Numerical Investigation of the Temperature Field of Freeze-proof Separate Lining in a Cold-region Tunnel

J.X. Lai [1)*]***, H.B. Fan*** [2)]***, W.W. Dong*** [3)] ***and Q. Liu*** [4)]

[1)] Assistant Professor, Shaanxi Provincial Major Laboratory for Highways, Bridges and Tunnels, Chang'an University, Xi'an 710064 China
[2)] PhD candidate, School of Highway, Chang'an University, Xi'an 710064 China.
[3)] Postgraduate, School of Highway, Chang'an University, Xi'an 710064 China.
[4)] Postgraduate, School of Highway, Chang'an University, Xi'an 710064 China.
* Corresponding Author: E-Mail: 373159626@qq.com

ABSTRACT

To analyze the temperature field of freeze-proof separate lining in cold-region tunnels, based on a tunnel on national highway number 307, the numerical model was established by the finite element software ANSYS, combined with the heat transfer theory using a cylindrical coordinate system. The change law of temperature field of the separate lining was investigated when the ventilation temperatures were -5℃, -10℃ and -15℃. The heat insulation effect of separate lining was also analyzed when the diameters of holes in the insulating layer were 5 mm, 10 mm and 15 mm, respectively. The results show that the temperature of lining and rock masses decreases gradually with the decrease of ventilation temperature and that the maximum temperature difference occurs in a closed air layer; considering that the temperature is still above 0℃. When the ventilation temperature is -15℃, the separate lining structure can protect the tunnel from freezing damage. The temperature field of the lining changes significantly if the diameters of holes in the insulating layer are large; the temperature of rock masses is -8.5℃ when the diameter is 15 mm, and the structure of the tunnel may suffer freezing damage. The tightness of the insulation layer has significant influence on the heat insulation effect of separate lining.

KEYWORDS: Tunnels in cold regions, Separate lining, ANSYS, Temperature field, Ventilation temperature, Insulating layer.

INTRODUCTION

With the rapid development of transportation in China, increasing numbers of tunnels were built in the cold north-west and north-east regions. However, the main problem of constructing tunnels in cold regions was freeze-thaw. Due to the force of frost, cracks in the lining of the tunnel could reach up to 5 cm, hindering the traffic service greatly (Liu et al., 2011). Adding an insulating layer is the simplest and most effective way to resolve the freezing damage; however, the research of thermal field is crucial to address the problem. At present, there are considerable researches concerning heat insulation and the thermal field of tunnels. For example, Bonacina et al. (1973) proposed numerical calculation methods of phase change thermal field; Comini et al. (1974) analyzed a nonlinear problem of the phase change thermal field using FEM; Lai et al. (1998) carried out a nonlinear analysis of the couple problems of temperature, seepage and stress field in

Accepted for Publication on 7/5/2015.

cold-region tunnels. Results revealed that the influence of frost-heaving force on the stresses of the tunnel lining is very large and the effect of this factor on the tunnel lining should be taken into account in the design of cold region engineering; Lai et al. (2002) deduced the analytic solution of the thermal field in circular section tunnels in cold regions. It can be seen that the approximate analytical solution is of higher precision when comparing the approximate analytical results with finite element results. Zhang et al. (2002, 2003 and 2004) conducted a numerical analysis and nonlinear analysis of the three-dimensional thermal field of tunnels in cold regions and made a forecast that there would be a re-freezing problem in the Qinghai-Tibet railway permafrost tunnel in the Kunlun Mountains. Lai et al. (2005) carried out a three-dimensional nonlinear analysis on heat transfer and heat convection in a cold-region tunnel. Zhang et al. (2006) conducted a three-dimensional nonlinear analysis for the coupling problems of seepage fields and thermal fields. The accurate results could be got by using nonlinear analysis; however, the process of calculation was more complex, and the analytic solution was difficult to obtain. Chen et al. (2007) tested a highway tunnel in a cold region for a year and a half, demonstrating that temperature changes in the tunnel were cyclical (approximately like a sinusoidal curve). Although a lot of useful data has been obtained in the field test, the cost of time and money were also enormous. Zhang et al. (2010) obtained a theoretical solution for the thermal field of tunnels by orthogonally deploying the superposition principle and the Bessel functions. The formula of temperature amplitude changed along an axis of time derived using empirical formulae and energy conservation equations. Xia et al. (2010) obtained the analytic solution of the thermal field concerning the effect of the lining and insulating layers *via* a combination of variable separation and Laplace transformation. In the recent decades, considerable research effort has been devoted to heat insulation of cold region tunnels. Tan et al. (2011, 2013 and 2014) made a numerical simulation of the thermal field of rock masses, considering the effect of phase change and ventilation and applied it to the design of tunnel insulating layer. Zhang et al. (2013 and 2014) applied a new heat exchanger to the electrical trace heating system of tunnels in cold regions and established a new heat exchange model of tunnel lining. The analytic solution of a thermal field was obtained and the functions of the heat exchanger were also investigated. The above heat insulation methods have been widely used in cold region tunnels. Though they could protect the tunnel from freezing damage efficiently, the cost of the heat insulation system was also very high.

