Numerical Study on Thermal Insulation of a Roadway Tunnel at Southeast Edge of the Qinghai-Tibet Plateau

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Abstract. Tunnels in seasonal frost regions are heavily affected by damage related to icing problem and cyclic freeze-thaw of surrounding rock. To mitigate frost related damage, thermal insulation is widely used at entrance and exit section of tunnels. In thermal insulation design, length of the insulated section and thickness of the thermal insulation layer (TIL) are two important parameters. In this study, a coupled mathematical model of heat and moisture transfer was built for tunnels in cold regions. Then, field observed air temperatures at entrance section of a roadway tunnel at Altun Mountain, southeast edge of the Qinghai-Tibet Plateau, were collected and analysed. Based on the mathematical model and field observed inside air temperatures, seasonal freeze-thaw of surrounding rocks of the tunnel entrance was numerically investigated with consideration of the thicknesses and thermal conductivities of insulation layer. The results showed that, within the tunnel, the air has its mean annual temperature increase and the its amplitude decrease with increase in the distance from the entrance. The significant variations mainly occurred within the section 375 m from the entrance. Without the TIL, the maximum seasonal freeze depth of surrounding rocks at the entrance can reach to 1.5 m. To ensure that the surrounding rocks do not experience freezing, the minimum thickness of the TIL with a thermal conductivity of 0.037 W/(m·°C) should be 7 cm. While when the thickness of the TIL is 5 cm, its thermal conductivity should be not greater than 0.014 W/(m·°C).

1. Introduction

In cold regions, seasonal freeze-thaw of shallow ground layer can cause severe damage to a wide range of infrastructure [1-4]. For tunnels in seasonal frost regions, the excavation will result in a significant disturbance to heat, moisture, and stress fields of the surrounding rocks [3, 5, 6]. Moreover, accompanying with seasonal changes of air temperatures inside the tunnel, the surrounding rocks generally experience cyclic freeze-thaw, particularly at the entrance (exit) section. The cyclic freeze-thaw and related icing and frost heave problems can cause various damage to tunnel’s structure (figure 1), which severely undermines the structure stability and also threatens traffic safety, and finally lead
to a significant increase in the maintaining cost and even decreases the lift span of tunnel [7-9]. To mitigate these frost related problems, lots of thermal protection techniques have been developed for tunnels built in seasonal frost regions. One of the widely used techniques is thermal insulation. Kinds of thermal insulation layers (TIL) are laid either on the surface of the second lining or between the preliminary and the second linings of tunnel [3, 10, 11]. In thermal insulation design of a tunnel in cold regions, length of the insulated section from entrance (exit) and selection of the insulation layer are crucial because they determine not only the degree of the mitigation and also the cost [7, 12].

Figure 1. Frost related damage to tunnels in Gansu Province, northwest China: (a) Icing hanging on lining; (b) leakage of lining; and (c) icing on pavement.

