NUMERICAL SIMULATION CONSIDERING THE EFFECT OF UNEVEN FROST HEAVE ON TUNNEL STRUCTURE IN COLD REGIONS

by

Ning LI [a]**, *Zhi-Qiang LIU*** [a*]**, *Guo-Dong NIU*** [b]**, *Jian ZHANG*** [a]**,**
Jun-Ping LI [a]**, *and Fan ZHANG*** [a]

[a] School of Civil Engineering, Lanzhou Jiaotong University, Lanzhou, China
[b] China Railway Eryuan Engineering Group Co. Ltd. Guiyang, Guiyang, China

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Freezing damage is one of the main diseases of tunnels in cold regions. Water storage behind the lining is a necessary condition for freezing damage. Compared with the previous condition of uniform water storage behind the lining, this paper explores the influence of water storage and frost heave at different positions on tunnel structure in cold regions. Based on the theory of thermo-hydro-mechanical coupling. The finite element model of tunnel surrounding rock in cold area under different positions and different water content is established and compared by using COMSOL software, the mechanical characteristics of tunnel lining under different water storage positions behind the lining are studied, and the influence of frost heave at different positions on tunnel structure is explored. The numerical simulation results show that no matter where the local water storage area is located, the area with the largest frost heave force is located in the lining structure, close to the surrounding rock. Different local water storage positions will also have different influences on the tunnel structure. In the same water storage area, the frost heave force will increase with the decrease of temperature.

Key words: *uneven frost heave, frozen soil, thermal-hydro-mechanical coupling, COMSOL, tunnel, local water storage*

Introduction

The diseases of tunnels in cold regions, such as ice hanging on the lining wall, water seepage and icing at the bottom of the tunnel, water leakage and icing at the top of the tunnel, are mostly related to the water storage behind the lining. Many experts and scholars at home and abroad have conducted in-depth and comprehensive studies on thermal-hydro-mechanical (THM) coupling and frost heave behind the lining. The THM coupling governing equations of frozen rock mass at low temperature were established by Gatmiri *et al*. [1], and simulated and analyzed by compiling finite element program. The Canadian frozen soil scientist Harlan [2] applied the Darcian method to the thermal-hydro transport of freeze-thaw porous media, and proposed a mathematical model of thermal-hydro coupling. Taylor *et al*. [3] numerically analyzed and tested the heat and water flow equations according to the modified form of Harlan model, and the results of numerical simulation and test results were in good agreement, but did not consider the change of some unfrozen soil parameters during the

[*] Corresponding author; e-mail: liuzq1100@outlook.com

freezing process. Based on the viscous flow theory of liquid water in porous media and the principle of heat balance. Wang *et al.* [4] established a 1-D water-heat coupling motion model of seasonal frozen soil. Barton *et al.* [5] preliminarily understand the coupling relationship among seepage field, stress field and temperature field by studying engineering rock mass. Comini *et al.* [6] used finite element method to study the frost heave of rock and soil under phase change heat conduction. Zhou *et al*. [7] established a new model of water migration in unsaturated frozen soil. Water migration is characterized by using an imaginary mobile pump and a small reservoir. Li *et al.* [8] collected a large number of temperature data at different depths and horizontal distances from the center of thermal karst pool in a field experimental station on Qinghai-Tibet Plateau for many years. The temperature and humidity processes of surrounding permafrost are simulated and compared with the measured temperature data. He *et al.* [9] put forward a new theoretical formula for coupled transfer analysis of heat, water and air, which is applicable to deformable unsaturated soil. Liu *et al*. [10] described the influence of freezing by using the similarity between drying and freezing processes and the Clapeyron equation of thermodynamic equilibrium in the phase transition process.

Previous studies on water storage behind the tunnel lining are of great engineering significance, but few have considered the effects on the tunnel structure at different water storage locations and at different temperatures under the THM coupling factor, considering uneven frost heave. In this paper, based on the aforementioned research, a finite element model of THM coupling is established based on geotechnics, and the COMSOL multi-field coupling function focuses on exploring the distribution of the tunnel temperature field and its effect on the tunnel structure at different water storage locations and different temperatures.