Overall, the researches on the composite lining in cold region tunnels have obtained abundant results. However, few studies have focused on the temperature field of separate lining (Einar et al., 2002). Deng et al. (2012) carried out preliminary research on the thermal insulation principle of separate lining and conducted a laboratory test on the effect of heat insulation, but they have not proceeded to do further research on its thermal field. In this paper, the geothermal field of cold region tunnels was taken as an energy source, and the temperature field of separate lining was analyzed combining with the test results of preliminary temperatures of a tunnel in cold regions. The research can provide a theoretical basis for the design of heat insulation and freeze-proof separate lining.

ABSTRACT OF SEPARATE LINING

The anchor-plate is used as permanent support in the separate lining, which supports the entire weight of rock masses of the tunnel. The bush, installed closed with anchor-plate retaining, serves to preserve heat, prevent fire and improve the smoothness of the tunnel; it does not bear the load of rock masses. The basic design concept of separate lining is shown in Figure 1.

Two heat transfer methods shall be taken into consideration in the research of the thermal field of cold-region tunnels. The main heat exchange way of the rock mass is heat transference; convection mainly happens between the air and the surface of the cold region tunnel. Heat transfers among the rock mass, the lining, the confined air layer, the liner and the cold air in the tunnel. Its insulation principle is to decelerate heat transfer by installing a confined air layer and insulating layer so as to prevent the rock masses and lining from freeze damage. The process of heat transfer of separate lining is shown in Figure 2.

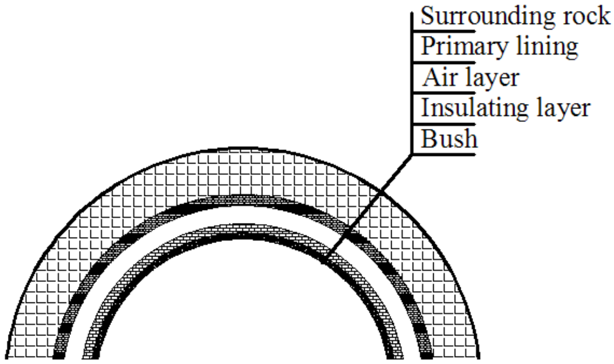


Figure (1): Separate lining structure

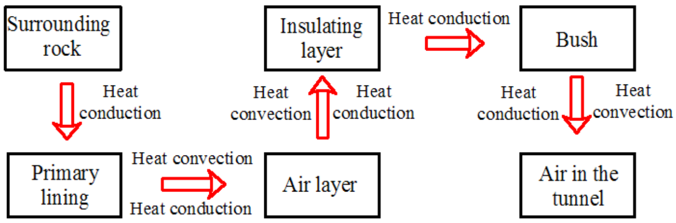


Figure (2): Heat transfer process of the separate lining

ASSUMPTIONS AND PARAMETERS OF CALCULATION

Assumptions of Calculation

The assumptions are as follows:

(1) The thermal resistance of bush and heat insulating layer, lining and surface of rock masses is not considered. The temperature is equal to the heat flow at the contacting frontier. The flow velocity of air in the tunnel is constant, and the concrete is well-distributed and isotropic.

(2) It can be assumed that the thermodynamic features of polyurethane foam do not change when the temperature of the earth changes during the calculation. The rock masses are well-distributed and isotropic.

(3) The annual average temperature value of the entrance area is adopted as the boundary condition, regardless of temperature changes as one travels further into the tunnel (Deng et al., 2012).

Earth Temperature Gradient

One tunnel is located on the national highway No.307 in Sichuan Province. The earth temperature gradient of Sichuan Basin is 1.7~2.5℃/100m and 4~8.5℃/100m in the Kunlun Mountains along the Qinghai Tibet highway. Taking the location, altitude and lithology of the tunnel into consideration, the gradient of earth temperature adopted was 3.5℃/100m.

