 0°C isotherm becomes flatter as the depth increases.

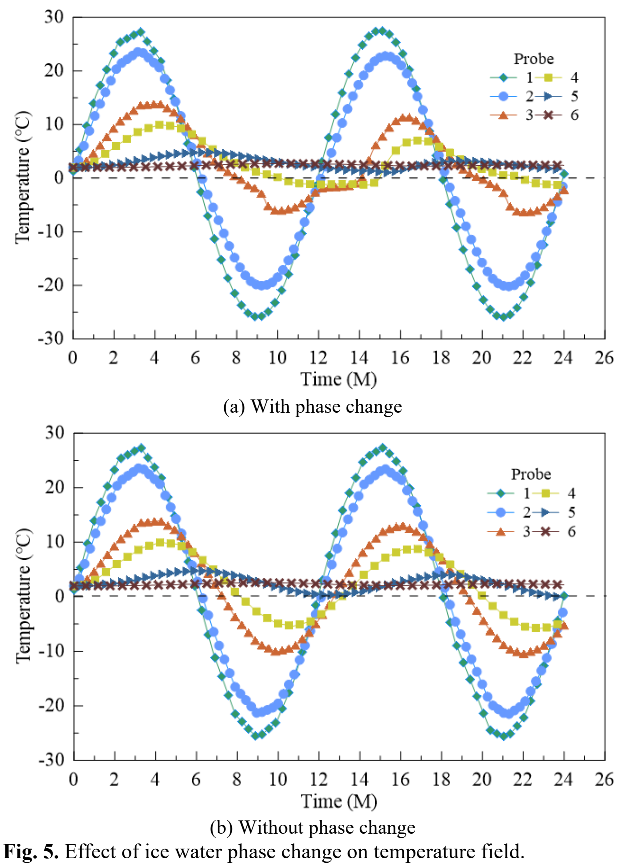


Fig. 5. Effect of ice water phase change on temperature field.

Comparing with Fig. 5(b), the temperature at different depths of the model without a phase change is distributed as a sinusoidal function with a smooth curve and does not change at the 0°C isotherm. Additionally, the temperature amplitude of probe 1, 2, and 3 in the temperature field with a phase change is lower than that of probe 1, 2, and 3 in the temperature field without a phase change. For probe 3 (standing 1.0 m behind the liner), the minimum temperature of the model without a phase change is -10.5°C, while the minimum temperature of the model with a phase change is -6.3°C, reflecting a difference of 4.2°C. When the temperature falls below 0°C, the water in the pore of the surrounding rock freezes into ice and releases a large amount of latent heat, which slows down the cold propagation. As a result, the temperature obtained by the model without a phase transition in calculating the temperature field will be larger than that of the model considering phase change. In summary, it can be inferred that the ice-water phase change has a significant effect on the temperature field of the tunnel in cold regions.

As seen from Fig. 6, the temperature of surrounding rock varies with depth at different times of the year. On the 90th day where the temperature peaks, the hottest in the year, the temperature reduces from the surface to the depth of the surrounding rock. On the other hand, on the 270th day, the coldest in the year, the temperature increases from the surface to the depth of the surrounding rock. This is because that the lag in the heat transfer process contributes to this phenomenon where the propagation of heat from the surface of the surrounding rock to the depth requires a significant period to generate an effect.

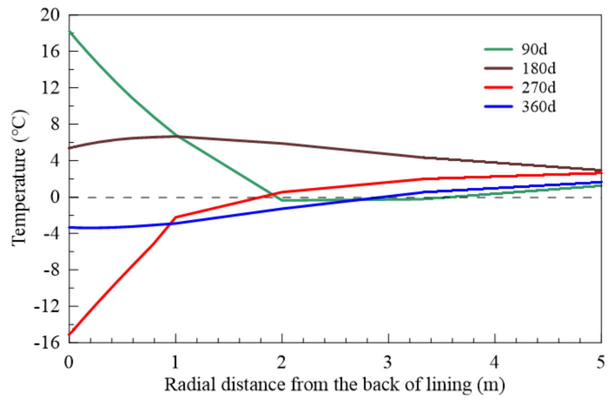
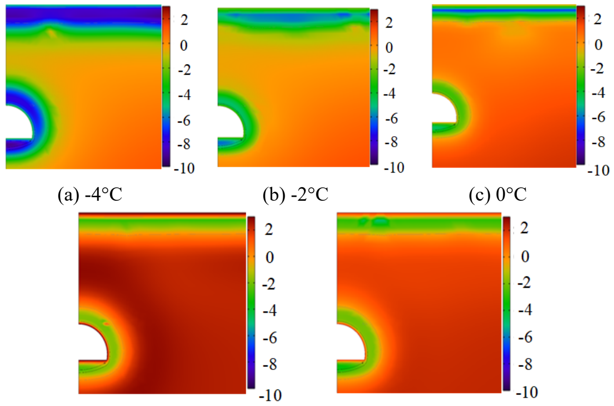


Fig. 6. Variation of surrounding rock temperature with depth in cross-section tunnel.