The air temperatures inside and its distribution along tunnels are very important for the thermal insulation design. Methods including field measurement and numerical simulation are widely used to gain the air temperature distribution along tunnels in cold regions. Johansen et al. [13] carried out long-term observations of the air temperature in a cold region tunnel in Alaska to gain the air temperature distribution and its seasonal variations along the tunnel. Nie et al. [14] observed the air temperature inside and outside a seasonal frost tunnel (Xiluoqi No.2 tunnel, 1160m in length) in Daxing'anling Mountain, Northeast of China. The results showed that the section where the air temperature variation rate of was zero inside the tunnel accounted for about half of the total length of the tunnel. Lai et al. [15] observed the air temperatures inside a roadway tunnel, located at Qinghai Province, Northwest of China and with an elevation of 3886.4 m, with the thermal insulation gate open and close. The observations showed that the thermal insulation gate could effectively rise the air temperature in the tunnel. Chen et al. [16] measured the temperatures of air, lining surface and surrounding rocks inside Daban Mountain tunnel at the Northeast Qinghai-Tibet Plateau and summarized the variations of these temperatures with time. Based on the air temperature inside the tunnel, temperature field of surrounding rocks and effects of TIL were generally investigated using numerical analytic methods. Harlan [17] proposed the Harlan Model to describe heat-fluid transport in partially frozen soil, which was widely applied in frozen soil engineering. Taylor and Luthin [18] proposed a model for coupled heat and moisture transfer during soil freezing, which was modified from the Harlan Model. Shoop and Bigl [19] used a coupled heat flow and moisture flow to simulate large-scale freeze-thaw experiments. These researches provided basis for numerical simulation and prediction of temperature fields of tunnels built in cold regions. Lai et al. [20] proposed a numerical model to study the coupled problem of temperature, seepage and stress fields in cold region tunnels, which was widely used in the following related research. Zhang et al. [21] studied the freezing-thawing situation of surrounding rocks in cold region tunnels under conditions of different construction seasons, initial temperatures and insulations. Considering the influence of airflow inside the tunnel, Tan et al. [22] used a numerical method to investigate the temperature field of the surrounding rocks and the air inside Galongla tunnel in the Qinghai-Tibet Plateau. Yao et al. [23] analyzed the temperature field of the surrounding rocks in seasonal frost tunnels under different laying methods of TIL. To gain optimal design parameters of the TIL, some researchers built mathematical optimization models for tunnels in cold regions [7, 8, 9, 24].

In this paper, a roadway tunnel at Altun Mountain, southeast edge of the Qinghai-Tibet Plateau, were taken as an example to study the thermal insulation of tunnels built in seasonal frost regions.
Firstly, a coupled mathematical model of heat and moisture transfer was built for study on seasonal freeze-thaw of surrounding rocks. Then, field observed air temperatures at different sections from the entrance of the tunnel were collected. The air temperature distribution along the tunnel was analyzed. Based on the mathematical model and field observed air temperatures, characteristics of seasonal freeze-thaw of surrounding rocks at different sections from the entrance were investigated through using numerical simulations. In the numerical model, both thickness and thermal conductivity of TIL were considered. With the numerical results, the relationship between the seasonal freezing depth of surrounding rocks and the thickness and thermal parameters of TIL were discussed. It is hoped that the field observations and numerical simulations in this study would provide references for thermal insulation design of tunnels built in seasonal frost regions.

2. Coupled Mathematical Model of Heat and Moisture Transfer

2.1. Liquid Water Flows

According to the law of mass conservation, the equivalent volume of water content $\theta$ in frozen soil without consideration of the effects of vapor can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial \theta_u}{\partial t} + \frac{\partial \theta_i}{\partial t} = \nabla(q_{lh})$$  

(1)

where $\theta$ is the equivalent volume of water content ($m^3 \cdot m^{-3}$); $\theta_u$ is the volume of unfrozen water content ($m^3 \cdot m^{-3}$); $\theta_i$ is the volume of ice content ($m^3 \cdot m^{-3}$); $\rho_i$ is the density of ice (kg·m$^{-3}$); $\rho_w$ is the density of water (kg·m$^{-3}$); $t$ is the time; $q_{lh}$ is the liquid water flux density which can represent liquid flows due to a pressure head gradient (m·s$^{-1}$).

According to the Harlan model [17], liquid water migration in frozen soil is similar to that in unfrozen unsaturated soil. Then, it can be described by Richards equation [25] and is mainly influenced by water potential gradient and hydraulic conductivity of soils. The values of water potential gradient and hydraulic conductivity are different in unfrozen and frozen soils. But the water migration in frozen soil can still be assumed to follow Darcy’s law [26]. Only the water potential gradient is considered as driving force of liquid water migration in both frozen and unfrozen soils in this study. Then, the flux density of liquid water can be written as [27-28]:

$$q_{lh} = -K_{lh} \nabla(h + y)$$  

(2)

where $y$ is the vertical coordinate (m); $h$ is the pressure head (m); $K_{lh}$ is the water conductivity coefficient of liquid water under the action of soil water potential gradient (m·s$^{-1}$).

