STUDY ON TEMPERATURE FIELD OF ENTRANCE SECTION AT HIGH ALTITUDE TUNNEL CONSIDERING WATER SUPPLY FROM SNOWMELT

by

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To explore the influence of snowmelt supply at the entrance section at high altitude tunnel on tunnel engineering, several indoor model tests were carried out by setting a water-supply system above the model device for simulating the actual snowmelt supply environment. The model tests were based on a project at high altitude tunnel in Qinghai. The varied characteristics of temperature field in typical cross-sections of tunnel entrances with and without water-supply condition under freeze-thaw cycles were analyzed accurately by the model. This study shows that the external water supply has a great influence on the tunnel entrance. When the surrounding rock freezes at the tunnel entrance, it first freezes from the arch, then develops to the side wall, and then spreads to the inverted arch to form a freezing circle. The faster the freezing development rate is, the greater the thickness of the freezing ring is under the water-supply condition. The development of temperature field under water-supply condition is obviously faster than that under normal condition. The distribution characteristics of freezing depth in both conditions are the arch is the largest, the side wall is the second, and the inverted arch is the smallest. This study can provide a reference for analyzing the process of freezing injury caused by high altitude snowmelt water supply into tunnel entrances in western Sichuan.

Key words: *high altitude tunnel, snowmelt water supply, temperature field model test*

Introduction

Most of the constructing Sichuan-Tibet railway passes through the high altitude cold area in the west of Sichuan, of which the tunnel engineering accounts for about 80%. The engineering structural cracking, seepage, and water leakage issues occurs frequently due to the freeze-thaw cycles caused by the periodic change of ambient temperature, coupled with the water supply formed in the special natural environment. It will aggravate the freezing damage and seriously affect the safety of the tunnel operation when the snowmelt in the entrance reaches the surrounding rock through the seepage channel. Therefore, it is necessary to study the characteristics of environmental temperature field and moisture field of the snowmelt supply to solve the structure antifreeze issues of the entrance section at high altitude tunnel. Many scholars have conducted a large number of studies on the frost heave issues of engineering at the cold area. Bonacina [1], Comini [2], and Guidice [3] studied the numerical solution of

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transient non-linear temperature field with phase transition by using finite difference method. Harlan [4] and Harlan and Nixon [5] studied the transport mechanism of unfrozen water in frozen soil, and proposed a hydrothermal coupled numerical model to analyze the freeze-thaw coupled transport relationship of hot fluid in porous media, which can basically describe the hydrothermal migration in frozen soil. Ladanyi and Mu [6] established a coupled hydrothermal model to solve the coupled frost heave issue of actual frost heave and creep, and verified the model applicability. Hu *et al.* [7] adopted the finite difference method to solve the mathematical model of 1-D hydrothermal coupling migration of unsaturated frozen soil under freezing conditions and obtained the general law of soil freezing process [7]. Shang *et al.* [8] constructed the fully implicit finite difference equation calculate the hydrothermal coupling equation, and carried out laboratory tests to verify the accuracy of model calculation. Lai *et al.* [9, 10] derived the governing differential equations coupling water, heat and stress with phase transition, and conducted the relevant finite element calculation formulas by Galerkin method. The rationality of the calculating theoretical model was verified by taking an actual tunnel engineering in cold region as an example, which provided a theoretical basis for related engineering design. Zhang *et al.* [11] using Galerkin's method derived the finite element formula of the governing differential equation of the 3-D transient temperature field with phase transition, which illustrated the necessity of the 3-D temperature field research for tunnels in cold region, and provided theoretical reference for engineering design. Tan *et al.* [12] taken the law of water flow and heat transfer in porous media under freezing and thawing conditions, established a hydrothermal coupling control equation, and applied it to the study of materials for the Galongla tunnel in Tibet. Cai *et al.* [13] studied the freezing temperature distribution and frost heave displacement of double subway tunnels through model tests. Zhou and Li [14] adopted the Clapeyron equation model the relationship between temperature, water pressure and ice pressure in frozen soil, and carried out soil column simulation verify its applicability. Based on the similarity theory, Feng [15] carried out an indoor model test on the Yuximolegai tunnel to study the temperature field and frost heave force, and compared the obtained results with theoretical and numerical solutions, and verified the rationality of the model test. Li *et al.* [16] carried out indoor model tests on the temperature field of tunnels in cold regions with and without an impermeable layer, and obtained the radial temperature change law of the tunnel surrounding rock. To sum up, many scholars have ignored the convective heat transfer effect of external water supply in unsaturated surrounding rock masses in the study of high altitude tunnels, and most of the model tests did not take the external environmental water-supply conditions into account.