4.1.2 Influence of annual average temperature on temperature field of tunnel

The temperature field of tunnel in cold region is affected by the meteorological condition (air temperature) at the tunnel portal. In this section, the above radial temperature field calculation model is used to quantitatively analyze the influence of the above factors on the temperature field of tunnel in cold area. According to Eq. (6), the temperature at the tunnel portal is determined by the annual average temperature and amplitude of annual temperature. The numerical simulation method is utilized to alter the annual average temperature and the amplitude of the annual temperature separately to assess their respective impacts on the distribution of temperature field inside the tunnel.

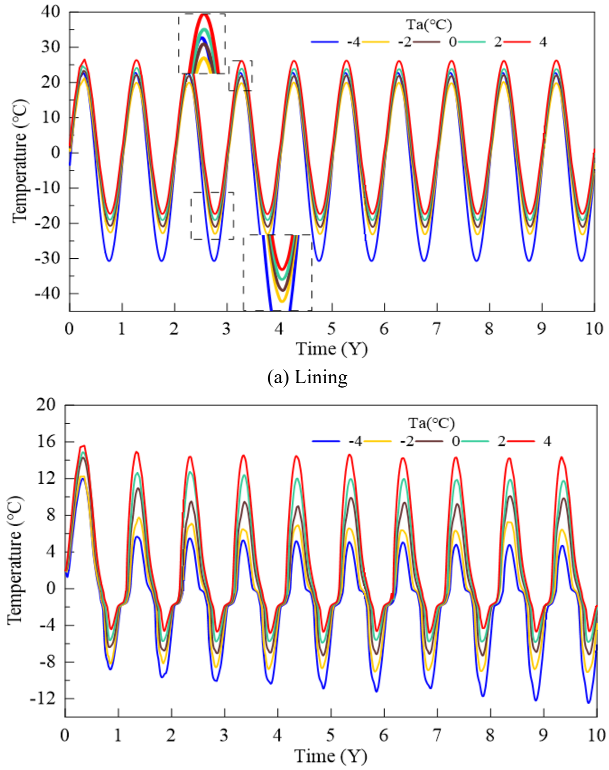
The annual average temperature was set to -4°C, -2°C, 0°C, 2°C and 4°C, respectively. The distribution of temperature field was observed for 10 years was calculated. Fig. 7 shows the temperature distribution after 10 years for different annual average temperature tunnels. It is evident from the Fig. 7 that the freezing depth of the surrounding rock increases as the annual mean temperature decreases. When the average annual temperature is lower than 0 °C, the cold released during the year surpasses the heat, leading to the gradual expansion of the freezing range of the surrounding rock over time. As a result, the surrounding rock freezing circle and the surface freezing depth are interconnected, as shown in Figs. 7(a) and 7(b). When the average annual temperature is greater than 0 °C, the heat released during the year is greater than the cold, and the freezing depth of the surrounding rock will not always increase with time but change periodically with time. The maximum freezing depth of the surrounding rock in Figs. 7(c) and 7(d) is 3.58 m, 3.16 m and 2.75 m, respectively. The lower the average annual temperature, the colder is released during the year, resulting in an increase in the freezing depth.



(a) -4°C (b) -2°C (c) 0°C (d) 2°C (e) 4°C

Fig. 7. Distribution of tunnel temperature at different annual average temperatures after 10 years.

To analyze the temperature field variation at different annual average temperatures, Probe 1 (lining) and Probe 3 (1 m deep in the surrounding rock) were chosen as two locations. As seen from Fig. 8(a), the lining temperature variation varies periodically with time and the temperature profile is smooth. The minimum liner temperature and time phase do not change with time.



(a) Lining

(b) Surrounding rock

Fig. 8. Variation of tunnel temperature with time for different annual average temperatures.

