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Analysis on the laying method and thermal insulation effect of tunnel insulation layer in high-altitude cold regions

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Abstract

To mitigate freeze-thaw damage in tunnels located in high-altitude cold regions, insulation layers are implemented to prevent the freezing of surrounding rocks. Currently, the selection of laying methods lacks a solid scientific basis, with the merits and demerits of various techniques remaining insufficiently evaluated. This study seeks to establish a scientifically grounded equilibrium between the anti-freezing efficacy and the construction impact of tunnel insulation in cold regions through the optimization of insulation design via numerical calculations. First, the advantages and disadvantages of the four insulation layer laying methods were summarized. Then, a multilayer media heat transfer model that accounts for the latent heat of phase change was developed, grounded in solid heat transfer and porous media heat transfer theories, and corroborated by typical case studies. Finally, taking Duolong tunnel as a case study, the insulation effect of various laying methods at different positions of the tunnel was analyzed based on the finite element method. The results show that the unfavorable position of the four laying methods is at the inverted arch of the tunnel, and the unfavorable time point occurs when the temperature rises from below 0℃ to above 0℃. Among the four laying methods, off-wall laying exhibits the superior insulation performance at tunnel vault, while sandwich laying has best insulation effect at the arch foot and inverted arch. The research results can provide reference and basis for thermal insulation and anti-freezing design of tunnels in high-altitude cold regions.

Keywords

Tunnels in high-altitude cold regions, Insulation layer, Laying method, multi-layer medium heat transfer model

1. Introduction

In high-altitude cold regions, the temperature variations due to seasonal variations and day and night cycles can greatly affect the construction and the stability of tunnel projects. In cold seasons, water in the soil pores freezes into ice, expanding by about 9% in volume and resulting in frost heave (Wu et al. 2021; Lai et al. 2014). In warm seasons, as the ice thaws and soil shear strength weaken, thaw settlement occurs (Xu et al. 2015). These freezing and thawing actions cause engineering problems, including cracking and settlement of pavements, damage to canals, and fracture and leakage of tunnels. (Yu et al. 2017; Wan et al. 2017). These frost damages frequently occur in many railway and highway tunnels in various cold regions (Zhao et al. 2020), thus significantly impacting the normal operation of the tunnels (Luo et al. 2017; Wu et al. 2020). In China, 52.4% of railway tunnels experienced frost damage (Tan et al. 2012).

Numerous engineering practices demonstrate that the freezing damage in tunnels is mainly the problem of waterproof and drainage and thermal insulation (Tan et al. 2018). Considering the low temperature conditions causing tunnel diseases in cold regions, implementing measures like installing suitable insulation layers, configuring electric heating system, setting cold-proof insulation door, ventilating and heating the tunnel, and using air-source heat pump or water-source heat pump are taken to improve the temperature inside the tunnel. Alternatively, maintain the temperature behind the lining above 0℃ and narrow the freezing circle, preventing serious freezing of water in the surrounding rock and initial lining (Zhang et al. 2013; Holter et al. 2016). For example, Heat preservation center ditch and GSHP system were used in Linchang tunnel (Zhang et al. 2014). Antifreeze thermal insulation layer was used in Dabanshan tunnel (Lai et al. 2013). EHT system was used in Dongnanli tunnel (Lai et al. 2016).

Laying the insulation layer on the tunnel lining structure is a simple and effective measure in high-altitude cold regions (Broch et al. 2002; Chen et al. 2001). The insulation material's low thermal conductivity effectively blocks heat transmission from the tunnel to the surrounding rock, so as to keep the surrounding rock behind the lining in its original state and prevent the freeze-thaw damage of the surrounding rock. Scholars at home and abroad have carried out a series of studies on tunnel insulation technology in cold regions. Li et al. (2021) conducted a case study on the Guigala Tunnel, developing a thermal-fluid-solid coupling model for tunnels in seasonally frozen soil, to analyze the insulation effect and optimize the structure of the current insulation measures. Yao et al. (2015) employed the finite element software to investigate the temperature fluctuations under diverse tunnel insulation layer laying methods and utilized a fuzzy comprehensive evaluation method to assess the insulation materials. Zhou et al. (2014) developed a mathematical optimization model for the insulation layer's parameters, grounded in the characteristics of seasonally frozen soil and optimization theory. Fan et al. (2014) investigated the efficacy of various laying methods for tunnel thermal insulation layers across different types of frozen soil, concluding that off-wall laying in non-frozen soil offers the most effective anti-freezing performance. In cases where off-wall laying is impractical, surface laying (applying the insulation layer to the surface of the secondary lining) demonstrates superior anti-freezing properties compared to sandwich laying, which involves positioning the insulation layer between the initial and secondary linings. Tan et al. (2013) performed a numerical simulation on a Tibetan tunnel, evaluating the function of thermal insulation materials, and determined that a 6cm-thick polyphenolic insulation layer is sufficient to protect the lining and surrounding rock from freeze-thaw damage. Ma et al. (2018) investigated the thermal insulation efficacy of both surface and sandwich laying methods, establishing a correlation between the insulation performance, and the thermal conductivity and thickness of the insulation material. Li et al. (2017) formulated a coupled heat-water model for tunnels in cold regions based on the principles of energy and mass conservation and ascertained the optimal thickness for the thermal insulation layer in permafrost tunnels via simulation of the heat-water interaction. Zhao et al. (2021) introduced a simplified one-dimensional tunnel model that accounts for convective and radial heat transfer between the air and the surrounding rock, utilizing COMSOL to simulate the insulation layer's impact. Kang et al. (2020) created a two-dimensional axisymmetric model incorporating convection-conduction coupling and conducted a numerical simulation of the temperature field of airflow in a high-temperature tunnel with an insulation layer, employing COMSOL software. The research primarily concentrates on one or several laying techniques of tunnel insulation layer, without conducting a comprehensive analysis of the four existing laying techniques. Concurrently, there are scarce reports on the insulation effects of diverse laying techniques at varying positions.

In view of this, this study aims to develop a multi-layered medium heat transfer model that incorporates phase transitions, drawing on the principles of porous medium and solid-state heat transfer theories. Subsequently, the finite element method (COMSOL Multiphysics) is employed to conduct a systematic investigation of four insulation layer laying techniques for tunnels in high-altitude cold regions, aiming to identify the critical periods and locations where insulation is least effective, corresponding to the various laying techniques, and to analyze the efficacy of the insulation provided by each technique at varying tunnel positions. Finally, based on the above research, the optimized scheme of tunnel insulation design in high-altitude cold regions is proposed. The research results can provide reference and basis for thermal insulation and anti-freezing design of tunnels in high-altitude cold regions.

2. Function and laying method of tunnel insulation layer in high-altitude cold regions.

2.1 Functions of tunnel insulation layer

Typically, the entrance sections at both ends of tunnels in high-altitude cold regions are situated within seasonally frozen soil, while the main body of the tunnel traverses' non-frozen soil, as illustrated in Fig. 1.

1) The role of the thermal insulation layer in shallow-buried entrance section in seasonally frozen soil

The lower boundary of seasonally frozen soil typically extends to a depth of several meters beneath the surface. Prior to tunnel construction, during the colder autumn and winter months, the soil loses heat to the surface and progressively freeze. As time progresses, the external temperature incrementally rises, causing the frozen soil to absorb external heat, slowly thaw, and eventually fully melt by summer, thereby establishing a cyclical freeze-thaw pattern (Liu et al., 2019).