Taking equivalent volume water content $\theta$ as a dependent variable, the mass conservation equation of liquid water in frozen soil can be described as [28]:

$$\frac{\partial \theta}{\partial t} = \nabla \cdot [K_{lh} \nabla(h + y)]$$  

(3)

2.2. Hydraulic Properties

Soil-water characteristic curve (SWCC) can represent the relationship between matric suction and volume water content or saturation, and reflects the relationship between the amount of water and energy in the soil [28]. In this study, the hydraulic properties of unsaturated freeze-thaw soil were described by van Genuchten model [29] and Mualem model [30] as:

$$h = -\left(\frac{1}{S_e^{-m} - 1}\right)^{\frac{1}{m}} / \alpha$$  

(4)

$$S_e = \frac{\theta_{s} - \theta_{r}}{\theta_{s} - \theta_{r}} = \left\{ \begin{array}{ll} \frac{1}{1 + [\alpha h]^m} & h < 0 \\ 1 & h \geq 0 \end{array} \right.$$  

(5)
where $S_e$ is effective saturation; $K_s$ is saturation water conductivity coefficient (m·s$^{-1}$); $\theta_l$, $\theta_s$, and $\theta_r$ are liquid water content, saturated liquid water content and residual water content (m$^3$·m$^{-3}$); $\alpha$ is the derivative of the soil intake value (m$^{-1}$); $m = 1 - 1/n$; $n$ and $l$ are experience parameters and Mualem suggested that $l$ could be determined as 0.5 [30].

2.3. Heat Transfer

Compared to heat conduction with latent heat from phase change of ice to water, the energy released related to the convection was very small and could be neglected during the heat transfer analysis of freeze-thaw soil [28, 31, 32]. In this study, the heat conduction and ice-water phase change were considered and the governing equations of heat transfer within freeze-thaw soil can be written as [10, 33, 34]:

$$ C_m \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda_m \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda_m \frac{\partial T}{\partial y} \right) $$

(7)

where $C_m$ is equivalent volume heat capacity; $\lambda_m$ is equivalent thermal conductivity.

In this study, the latent heat of phase change is dealt with sensible heat capacity method. It is assumed that phase change occurs in a temperature range ($T_f \pm \Delta T$). When the equivalent volume heat capacity is established, the effect of temperature interval $\Delta T$ should be taken into account. The volume heat capacity $C_f$ and $C_u$ and the thermal conductivity coefficient $\lambda_f$ and $\lambda_u$ are assumed to be not dependent on the temperature of the medium. Then, the expressions of $C_m$ and $\lambda_m$ are simplified as follows [10, 15]:

$$ C_m = \begin{cases} 
\frac{C_u + C_f}{2} + \frac{L_s}{\Delta T} & T < T_f - \Delta T \\
C_u & T_f - \Delta T \leq T \leq T_f + \Delta T \\
C_f & T > T_f + \Delta T
\end{cases} $$

(8)

$$ \lambda_m = \begin{cases} 
\frac{\lambda_u - \lambda_f}{2} [T - (T_m - \Delta T)] + \lambda_f & T_f - \Delta T \leq T \leq T_f + \Delta T \\
\lambda_u & T > T_f + \Delta T
\end{cases} $$

(9)

where $T_f \pm \Delta T$ is the temperature range of phase change; $C_u$ and $\lambda_u$ are the volume heat capacity and thermal conductivity of unfrozen soil; $C_f$ and $\lambda_f$ are the volume heat capacity and thermal conductivity of frozen soil; $L_s$ is the latent heat of phase change in per unit volume.

