Analysis of Temperature Field of Tunnel Surrounding Rocks in Freezing-Thawing Environment

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Abstract. On the background of large scale rocks engineering in cold regions, Temperature Field and Stress Field of Tunnel Surrounding Rock under the freeze-thaw environment are numerically analysed. According to the single temperature field equation of tunnel surrounding rock and Da Ban mountain tunnel project in Qinghai province as an example, large scale finite element software is used to simulate temperature distribution under freeze-thaw cycles, which is from the rising temperature to the decreasing temperature and from the rising temperature to the decreasing temperature again. The frost heaving force of the tunnel in the cold region is introduced and the mathematical model about rocks temperature field is also researched. Finally, finite element method is used to calculate the frost heaving force of rock tunnel in the cold regions. The results show that in the freezing and thawing environment, the area near the inner wall of the tunnel is more likely to be affected by the ground temperature and the effect of open ventilation and convection, and the temperature and stress changes more violently. In the design and construction of the cold regions, the influence of the frost heave force of the surrounding rock must be considered. Because freeze-thaw circles could cause the destruction of the tunnel structure, convective heat transfer will occur between tunnel mouth and walls and the environment, resulting in large temperature difference. Therefore, in order to reduce freeze-thaw disasters in the cold regions, we should consider the Protection measures about the hole and the wall. In this way, it reduces the range of freeze-thaw circles and prevent the convective heat transfer effectively.

1. Research background
Seasonal frozen soil is widely distributed in Northeast China, North China, northwest and other regions. About 2 million 150 thousand square kilometers permafrost is distributed in the northeastward and Xiao Hinggan Mountains, the western mountains and Qinghai-Tibetan Plateau. Among this, the Qinghai-Tibetan Plateau permafrost area is 1 million 490 thousand square kilometers, accounting for 70% of the total permafrost area in China, which is rich in minerals, land, biology and tourism resources [1]. Thus, as can be seen, the construction and utilization of resources in cold regions play a very important role in our national economy.

This paper is based on the tunnel engineering of rock mass in cold region, taking the section K106+025 of the exit section of the Qilian Mountains in Qinghai Province as the object of analysis. Numerical simulation of single temperature field and thermal mechanical coupling of tunnel surrounding rock using large general finite element software ANSYS put into use, it analyses the interaction and changing rule of rock temperature and stress field. Measures for restraining freezing and thawing disasters are put forward. Therefore, it provides a scientific basis for quantitatively evaluating the engineering stability of rock mass in cold regions.
2. Fundamental theory

After the tunnel through the cold zone, the original stable thermodynamic conditions were destroyed instead of a new thermal system with no direct solar radiation and open ventilation convection. The new heat exchange system results in the new freeze-thaw characteristics of the surrounding rock mass, and creates the conditions for forming permafrost [2]. According to the annual variation rule of tunnel wall temperature based on the data of meteorology, geology and hydrogeology of the Qilian Mountains in Qinghai Province, and on this basis the freeze-thaw condition of surrounding rock and the condition of permafrost formation after tunnel penetration are preliminarily analysed with different annual average wall temperature.

\[ T(t, x, y) \] is the temperature value which is at the \( t \) time point at \((x, y)\). \( T(t, x, y) \) satisfies the heat conduction equation with the following phase transition [3]:

\[
\begin{align*}
C_f \frac{\partial T_f}{\partial t} &= \nabla (\lambda_f \nabla T_f), & 0 < t < D, x \in S_f(t) \\
C_u \frac{\partial T_u}{\partial t} &= \nabla (\lambda_u \nabla T_u), & 0 < t < D, x \in S_u(t) \\
T_f \left[ t, \xi(t) \right] &= T_u \left[ t, \xi(t) \right] = T_0, & 0 \leq t \leq D \\
\left( \lambda_f \frac{\partial T_f}{\partial t} - \lambda_u \frac{\partial T_u}{\partial t} \right)_{x=\xi(t)} &= L \frac{d \xi}{dt}, & 0 \leq T \leq D
\end{align*}
\]

Where, \( S_f(t), S_u(t) \) are freeze-thaw districts; \( \lambda_f, \lambda_u \) are coefficient of heat conduction in freeze-thaw state; \( C_f, C_u \) are volumetric heat capacity in freeze-thaw state; \( x = (x, y), \xi(t) \) are phase transition interface of freeze-thaw; \( T_0 \) is Critical temperature of rock freezing;

\( L = \gamma_d \times (W - W_u) \times 80 \) is latent heat of water; \( \gamma_d \) is dry density of rock; \( W \) is moisture content; \( W_u \) is Unfrozen water content [4].