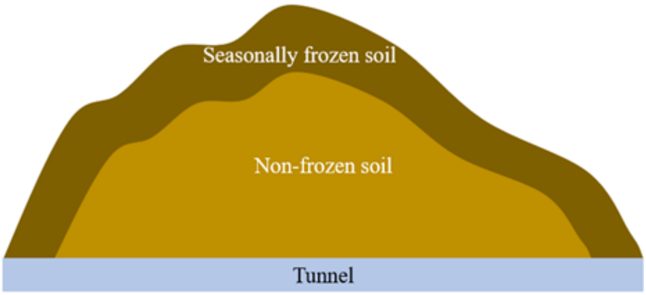


Fig. 1 Tunnel crossing seasonally frozen soil and non-frozen soil.

Following the construction of the tunnel, the interface between seasonally frozen soil and the external atmosphere increases from a single surface to a dual-surface configuration. The freeze-thaw cycle of the surrounding rock within the seasonally frozen soil proceeds as follows. In winter, the temperature both at the surface and within the tunnel progressively declines, leading to the dissipation of heat from the soil mass to both the surface and the tunnel's interior. The previously thawed soil mass begins to freeze, progressing from both the surface towards the tunnel's interior and vice versa. In summer, as temperature rises both at the surface and within the tunnel, the once fully frozen soil starts to thaw, again in both directions from the surface inward and from the tunnel outward. This process establishes a periodic freeze-thaw cycle. Throughout this cycle, the tunnel lining is subjected to repeated stress from the frost heave forces arising within the freeze-thaw cycle of the seasonally frozen soil (Lv et al. 2019).

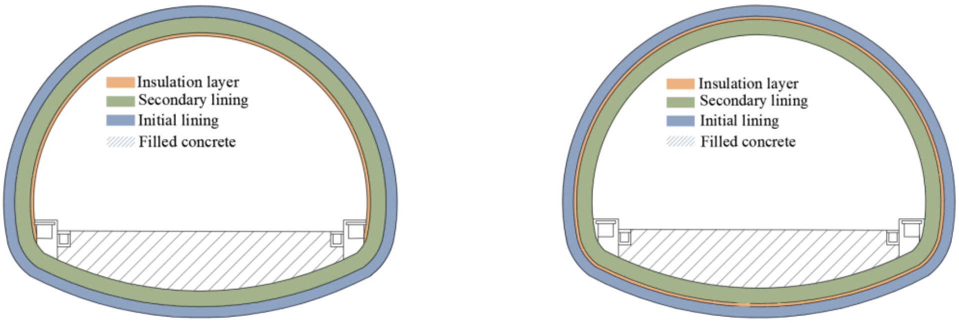
After the tunnel is laid with thermal insulation layer, although the thermal insulation layer can prevent the loss of heat from the surrounding rock to the tunnel, it cannot prevent the loss of heat from the surrounding rock to the surface. In the winter, as the atmospheric temperature progressively decreases, the seasonally frozen soil inexorably transitions to a fully frozen state. Conversely, the presence of the thermal insulation layer does not obstruct the influx of heat from the surface to the surrounding rock. Consequently, with the advent of warmer conditions, the seasonally frozen soil inevitably undergoes a complete thaw. It follows that for shallowly buried tunnel entrances situated within seasonally frozen soil, the implementation of an internal thermal insulation layer is insufficient to forestall the natural occurrence of a periodic freeze-thaw cycle. As a result, the tunnel lining is compelled to endure the cyclical frost heave forces engendered by these thermal oscillations within the seasonally frozen soil.

2) The role of the thermal insulation layer for non-frozen soil section

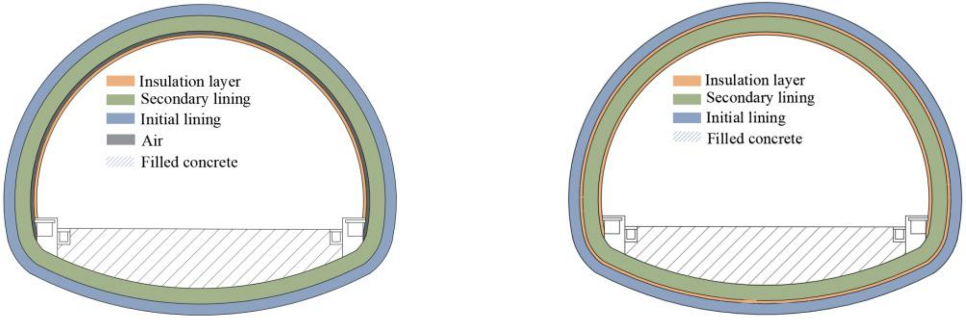
In regions characterized by seasonal freezing, the annual mean temperature exceeds 0℃, resulting in the surrounding rock absorbing more heat annually than it dissipates. Consequently, over time, the surrounding rock undergoes multiple freeze-thaw cycles without the formation of persistent permafrost. Under these circumstances, the insulation layer serves to inhibit the thermal energy transfer from the surrounding rock to the tunnel interior, and to protect the surrounding rock as well as the waterproofing and drainage systems from winter freeze, thereby maintaining a perennially unfrozen condition.

2.2 Laying methods of thermal insulation layer for tunnels in cold regions

Currently, four principal structural configurations for tunnel insulation layers are recognized in cold regions, both domestically and internationally. These include (1) surface laying, wherein the insulation layer is affixed to the inner surface of the secondary lining, as shown in Fig. 2(a); (2) sandwich laying, whereby the insulation layer is positioned between the initial lining and the secondary lining, as shown in Fig. 2(b); (3) off-wall laying, involving the creation of an air gap between the insulation layer and the inner surface of the second lining, as shown in Fig. 2(c)(Cui et al. 2021); and (4) double-layer laying, consisting of one insulation layer inserted between the initial lining and the second lining, and the other affixed to the inner surface of the second lining, as shown in Fig. 2(d). Each of these four methods possesses distinct advantages and disadvantages. Qualitative methods are employed to compare and analyze the advantages and disadvantages of each laying method, as shown in Table 1. (Yao et ai. 2015; Wang et al. 2020; Xia et al. 2013)



(a) Surface laying (b) Sandwich laying



(c) Off-wall laying (d) Double-layer laying.

Fig. 2 Laying methods of thermal insulation layer for tunnels in cold regions

Table. 1 Comparison of different laying methods of tunnel insulation layer in cold regions

	Surface laying	Sandwich laying	Off-wall laying	Double-layer laying
Advantages	Ensure that the secondary lining concrete above the arch foot is not frozen; Easy to install, maintain and replace; The insulation layer is not stressed, and the insulation effect can be ensured.	Ensure that the initial lining concrete is not frozen; Acts as a buffer layer to relieve the force acting on the secondary lining.	Ensure that the secondary lining concrete above the arch foot is not frozen; Easy to maintain and replace; The insulation layer is not stressed, and the insulation effect can be ensured. Sealed air enhances the insulation effect.	Ensure that the secondary lining concrete above the arch foot is not frozen; Acts as a buffer layer to relieve the force acting on the secondary lining.
Disadvantages	The concrete at the inverted arch is vulnerable to freeze-thaw damage; High requirements for fireproof.	The secondary lining concrete is vulnerable to freeze-thaw damage; Difficult to maintain and replace; Likely to retain ponding space.	Complex construction; High cost; High requirements for fireproof.	Difficult to maintain and replace; Likely to retain ponding space.

