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# Frost front research of a cold-region tunnel considering ventilation based on a physical model test

Lulu Liu[a,b,*], Zhe Li[b], Xiaoyan Liu[a], Youyun Li[b]

[a] *Institute of Geotechnical Engineering, Southeast University, Nanjing 211189, China*
[b] *Key Laboratory of Special Area Highway Engineering, Ministry of Education, Chang'an University, Xi'an 710064, China*

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## ABSTRACT

The frost front of a cold-region tunnel is important parameter to determine insulation layers. However, the analysis of frost front under ventilation remains changing due to terrible field conditions. In this paper, in order to obtain the distribution law of frost front in a cold-region tunnel under ventilation, the model experiment system with similarity ratio of 1:37 was built relying on the Daban Mountain tunnel. The temperature field of model was analyzed under different airflow temperatures and inlet wind velocities. The radial three-domain governing equations and longitudinal parabolic governing equations of frost front were established. The correctness of the governing equation for frost front was verified in comparison with field data. The modified calculation model of frost front could be used to the approximate estimation for frozen depth of a cold-region tunnel and check the correctness of the numerical solution and computer program.

## 1. Introduction

Many cold region tunnels appear in Canada, Norway, China, Russia and Japan (Tan et al., 2014). In the northwest and northeast of China, under the condition of ventilation, strong heat transfer occurs between tunnel lining and air in a cold-region tunnel, resulting in structure cracking, water leakage, ice covering and blocking drains with ice (Zeng et al., 2017). Even, some of tunnels cannot be used for up to 8–9 months a year, which affected the transportation negatively (Lai et al., 2000, 2002, 2005). Frost front is significant to analyze frozen expansion of surrounding rocks and is an important reference to insulation layer calculation. Therefore, the frost front becomes an urgent important issue to solve frost-resistant problems in cold-region tunnels (Huang et al., 1986; Johansen et al., 1988).

Some scholars have done some researches of frost front, including a pipe or multi tubes. For example, Pekeris et al. obtained a first-order correction to pseudo-steady-state solutions applied to the freezing soil around a long pipe (Pekeris and Slichter, 1939). With reference to findings (Carslaw and Jaeger, 1965), Hwang (1977) tested the validity of the two-dimensional solution for a buried pipe by finite element software. Based on temperature boundary conditions along the axial direction of pipeline, Shamsundar (1982) proposed the analytical solution of outside temperature field of the circular pipe.

Jacovides and Mihalakakou (1995) performed the analysis of temperature field of buried pipes. Combining with the plate freezing theory and single pipe freezing theory, Cai (2009) analyzed the extended thickness of frozen wall under the condition of intersectional freezing multi tubes. Considering the existence of the unfrozen water in the frozen soil, Zhou and Zhou (2012) established the discrete phase change model of temperature field around the circular pipe. In view of frozen domains and unfrozen domains, Wu et al. (2010) explored influence factors on the temperature distribution of frozen soil, and investigated the effect of moisture content, dry density and soil type on the expansion speed of frost front. By means of the time-comparison method, Zhang et al. (2016) obtained the internal relation between stability depth of frozen front and frozen time after freeze-thaw cycle. Although above researches of frost front involved the analytical solution of temperature field, mainly focused on the pipeline rather than the cold-region tunnel.

Investigations of the analytical solution of temperature field in a cold-region tunnel centralized the theoretical derivation, numerical simulation and circular tunnel without considering the different domains around the tunnel. However, few studies have focused on the analytical solution of frost front comprising different domains, ventilation and tunnel length in cold-region tunnel. Lai et al., 2002a,b obtained the approximate analytical solution for simplified heat transfer equation using the dimensionless method and the perturbative method. Employing the energy conservation principle, Krarti and Kreider (1996) proposed a computational model of temperature amplitude and average temperature in underground tunnel. Takumi et al. (2008) utilized the

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[*] Corresponding author at: Institute of Geotechnical Engineering, Southeast University, Nanjing 211189, China.
*E-mail address:* believeliululu@163.com (L. Liu).