Theory of thermal-hydro-mechanical coupling

Since the water field, temperature field, and stress field will interact with each other during the freeze-thaw process of soil, it leads to the complexity of water thermal coupling in frozen soil. At present, the three coupling fields are mainly divided into direct coupling and iterative coupling. The direct coupling is to calculate all the parameters involved in the physical field, while the iterative coupling is calculated in steps, using the results of the previous calculation as the initial values for the next calculation.

Basic assumptions

- Soils with high water content and soils with normal water content are considered isotropic, linearly elastic materials.
- Heat transfer in accordance with Fourier's law.
- Water transport in accordance with Darcy's law.
- Water, ice and soil particles cannot be compressed.

Thermal-hydro-mechanical three-field control equation

When the phase change of water and ice occurs, the phase change heat exists in the soil as a heat source, so the heat transfer equation containing the phase change heat reads:

$$\rho C(\theta)\frac{\partial T}{\partial t} = \lambda(\theta)\nabla^2 T + L\rho_I \frac{\partial \theta_I}{\partial t} \tag{1}$$

where C is the volumetric heat capacity, L [kJkg^{-1}] – the latent heat of phase change, which is usually taken as 334.56 kJ/kg, T – the temperature, t – the time, ρ_I – the density of ice, θ_I – the volume content of ice, and $\lambda(\theta)$ – the unknown variable.

Therefore, the solid-liquid ratio between the temperature field and the water field equation, is introduced, and the solid-liquid ratio, B_i, is chosen as the coupling term, which is calculated [11]:

$$B_i = \frac{\theta_I}{\theta_u} = \begin{cases} 1.1\left(\dfrac{T}{T_f}\right)^B - 1 & T < T_f \\ 0 & T \geq T_f \end{cases} \tag{2}$$

where T_f is the freezing temperature of soil, B – the constant that varies with soil quality and salt content, and θ_u – is the volume unfrozen water content.

In this paper, we choose the VG hysteresis model with Gardner permeability coefficient model and define the relative saturation:

$$S = \frac{\theta_u - \theta_r}{\theta_s - \theta_r} \tag{3}$$

where θ_s is the saturated water content and θ_r represents the residual water content.

Now introduce the diffusivity, D, which represents the ratio of soil hydraulic conductivity to specific water capacity:

$$D(\theta_u) = \frac{k(\theta_u)}{c(\theta_u)} I \tag{4}$$

where $k(\theta_u)$ represents the hydraulic conductivity of the soil, $c(\theta_u)$ – the specific water capacity and I – the impedance factor:

$$I = 10^{-\theta_I} \tag{5}$$

The relationship between specific water capacity and relative saturation is given [12]:

$$c(\theta_u) = \frac{am}{(1-m)S^{l/m}(1-S^{l/m})^m} \tag{6}$$

Gardner proposed a relationship between relative saturation and permeability coefficient:

$$k(\theta_u) = k_s S^l \left[1-(1-S^{l/m})^m\right]^2 \tag{7}$$

where m, a, and l are constitutive parameters that vary with soil quality and k_s is the saturated soil permeability coefficient.

Considering the water-ice phase change, the Richards equation for water migration in frozen soil is given:

$$\frac{\partial \theta_u}{\partial t} + \frac{\rho_I}{\rho_w}\frac{\partial \theta_I}{\partial t} = \nabla\left[D(\theta_u)\nabla\theta_u + k(\theta_u)\right] \tag{8}$$

where k is the permeability coefficient of soil.