3. Numerical analysis method of thermal insulation effect of tunnel insulation layer in high-altitude cold regions

3.1 Model building

After tunnel excavation, thermal exchange occurs between the surrounding rock and the tunnel interior, attributable to the lower internal tunnel temperature relative to the surrounding rock in cold regions. After the initial lining of shotcrete, the secondary lining of formwork concrete and the laying of insulation layer, the influences of tunnel linings, inverted arch backfilling and insulation layer on the radial heat transfer of the tunnel should also be considered. Consequently, it is necessary to develop a multi-layer medium heat transfer model to analyze the thermal insulation effect of tunnel insulation layer in cold regions. The analytical model can clearly demonstrate the heat transfer process among the media layers, but it fails to accurately represent the actual tunnel structure. In addition, the calculation is complex, and it needs to clarify whether the tunnel is shallow-buried or deep-buried before calculation. Meanwhile, the analytical model disregards the alterations in the ice-water phase transition state and latent hear released by phase transition, which is paramount in the temperature field analysis of tunnels in cold regions. To derive the numerical solution for the tunnel lining and temperature field, the following simplifications and assumptions are posited. (1) The surrounding rock, lining, insulation layer and pavement are homogeneous and isotropic materials; (2) The porosity within surrounding rock remains constant and is unaffected by temperature and spatial variations; (3) The interface between lining and surrounding rock is assumed to be ideal, with contact thermal resistance being neglected; (4) The rock mass is saturated, and the influence of air is not considered; (5) The secondary lining, initial lining and pavement are composed of a material skeleton, with moisture content being disregarded.

When the external temperature descends below 0°C, the water in the rock mass freezes into ice and releases heat. As the temperature continues to diminish, the freezing depth of surrounding rock gradually increases. The latent heat associated with this phase transition must be accounted for. According to the principles of porous media and thermodynamics, the governing equation for heat conduction in low-temperature rock mass is delineated as follows (Harlan et al.1973; Jame et al. 1980; Zhou et al. 2016),

$$(\rho C)_{eff}\frac{\partial T_1}{\partial t}+\rho_l L\frac{\partial \theta_i}{\partial t}=\nabla(k_{eff}\nabla T_1) \qquad (1)$$

Where $(\rho C)_{eff}$ is the equivalent heat capacity (J/(m3·K)), T_1 refers to temperature of surrounding rocks (K), ρ is density (kg/m3), L refers to the latent heat released when water per unit mass turns into ice, k_{eff} refers to equivalent thermal conductivity (W/(m·K)), θ is the volume content, and s,l,i represent rock mass skeleton, water and ice respectively.

The equivalent heat capacity $(\rho C)_{eff}$ indicates the heat required for the temperature of unit volume medium to change by 1°C. For low-temperature rock mass, the equivalent heat capacity is expressed by the volume weighted average, namely:

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

The equivalent thermal conductivity refers to the heat passing through the medium per unit area in unit time at each unit temperature (Pei et al. 2013). In this paper, the volume weighted average is used to express the equivalent heat conductivity, namely:

$$k_{eff}=(\theta_s k_s+\theta_l k_l+\theta_i k_i) \qquad (3)$$

As assumed, the insulation layer, secondary lining, initial lining, and pavement consist of a material matrix devoid of moisture content, precluding the consideration of phase transitions; thus, the heat transfer within these components is characterized as solid medium conduction. In accordance with thermodynamic principles, the governing equation for the heat conduction in a low-temperature solid medium is delineated as:

$$\rho_m C_m\frac{\partial T_2}{\partial t}=\nabla(k_m\nabla T_2) \qquad (4)$$

where T_2 refers to temperature of non-phase change material (K), m represents non-phase change material.

To compute the temporal evolution of the temperature distribution, from the heat transfer differential Equations (1) and (4), it is imperative to ascertain the specific solution conditions for these equations, namely, the boundary and initial conditions of the object (that is, the initial temperature distribution or the initial temperature field).

As the heat transfer of surrounding rock considering phase change is a strongly nonlinear problem, it is impossible to obtain an accurate solution by analytical method. COMSOL Multiphysics is a numerical simulation software based on finite elements, which has a strong ability to solve strongly nonlinear differential equations. Utilizing the multi-layered medium heat transfer model previously established, a numerical analysis methodology is developed to assess the thermal insulation efficacy of tunnel insulation layers in high-altitude cold regions. The specific procedural implementation of this methodology is delineated as follows. (1) Select porous media for heat transfer and physical field of solid heat transfer; (2) Establish the finite element model; (3) Set the basic physical parameters of ice, water, insulation layer and concrete (primary support concrete and secondary lining concrete), and assign them to the finite element model; (4) Add boundary conditions and set the initial temperature field for transient analysis; (5) Generate the mesh; and (6) Set the calculation time and seek the solution. The flowchart is shown in Fig. 3.

3.2 Model validation

Smith et al. (1989) observed and analyzed the temperature field of silty soil around gas transmission pipelines in cold regions by means of model tests. Both transmission pipes and tunnels in cold regions represent heat transfer under low-temperature conditions. Considering the typicality of this example, a finite element analysis of the freezing phenomena observed in the Smith model test was carried out using the porous medium heat transfer model developed in this paper and compared with the actual measured values of the temperature field around the gas transmission pipeline.

The schematic of the Smith model test is shown in Fig. 4. In this paper, half of the model test is selected as the soil calculation area, with a width of 2m and a height of 1.5m. The gas transmission pipeline is 273mm in diameter and buried to a depth of 0.43m. The initial soil temperature is set at 4°C, with a porosity of 38%. The temperature along the pipeline segment BCD is maintained at -5°C, while the surface segment AG is held at -0.75°C. The values for the remaining principal calculated physical parameters are listed in table 2.