2.4. Soil Freezing Characteristics

The rest of liquid water after soil freezing is called as unfrozen water. The unfrozen water content depends on factors including the temperature, pressure, water salinity, mineralogy, soil specific surface area and soil surface chemistry [35-39]. Generally, there is a dynamic equilibrium relationship between the unfrozen water content and the temperature of soil [40]. Thus, the change of unfrozen water can regard as the driving force of liquid water migration in frozen soil. In this study, the empirical expression as follow is used to determine the maximum unfrozen water content in the freezing process [25, 26, 41]:

$$ \theta_{u,max} = a(T - 273.15)^{-b} $$

(10)

where $a$ and $b$ are parameters related to the soil properties. Since temperature $T$ and equivalent volume water content $\theta$ are dependent variables in the hydrothermal coupling equation, the volume liquid water content and ice content can be determined by equivalent volume water content and temperature [26, 27, 41]:

$$ K = \begin{cases} 
\frac{K_s S_e}{K_s} \left[ 1 - \left( 1 - S_e \right)^{m} \right]^2 & h < 0 \\
K_s & h \geq 0
\end{cases} $$

(6)
\[ \theta_1 = \begin{cases} \theta & \text{otherwise} \\ \theta_{umax} & T < T_f \text{ and } \theta > \theta_{umax} \end{cases} \]  

(11)

\[ \theta_i = \frac{\rho_w}{\rho_i} (\theta - \theta_i) \]  

(12)

where \( T_f \) is the freezing point of saturated soil (0 °C). Previous studies showed that the freezing point of soil is not a fixed value, and the ice crystal growths only when the water content exceeds \( \theta_{umax} \) [26, 42].

3. Field Observations on Air Temperature inside a Roadway Tunnel

3.1. Studied Tunnel

In this study, a roadway tunnel at Altun Mountain was taken as an example to study thermal insulation of tunnels in seasonal frost regions. The Altun Mountain roadway tunnel is located at southeast edge of the Qinghai-Tibet Plateau, with an elevation ranging from 3,200 to 3,760 m. The tunnel site is in an alpine and semi-arid climate zone, with a large seasonal air temperature variation and little annual precipitation. According to the closest weather station at Akesai country, the mean annual air temperatures is 3.1 °C, and the maximum and minimum air temperatures are 35.9 and -34.3 °C, respectively.

A standard weather station was set up at the tunnel entrance in January 2019. Figure 2 shows the air temperatures during the period from 19 January to 31 October in 2019. In the period, the maximum air temperature in the monitoring period reached to 25 °C, which appeared in mid-August. The minimum air temperature was -22.3 °C, which appeared in late-January. Based on the measured data, the air temperature outside the tunnel was fitted using a sinusoidal function as:

\[ T_{out} = 0.91 + 11.62 \sin \left( \frac{2\pi}{365} t - 7.84 \right) \]  

(13)

Figure 2. Measured air temperatures outside the tunnel.

3.2. Air Temperatures inside the Tunnel

The tunnel has a length of 7,527 m. To gain the variations of air temperature inside the tunnel, air temperature sensors were installed within a section of 1500 m long from the tunnel entrance. A total of nine air temperature sensors were placed at 5 (J1), 20 (J2), 50 (J3), 100 (J4), 200 (J5), 400 (J6), 700 (J7), 1000 (J8), and 1500 m (J9) from the entrance, respectively (figure 3). The air temperature sensors used in this study were manufactured and calibrated by TASCO (Japan). The calibrated range of the sensors is -30 to 60 °C, with a resolution smaller than 1.0 °C and an accuracy of ±1%. The data acquisition interval was set as 4 hours.
Figure 3. Schematic diagram of air temperature monitoring at the tunnel entrance.

Figure 4 shows the air temperature at J1 section during the period from March 3, 2019 to May 23, 2020. At the section, the maximum air temperature in the monitoring period reached to 17.3 °C, which appeared in early-August. The minimum value was -17.5 °C and appeared in mid-January. The mean monthly air temperatures in the two months were 10.9 and -9.9 °C, respectively. During the monitoring period, there were 193 days that the air temperature at the section was lower than 0 °C. Through the year from March 3, 2019 to March 2, 2020, the freezing and thawing indexes of the daily air temperatures at J1 section were -1183.4 and 1651.7 °C·d, respectively.

Figure 4. Air temperature of J1 section inside the tunnel.

