Numerical simulation of tunnel surrounding rock temperature field

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Abstract—Severe freezing injury can lead to tunnel encroachment and affect the safety of tunnel operation. The temperature field of surrounding rock and lining can be changed obviously by laying insulation layer on the outside surface of tunnel lining. Taking Wunvfeng tunnel as the engineering background. ANSYS program is used to simulate the surrounding rock temperature field, by comparing the two cases with and without protective layer, the variation law of surrounding rock temperature with time and space is obtained.

1. Introduction
Xie Hongqiang etc\textsuperscript{1}. in order to prevent the occurrence of tunnel freeze disaster, surface insulation laid outside the tunnel lining. The field measurement and numerical simulation of the tunnel surrounding rock and lining temperature field prove that the setting of insulation layer can effectively prevent the heat dissipation of surrounding rock and play a heat preservation effect, and at the same time obtain the optimal parameters of insulation material and material thickness of tunnel in cold area Zhang Xuefu etc\textsuperscript{2}. According to the analysis of the ambient temperature inside the Kunlun Mountain tunnel and the surrounding rock temperature measured on site, the following laws are obtained: during the tunnel excavation, the concrete in the lining produces a large amount of hydration heat; exhaust gas emissions from construction machinery will also generate a large amount of heat. Due to the closed environment and poor ventilation environment in the tunnel, convection with ambient low temperature air cannot be formed, resulting in timely heat discharge, rising surrounding rock temperature, and thawing of frozen soil. To freeze circle freezing, melting, freeze, this process has carried on the numerical analysis, obtained the following pattern: during melting permafrost, when entering the cold season, ambient air temperature is reduced to less than 0\degree C, under the effect of long time of cold air. The surrounding rock and the cold air form convection, surrounding rock began to heat, when the temperature drops to minus.
temperature of surrounding rock, melting permafrost started back to the frozen. The thermal insulation material is laid in the tunnel, which effectively prevents the heat transfer from surrounding rock to air. Therefore, the surrounding rock temperature is higher than that without insulation layer. The influence of freeze-thawing - freezing process should be fully considered when the stress of surrounding rock, primary support stress and secondary lining stress caused by frost heave force are measured. The more fully the freezing-thawing is considered, the stronger the reliability and authenticity of the data will be. Chen Jianxun, Luo Yanbin[3-5], a lot of field measured temperature data of highway tunnel are obtained. After analyzing the surrounding rock temperature field and the ambient temperature inside the tunnel, the following laws are obtained: (1) the surrounding rock temperature shows periodic oscillation with the variation of ambient temperature; the temperature of the surrounding rock at the same position of the tunnel changes with time in a sine curve. Due to the great influence of ambient temperature at the tunnel entrance, the variation range of surrounding rock temperature at the same radial depth is larger. The temperature amplitude also began to decrease as the longitudinal depth deepened. The temperature amplitude of surrounding rock decreases and the average temperature increases along the radial direction.

2. Tunnel Overview
Wunfeng tunnel is about 7.9km long and extremely deep buried. It is located in a temperate continental monsoon climate with four distinct seasons. It is dry in spring, warm and rainy in summer, cool and sunny in autumn, and cold in winter. The maximum frozen soil depth is 1.45m, and the standard freezing depth is 1.30m. There are many bad geological sections with complex conditions, and the main bad geology includes weak surrounding rock, fault rupture zone, water gusher and rock burst of hard rock with high ground stress.

3. Calculation model, thermal parameters and boundary conditions

3.1. Calculation Model
The finite element software ANSYS was used to establish a two-dimensional tunnel model to simulate the surrounding rock temperature field. When there is insulation layer, the finite element model includes three parts: insulation layer, lining and unfrozen surrounding rock. When there is no insulation layer, the finite element model consists of two parts: lining and unfrozen surrounding rock. The range on the left and right sides of the model is set at 40m, the lower boundary is 65m from the tunnel center, and the upper boundary is 35m from the tunnel vault (lining surface). The finite element model is established as shown in Figure 1.

Figure 1. Finite element calculation model of rock temperature field
3.2. Thermal parameters
The model includes three parts: insulation layer, supporting structure and surrounding rock. The thermal insulation material is made of polyurethane foam. The thermodynamic parameters of the supporting structure are considered according to C30 concrete. The thermodynamic parameters of surrounding rocks are generally obtained by field measurement. The thermodynamic parameters of each part of the tunnel model are shown in Table 1.

| Material                        | Rate of frost heave | The thermal conductivity $\lambda$ (W·m$^{-1}$·K$^{-1}$) | Specific heat $C$ (J·kg$^{-1}$·K$^{-1}$) |
|---------------------------------|---------------------|--------------------------------------------------------|----------------------------------------|
| C30 concrete                    | -                   | 1.510                                                  | 840                                    |
| Frozen surrounding rock (IV)    | -                   | 1.901                                                  | 970                                    |
| Unfrozen surrounding rock (IV)  | Max:5%              | 1.124                                                  | 1164                                   |
| Polyurethane foam               | -                   | 0.027                                                  | -                                      |

3.3. Boundary conditions
The temperature boundary of the model should be determined when simulating the temperature field of wu-nu peak tunnel[6]. By fitting and analyzing the measured data of ambient temperature outside the tunnel, the function of ambient temperature outside the tunnel with time change (temperature function for short) is determined.