Through literature research, in view of the snowmelt supply for high altitude tunnel entrance section of the research on the effects of temperature field is rare, many of the high altitude cold regions tunnel model test without considering the external environment water-supply condition. Therefore, this study through the analysis of entrance section at high altitude tunnel with snowmelt supply, and model tests of the tunnel entrance section with and without water supply were carried out to study the varied characteristics of temperature fields in typical cross-sections of tunnel entrances. This study can provide reference for the design of the entrance section at high altitude tunnel.

Model test design

Introduction the tunnel

In this study, the entrance section at a high altitude railway tunnel is used as a research project. The engineering is located in a mountain on the left side of Huangshui River in Qinghai Province. The longitude is about 101°, the latitude is about 37°, and the altitude is about

2635 m. The tunnel area has a semi-arid continental climate with concentrated rainfall and large temperature differences. The annual average temperature is 3.3 °C, the extreme maximum temperature is 30.7 °C, the extreme minimum temperature is –27.7 °C, the annual average rainfall is 408.9 mm, the maximum snow thickness is 9 cm, and the maximum seasonal frozen soil depth is 299 cm. According to the study of Feng and Cai [17], through the conversion of latitude and altitude, the environment temperature of the tunnel entrance is similar to that of the Sichuan-Tibet Railway tunnel entrance within an altitude range of about 4050~4150 m. During the operation period of the tunnel, the tunnel occurred frost damage issues such as water seepage at the arch of the tunnel entrance and cracking of the lining, as shown in fig. 1.

Figure 1. Schematic diagram of the tunnel location in Qinghai province

Model test profile

Considering the actual environment of the tunnel entrance section, the research purpose, the arrangement of monitoring instruments and fine test effects, the similarity ratios of geometry, temperature and time in this study are 1:50, 1:1, and 1:46, respectively. The test surrounding rock mass is taken from the loess in Northwest China. The initial water content is 18%, the liquid limit and plastic limit are 26.4% and 13.5%, respectively, and the dry density is 1.69 g/cm^3. The tunnel model lining and entrance are made of PVC materials, the model slope ratio of the tunnel entrance section is 1:2, the size is 100 cm × 70 cm × 55 cm, and the inner diameter of the entrance cavity is 15 cm. According to the consistent varied environment, the model of the tunnel entrance section was made. In order to adjust the initial temperature state, the model was placed at room temperature (15~20 °C) for 6 hours after the completion of the lay-out, and the freeze-thaw cycle test with a period of 8 days was carried out after the computer showed that all the data were stable.

During the test, the temperature control function is $T(t) = 3.3 - 21.2\sin(2\pi t / 192)$, where the freezing period was 3.8 days (91.2 hours), and the thawing period was 4.2 days (100.8 hours). To simulate the snowmelt-supply condition of the entrance section at high altitude tunnel, a water-supply device was set at the entrance of the model, and the water-supply amount at the entrance of the tunnel was adjusted to be approximately natural snowmelt supply amount. To simulate the thawing condition at the entrance of the tunnel, a bath bully bulb and a heater were placed on the top and front of the model to enhance the environmental temperature. Due to the limitations of temperature control equipment, the temperature function was discretized at 4 hours intervals in this study, which can be obtained 48 discrete points. The fitted curve is shown in fig. 2.

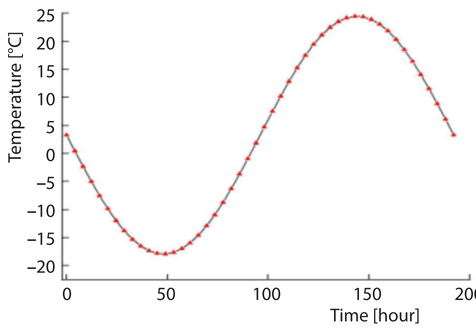

Figure 2. Ambient temperature curve

Under the water-supply condition, it is considered that during the snowmelt period in the high altitude area of western Sichuan, some of the water generated by snowmelt at the tunnel entrance will infiltrate into the surrounding rock, and some of it will directly from surface runoff near the tunnel entrance. In this way, the water supply formed by thawing water will have a great influence on the water field at the entrance of the cave. According to Chen [18] on the water yield of seasonal snow in the thawing period, the snow yield can be obtained:

$$W_0 = \frac{W_{sp} + h_L}{1 + c_{L3} e^{c_{L4} h_L \rho_{sp} / \rho_l / d_{sp}}} \tag{1}$$

where h_L is the depth of lagging remaining water in the snow layer, W_{sp} – the remaining water stored, c_{L3} and c_{L4} are the empirical coefficients, ρ_l – the density of liquid water, d_{sp} – the thickness of the snow layer, and ρ_{sp} – the density of ice in the snow layer.

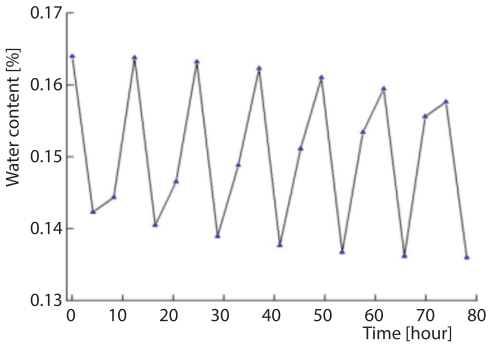

Figure 3. Moisture curve

To simplify the analysis and calculation process, in accordance with the actual conservative principle of the project, the amount of snowmelt is regarded as the all amount of water supply at the entrance of the tunnel. According to Cha *et al*. [19], the increase in water content caused by water $w_1(t)$:

$$w_1(t) = 0.15 + 0.014 \sin\left(\frac{\pi t}{6} + \frac{\pi}{2}\right) \tag{2}$$

Assuming that the freeze-thaw supply period is 78 hours, discrete at 4 hours intervals, 20 discrete points are obtained, the fitted curve is shown in fig. 3.

Test device and function

The model test device of the tunnel entrance section is mainly composed of five parts:
- The model box is an incubator with a size of 120 cm × 80 cm × 65 cm (the upper cover can be opened), and the surrounding rock of the model is in contact with the box body and a 5 cm thick foam insulation board is closely attached to the surrounding area to approximate the actual freezing and thawing environment of the tunnel entrance section in the cold zone.
- The temperature system consists of Dongbei NE6210 compressor unit, pure copper refrigeration tube, evaporator, condenser, Gree NSD-12-WG heater, and Op E27 Yuba bulb.
- The temperature control system is manually set by the temperature control process, read through the computer temperature control program, the temperature range is –20~20 °C, and the accuracy is 0.1 °C;
- The water supply system is composed of a Markov bottle and a flexible water delivery hose. During the heating process, the water supply is similar to the actual amount of snowmelt on site;
- The monitoring system is composed of a temperature chain containing 60 thermistor temperature sensors, a deep hole ground temperature TRM128 expansion board, a CR6 data acquisition instrument, an AM16/32B expansion board and a computer independently developed by the Institute of Cold and Drought of the Chinese Academy of Sciences. During the test, data was collected every 5 minutes as shown in fig. 4.

Test point lay-out

When arranging water-supply conditions for the model of the tunnel entrance section, a 5 cm thick foam insulation layer is laid around and at the bottom of the model box. The lay-out of the model temperature sensor is shown in fig. 5. Two temperature monitoring sections are