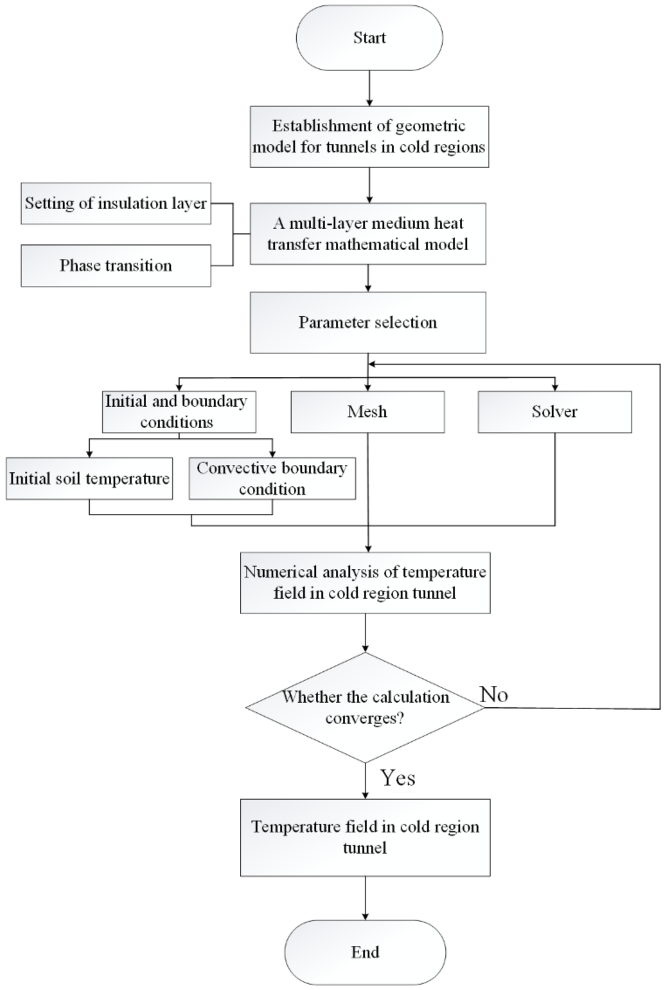


Fig.3 Numerical simulation flowchart

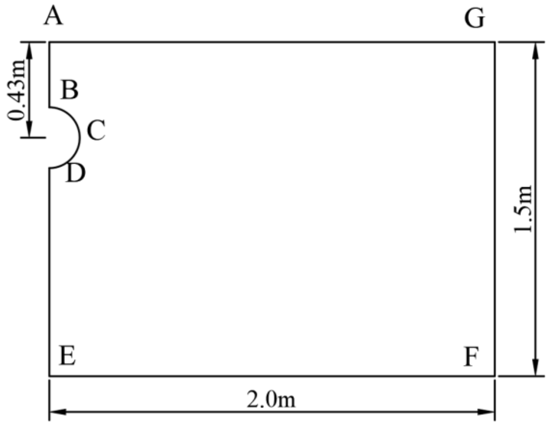
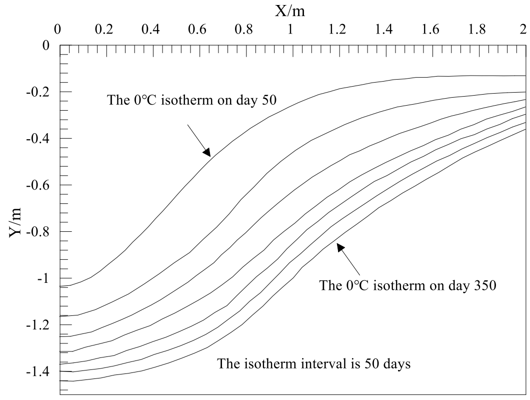


Fig.4 Smith model test

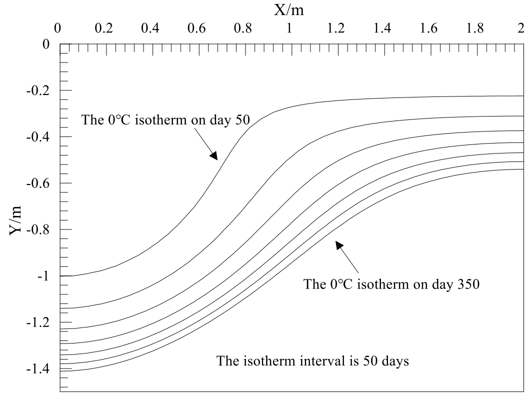
Table.2 Physical parameters in Smith model

Materials	Heat conductivity coefficient $\lambda/(W/(m\cdot K))$	Specific heat capacity $C/(J/(kg\cdot K))$	Density $\rho/(kg/m3)$
Ice	2.14	2100	917
Water	0.56	4180	1000
Silty soil	1.7	900	2650

Smith's study yielded 0°C isotherms at various intervals around the gas transmission pipeline, as depicted in Fig. 5(a). Corresponding 0°C isotherms, generated by the computational model presented in this paper under identical conditions, are illustrated in Fig. 5(b). A comparison of Fig. 5(a) and 5(b) reveals that the temperature field simulated with COMSOL closely mirrors the empirically measured temperature field, both in spatial distribution and numerical values. The freezing depth measured by Smith reached 139cm after 350d, and the freezing depth obtained by numerical calculation was 141cm after 350d, with an error of only 1.43%. Consequently, the numerical model established herein demonstrates a high degree of reliability.



(a) Smith model test



(b) Numerical simulation

Fig.5 0℃ isotherms at different times

4. Engineering case and numerical calculation model

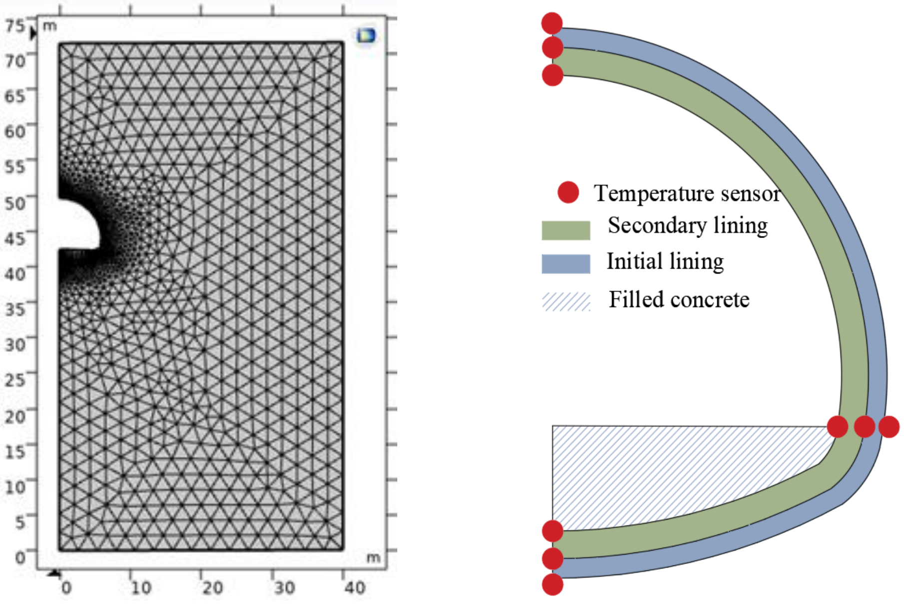
4.1 Engineering case

The Duolong Tunnel, extending from Panpo through Datongheqiao to Reshui along National Highway 338, serves as the engineering case study. Situated in the eastern reaches of the Qilian Mountains, at the northeastern edge of the Qinghai-Tibet Plateau within the mid-latitude westerly belt, the tunnel is subject to a plateau continental climate. The region's climate, influenced by Siberia's arid and frigid conditions, manifests as cold and dry winters. The area is characterized by scant precipitation, significant evaporation, substantial diurnal temperature variations, and lacks an absolute frost-free season. The annual average temperature is 0.8°C, and the extreme maximum and minimum temperature is 27.9°C and -25.8°C respectively. Annual sunshine duration ranges from 2264.8 to 2739.8 hours, while solar radiation is measured between 130.68 and 154.0 kcal/cm².

4.2 Numerical calculation model

The tunnel section at K41+780 is selected for computational analysis. Due to the symmetry of the tunnel section, the right half tunnel is taken for research and analysis. The arch vault is situated 21m from the upper boundary, while the arch bottom is 40m from the lower boundary, with the model spanning 40m in wide. The initial lining of concrete is 30cm thick, and the secondary lining is 50cm thick. The model is shown in Fig. 6. The grid division is shown in Fig.6(a), and the grid type is free-form triangular grid. Based on the grid independence verification, the model was discretized into 5300 elements, with the largest measuring 2.65 m and the smallest 0.009 m. The initial temperature of surrounding rock is 2°C. In the model, AG and ED represent symmetrical boundaries, BC is designated as a thermal insulation boundary, and DC is defined as a flow boundary with a heat flux of $\vec{q}$=3.33W⁄m2. AB and GFE take the convection boundary, and the convection heat transfer coefficient between air and surrounding rock and lining is h=15W⁄(m^2·K). According to the data of local meteorological records, the air temperature in the area where the Duolong Tunnel is located is fitted according to the sine function, and the fitting formula is shown in Equation (5). The physical parameters of concrete, surrounding rock and insulation layer are obtained from field measurement, and their main physical parameters are shown in Table 3. The backward difference equation was employed for this simulation with a time step of 0. 001d.

