Field measurements and parametric studies for the thermal environment of underground tunnel entrance in cold climate zones

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Abstract. In frozen regions, especially metro tunnel portal sections, which are vulnerable to an externally low-temperature atmosphere, would lead to frozen damage affecting traffic safety. To clarify how the air temperature field at tunnel portal sections varies with periodically changing atmospheric temperature, a site test was conducted on Metro Line 1 in Hohhot in the Inner Mongolia Autonomous Region, and the basic heat transfer equation and principle of energy conservation were introduced to establish a basic theoretical model, which was compared with the results from other regions. By comparison with testing results in other regions, the theoretical model was essentially consistent with the variation rules of the tested temperature. Therefore, the research could theoretically direct the heat preservation and freeze prevention of key facilities and equipment in metro tunnel portal sections in frozen regions.

1 Introduction

The outdoor air temperature of cold climate zones is usually below 0°C in winter [1], which could result in the low air temperature near the underground tunnel entrance. The the freezing hazardousness of water pipes and hydrant systems is increased, thus affecting the regular operation of the subway line [1-3]. Hence, the prediction of air temperature form the tunnel entrance to shallow buried tunnel section is important for engineering design in cold climate cities.

In order to describe the temperature field of the underground tunnel, some theoretical studies [4-6], experimental [7, 8] and numerical methods [9, 10] have been conducted. The research by Bharadwaj showed that shallow-buried and deep-buried tunnels would have different temperature environments [11].

Only a few studies have been conducted on shallow-buried tunnels, despite many studies being conducted in the fields of deep-buried tunnels. In this paper, a gas-solid-coupled heat transfer model of rectangular subway tunnel wall is established.

2 Methodology

Based on the heat transfer differential equation and energy conservation principle, a coupled heat transfer model between air and wall surface in the tunnel entrance is deduced. The fitting formulas of air temperature varied with tunnel length or time were carried out respectively by the data measured at Hohhot Metro Line 1. And then, the theoretical model can be obtained and validated to predict the air temperature near the tunnel entrance in cold climate zones.

2.1 Theoretical Basis

Air temperature $T_j$ in the shallow-buried tunnel is mainly focused in the study. The following hypotheses are proposed before theoretical analysis: (1) The isotropy and thermophysical property parameters of wall rock are assumed to be constants. (2) It is assumed that there is no internal heat source on the wall rock outside the tunnel.

According to the heat transfer differential equation, the heat transfer along the $z$ direction is considered. The wall rock temperature $T_s$ can be expressed as [12]:

$$T_s = T_{am} + \phi T_{aw} \exp\left(-z\sqrt{\frac{\pi}{\alpha T}}\right) \cos\left(\frac{2\pi}{T} t + \varphi - z\sqrt{\frac{\pi}{\alpha T}}\right)$$

(1)

Where, $T_{am}$ is the annual mean temperature, $T_{aw}$ is the fluctuation amplitude, $T$ is the period, $\varphi$ is the initial
phase, $\phi$ and $\psi$ are both functions of $\nabla^2 T/\lambda^2$, $\alpha$ is the thermal diffusivity of the wall rock, $m^2/s$, $h$ is the convective heat transfer coefficient between atmosphere and ground, $W/(m^2K)$, $\lambda$ is the temperature conductivity coefficient of the wall rock, $W/(mK)$.

The energy conservation equation of the air element is given by analyzing the heat balance of the air element. During the time of $d\tau$, the heat penetrating into the element from $y$ surface is shown as follows:

$$d\Phi_y = \rho Aw_{y}T/d\tau$$

(2)

Where, $\rho$ is the air density, $kg/m^3$, $A$ is the area of standard cross section of the tunnel, $m^2$, $c_p$ is the specific heat capacity of air, $kJ/(kg \cdot K)$, and $w_{y}$ is the air velocity in the tunnel, $m/s$.

In addition, the heat transfer between the air element and four surfaces of tunnel is carried out, which is described as follows:

$$d\Phi_y = U_h(T_{w} - T_{r})dyd\tau$$

(3)

Where, $U$ is the perimeter of the tunnel standard plane, $m$, $h_f$ is the convective heat transfer coefficient between the wall and the air in the tunnel, $W/(m^2K)$, and $T_{w}$ is the temperature of wall rocks in the tunnel, $K$; $I$ is the slope of the tunnel, %.

Because it can be regarded as one-dimensional incompressible flow for the air flows in the tunnel, we can obtain the energy conservation equation as:

$$- \rho Ac_p w_{y} \frac{\partial T}{\partial y} + U_h(T_{w} - T_{r}) + Q = \rho Ac_p \frac{\partial T}{\partial t}$$

(4)

Where, $Q$ is the intensity of the heat source per unit time in unit time, $W/m$.

### 2.2 Experimental method

A shallow-buried tunnel from Hou butaqi station to Shilandai station of the Metro Line 1 was selected for the field test in Hohhot, Inner Mongolia, China. The field measurements of this study lasted for a full winter.

The subway was not yet on operation between Nov 1st and Dec 28th in 2019, and was suspended during Jan 28th to Feb 27th in 2020 due to the epidemic. The period of 2019.12.29-2020.1.28 shall operate normally, and the interval between trains shall be 10 minutes. Owing to the impact of the epidemic, the interval between Feb 28th and Apr 19th in 2020 is 20 minutes.

As shown in Fig. 1, fourteen testing points were set in the tunnel, and one outdoor testing point was placed away from the tunnel portal to record temperature. The testing point 4 was selected to measure air velocity. The test time was from 12:00 to 16:30 on Oct 4th, 2019.