The change of the surrounding rock temperature is shown in Fig. 8(b). Unlike the standard sinusoidal function distribution observed in the liner temperature, the surrounding rock temperature doesn't follow the same pattern and displays changes in its minimum temperature and time phase with time. Additionally, the minimum temperature of the surrounding rock is gradually decreasing with time. Meanwhile, the curve flattens near 0°C, which can be attributed to the freezing of pore water into ice, releasing a significant amount of latent heat and thus delaying the freezing process.

The minimum temperatures of the surrounding rock and lining at different annual average temperatures during the 10 years are shown in Fig. 9. When the average annual temperature is -4°C, -2°C, 0°C, 2°C and 4°C, respectively. The minimum temperature of lining is -30.74°C, -28.70°C, -26.73°C, -24.74°C and -22.71°C, respectively. The minimum temperature of surrounding rock is -9.64°C, -7.33°C, -4.42°C, -1.98°C and -1.05°C, respectively. The lining minimum temperature decreases uniformly with the decrease of annual average temperature, and the impact of negative annual average temperature on the minimum temperature of the surrounding rock is more pronounced than that of positive annual average temperature.

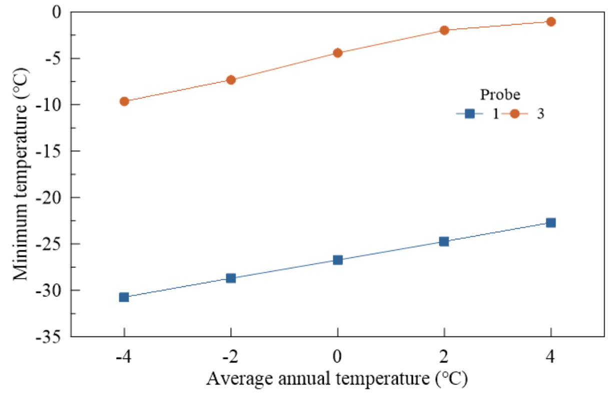


Fig. 9. Average annual temperature and minimum temperature.

4.1.3 Influence of annual temperature amplitude on temperature field of tunnel

The annual temperature amplitudes were varied to 10 °C, 15 °C, 20 °C, 25 °C, and 30 °C, respectively. The temperature field distribution was then calculated over a decade of observation. Fig. 10 represents the temperature distribution after 10 years for tunnels with varying annual temperature amplitudes. The change of annual temperature amplitude only impacts the lining and the upper surface of the tunnel, while the rest of the surrounding rock experiences a negligible change in temperature. When the average annual temperature is 0.8°C and the annual temperature amplitude is 10°C, 15°C, 20°C, 25°C and 30°C, the corresponding freezing depth is 2.76 m, 3.06 m, 3.35 m, 3.40 m and 3.81 m, respectively.

To analyze the variation of the temperature field under different annual temperature amplitudes, Probe 1 (lining) and Probe 3 (1 m deep in the surrounding rock) were selected. As seen from Fig. 11 (a), the lining temperature variation varies periodically with time. The liner minimum temperature and time phase do not change with time, but still show a standard sinusoidal function distribution. On the other hand, the temperature variation of the surrounding rock, depicted in Fig. 11 (b), does not exhibit a standard sinusoidal function distribution with time. With the exception of the first year, the minimum temperature and phase of the surrounding rock remains unaltered in the following 9 years.

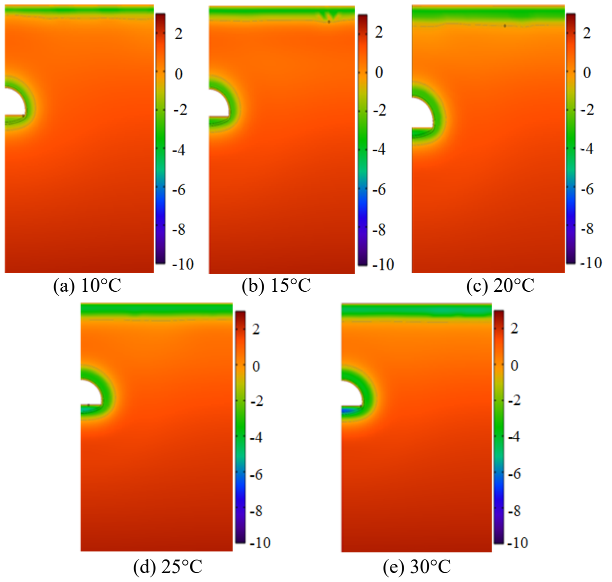


Fig. 10. Distribution of tunnel temperature at different annual temperature amplitudes after 10 years.