The thermal expansion is used to calculate the frost heave force. The water content of the soil will determine the volume expansion of the frozen soil, so the frozen soil can be considered as a thermally expanded material for calculation. Strain due to thermal expansion can be given:

$$\varepsilon_i = \alpha(T - T_f) \tag{9}$$

where α is the linear expansion coefficient of frozen soil and T and T_f represent the instantaneous temperature of the soil and the freezing temperature, respectively.

Frost heave of tunnel surrounding rock in cold region is reflected by frost heave rate. Frost heave rate can be expressed:

$$\eta = \frac{1.09\rho_d}{2\rho_w}(w - w_p) \tag{10}$$

where ρ_d is the dry density of soil, ρ_w – the density of water, w – the total water content, and w_p – is the plastic limit water content.

Since the soil expands in all directions, the frozen soil linear expansion coefficient:

$$\alpha = -\left(\sqrt[3]{\eta + 1} - 1\right) \tag{11}$$

So the equation calculate the freezing and frost heave force is given:

$$\varepsilon_i = \left(1 - \sqrt[3]{\eta + 1}\right)\left(T - T_f\right) \tag{12}$$

Engineering cases and calculation parameters

Take a tunnel under construction in a cold area as an example, the tunnel site elevation is between 2864~3700 m, with a relative elevation difference of 500~1000 m. The coldest monthly average temperature in the tunnel site area is –13.1°C, and the maximum freezing depth is more than 2 m.

The section at 10 m burial depth of the tunnel entrance is selected as the object of study, and its section size and tunnel calculation model are shown in figs. 1, figs. 1(a)-1(c) represent the water storage at the side wall, arch foot, and invert arch, respectively, and the water storage area is tentatively set as a curved rectangle. The length of the short side of the side wall is 2.4 m, the length of the long side is 5 m, and the area is 10.71 m^2.

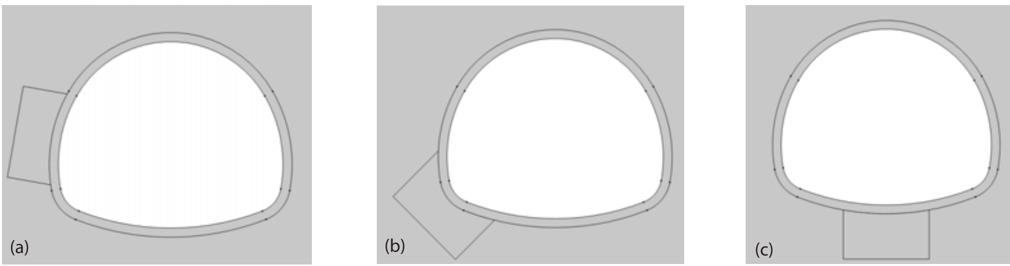

Figure 1. Schematic diagram of the numerical calculation model; (a) sidewall water storage calculation model, (b) calculation model of water storage at the arch arch, and (c) water storage model for the invert arch

The length of the short side of the arch foot water area is 3.4 m, the long side is 5 m, and the area is 12.83 m^2. The water storage area of the back arch is 2.8 m in length and 5 m in length. The length of the short side of the water storage area of the invert arch is 2.8 m, the length of the long side is 5 m, and the area is 13.42 m^2.

The temperature boundary conditions and calculation parameters are the temperature at the tunnel site, the average temperature throughout the year is 2 °C, with the lowest temperature in January at an average of –15 °C and the highest temperature in July with an average temperature of 19 °C.

The temperature is generally considered to vary periodically during the year and can be written as a sine function:

$$T = 17\sin\left(\frac{2\pi}{365} + \pi\right) + 2 \tag{13}$$

The function schematic is shown in fig. 2.

Suppose that we set this temperature function as the temperature boundary condition at the top of the model. The internal temperature of the tunnel and the surface temperature change trend tends to be the same, while the temperature is lower:

$$T = 17\sin\left(\frac{2\pi}{365} + \pi\right) - 6 \tag{14}$$

Based on the tunnel design information, the initial temperature of the calculation model was taken to be 2 °C, the annual average temperature. The main parameters of the computational model are shown in tabs. 1 and 2.