Analysis of Tunnel Temperature

The temperature changes can be divided into two sorts: daily variation and annual variation. The daily variation can be ignored for its little effect on the tunnel. The annual variation, however, may exert a significant effect on it. On the basis of meteorological data, the minimum temperature occurs in January, and the maximum occurs in July. The annual change of temperature can be formulated as (Deng et al., 2012):

$$T(t) = T_m + A\cos[\frac{\pi}{6}(t - t_0)] \quad (1)$$

where T is the temperature; T_m is the annual average temperature; A is the annual temperature amplitude; t is time and t_0 is the month of max. temperature.

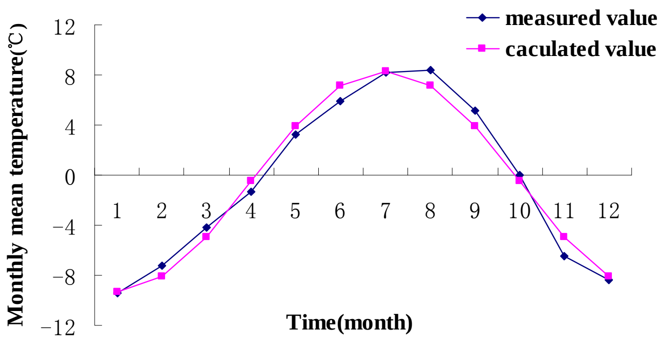


Figure (3): Calculated and measured temperature values of the west entrance of the tunnel

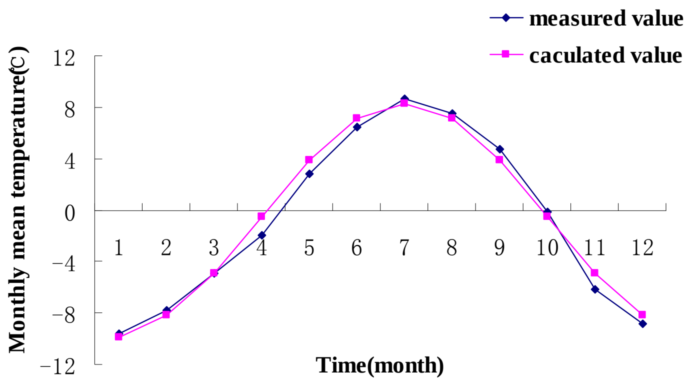


Figure (4): Calculated and measured temperatures value of the east entrance of the tunnel

Seven measuring points were set up in the eastern and western entrances of the tunnel to record the monthly average temperatures. The monthly mean temperatures of the east and west entrances of the tunnel are shown in Table 1.

Based on the test results of tunnel temperatures, the temperature formulae of the eastern and western entrances are as follows:

$$T(t) = -0.52 + 8.80\cos[\frac{\pi}{6}(t - 7.0)]$$
$$T(t) = -0.77 + 9.15\cos[\frac{\pi}{6}(t - 7.0)] \quad (2)$$

As Figures 3 and 4 show, the test results are consistent with the calculated results. It can be concluded that there are 5 months when the temperatures of the eastern and western entrances fall below 0℃. Hence, it is critical to take some heat-preserving measures.

Parameters of Materials

The parameters of different materials are shown in Tables 2, 3 and 4.

Table 1. Monthly mean temperature of the east and west entrances of the tunnel

Month	1	2	3	4	5	6	7	8	9	10	11	12
West entrance	-9.4	-7.2	-4.2	-1.3	3.2	5.9	8.2	8.4	5.1	0	-6.5	-8.4
East entrance	-9.6	-7.8	-4.9	-2	2.8	6.5	8.7	7.5	4.7	-0.1	-6.2	-8.8

Table 2. Thermophysical parameters of concrete

Temperature	Thermal Conductivity	Specific Heat	Density
（℃）	(J/（m ℃）)	(J/（kg ℃）)	（kg/m^3）
-15	2.56	1390	2480
20	2.23	1920	

Table 3. Thermophysical parameters of rock mass

Temperature	Thermal Conductivity	Specific Heat	Density
（℃）	(J/（m℃）)	(J/（kg℃）)	（kg/m^3）
-15	1.16	762	2700
-3	1.14	845	
-1	1.13	894	
20	1.09	1071	

Table 4. Thermophysical parameters of insulating medium

Medium	Thermal Conductivity	Specific heat	Density
	(J/（m℃）)	(J/（kg℃）)	（kg/m^3）
Air	0.0259	0.24	1.29
Polyurethane foam board	0.021	2475.2	30