### 3 Results

#### 3.1 External Atmospheric Temperature

According to the results of field test, we found that the coldest month of daily mean temperature is January in Hohhot. From Fig. 2 we can see that a fitting formula of $T_a = 9.74 + 16.82\cos\left(\frac{2\pi t}{365} - \frac{3\pi}{5}\right)$ can present the periodic variation of external atmospheric temperature.

![Fig. 2 Daily average temperature of atmospheric temperature.](https://doi.org/10.1051/e3sconf/202235602031)

#### 3.2 Air Temperature During Operating Hours

Measuring results of the daily average temperature of all testing points are shown in Fig. 3. The hourly temperature from 06:00 to 22:00 was averaged as the daily average temperature during operating hours.

Fig. 3 illustrates that air temperature in the tunnel in winter gradually increased with tunnel depth, and the air temperature changed little after a certain point.

![Fig. 3 Air temperature variation with distance $y$ in the tunnel.](https://doi.org/10.1051/e3sconf/202235602031)
3.3 Air Velocity During Non-operating Hours

The testing results revealed the performance of air flow caused by the temperature difference between the testing point 4 and outdoor atmosphere. From Fig. 4 we can see that the air velocity ranges from 0 to 1.2 m/s.

Fig. 4 The air velocity of point 4.

3.4 Air Temperature During Non-operating Hours

During the non-operating hours of 22:00—06:00, air flow is mainly driven by thermal buoyancy through the tunnel. Fig. 5 illustrates that the outdoor temperature was usually below 0℃ in winter. The air temperature increased rapidly within a distance of 240 m, and then the air temperature has gradually stabilized in the tunnel.

Fig. 5 Variation in air temperature with tunnel distance during non-operating hours.

4 Discussion

According to the results of field test in cold regions, the worst condition often happens at non-operating hours in the coldest month. A theoretical model of air temperature near the tunnel entrance in cold climate zones should be studied.

4.1 Simplification of the Theoretical Model

During 22:00—06:00, there is no heat production or piston wind generated by trains, and with $A' = \frac{U_B}{\rho A_c}$. Therefore, Eq. (4) can be simplified as follows:

$$u_f \cdot \frac{\partial T_f}{\partial y} + \frac{\partial T_f}{\partial t} = A' \cdot (T_u - T_f)$$

(5)

where $u_f$ is the air velocity of buoyancy-driven ventilation.

We carried out the fitting of air temperature between the tunnel portal and Test Point 7. After fitting, the rules of air temperature variation with tunnel distance $y$ at different dates were obtained, as shown by Formula 6.

$$T_f = a - b \cdot 0.99^y$$

(6)

In the above, $a$ can be regarded as the air temperature, $b$ is the value of the stabilized air temperature at the tunnel depth minus the external temperature.

Then, we conducted a fitting of the air temperature between Test Point 1 and Test Point 7, thus obtaining the rules of air temperature variation with a time of $t$:

$$T_f = d + e \cdot \cos \left( \frac{2\pi}{T} \cdot t + f \cdot \pi \right)$$

(7)

Where $d$ represents the annual average air temperature in the tunnel, $e$ is the amplitude temperature of the air in the tunnel, $f$ is the internal air phase value with a small changing range, regarded as remaining consistent with the phase of the external atmosphere. Parameter $e$ is fitted according to distance $y$, and $e = a' - b' \cdot 0.99^y$.

By placing the function in Eq. 5 after derivation, the expression of $T_f(y,t)$ can be obtained as follows:

$$T_f(y,t) = T_u - \frac{1}{A'} \left[ hu_f \cdot 0.99^y \ln(0.99) + e \cdot \frac{2\pi}{T} \sin \left( \frac{2\pi}{T} \cdot t + \phi \right) \right]$$

(8)

By substituting into $b$ and $e$, the formula can be transformed as follows:

$$T_f(y,t) = T_u - \frac{1}{A'} \left[ (a - T_u) u_f \cdot 0.99^y \ln(0.99) + \left[ a' - 0.99^y (a' - T_u) \right] \frac{2\pi}{T} \sin \left( \frac{2\pi}{T} \cdot t + \phi \right) \right]$$

(9)

where $a$ is the stable-state air temperature in the deepest part of the tunnel and $a'$ is the amplitude temperature of the stable-state air in the deepest part of the tunnel.

4.2 Verification of the Theoretical Model

To verify the theoretical model, we tested Metro Line 1 in the city of Lanzhou, Gansu Province. The tunnel portal section was tested, as shown in Fig. 6, which provides a diagram of the test points in Lanzhou.
Fig. 6 The arrangement of test points in Lanzhou

Fig. 7 shows the verification of the theoretical model by the Test Point 3 of Lanzhou Metro. From this figure, the period from January 7 to February 20, 2020 showed a larger theoretical value than the experimental period because a higher air temperature in the tunnel in this period brought thermal compression ventilation into the tunnel from outside, leading to a lower temperature at test points near the tunnel portal. Similarly, during the period of May 1 to 30, 2020, the theoretical values smaller than the experimental values had essentially the same variation trend as each other.

Fig. 7 Verification of the theoretical model

5 Conclusion

In this paper, the air temperature environment of the tunnel portal section in frozen regions in China was analyzed by theoretical analysis and site testing.

1) The extremely lowest air temperature in the tunnel generally occurs during the non-operating hours in the coldest month each year, so the existing laying distance of the insulation layer should be improved based on the external temperature environment during non-operating hours.

2) By comparing the theoretical model with testing results in other regions, the theoretical model agreed with the tested data, which has significant instruction for pipeline insulation strategies.

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Reference