According to the altitude (3800m) and the annual mean temperature (-3°C) of the Daban Mountain tunnel, the air density is calculated out: \( \rho = 0.774 \text{kg/m}^3 \); Because of water vapor in the atmosphere, the specific heat at constant pressure is taken as \( C_p = 1.847 \text{KJ/(kg•°C)} \);

The dynamic viscosity coefficient of air is taken as \( \mu = 9.218 \times 10^{-6} \text{kg} \cdot \text{s} \);

Thermal conductivity: \( \lambda = 2.0 \times 10^{-2} \text{W/(m·°C)} \)

The thermal diffusivity of air is obtained: \( \alpha = 1.3788 \times 10^{-5} \text{m}^2/\text{s} \);

The kinematic viscosity: \( \nu = 1.19 \times 10^{-5} \text{m}^2/\text{s} \)

The thermal conductivity of rock mass is treated according to the condition of broken rock. Dry bulk density of rock: \( \gamma_d = 1835 \text{kg/m}^3 \). The moisture content and unfrozen water are respectively:

\( W = 9\%, \ W_u = 1.5\%, \ \lambda_f = 1.4338 \text{W/(m·°C)}, \ \lambda_f = 1.8247 \text{W/(m·°C)} \); The specific heat capacity of rock is taken as 0.8\text{kJ/(kg·°C)}.

\[
C_f = \frac{(0.8 + 4.128W_u)}{1+W}, \quad C_u = \frac{(0.8 + 4.128W)}{1+W} \times \gamma_d
\]

The initial boundary value of the temperature is taken as:

\[
T(0, x, R_0) = [f(x) - R_0] \times 0.03
\]

\[
T(0, x, r) = \begin{cases} [f(x) - r] \times 0.03 & 0 < r \leq R_0 \\ A - B & \text{otherwise} \end{cases}
\]

Here \( f(x) \) is the distance of permafrost lower limit to tunnel vault. The geothermal gradient is 3%.
The natural annual average temperature of the outside of the tunnel is $A = -3 ^\circ C$, and the annual temperature variation amplitude is $B = 12 ^\circ C$ [5].

![Figure 1. Physical model of single temperature field.](image1)

![Figure 2. Model grid partition diagram.](image2)

![Figure 3. Temperature field of tunnel surrounding rock temperature at -3°C.](image3)

The annual average temperature of the Daban Mountain tunnel is $-3 ^\circ C$. The section of K106+025 at the tunnel exit is taken as the computational model (figure 1). In the vicinity of the section, the groundwater is abundant, and the seepage is very large. The daily discharge is more than 200 m in the tunnel. At this section, the tunnel tip is located at the lower limit of permafrost 100 m. DE is located in the lower limit of permafrost 20 m, OA = 40 m, AF = DE = 40 m. According to the symmetry, CD and AB are adiabatic boundary, and the BC side is communicated with the atmosphere. From the climatological data of Daban Mountain [6], the temperature variation curve can be obtained as follows:

$$T_a = -3 + 12 \sin \left( \frac{2}{8760} \pi k + \frac{\pi}{6} \right)$$

The physical model is shown in figure 1.

### 3. Numerical simulation of temperature field of tunnel surrounding rock in cold region

The finite element software ANSYS is used to simulate the single temperature field of the surrounding rock of the tunnel in cold region. The thermal unit PLANE55 is selected and the characteristic of materials parameters are selected as the thermal conductivity. According to the default form adopted by the ANSYS meshing tool, the model is divided into 1784 nodes and 1679 four node nonparametric elements. The result of the model grid partition is shown in figure 2.