$$T = 0.8 + 22\sin\left(\frac{2\pi}{365}t\right) \quad (5)$$



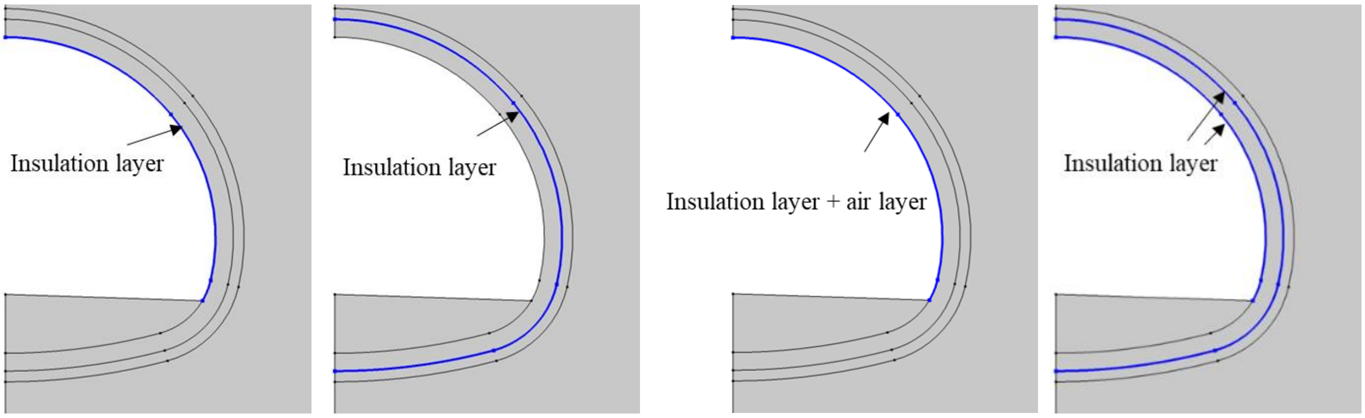
(a) Finite element calculation model mesh (b) Temperature sensor

Fig. 6 Numerical calculation model

Table 3 Main parameters for model calculation

Materials	Heat conductivity coefficient $\lambda/(\mathrm{W}/(\mathrm{m}\cdot\mathrm{K}))$	Specific heat capacity $C/(\mathrm{J}/(\mathrm{kg}\cdot\mathrm{K}))$	Density $\rho/(\mathrm{kg}/\mathrm{m}^3)$	Porosity
Ice	2.14	2100	917	
Water	0.56	4180	1000	
Surrounding rock	3.00	850	2530	0.3
Concrete	1.74	970	2400	
Insulation layer	0.027	5000	40	

Fig. 7 shows the partial schematic diagram of four distinct laying methods of the thermal insulation layer. Specifically, the surface laying method is to lay insulation layer onto the surface of the second lining from the arch vault to the arch foot, and the sandwich laying method is to lay insulation layer along the whole ring of the tunnel between the initial lining and the secondary lining.



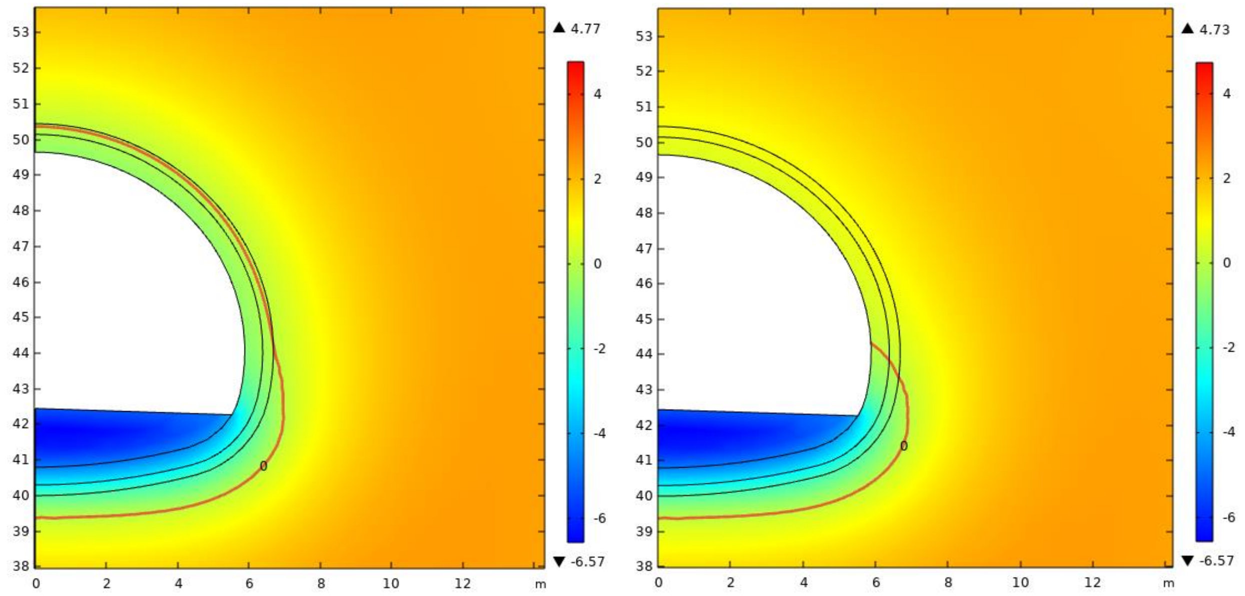
(a) Surface laying (b) Sandwich laying (c) Off-wall laying (d) Double-layer laying

Fig. 7 Schematic diagram of varied laying methods of tunnel insulation layer in cold regions

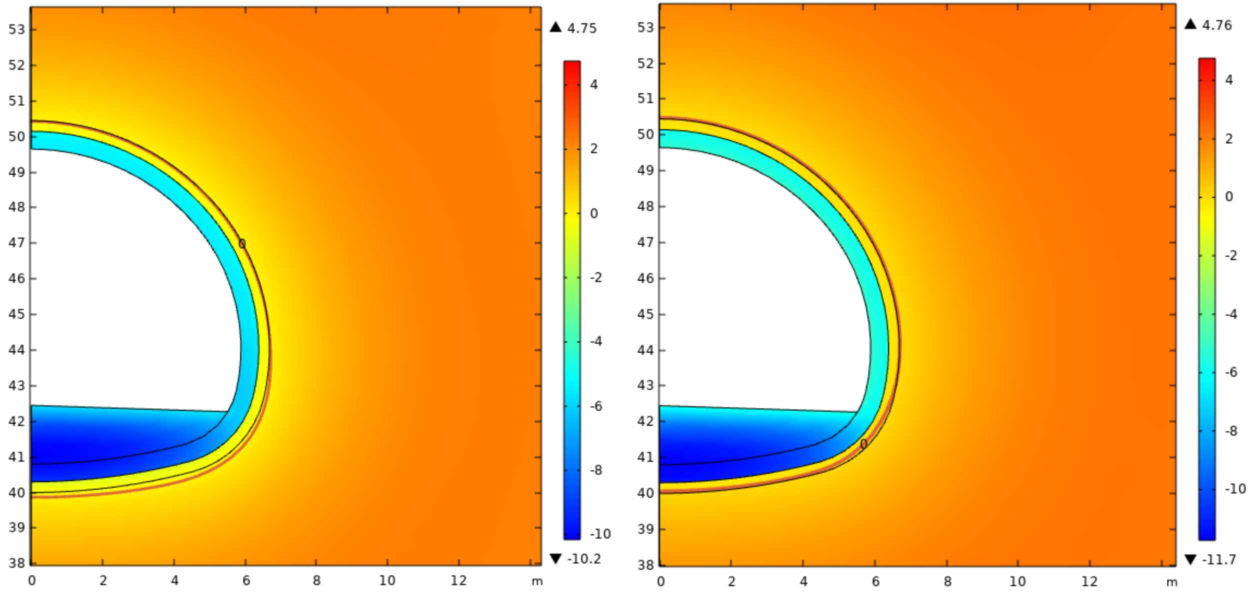
5. Analysis of thermal insulation effect of tunnel insulation layer in high-altitude cold regions