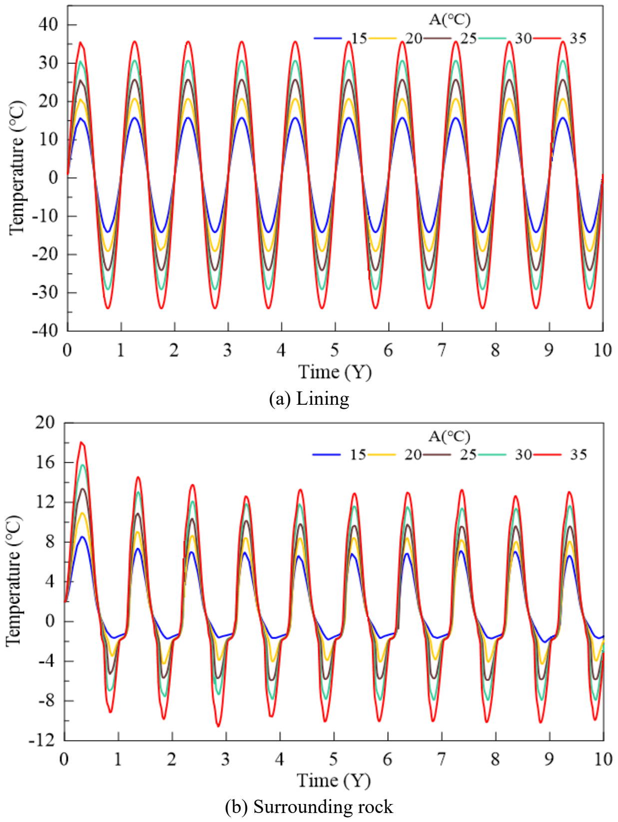


Fig. 11. Variation of tunnel temperature with time for different annual average temperatures.

The lowest temperature of surrounding rock and lining under different annual temperature amplitudes in 10 years is shown in Fig. 12. The minimum temperatures of the surrounding rock and lining under different annual temperature the annual temperature amplitude is 15°C, 20°C, 25°C, 30°C and 35°C, the minimum temperature of liner is -14.13°C, -19.11°C, -24.01°C, -29.07°C and -34.06°C, respectively. The minimum temperature of perimeter rock is -1.69°C, -3.96°C, -5.81°C, -7.9°C and -9.91°C, respectively. The minimum temperatures of the liner and surrounding rock exhibit a linear decrease with the annual temperature amplitude.

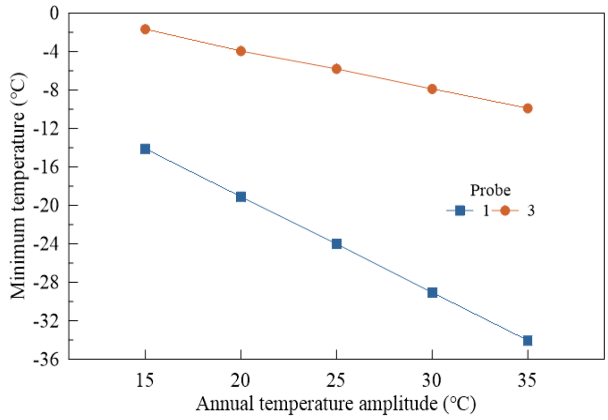


Fig. 12. Annual temperature amplitude and minimum temperature.

4.2 Spatio-temporal distribution model of radial temperature field in surrounding rock

The variation rules of the surrounding rock temperature field are relatively complex as it is influenced by the ambient temperature. Although strict analytical solutions can be derived from the principle of heat transfer [42], the derivation process is complicated, and the resulting expression is not very practical due to the need for many assumptions. Therefore, this paper establishes the expression of the surrounding rock temperature field and provides a fitting empirical formula based on the numerical simulation test results and the use perspective. Surrounding rock temperature is related to tunnel depth, time, and radial depth of surrounding rock, which is a four-dimensional problem. Moreover, surrounding rock temperature is closely related to ambient temperature. Furthermore, to simplify calculations, this paper has initially eliminated the variable of tunnel depth and instead established the relationship between surrounding rock temperature and ambient temperature.