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**Table 1**
Scaling parameters of model of geometry dimension.

| Parameters | Prototype | Model |
|---|---|---|
| Inner radius of the tunnel | 454 (cm) | 12.2 (cm) |
| Thickness of the initial lining | 40 (cm) | 1.08 (cm) |
| Thickness of the second lining | 68 (cm) | 1.84 (cm) |

**Table 2**
Thermal parameters.

| Parameters | Prototype | Model |
|---|---|---|
| Thermal conduction of surrounding rocks | 2.474 (W/m K) | 1.551 (W/m K) |
| Heat specific coefficient surrounding rocks | 0.114 ($m^2$/d) | 0.098 ($m^2$/d) |

**Table 3**
Relevant parameters of lining insulation layer.

| Parameters | Lining surface insulation layer | | Lining inner insulation layer | |
|---|---|---|---|---|
| | Hard polyurethane board | Rubber plastic insulation board | Hard polyurethane board | Rubber plastic insulation board |
| Inner radius | 12.2 cm | 12.2 cm | 14.04 cm | 12.04 cm |
| Outer radius | 12.335 cm | 13.2 cm | 12.175 cm | 13.54 cm |
| Calculation length | 300 cm | 300 cm | 300 cm | 300 cm |
| Thermal conduction | 0.018 (W/m K) | 0.034 (W/m K) | 0.018 (W/m K) | 0.034 (W/m K) |

principle of energy conservation and superposition to give the analytical solution of airflow temperature field in a cold-region tunnel. Xia et al. (2010) adopted the separation variable method and the Laplace integral transform principle to gain explicit analytic solutions of transient temperature field in cold-region tunnel with an insulation layer. Prashantk and Singh (2009) applied the superposition principle and the separation variable method to get the analytic solution of transient temperature field of circular section at the convective boundary.

In this paper, the distribution laws of temperature field under different entrance temperatures and wind velocities were investigated by a model test. Based on tested results of model, the radial three-domain governing equations and longitudinal parabolic governing equations of frost front were established. Compared the analytical solution results with field monitoring results, it can be seen that the modified analytical solution results have good consistence with field monitoring results. This modified analytical solution can serve as a guide for the engineering computation and checking correctness of numerical solution and computer program.

## 2. Physical model test

### 2.1. Similarity law

A physical model must satisfy a series of similarity requirements in terms of the geometry, thermal parameters of various materials (thermal insulation, lining, surrounding rock) (Wang, 1990). Due to the poor geological condition of tunnel entrance, the thickness of the initial lining is approximately 40 cm, and the thickness of the second lining exceeds 68 cm (Wu et al., 2001). Taking into account the size of laboratory, the economy and the operability of this tunnel model, the reduced scale of 37 in geometric dimension was selected. According to the reduced scale of 37, the longitudinal length of this tunnel model is 41 m, which is far beyond the size of refrigeration system. Considering the convenience and referring to the tunnel ventilation model test (Wang et al., 2014, Chen et al., 2016, Feng et al., 2016), the model length of 3 m was selected. Table 1 shows the scaling parameters of tunnel model of geometry dimension.

According to the Kosovic principle ($C = \alpha/\lambda$, $K_o = Q_p/T_pC_p = Q_m/T_mC_m$), the following equations can be obtained.

$$C_Q/C_TC_C = 1,\ \ C_Q = Q_p/Q_m,\ \ C_Q = T_p/T_m,\ \ C_Q = C_p/C_m \tag{1}$$

where subscript p and m stand for prototype and model, respectively. $T$ represents the temperature of surrounding rocks, °C; $Q$ is the latent heat released during freezing, kJ/$m^3$, °C; $\alpha$is the heat specific coefficient, $m^2$/d; $\lambda$denotes the thermal conductivity, kJ/$m^3$ d °C.

The lining concrete used in model and prototype is same, and parameters in Eq. (1) are determined as $C_C = 1$, $C_Q = 1$, $C_T = 1$, $T_p = T_m$. Hence, the reduced scale of temperature in lining concrete is 1. Detailed calculation process of reduced scale of temperature in surrounding rock and insulation layer is included in the test material (2.2).

### 2.2. Test material

#### 2.2.1. Surrounding rock

The material of surrounding rock for Daban Mountain tunnel is complicated and variable. Moreover, field rocks are very tough to be taken back to laboratory. Therefore, configuration materials were selected in this test as surrounding rock material. After crushing and screening, the configuration materials were reconstituted, namely, 7.5% water, 32.2% sand, 4.3% lime, 12.9% gravel and 43.0% soil. According to calculation, the density, porosity and moisture content of surrounding rock material are 2.6 kN/$m^3$, 34%, and 14% respectively.


(a) Power system (b) External circulation system

**Fig. 1.** Refrigeration system.