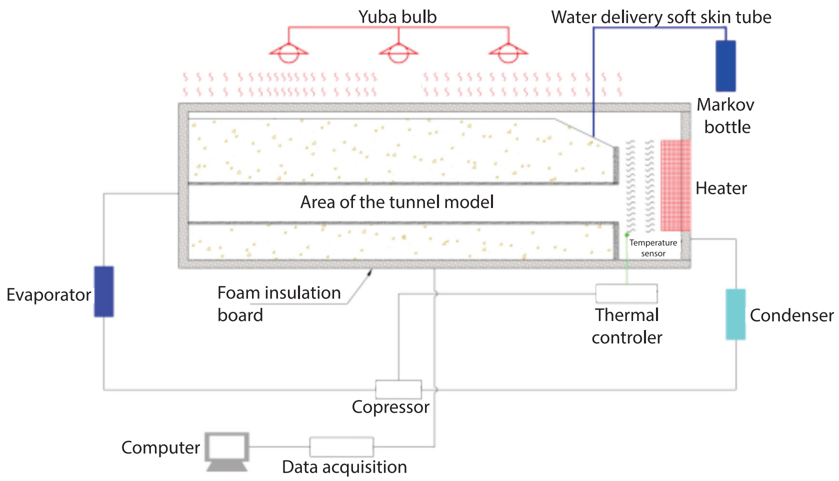

Figure 4. Schematic diagram of freeze-thaw model test system

taken along the tunnel longitudinal, respectively: Section A (with water-supply) is 0.2 m away from the entrance of the tunnel, and Section B (without water-supply) is 0.5 m away from the entrance of the tunnel. Each monitoring section is arranged with five measuring points on the horizontal side: TH1~TH5, TH6~TH10. Two measuring points are arranged on the upper part of the vault and the lower part of the invert: TV1~TV4, TV5~TV8, with a total of 18 temperature sensors. The distance from the horizontal measuring point to the lining is 0 cm, 5 cm, 10 cm, 15 cm, 20 cm, and the distance from the vertical measuring point to the lining is 5 cm, 10 cm, respectively. The model test process diagram is shown in fig. 6.

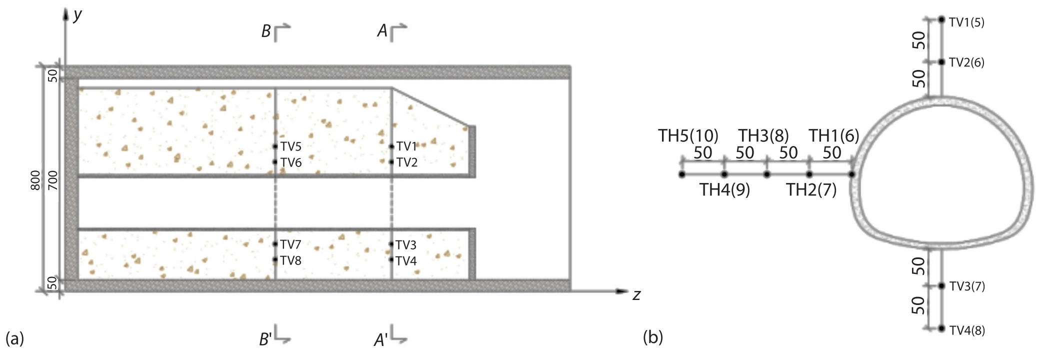

Figure 5. Burying scheme of monitoring instrument [mm]; (a) vertical and (b) horizontal

Figure 6. Model test process diagram; (a) freeze, (b) melt, and (c) water supply

Test results and analysis

Temporal and spatial distribution of temperature

As can be seen from fig. 7, the surrounding rock of the tunnel began to experience negative temperature and continued to decrease in temperature since November. Under normal working conditions, the surface temperature decreased from –1.5 °C to –8.5 °C, and the lining temperature decreased from –6.5 °C to –9.5 °C. Under the water-supply condition, the surface temperature decreases from –3.2 ℃ to –14 ℃, and the lining temperature decreases from –6 °C to –13 °C. The temperature of the surrounding rock decreases continuously and develops from the surface to the inside of the surrounding rock. Under the two working conditions, the 0 °C isotherm of surrounding rock from December to March was circumferentially distributed, and the freezing circles with the thickness of 1-3.8 cm and 1.4-4.4 cm were formed in the radial direction of surrounding rock, respectively. It can be seen that the maximum freezing depth at the tunnel entrance is 3.8 cm and 4.4 cm under the water-supply condition and normal working condition, respectively. According to the geometricsimilarity ratio of 1:50, the maximum freezing depth of the entrance section of the high altitude tunnel under the two working conditions is 1.9 m and 2.2 m, respectively.