As seen from Fig. 5, the surrounding rock temperature within a certain radial depth also presents a sinusoidal function, so the surrounding rock temperature field can also be described by Eq. (7).

$$T_m = T_0 + A_0 \sin\left[\frac{2\pi\left(t-t_0\right)}{12}\right] \tag{7}$$

where, T_m is the temperature of a section. T_0 is the average temperature. A_0 is amplitude; t is the month. t_0 is the phase.

The analysis in this study focused on the surrounding rock temperature field at a particular section. Table 4 presents the correlation between the average surrounding rock temperature, amplitude, and radial depth, whereas Fig. 13 clearly depicts their relationship.

Fig. 13 indicates a certain relationship between the annual average temperature and amplitude of the surrounding rock and its radial depth. The literature also pointed out that the annual temperature amplitude decreases exponentially with the radial depth of surrounding rock [43]. Once a certain depth is reached, the amplitude approaches zero and the average temperature of the surrounding rock exhibits a logarithmic shift.

$$A_w = a\exp\left(bx\right) \tag{8}$$

$$T_w = c\ln x + d \tag{9}$$

where, a, b, c, d are the fitting values, which are 26.45, 0.63, 0.41, 1.29, respectively. x is the radial depth of surrounding rock. A_w is the annual temperature amplitude. T_w is the average temperature of surrounding rock. Substituting Eqs. (8) and (9) into Eq. (10), then:

$$T_w = a\,exp\left(bx\right) + \left(c\,ln\,x + d\right) sin\left[\frac{2\pi\left(t - t_0\right)}{12}\right] \qquad (10)$$

where, T_w is the variation law of surrounding rock temperature with radial depth and time at a certain section. t_0 is the temperature lunar phase of surrounding rock.

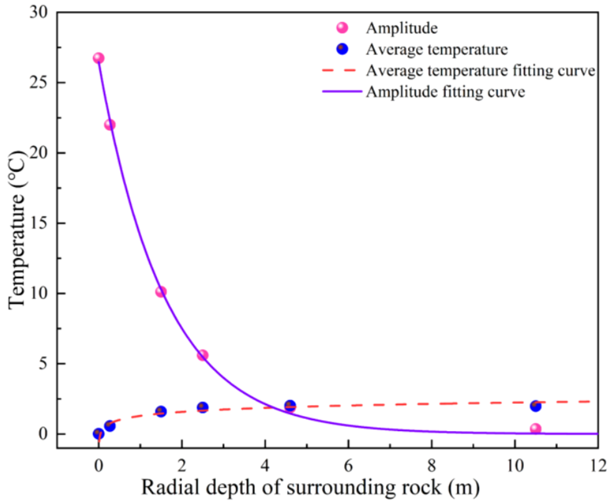


Fig. 13. Amplitude and average temperature of surrounding rock.

Table 4. Amplitude and average temperature varying with radial depth.

Probe measuring points	1	2	3	4	5	6
Radial depth of surrounding rock (m)	0	0.27	1.5	2.5	4.6	10.5
Amplitude (°C)	26.74	22	10.12	5.6	1.88	0.36
Average temperature (°C)	0.02	0.57	1.6	1.89	2.02	1.98

5. Conclusions

The distribution law of radial temperature field of tunnel in cold region with high altitude was analyzed, and the influence of meteorological condition on temperature field of tunnel was studied according to the recently developed model for analyzing temperature field considering phase change. The main conclusions are obtained as follows:

(1) The simulation results confirm the critical role of the latent heat associated with phase change in accurately calculating the temperature field in cold region tunnels.

(2) The freezing depth of the surrounding rock is significantly impacted by the average annual temperature. In particular, when the average annual temperature falls below 0°C, the overburden layer above the tunnel completely freezes. However, when the average annual temperature rises above 0°C, the freezing depth of the surrounding rock surrounding the tunnel varies cyclically.

(3) The change of annual average temperature and annual temperature amplitude has less effect on the lining and more on the surrounding rock. The minimum temperature of lining and surrounding rock decreases with the decrease of annual average temperature and increases with the decrease of annual temperature amplitude.

The influence of the external temperature of tunnel surrounding rock on the temperature field in cold regions is not only limited to the radial direction, but also extends to the longitudinal direction. It is imperative to conduct extensive research on the longitudinal temperature field. Through the establishment of a three-dimensional numerical calculation model for tunnels in cold regions, the effects of changes in the external temperature on the radial and axial temperature fields of the surrounding rock can be analyzed. So, based on the characteristics of temperature distribution, the appropriate insulation measures can be proposed.

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