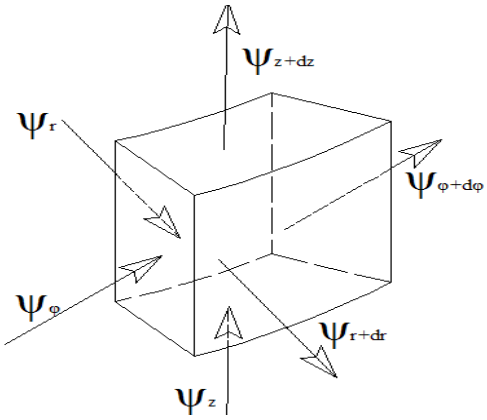


Figure (5): Infinitesimal volume in cylindrical coordinates

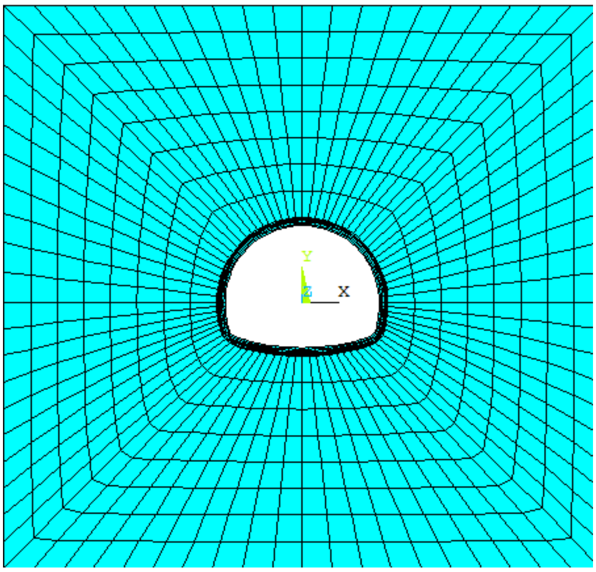


Figure (6): Two-dimensional finite element model

THE EFFECT OF VENTILATION TEMPERATURE ON THE SEPARATE LINING

The Establishment of the Models

(1) The Mathematical Model

In light of the convenience of setting up the mathematical model, the U-shaped tunnel is simplified as circular and the elements of volume are analyzed using cylindrical coordinates. The heat flow from any direction can be divided into *r*, φ, *z* directions, and we only take the heat transference of *r* direction into account. As shown in Figure 5, the heat flow of volume elements can be expressed using the Fourier's law:

$$\psi_r = -\lambda \frac{\partial t}{\partial r} d\varphi dz \cdot \quad (3)$$

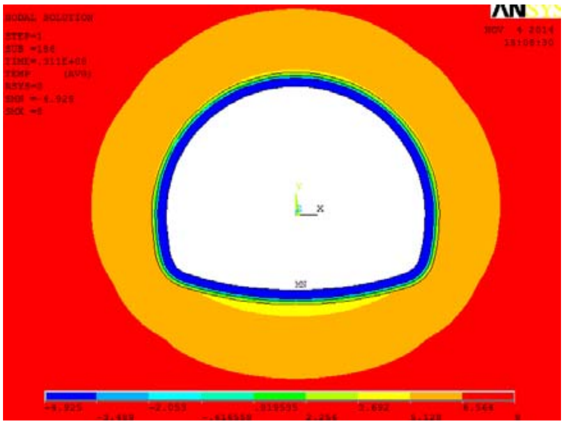
The heat flow of volume elements deducted by the formula $r = r+dr$ can also be expressed using the Fourier's law:

$$\psi_{r+dr} = \psi_r + \frac{\partial \psi}{\partial r} dr$$
$$= \psi_r + \frac{\partial}{\partial r}(-\lambda \frac{\partial T}{\partial r} d\varphi dz) dr \quad (4)$$