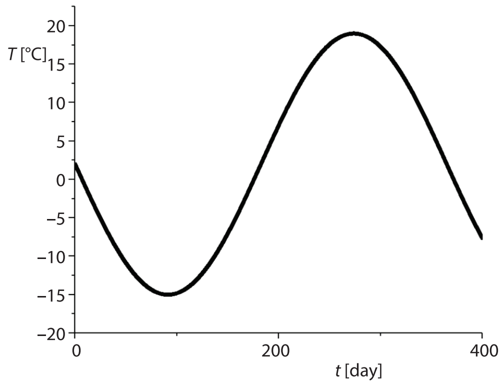

Figure 2. Annual average temperature trigonometric graph

Table 1. Basic physical parameters

Parameter name	Coefficient of thermal expansion [K^{-1}]	Poisson's ratio	Young's modulus [GPa]	Density [Kgm^{-3}]	Initial water content
Water storage areas	–0.0373	0.495	0.008	1522.2	0.3
Surrounding rock	–0.0104	0.495	0.008	1290.0	0.18
Lining	0	0.35	20	2500.0	0.05

Table 2. Model thermal parameters

Temperature [°C]	Thermal conductivity [Wm^{-1}K^{-1}]	Heat capacity [Jm^{-3}K^{-1}]
–18	1.98	1.52
–5	1.98	1.59
8	2.17	1.45
15	2.17	1.45

Analysis of numerical calculation results

The effect of local water storage on the Dangjinshan tunnel is mainly concentrated in the low temperature season, so this paper selects the tunnel from November to April, which is the colder half of the year, to analyze the effect of local water on the tunnel structure. Considering that local water storage mostly occurs at the bottom of the tunnel and the sidewall area, this paper selects three working conditions: water storage in the invert arch, water storage in the arch foot, and water storage in the sidewall as a control. Figure 3 shows the distribution of tunnel temperature field.

Figure 4 shows that the temperature reached its lowest point in January and warmed up significantly in February. In April, the temperature in the tunnel went from below zero to above zero, compared with January, but at the same time the thickness of the freezing circle reached its maximum, with a maximum freezing depth of 3.4 m.

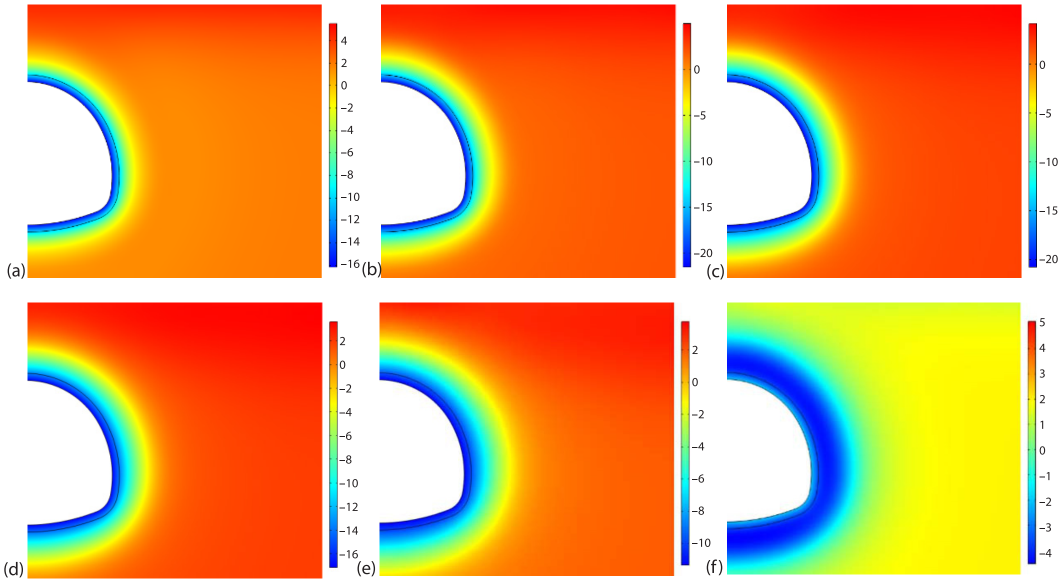

Figure 3. Temperature field distribution in the tunnel; (a) November 15, (b) December 15, (c) January 15, (d) February 15 (e) March 15, and (f) April 15