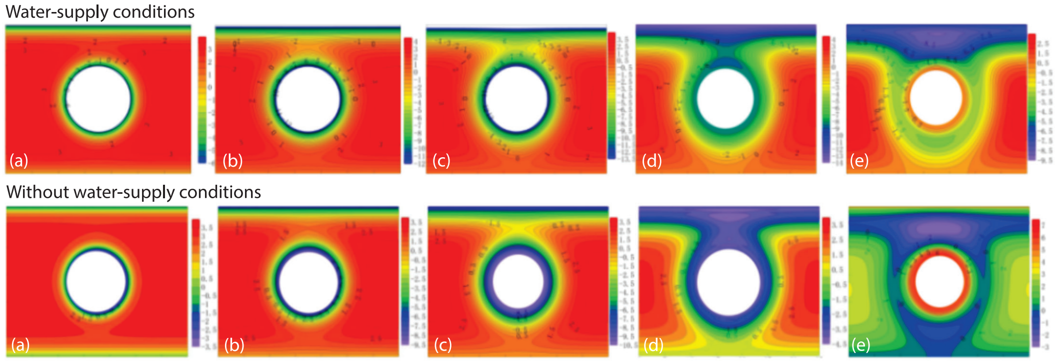

Figure 7. Temperature field [℃]; (a) November, (b) December, (c) January, (d) February, and (e) March

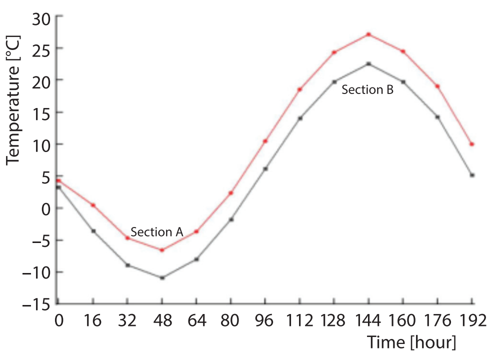

Figure 8. Lining temperature change curve

Lining temperature field analysis

By taking the average value of monitoring data corresponding to the 16 hours of freeze-thaw cycle as the referenced temperature value. Figure 8 shows the variation law of the lining temperature with time in the typical section. It can be seen that the test lining temperature of the two sections show a sine function law with time, but there are differences between the maximum and minimum temperatures, that is, the amplitude of the sinusoidal function was different. The closer the lining is to the entrance, the larger the negative temperature is, and the lower the positive temperature is.

Analysis of radial temperature field of surrounding rock

Figure 9 shows the change law of surrounding rock temperature with time at different radial depths in two sections. It can be seen that the surrounding rock temperature within a certain depth range in the radial direction also changes regularly due to the influence of environmental temperature, and the closer it is to the lining surface. The more obvious it is, the change gradually decreases with the increase of radial depth, and it gradually tends to the original surrounding rock temperature.

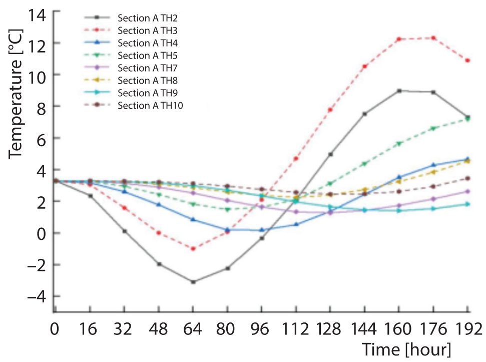

Figure 9. Surrounding rock temperature change curve

Conclusion

According to the analysis of the temperature field results of the model test, it can be seen that the surrounding rock at the entrance of the tunnel freezes from the arch to the side wall, and then spreads to the invert to form a freezing circle. The freezing depth is the largest at the arch, the side wall is the second, and the invert is the smallest. There are water supply conditions at the entrance of the tunnel, and the trend is more pronounced, indicating that the prevention and control of tunnel frost damage should focus on the waterproof measures of the arch. From the cross-sectional diagram of the temperature field, the temperature field of the water supply section has a faster change trend, and the thickness of the freezing circle is larger. The development trend of the temperature field under the two working conditions is from the arch to the side wall, and finally the invert. The hydrothermal condition model test on the entrance section of the high altitude tunnel proofs that the water supply leads to changes in the thermophysical parameters of the surrounding rock, which in turn causes the temperature field of the surrounding rock to change.

Acknowledgment

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Nomenclature

d – thickness of the snow layer, [mm]
t – time, [s]

Greek symbols

ρ_l – density of liquid wate, [kgm^{-3}]
ρ_{sp} – density of ice, [kgm^{-3}]

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