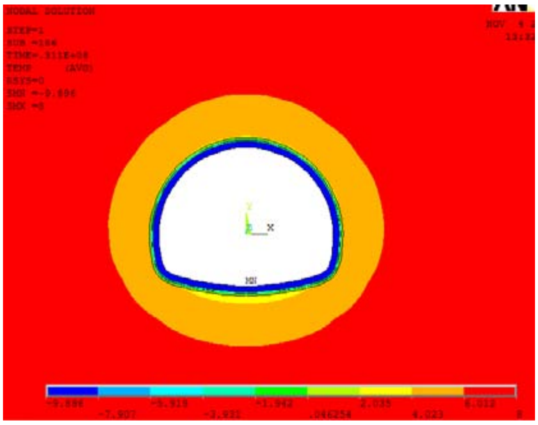
Increments of volume elements' thermodynamic energy can be presented *via* the following formula:

$$E = \rho c \frac{\partial T}{\partial t} dr d\varphi dz \qquad (5)$$

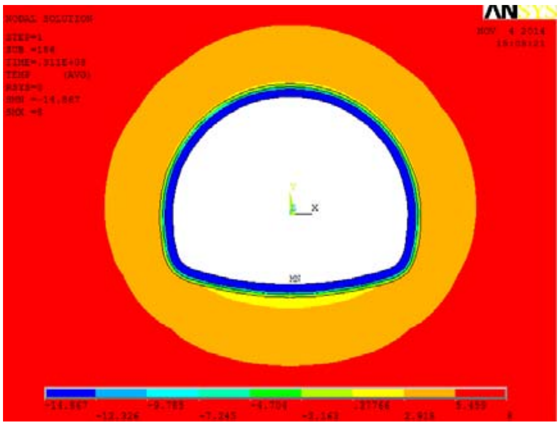
where λ is the thermal conductivity of the volume element; c is specific heat; ρ is density; T is temperature and t is time.



(a) -5℃



(b) -10℃



(c) -15℃

Figure (7): The temperature field of the separate lining under different ventilation temperatures

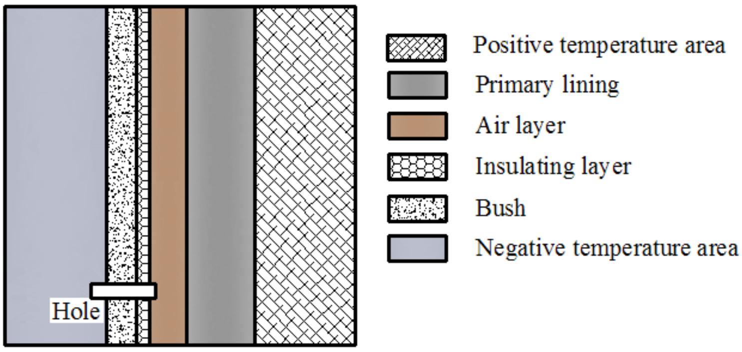


Figure (8): Insulating layer with hole

In accordance with the law of energy conservation, the volume element has a thermal equilibrium relationship in any time:

$$\psi_r = \psi_{r+dr} + E \quad (6)$$

where c is specific heat; ρ is density; T is temperature and t is time.

Substituting Formulae (3), (4) and (5) into Formula (6), the one-dimensional transient differential equation of heat conduction for the tunnel model can be obtained as:

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(\lambda r \frac{\partial T}{\partial r}) \quad (7)$$

Therefore, the two-dimensional transient differential equation of heat conduction for the tunnel model is as follows:

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(\lambda r \frac{\partial T}{\partial r}) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}(\lambda \frac{\partial T}{\partial \varphi}) \quad (8)$$

(2) The Finite Element Model:

The specific heat and thermal conductivity of rock masses change with temperature. Therefore, the energy conservation on the interface is nonlinear, and analytic solution is difficult to get. FEM was used to find the numerical solution, and the calculation formula for the finite element is as follows:

$$[c(T)]\{\dot{T}\}+[K(T)]\{T\}=\{Q(T,t)\} \quad (9)$$

where $[c(T)]\{\dot{T}\}$ is heat preservation and K is heat transfer coefficient.

The ANSYS software, featured with the function of analyzing heat in a steady state or a transient state in a two-dimensional situation, is applied to the calculation model. The PLANE55 unit is adopted to simulate the framework of the tunnel. The upper and lower boundaries of the model depend on the ground temperature gradient and the depth of the tunnel. The left and right boundaries depend on the heat insulation boundary. Finite element model is shown in Figure 6.