5.1 Unfavorable positions of thermal insulation

During tunnel construction in cold regions, the tunnel section is exposed to a low-temperature environment, with the freeze-thaw state of the surrounding rock being affected by the ambient air temperature. Given that the cross-section is non-circular, and the inverted arch is filled with concrete, the degree of freezing varies at different positions within the tunnel. Consequently, the most susceptible location to freezing is designated as the unfavorable position. Fig. 8 shows the temperature field distribution cloud map of typical cross-section of Duolong Tunnel after 350 days, under four distinct insulation layer laying methods. The Fig. 8 reveals significant variations in the 0°C isotherms corresponding to the different insulation layer installation methods. Specifically, the surface laying method (Fig. 8(a)) and the off wall laying method (Fig. 8(b)) involve the placement of the insulation layer above the arch foot, resulting in isotherms above the arch foot that fall within the lining range, and an extensive isotherm range at the inverted arch, indicating a higher susceptibility to freeze damage. This implies that the inverted arch is the unfavorable position of thermal insulation for surface laying method and off-wall laying method. The double-layer laying method (Fig. 8(c)) is to lay the insulation layer above the arch foot for the outer layer. Clearly, there is a larger range of 0°C isotherm at the inverted arch, which is an unfavorable position. The sandwich laying method (Fig. 8(d)) is to lay the insulation layer between the initial lining and the second lining, uniquely positioning the insulation layer beneath the arch foot, in contrast to the other three methods. According to Fig. 8(d), the 0°C isotherm closely aligns with the contour of the tunnel lining, indicating the absence of a discernible unfavorable position. Thus, the inverted arch is identified as the unfavorable position for thermal insulation across all four laying methods.



(a) Surface laying (b) Off-wall laying



(c) Sandwich laying (d) Double-layer laying

Fig. 8 Unfavorable positions of thermal insulation for various laying method

5.2 Unfavorable times of thermal insulation

Air temperature undergoes periodic fluctuations in a sinusoidal pattern, influencing the thermal state of the surrounding rock and consequently inducing a corresponding periodic variation in the rock temperature. The time when the unfavorable position reaches the minimum temperature is determined according to the freeze-thaw process of surrounding rock, and it is defined as the unfavorable time. Fig. 9 shows the decadal temperature variations at the unfavorable positions (the interface between inverted arch and surrounding rock) of four various laying methods. The temperature at the unfavorable position of the four laying methods begins to change periodically after the second year, because the temperature distribution in the first year calculated by numerical simulation is affected by the initial value. In winter, the temperatures inside tunnels in cold regions drop below 0°C, and the cooling capacity is transferred to the depth of the surrounding rock. As temperatures rise, the transferred cooling capacity diminishes progressively. Theoretically, the temperature at the unfavorable position is the lowest when the temperature rises to above 0°C. As illustrated in Fig. 6, the unfavorable time for double-layer and sandwich laying methods aligns with the instance when ambient temperatures exceed 0°C in the second year, whereas for the surface and off-wall laying methods, this occurs approximately 10 days prior to the ambient temperature surpassing 0°C. Sharing the same structure above the inverted arch, both the surface and off-wall laying methods omit the placement of the insulation layer at the inverted arch. Conversely, double-layer and sandwich laying methods involve laying the insulation layer between the inverted arch and the primary lining, which results in a lag in heat transfer and consequently delays the onset of the unfavorable time by approximately 10 days.

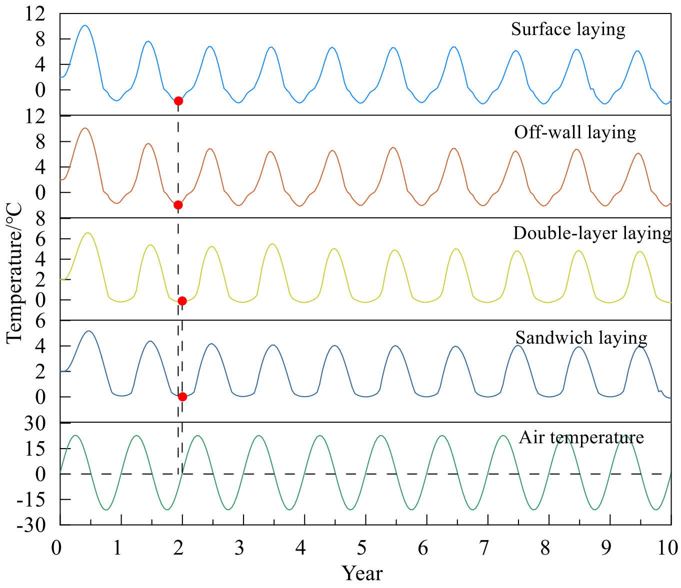


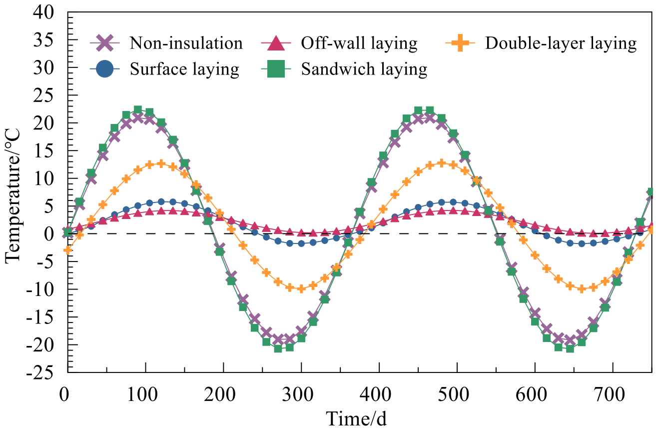
Fig. 9 The 10-year temperature change at unfavorable positions of thermal insulation for four laying methods

5.3 Analysis of insulation effect under different insulation layer laying

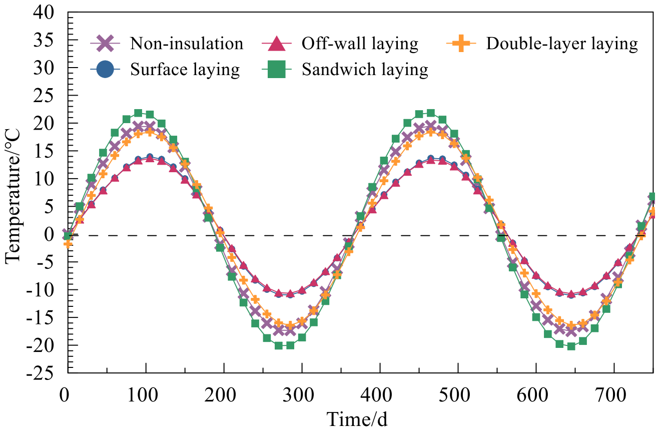
The primary function of the insulation layer is to maintain the surrounding rock and lining in a non-freezing state, thereby averting freeze-thaw damage to both. Drawing upon the established conclusions regarding the unfavorable time, we conduct an analysis of temperature variations at the secondary lining surface (vault, arch foot), as well as in the interstitial spaces between the secondary lining and the initial lining (vault, arch foot, inverted arch), and between the initial lining and the surrounding rock (vault, arch foot, inverted arch) at a model calculation time of 740 days. This analysis facilitates a comparative assessment of the thermal insulation efficacy of the four insulation layer laying methods.