The temperature function is:

$$T = t_{av} + t_A \sin\left(\frac{2\pi \times t}{12} + \frac{4\pi}{3}\right)$$ (1)

Type in the

$t_{av}$ -- Annual average temperature, unit °C;
$t_A$ -- Temperature amplitude, unit °C.

According to the literature survey, the ambient temperature near the tunnel entrance is close to the ambient temperature outside the tunnel, so the ambient temperature function outside the tunnel can be used to replace the ambient temperature near the tunnel entrance[7-9]. For the convenience of calculation, the distribution law of ambient temperature field in tunnels in several cold regions is compared. It can be seen that with the increase of tunnel depth, the annual mean temperature of ambient temperature in tunnels gradually decreases, and the temperature amplitude gradually decreases.

When the temperature function is determined, the temperature function at the tunnel opening is taken as the ambient temperature function outside the tunnel[10]. With the increase of depth, the annual mean temperature and temperature amplitude of the temperature function at other sections are reduced correspondingly. The temperature function at each section of the tunnel is as follows.

The temperature function at the tunnel entrance is:

$$T_0 = 5.75 + 18.25 \sin\left(\frac{2\pi \times t}{12} + \frac{4\pi}{3}\right)$$ (2)

The temperature function 50m away from the tunnel entrance is:

$$T_{w0} = 4.75 + 10.25 \sin\left(\frac{2\pi \times t}{12} + \frac{4\pi}{3}\right)$$ (3)

The temperature function at 100m away from the tunnel entrance is:
\[ T_{150} = 3.75 + 8.25 \sin \left( \frac{2\pi \times t}{12} + 4 \pi \frac{t}{3} \right) \]  
(4)

The temperature function at 150m away from the tunnel entrance is.

\[ T_{200} = 2.75 + 7.25 \sin \left( \frac{2\pi \times t}{12} + 4 \pi \frac{t}{3} \right) \]  
(5)

The temperature function at 200m away from the tunnel opening is:

\[ T_{200} = 2.0 + 6.5 \sin \left( \frac{2\pi \times t}{12} + 4 \pi \frac{t}{3} \right) \]  
(6)

At 300m away from the tunnel entrance, the temperature function is:

\[ T_{300} = 1.5 + 4.5 \sin \left( \frac{2\pi \times t}{12} + 4 \pi \frac{t}{3} \right) \]  
(7)

Since the calculation time of transient temperature field is long and the calculation conditions are limited, in order to make the calculation more simple, the steady-state temperature field of surrounding rock is calculated this time, and the steady-state temperature field of surrounding rock is replaced by the steady-state temperature field of surrounding rock\(^{11}\).

4. Analysis of calculation results

Five typical sections with Z distance of 0m, 50m, 100m, 150m, 200m and 300m were selected in the longitudinal direction of the tunnel to calculate the plane temperature field. At the vault of each section, 5 nodes with distances of 0m, 0.5m, 1.0m, 1.5m and 2.0m from the lining surface were selected along the radial direction, and the curve of temperature change over time was recorded.

4.1. Time-history variation law of surrounding rock temperature (without insulation layer)
Figure 2. Time-history variation curve of surrounding rock temperature (without insulation layer)

The temperature curves of 5 nodes along the radial direction of 5 sections with time change were analyzed. Through comparative analysis, the variation law of surrounding rock temperature over time is obtained as follows:

1) Within a calculation period (12 months), the temperature at 5 nodes of 5 sections presents periodic fluctuations. The temperature reaches its lowest point in January and its highest point in July.

2) In January, along the radial direction of the vault, the temperature increases gradually with the increase of depth. The temperature is the lowest at 0m and the highest at 2m (the range for this calculation is 2m).

3) In July, along the radial direction of the vault, the maximum temperature gradually decreases with the increase of depth. The temperature is the highest at 0m and the lowest at 2m (the range for this calculation is 2m).

4) By analyzing the time-varying amplitude of node temperature at different depths on the same section (the difference between the highest temperature and the lowest temperature), it can be seen that the temperature amplitude at different depths is not the same\[12\]. It’s largest at 0m and smallest at 2m. It can be seen that, with the increase of radial depth on the same section, the change of ambient temperature has less and less influence on the surrounding rock temperature.

5) By analyzing the temperature change curve at the junction point of the same depth at different sections, it can be seen that with the increase of longitudinal depth, the node temperature change amplitude becomes smaller and smaller\[13\]. It indicates that the surrounding rock temperature is less and less affected by the ambient temperature outside the tunnel within a certain longitudinal range.
4.2. Time-history variation law of surrounding rock temperature (with insulation layer)

The temperature curves of 5 nodes along the radial direction of 5 sections with time change were analyzed. Through comparative analysis, the variation law of surrounding rock temperature over time is obtained as follows:

1) Within a calculation period (12 months), the temperature at 5 nodes of 5 sections presents periodic fluctuations. The temperature reaches its lowest point in January and its highest point in July.