With increase in the distance from the entrance, the mean annual air temperatures inside the tunnel increased and the amplitudes decreased rapidly. Based on their variations with time, the air temperatures at the nine sections were all fitted using a sinusoidal function as:

\[
T = T_y + A \sin \left( \frac{2\pi}{365} t - B \right) \tag{14}
\]

where \( T \) is the air temperature inside the tunnel (°C); \( T_y \) is the mean annual air temperature (°C); \( A \) is the amplitude (°C); \( t \) is the time (d); \( B \) is the phase position, which ranges from 0.56–0.80 at the nine sections. Table 1 lists the fitted parameters for equation (14) at the nine sections and freezing index can reach to 0 °C·d when the distance to entrance is close to 375m using interpolation method.

Table 1. Fitted parameters for equation (14) at nine sections.

| Sections | Distance to entrance | Mean annual air temperature | Amplitude | Freezing index | Thawing index |
|----------|----------------------|----------------------------|-----------|---------------|---------------|
| J1       | 5                    | 1.57                       | 9.34      | -1183.4       | 1651.7        |
| J2       | 20                   | 2.30                       | 8.21      | -996.4        | 1704.9        |
| J3       | 50                   | 2.60                       | 6.94      | -785.5        | 1619.1        |
| J4       | 100                  | 3.68                       | 5.44      | -462.3        | 1737.0        |
| J5       | 200                  | 4.24                       | 3.69      | -143.8        | 1742.6        |
| J6       | 400                  | 4.83                       | 2.71      | 0.0           | 2005.9        |
| J7       | 700                  | 5.12                       | 2.08      | 0.0           | 2143.6        |
| J8       | 1000                 | 5.74                       | 1.80      | 0.0           | 2395.9        |
| J9       | 1500                 | 6.81                       | 1.36      | 0.0           | 2818.8        |
4. Numerical Simulation and Results Analyses

4.1. Computational Model

Previous studies showed that the boundary error would be less than 10% when the computational domain is 3-5 times of the equivalent diameter of the tunnel [43]. In this study, the computational model, as shown in figure 5, was constructed based on the section J1 of Altun Mountain roadway tunnel. The points of H1, H2, H3 and H4 labeled in the figure were monitoring points in the numerical simulations. Two common laying methods of the TIL were considered in this study. The thermal and hydraulic parameters in the simulation are listed in table 2, which were gained based on borehole drillings from the tunnel and related literatures [25-28].

![Figure 5. Numerical model of the Altun Mountain roadway tunnel.](image)

**Table 2.** Thermal and hydraulic parameters of media in the simulation.

| Parameters                     | $\lambda_u$ W·m$^{-1}$·C$^{-1}$ | $\lambda_t$ W·m$^{-1}$·C$^{-1}$ | $C_u$ J·m$^{-3}$·C$^{-1}$ | $C_t$ J·m$^{-3}$·C$^{-1}$ | $a$ | $b$ |
|--------------------------------|-----------------|-----------------|-----------------|-----------------|-----|-----|
| Mudstone                       | 1.470           | 1.820           | 2.09×10$^6$     | 1.84×10$^6$     | 9.3 | 0.52|
| The preliminary lining         | 2.000           | 2.000           | 2.23×10$^6$     | 2.23×10$^6$     | \   | \   |
| The secondary lining           | 2.000           | 2.000           | 2.23×10$^6$     | 2.23×10$^6$     | \   | \   |
| Thermal insulation layer       | 0.037           | 0.037           | 9.40×10$^5$     | 9.40×10$^5$     | \   | \   |

| Parameters                     | $\alpha$ m$^{-1}$ | $\theta_e$ | $\theta_s$ | $K_s$ m·s$^{-1}$ | $\rho$ kg·m$^{-3}$ | $L_v$ J·m$^{-3}$ |
|--------------------------------|-------------------|-------------|-------------|------------------|-------------------|-----------------|
| Mudstone                       | 2.3               | 0.02        | 0.25        | 1.2×10$^8$       | 1700              | 3.77×10$^7$     |
| The preliminary lining         | \                 | \           | \           | \                | 2500              | \               |
| The secondary lining           | \                 | \           | \           | \                | 2500              | \               |
| Thermal insulation layer       | \                 | \           | \           | \                | 188               | \               |