In fact, the process of thermal analysis of ANSYS first divides the object to be treated as a finite element (including a number of nodes), and then based on the equation of heat balance of the heat transmission science classical theory, the heat balance equation at each node are under certain boundary conditions and initial conditions is solved. Thus the temperature of each node is calculated. And then other relevant quantities are solved. In the thermal analysis of ANSYS, the thermal analysis is divided into two categories: steady thermal analysis and transient thermal analysis, not by the familiar heat transfer mode as the classification standard, but it is based on the different temperature field properties. Steady state thermal analysis is used to determine the effect of a stable thermal load on the system or components. Before the transient thermal analysis is carried out, steady state thermal analysis is used to determine the initial temperature distribution. Through steady-state thermal analysis, the parameters such as temperature, thermal gradient, heat flux and heat flux density caused by stable thermal load can be determined. The values of these parameters do not vary with time. That is to say, the temperature field of the system is constant in steady-state heat transfer analysis.

Below is the temperature distribution of the surrounding rock of tunnel wall under the action of temperature: $-3 ^\circ C \rightarrow 10 ^\circ C \rightarrow -20 ^\circ C \rightarrow 10 ^\circ C \rightarrow -3 ^\circ C$. That is to say, the temperature distribution of tunnel surrounding rock is under the effect of heating up, cooling, warming up and freezing and...
thawing cycle, and there is no insulation layer. From the chart, we can see the temperature distribution trend of the surrounding rock and its roughly frozen depth, from which we can get the seasonal freeze-thaw change law.

From the figure 3, it can be found that when the wall temperature of the surrounding rock reaches -3°C, the temperature gradient of the tunnel wall is large, and the average temperature changes at 0.5 m. At around 0°C, the surrounding rock will start to freeze, and the freezing depth will be around 10m when the temperature changes.

In the same way, as is shown in figure 4, when the temperature of the inner wall of the surrounding rock rises to 10°C, the depth of melting is about 10m, and the depth belongs to the frozen area for many years, and the effect is not significant.

When the wall temperature drops to -20°C, the freezing depth has reached 12m, which has affected the freezing depth for many years.

![Figure 4](image4.png)  
**Figure 4.** Temperature field of tunnel surrounding rock temperature at 10°C.

![Figure 5](image5.png)  
**Figure 5.** Temperature field of tunnel surrounding rock temperature at -20°C.

4. Conclusion

According to the single temperature field equation of tunnel surrounding rock and Da Ban mountain tunnel project in Qinghai province as an example, large scale finite element software is used to simulate temperature distribution under freeze-thaw cycles. The temperature field distribution of tunnel surrounding rock under the action of temperature is: -3°C → 10°C → -20°C → 10°C → -3°C, which is from the rising temperature to the decreasing temperature and from the rising temperature to the decreasing temperature again:

1) The temperature field of surrounding rock gradually changes with the surrounding rock depth, and the temperature changes significantly near the wall.

2) When the wall temperature of the surrounding rock reaches -3°C, the temperature gradient of the wall will be larger, and the temperature will change at the average 0.5m. When it is near 0°C, the surrounding rock will begin to freeze, and the freezing depth is about 10m after the temperature change is stable. When the inner wall temperature of the surrounding rock rises to 10°C, the surrounding rock has melted. The depth of melting is about 10m, and the depth can be in the frozen area for many years, and the impact is not significant. When the temperature of the inner wall of the surrounding rock falls to -20°C, once again, the freezing depth of the surrounding rock will reach 12m, which will affect the freezing depth for many years. Therefore, engineering measures should be taken to effectively control the temperature range.

3) For the calculation model considered in this paper, because freeze-thaw circles can cause the destruction of the tunnel structure, convective heat transfer will occur between tunnel mouth and walls and the environment, resulting in large temperature difference. Therefore, in order to reduce freeze-thaw disasters in the cold regions, we should consider the protection measures about the hole and the wall. It is suggested that a protective door in the hole should be added, and insulating layer on
the wall should be filled to minimize the heat-exchange between the temperatures of the inside and outside of holes and surrounding rocks. In this way, it reduces the range of freeze-thaw circles and prevent the convective heat transfer effectively.

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