2) In January, along the radial direction of the vault, the temperature increases gradually with the increase of depth. The temperature is the lowest at 0m and the highest at 2m (the range for this calculation is 2m).
3) In July, along the radial direction of the vault, the maximum temperature gradually decreases with the increase of depth. The temperature is the highest at 0m and the lowest at 2m (the range for this calculation is 2m).

4) By analyzing the time-varying amplitude of node temperature at different depths on the same section (the difference between the highest temperature and the lowest temperature), it can be seen that the temperature amplitude at different depths is not the same. It's largest at 0m and smallest at 2m. It can be seen that, with the increase of radial depth on the same section, the change of ambient temperature has less and less influence on the surrounding rock temperature.

5) By analyzing the temperature change curve at the junction point of the same depth at different sections, it can be seen that with the increase of longitudinal depth, the node temperature change amplitude becomes smaller and smaller. It indicates that the surrounding rock temperature is less and less affected by the ambient temperature outside the tunnel within a certain longitudinal range.

6) By comparing the surrounding rock temperature in January on the same section and at the same radial depth with and without insulation, it is found that the surrounding rock temperature with and without insulation is significantly higher than that without. It can be known that the thermal insulation layer can effectively prevent the heat transfer from surrounding rocks to ambient air.

7) By comparing the surrounding rock temperature in July at the same section and at the same radial depth with and without insulation, it is found that the surrounding rock temperature with insulation layer is significantly lower than that without insulation layer. It can be known that the thermal insulation layer can effectively prevent the heat transfer from ambient air to surrounding rocks.

4.3. Radial Variation law of surrounding rock temperature (January)
The temperature fields of the five sections in the coldest month (January) were calculated, and the temperature distribution cloud map was shown in Fig. 4.
$Z = 100\text{m (insulation)}$

$Z = 100\text{m (noninsulation)}$

$Z = 150\text{m (insulation)}$

$Z = 150\text{m (noninsulation)}$

$Z = 200\text{m (insulation)}$

$Z = 200\text{m (noninsulation)}$
The following laws can be obtained from the analysis of surrounding rock temperature field cloud map:

1) On the same section and at the same radial depth, the surrounding rock temperature without insulation layer is significantly lower than that with insulation layer. It shows that thermal insulation materials affect the heat transfer between the environment and surrounding rocks, and setting thermal insulation materials can spread the heat resistance of surrounding rocks to the low-temperature environment, thus playing a heat preservation role.

2) Along the longitudinal direction of the tunnel and at the same radial depth, the surrounding rock temperature becomes higher and higher. It indicates that with the increase of tunnel depth, the ambient temperature outside the tunnel has less and less influence on surrounding rock temperature.

3) Compared the area of negative temperature zone of surrounding rock with and without insulation layer, the area of the latter is significantly smaller than that of the former. It indicates that the thermal insulation layer can prevent the expansion of surrounding rock freezing circle.

4) On different sections, the range of radial depth above 2m is always in the state of negative temperature, indicating that the thickness of surrounding rock freezing zone may reach 2m (the freezing of surrounding rock is not only related to temperature, but also related to other factors. Even if the surrounding rock is in the state of negative temperature, it may not be frozen).

**4.4. Radial variation law of surrounding rock temperature (July)**

The temperature fields of the five sections during the hottest month (July) are calculated respectively. The temperature distribution cloud map is shown in Fig. 5.
$Z = 50\text{m (insulation)}$

$Z = 50\text{m (non-insulation)}$

$Z = 100\text{m (insulation)}$

$Z = 100\text{m (non-insulation)}$

$Z = 150\text{m (insulation)}$

$Z = 150\text{m (non-insulation)}$
The following laws can be obtained from the analysis of surrounding rock temperature field cloud map:

1) On the same section and at the same radial depth, the surrounding rock temperature without insulation layer is significantly higher than that with insulation layer. It shows that the heat preservation material affects the heat transfer between the environment and surrounding rock, and setting the heat preservation material can spread the heat from the environment with high resistance value to surrounding rock, thus playing a heat preservation role.

2) Along the longitudinal direction of the tunnel and at the same radial depth, the surrounding rock temperature becomes lower and lower. It indicates that with the increase of tunnel depth, the ambient temperature outside the tunnel has less and less influence on surrounding rock temperature.

5. Conclusion

1) The surrounding rock temperature changes periodically under the influence of ambient temperature; Thermal insulation can effectively prevent heat transfer between surrounding rock and environment.

2) In the cold month (January), the surrounding rock temperature is higher than the ambient temperature. Along the radial direction of the tunnel, the surrounding rock temperature gradually rises; in the hot month (July), the surrounding rock temperature is lower than the ambient temperature, and along the radial direction of the tunnel, the surrounding rock temperature gradually decreases.

3) With the increase of tunnel depth, the ambient temperature outside the tunnel has less and less influence on surrounding rock temperature.
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