The boundary conditions were determined as follows. The upper boundary AB and the inner wall of the tunnel are set as heat convection boundary. The lateral boundary BC is thermal insulation boundary and AD is the symmetry boundary. According to the geothermal gradient at the tunnel site, heat flux at the boundary CD is 0.06 W/m$^2$. The water boundary conditions were determined as follow. The boundaries AB, BC and CD are set as waterproof boundaries taking no count of rainfall on the water content of surrounding rocks. The boundary AD is the symmetry boundary. The initial temperature of the numerical model was calculated using a long-term transient solution with the upper boundary condition of equation (13) and the lower boundary of heat flux as 0.06 W/m$^2$. The
simulation was conducted over a time period of 50 years before the tunnel excavation. After excavation, the boundary conditions were set as described above.

4.2. Results and Analyses

4.2.1. Temperature Field of Surrounding Rocks. To compare thermal insulation effects of the TIL laid at different places, figure 6 shows the temperature distributions of surrounding rocks without TIL, with 5-cm-thick TIL laid on the surface of the second lining and between the preliminary and the second linings of the tunnel. The time point of the temperature distribution was selected as April 15 in the fifth year after excavation. It can be seen that, without the TIL, the surrounding rocks experience considerable freezing in cold winter. On April 15, the maximum frozen depth calculated from the outer surface of the first lining is 1.5 m. While, with 5-cm-thick TIL, the frozen depth decreases significantly both under two laying methods of the TIL. When the TIL was laid on the surface of the second lining, the maximum frozen depth is only 0.5 m. While, when it was laid between the preliminary and the second linings, the maximum frozen depth is 0.6 m, being slightly greater than the former.

![Figure 6. Temperature distribution of surrounding rocks on April 15 in 5th year after excavation. (a) Without TIL; (b) With 5-cm-thick TIL laid on the surface of the second lining; (c) With 5-cm-thick TIL laid between the preliminary and the second linings.](image)

From figure 6, it also can be that, the frozen depths at vault (H1) and inverted arch (H4) are obviously greater than that at arch hance (H2) and foot (H3). To furtherly compare the thermal insulation effects of the laying methods of the TIL, the temperatures at H1 in 5 years after excavation are shown in figure 7. It can be seen that, with the TIL laid on the surface of the second lining, the seasonal variations of the temperature at H1 is smaller than that when the TIL was laid between the preliminary and the second linings. Based on the daily temperatures in fifth year after excavation, the freezing (thawing) indexes at H1 are -141.2 °C·d (3561.7 C·d) and -223.2 °C·d (3622.7 C·d), respectively, with the TIL laid on the surface of the second lining and between the preliminary and the second linings. The comparisons above showed that laying the TIL on the surface of the second lining would provide a better thermal insulation effect for surrounding rocks. Meanwhile, when laid between the preliminary and the second linings, the TIL needs to bear the pressure from surrounding rocks and frost heave and is difficult for maintenance during the tunnel operation. Thus, it is recommended that the TIL should be laid on the surface of the second lining of cold region tunnels.

![Figure 7. Variation of temperatures at H1 with two laying methods in 5 years after excavation.](image)
4.2.2. Effect of Different Thickness of Insulation Layer. The thickness and thermal conductivity are the key parameters for the TIL used for thermal insulation of cold region tunnels (Wu et al. 2003; Ma et al. 2018). To study the thickness impacts, seasonal freezing and thawing processes at H1 of J1 section with the thickness of the TIL of 0, 1, 2, 3, 4 and 5cm are shown in figure 8. It can be seen that, the maximum frozen depths under five conditions are 1.51, 1.13, 0.87, 0.68, 0.53 and 0.41 m, respectively. The corresponding frozen duration of surrounding rocks are 162, 158, 154, 147, 138 and 126 d, respectively. With increase in thickness of the TIL, the frozen depth and frozen duration of the surrounding rocks gradually decrease. Figure 9 shows the relationship between the minimum temperature at H1 throughout one year and thickness of the TIL. It can be seen that, with increase in thickness of the TIL, the minimum temperature at H1 increase exponentially. The relationship between thickness of the TIL and the minimum temperature at H1 can be fitted using an exponential function as:

\[ T_{\text{min}} = -4.39e^{\frac{-d}{3.05}} + 0.50 \]  \hspace{1cm} (15) \\

where the \( d \) is the thickness of TIL. It can be gained from the equation (15) that, when the \( d \) is 7 cm, the minimum temperature at H1 would be close to 0 °C, which means that the surrounding rocks would not experience any freezing process.

Figure 8. Seasonal freezing-thawing process of surrounding rocks at H1 with (a) 0, 1, 2, 3, 4, and 5-cm-thick TIL in 5 years after excavation.
Figure 9. Relationship between the thicknesses of TIL and the minimum temperature at H4.

4.2.3. Effect of Different Thermal Conductivity of Insulation Layer. Figure 10 shows the variations of temperature at H1 with 5-cm-thick TIL in 5 years after excavation. Six thermal conductivities of the TIL were considered, which were ranging from 0.037 to 0.537 W/(m·°C). With increasing of the thermal conductivity, the seasonal variations of temperature at H1 decrease obviously. Similarly, the relationship between the minimum temperature at H1 throughout one year and the thermal conductivity of TIL is shown in figure 11. It can be seen that there is also an exponential relationship between the two parameters. The relationship can be fitted using a function as:

\[ T_{\text{min}} = -3.75e^{\frac{-\lambda_1}{0.33}} - 3.35 \]  

(16)

where the \( \lambda_1 \) is the thermal conductivity of TIL. From equation (16), it can be gained that, when the thickness of TIL is 5 cm, the thermal conductivity should be smaller 0.014 W/(m·°C) to ensure the temperature at H1 being above 0 °C throughout one year.

Figure 10. Variation of H1 temperature in different thermal conductivity of insulation layer in 5 years after excavation.
5. Conclusion
In this study, a coupled mathematical model of heat and moisture transfer was built for tunnels built in cold regions. Then, field observed air temperatures at entrance section of Altun mountain roadway tunnel were collected and analyzed. Based on the mathematical model and field observed inside air temperatures, seasonal freeze-thaw of surrounding rocks at the tunnel entrance was numerically investigated with consideration of the thicknesses and of TIL. According to this study, the following conclusions can be obtained:

1. According to field observed air temperatures, the difference between the minimum and maximum value of air temperature could reach to 34 °C inside Altun Mountain roadway tunnel. The mean annual air temperatures inside the tunnel increased and the amplitudes decreased rapidly with the increase of the distance from the entrance.

2. The TIL can effectively decrease the freeze depth of surrounding rocks in winter. On April 15 in the fifth year after excavation, the maximum frozen depth calculated from the outer surface of the first lining is 1.5 m without TIL. When the TIL is laid on the surface of the second lining, the maximum freeze depth is only 0.5 m. While, when it was laid between the preliminary and the second linings, the maximum freeze depth is 0.6 m, being slightly greater than the former. Comparing the variation of temperatures at H1 with two laying methods in 5 years after excavation, the TIL should be laid on the surface of the second lining of cold region tunnels.

3. The thermal insulation effect of TIL is mainly determined by its thermal conductivity and thickness. The relationship between the minimum temperature at H1 and the parameters of TIL was established and can be fitted by exponential function. The optimal parameters of TIL can be obtained through the fitting formulas. When the thermal conductivity is 0.037 W/(m·°C), the thickness of TIL should be bigger 7cm to ensure that the surrounding rocks would not experience any freezing process. While, when the thickness of TIL is determined as 5 cm, its thermal conductivity should be smaller 0.014 W/(m·°C).

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