Results of Numerical Simulation

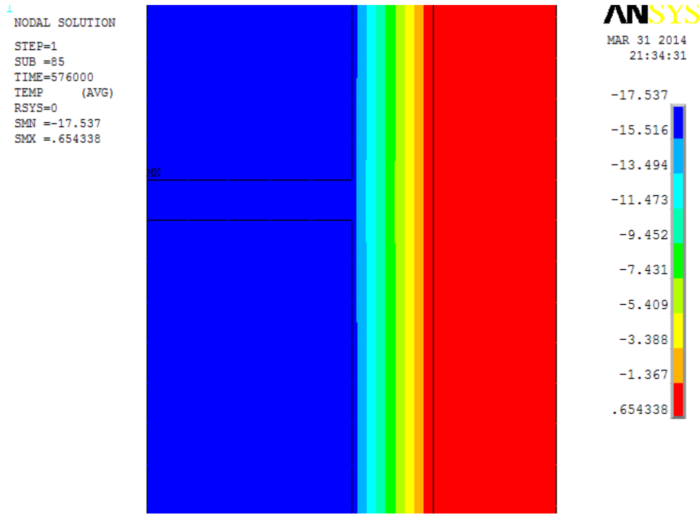
The distribution laws of thermal field with the ventilation temperature of -5℃, -10℃ and -15℃ are shown in Figure 7. As can be seen, the temperature is distributed in a linear fashion and the maximum amplitude of temperature lies in the confined air layer; it is shown that the separate lining decelerates heat transfer and preserves heat. As shown in Figure 7(c), the temperature of the rock mass exceeds 0℃, even if the ventilation temperature drops to -15℃. Hence, the separate lining can prevent rock masses from freezing.

EFFECTS OF HOLES IN INSULATING LAYER ON THERMAL FIELD

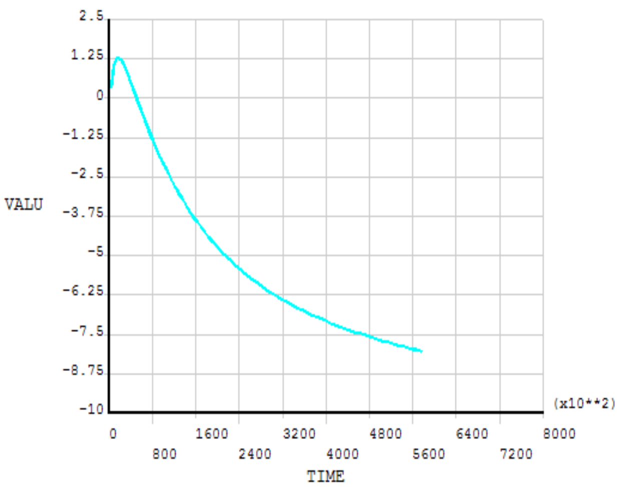
The insulation structure of separate lining is mainly based on a confined air layer between the insulating layer and the single shell lining. The insulating layer may be damaged during installation and production. And the thermal field will change if the insulating layer cracks and the confined air leaks. The cracks are equivalent to the holes with different diameters in this paper.

Simulated Conditions

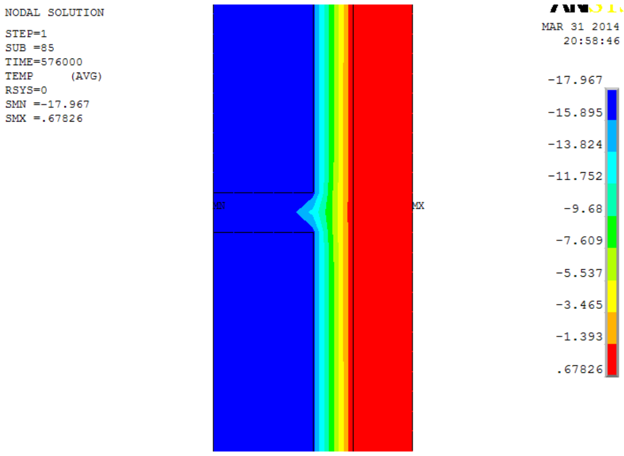
The effect of heat insulation of a separate lining with different sizes of holes (Figure 8) was investigated through numerical simulation. The temperature change *vs*. time of a point on the inner wall of the lining is shown in Figure 9.



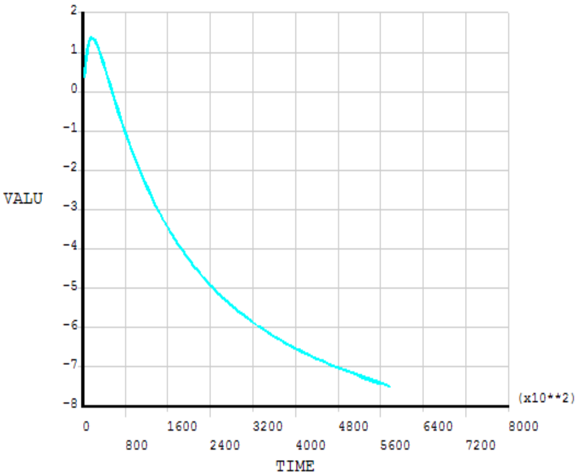
(a1) The temperature field of separate lining with a hole of 5mm