Variation law of secondary lining surface temperature

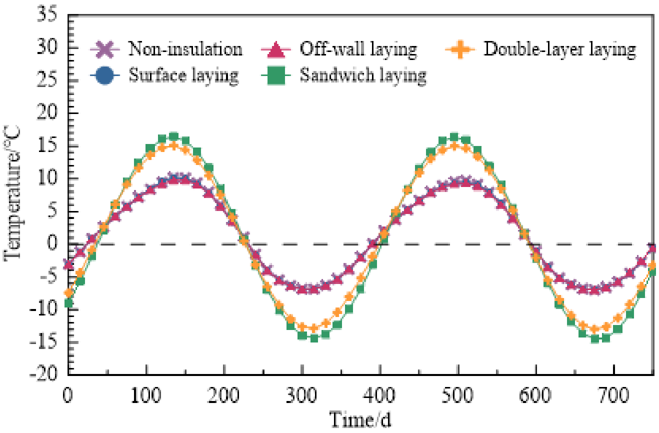
Figure 10 shows the temperature change with time at the vault, arch foot, and inverted arch of the secondary lining surface. According to Fig. 10 (a), when the surface laying and off-wall laying methods are used for insulation layer, the minimum temperature of the vault on the surface of the secondary lining is -1.74℃ and 0.06℃ respectively, so these two laying methods can play an obvious role in insulation of the secondary lining. The off-wall laying method incorporates a 10cm-thick sealed air layer between the insulation layer and the secondary lining surface, enhancing its insulative performance. An insulation layer positioned between the secondary and initial linings impedes the transfer of cooling capacity from the former to the latter, culminating in a reduced temperature at the secondary lining surface (lacking an insulation layer) compared to scenarios without such an insulation layer. Fig. 10 (b) shows the temperature dynamics at the arch foot of the secondary lining surface, with the pattern of variation mirroring that observed at the arch vault. However, when using the surface laying and off-wall laying methods, the arch foot's minimum temperature on the secondary lining surface registers at -10.95℃ and -10.64℃, respectively, substantially lower than that at the arch vault. Although the surface of the second lining at arch foot is laid with an insulation layer, the filled pavement is not insulated, resulting in the transmission of cooling capacity from the pavement to the arch foot and causing the failure to achieve thermal insulation effect at the arch foot. As to the inverted arch, surface laying and off-wall laying methods do not contribute to thermal insulation, whereas the sandwich and double-layer laying methods, by reducing the temperature, inadvertently exert a detrimental effect on thermal insulation.



(a) Vault



(b) Arch foot



(c) Inverted arch

Fig. 10 Change of secondary lining surface temperature with time

Temperature variation law between secondary lining and primary support

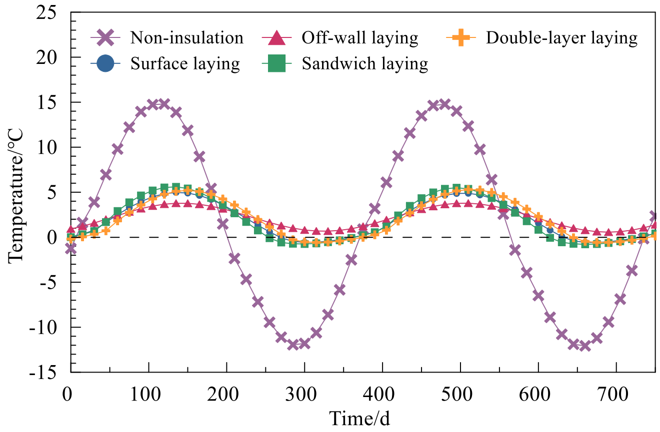
Figure 11 shows the temperature change with time between secondary lining and initial lining at the vault, arch foot and inverted arch. With the off wall laying method, the interstitial temperature between the initial and secondary linings at the vault remains above 0℃ (as shown in Fig. 11(a)), in contrast to the sub-zero temperatures observed with the other three laying techniques. According to Fig. 11(b), all four insulation laying methods result in negative temperatures at the arch foot between the initial and secondary linings: -2.93℃ for surface laying, -2.67℃ for off-wall laying, -0.63℃ for sandwich laying, and -0.95℃ for double-layer laying. This discrepancy arises because the insulation layer extends along the entire tunnel ring for sandwich and double-layer laying methods, whereas for surface and off-wall laying, the insulation is applied solely from the vault to the arch foot. The temperature change law at the inverted arch (Fig. 11 (c)) is the same as that at the arch foot, and the surface laying and the off wall laying methods failing to contribute to thermal insulation.

Temperature variation law between initial lining and surrounding rock

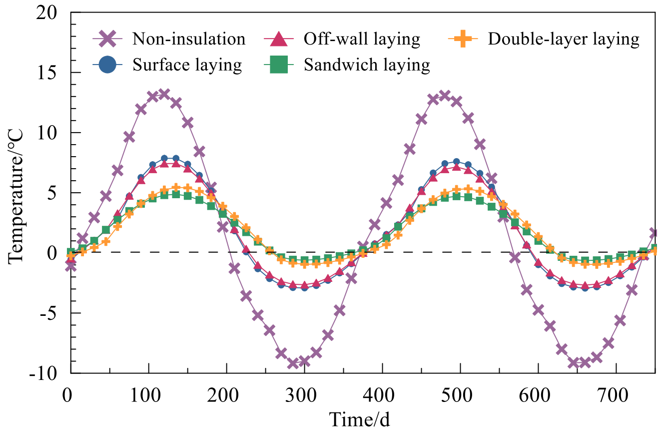
As can be seen from Fig.12, the temperature variation between the initial lining and the surrounding rock is roughly a sine function distribution when using the four laying methods. In Fig. 12(a), the temperature between the initial lining and the surrounding rock at the vault is positive. The minimum positive temperature was 0.63℃ and the vault was not damaged by freezing. It can be seen from Fig. 12(b) that when the laying mode of insulation layer is set as double-layer laying, the temperature between the initial lining and surrounding rock arch foot is above 0℃, and the minimum positive temperature is 0.35℃. The temperature of the other three ways is fluctuating around 0℃, which cannot guarantee that arch foot is free from freezing damage. As can be seen from Fig. 12(c), the employment of sandwich laying maintains the temperature of the inverted arch above the freezing threshold, effectively protecting the invert from freeze damage.

From the perspective of lining temperature field distribution, the sandwich laying method is the most effective, significantly reducing the heat exchange between the cold air flow in the tunnel and the lining structure. This results in minimal temperature fluctuations within the lining structure and a consequent reduction in the risk of freeze-thaw damage. Following the sandwich method, the double-layer laying method ranks second in effectiveness. However, the insulation performance of surface laying and off-wall laying methods is comparatively inferior.