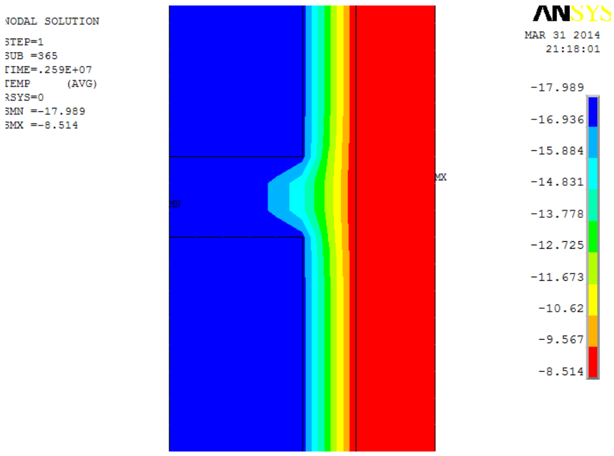
(a2) Temperature changes vs. time of a point on the inner wall of a single shell lining（the hole is 5mm）



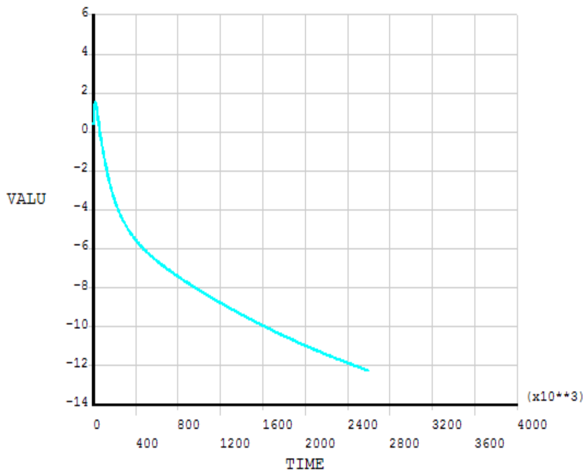
(b1) The temperature field of the separate lining with a hole of 10mm



(b2) Temperature changes vs. time of a point on the inner wall of single shell lining（ the hole is 10mm）



(c1) The temperature field of the separate lining with a hole of 15mm



(c2) Temperature changes vs. time of a point on the inner wall of single shell lining（the hole is 15mm）

Figure (9): The temperature field of separate lining with holes of different sizes and temperature changes *vs.* time of a point on the inner wall of single shell lining

Analysis of Simulation Results

As shown in Figure 9, the change of thermal field is obvious with the increase of the diameter of the hole. At the earlier stage, the temperature in cavum decreases with the increase of time and falls below 0℃ quickly, the temperature of rock masses is -8.5℃ when the diameter is 15mm, and the structure of the tunnel may suffer freezing damage. The insulation effect of separate lining depends on the tightness of the structure. The less tight the structure, the more quickly its temperature decreases and the worse the insulation effect.

CONCLUSIONS

- The temperatures of the lining layer, insulating layer and air layer distribute in a linear fashion in the heat-preserving process of separate lining. The maximum amplitude of temperature exists in the confined air layer.
- The temperature of rock masses changes with the changing of ventilation temperature. The temperature is still above 0℃ when the ventilation temperature is -15℃. And the effect of heat insulation is well.
- The temperature of the lining decreases sharply when the diameters of the holes are amplified. The temperature of rock masses is -8.5℃ when the diameter is 15 mm, and the structure of the tunnel may suffer freezing damage. The tightness of the insulating layer is the key to protect the tunnel from freezing damage.
- In this paper, the initial thermal field of rock masses is in accordance with the depth and temperature gradient. However, it is only suitable for deep tunnels. For some shallow tunnels, the margin of error in calculations is large.

Acknowledgements

This work is partially supported by the Applied Basic Research Project (main subject) of the Ministry of Transport of the People's Republic of China (No. 2015319812140) and the Special Fund for Basic Scientific Research of Central Colleges of Chang'an University (No.CHD2012JC072). The authors also gratefully acknowledge the helpful comments and suggestions of the reviewers, which have improved the presentation.

REFERENCES

Bonacina, C., Comini, G., and Fasano, A. (1973). “Numerical solution of phase-change problems”. Int. J. Heat Mass Transfer, 16(6), 1852-1832.

Chen, J.X., and Luo, Y.B. (2007). “Calculation method of antifreezing layer thickness in cold region tunnels”. Journal of Traffic and Transportation Engineering, 2(7), 76-79.

Comini, G., Guidice, S.D., and Lewis, R.W. (1974). “Finite element solution of nonlinear heat conduction problems with special reference to phase change”. Inter. J. for Numerical Methods in Engineering, 8 (6), 613-624.

Deng, G. (2012). “Investigation of frost protection design for tunnels in high altitude cold regions”. PhD Thesis: Southwest Jiaotong University.

Einar Broch, Eivind Grov, and Kjell Inge Davik. (2002). “The inner lining system in Norwegian traffic tunnels”. Tunneling and Underground Technology, 7 (17), 305-314.

Lai, Y.M., Wu, Z.W., and Zhu, Y.L. (1998). “Nonlinear analysis for the couple problem of temperature, seepage and stress fields in cold region tunnels”. Tunnel and Underground Space Technology, 4 (13), 435-440.

Lai, Y.M., Yu, W.B., and Wu, Z.W. (2002). “Approximate analytical solution for the temperature fields of a circular tunnel in cold regions”. Cold Regions Science and Technology, 1(34), 43-49.

Lai, Y.M., Zhang, X.F., and Yu, W.B. (2005). “Three-dimensional nonlinear analysis for the coupled problem of the heat transfer of the surrounding rock and the heat convection between the air and the surrounding rock in cold-region tunnels”. Tunnelling and Underground Space Technology, (20), 323-332.

Lai, J.X., Liu, C., and Gong, C.B. (2011). “Temperature field analysis of electric tracing for pavement of tunnel portal in cold regions by FEM”. Procedia Engineering, (15), 5468-5472.

Liu, H.J., Zheng, J.Y., and Chen, C.G. (2011). “Rehabilitation project of the Dabanshan highland road”. Journal of Chongqing University, 12 (34), 138-143, 150.

Tan, X.J., Chen, W.Z., and Tian, H.M. (2011). “Water flow and heat transport including ice water phase change in porous media: numerical simulation and application”. Cold Region Science and Technology, (68), 74-84.

Tan, X.J., Chen, W.Z., and Wu, G.J. (2013). “Numerical simulations of heat transfer with ice–water phase change occurring in porous media and application to a cold-region tunnel”. Tunneling and Underground Space Technology, (38), 170-179.

Tan, X.J., Chen, W.Z., and Yang, D.S. (2014). “Study on the influence of airflow on the temperature of the surrounding rock in a cold region tunnel and its application to insulation layer design”. Applied Thermal Engineering, (67), 320-334.

Xia, C.C, Zhang, G.Z., and Xiao, S.G. (2010). “Analytical solution to temperature fields of tunnels in cold regions considering lining and insulation layer”. Chinese Journal of Rock Mechanics and Engineering, 9(29), 1767-1773.

Zhang, X.F., Su, X.M., and Lai, Y.M. (2002). “Non-linear analysis for three-dimensional temperature fields in cold-region tunnels”. Science and Technology, 3 (35), 207-219.

Zhang, X.F., Lai, Y.M., and Yu, W.B. (2003). “Numerical analysis for three-dimensional temperature fields in cold region tunnels”. Journal of the China Railway Society, 3 (25), 84-90.

Zhang, X.F., Lai, Y.M., and Yu, W.B. (2004). “Forecast analysis of the refreezing of Kunlun mountain permafrost tunnel on Qing–Tibet railway in China”. Cold Regions Science and Technology, (39), 19-31.

Zhang, X.F., Yu, W.B., and Liu, Z.Q. (2006). “Three-dimensional nonlinear analysis for coupled problem of seepage field and temperature field of cold region tunnels”. Chinese Journal of Geotechnical Engineering, 9 (28), 1095-1100.

Zhang, G.Z., Xia, C.C., and Yin, Z. (2010). "Analytical solution to axial and radial temperature of tunnels in cold regions". Journal of Tong Ji University (Natural Society), 8 (38), 1117-1122, 1160.

Zhang, G.Z., Xia, C.C., and Sun, M. (2013). "A new model and analytical solution for the heat conduction of tunnel lining ground heat exchangers". Cold Regions Science and Technology, (88), 59-66.

Zhang, G.Z., Xia, C.C., and Yang, Y. (2014). "Experimental study on the thermal performance of tunnel lining ground heat exchanges". Energy and Buildings, (77), 149-157.