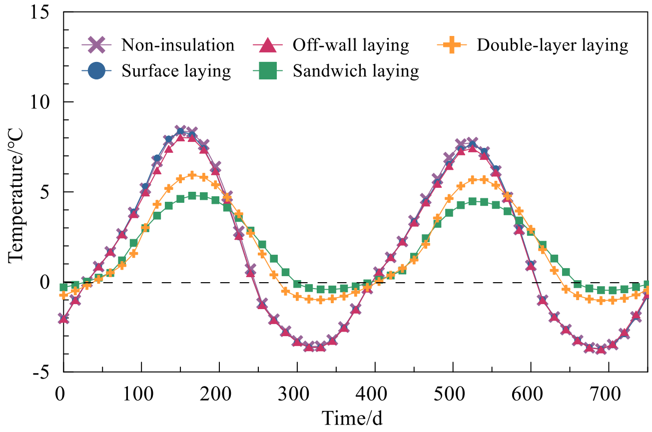
In summary, the anti-freezing efficacy of various laying methods at different structural positions has been evaluated and is presented in Table 4. According to Table 4, the off wall laying method exhibits superior insulation at the tunnel vault compared to the other three methods. Similarly, the sandwich laying method outperforms the alternatives at the tunnel arch foot and inverted arch. However, given the complexity of the off wall laying method's construction and the marginally inferior insulation performance of the surface laying method, the latter can occasionally serve as a substitute for the former. According to Table 1 and 3, surface laying method is preferred in areas with higher temperatures. Concurrently, the thermal insulation properties of the pavement filling material are utilized to mitigate freeze-thaw damage at the tunnel's inverted arch, compensating for the surface laying method's limitation in this area. In conditions of low temperature, the sandwich laying method is recommended to prevent extensive freeze-thaw damage to the surrounding rock.



(a) Vault

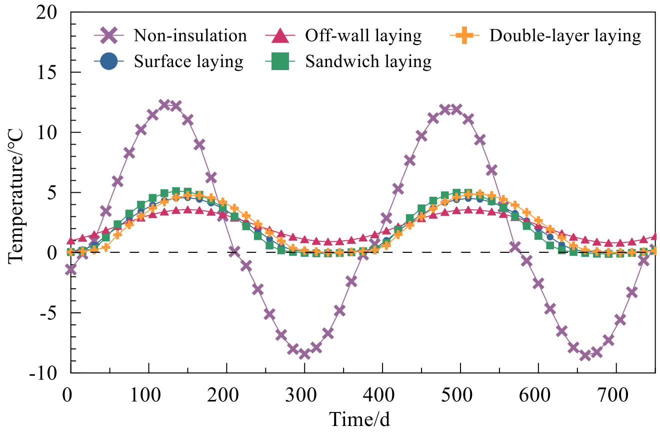


(b) Arch foot

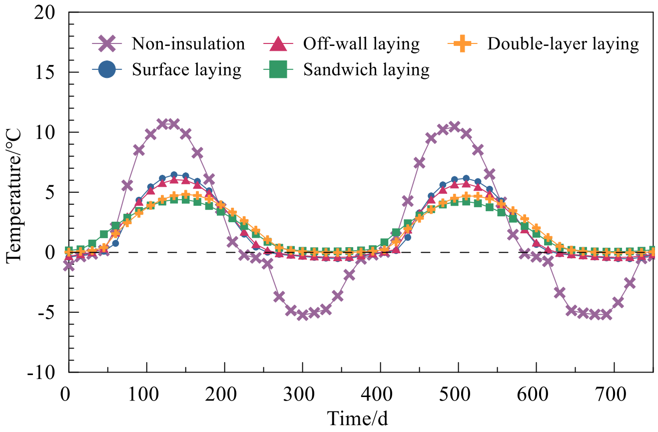


(c) Inverted arch

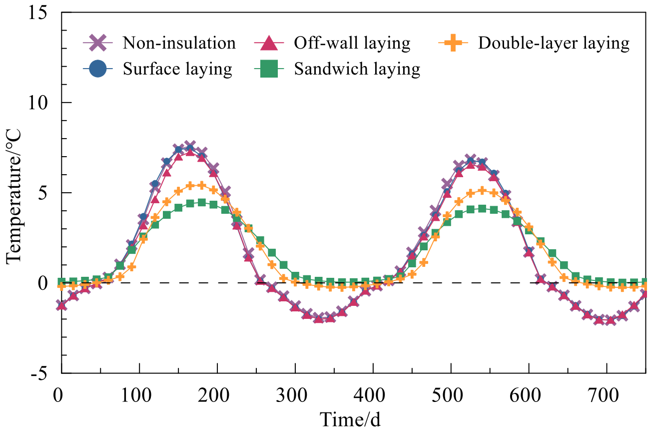
Fig. 11 Temperature change with time between secondary lining and initial lining



(a) Vault



(b) Arch foot



(c) Inverted arch

Fig.12 Temperature change with time between initial lining and surrounding rock

Table 4 Thermal insulation and anti-freezing effects of 4 laying methods at various positions of the tunnel

Position	Anti-freezing effect (> represents better than and ≈ represents almost the same)
surface of secondary lining (vault)	off-wall laying>surface laying>double-layer laying>sandwich laying
surface of secondary lining (arch foot and inverted arch)	off-wall laying ≈ surface laying>double-layer laying>sandwich laying
between secondary lining and initial lining (vault)	off-wall laying>surface laying ≈ double-layer laying ≈ sandwich laying
between secondary lining and initial lining (arch foot and inverted arch)	sandwich laying> double-layer laying> off-wall laying ≈ surface laying
between initial lining and surrounding rock (vault)	off-wall laying>surface laying ≈ double-layer laying ≈ sandwich laying.
between initial lining and surrounding rock (arch foot and inverted arch)	sandwich laying> double-layer laying> off-wall laying ≈ surface laying

6. Conclusions

Optimizing the design of tunnel insulation layer installation in high-altitude cold regions necessitates a comprehensive evaluation of the distinct advantages offered by various laying methods. This study establishes a multi-layer medium heat transfer model that accounts for phase-change latent heat. Using the finite element method, it quantitatively analyzes the insulation performance of various laying methods at different tunnel locations, leading to the following conclusions.

1. Based on the finite element method, the temperature field of multi-layer medium using various insulation layer laying methods is studied under the control condition of 0°C at distinct positions (the surface of secondary lining, between the initial lining and the secondary lining, between the initial lining and the surrounding rock). The unfavorable position of the four laying methods is at the inverted arch of the tunnel. At this critical juncture, the temperature fluctuates periodically in response to external climatic variations, with the most adverse period occurring as temperatures ascend from below 0°C to above 0°C.
2. Both the off-wall and surface laying methods are effective in mitigating freeze-thaw damage to the secondary lining concrete

above the arch foot, with the off-wall method demonstrating superior thermal insulation properties. Conversely, the sandwich and double layer laying methods have a detrimental impact on the insulation of the secondary lining concrete and the fill pavement below the arch foot. The secondary lining concrete and fill pavement beneath the arch foot cannot rely on the insulation layer for freeze protection and must depend on the intrinsic frost resistance of the concrete materials.

3. All four insulation laying methods can prevent freeze-thaw damage to the initial lining concrete and the surrounding rock above the arch foot. Below the arch foot, the sandwich laying method provides superior insulation to the initial lining concrete and surrounding rock compared to the double-layer method, while the other two methods do not offer a significant insulation benefit.
4. Surface laying is straightforward to install and maintain, offering an effective insulation solution above the arch foot. At higher temperatures, the thermal insulation properties of pavement filling materials contribute to mitigating freeze-thaw damage beneath the arch foot. Sandwich laying serves as a buffer layer, alleviating the stress on the secondary lining, and enhancing the overall thermal insulation of the surrounding rock. For tunnels in high-altitude cold regions, it is judicious to employ sandwich laying in the portal's low-temperature zones and surface laying in the central section's where temperatures are higher.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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