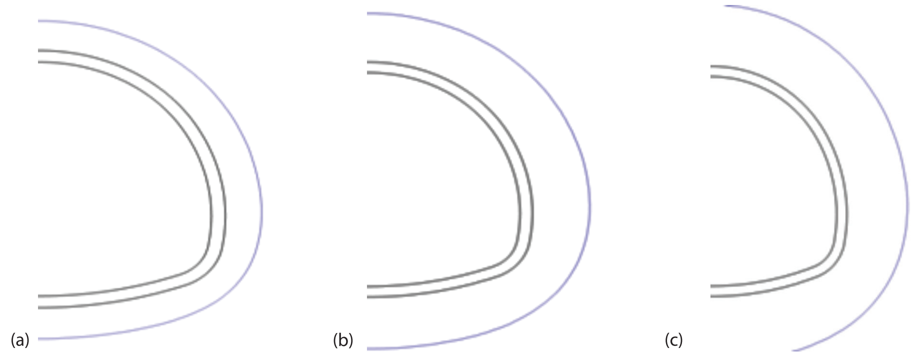

Figure 4. Distribution of freezing circles in November, January and April; (a) November freezing circle, (b) January freezing circle, and (c) April freezing circle

It can be seen from fig. 5 that the effect of water storage behind the lining on the tunnel structure is greater in December, January, and February, and its effect is much more pronounced than in April. The difference in Von mises stress between the four working conditions in April is not significant.

Conclusion

In this paper, by establishing a numerical model of tunnel water-thermal coupling, we investigate the influence of freezing and frost heave force on the tunnel structure at different temperatures and in different water-bearing regions, and by comparing several sets of data with each other, we obtain the following conclusions. In November, March, and April, when the

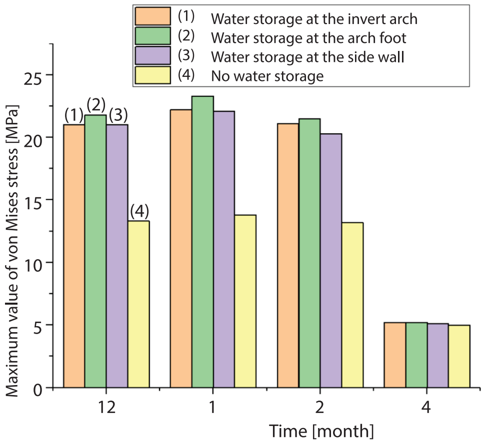

Figure 5. Comparison of maximum von Mises stress values for water storage in different parts from December to February

temperature is high, the tunnel is subjected to a small and relatively uniform distribution of the frost heave force, in December, January, and February, when the temperature drops sharply, the tunnel is subjected to a sharp increase in the frost heave force, reaching a maximum in January, when the temperature is lowest. When the temperature is relatively high, the local water storage on the tunnel structure is small, as the temperature decreases, the structural impact of uneven freezing and heave on the tunnel becomes more and more significant, as shown in the tunnel structure there is a significant stress concentration phenomenon, the maximum von Mises stress is much larger than other parts. By comparing the magnitudes of the frost heave force in different working conditions and at different times, it can be concluded that water storage in the sidewall area has a greater impact on the tunnel structure than in the arch foot and the invert arch.

Acknowledgment

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Nomenclature

C – volumetric heat capacity, [Jm^{-3}K^{-1}]
L – latent heat of phase change, [kJkg^{-1}]
T – temperature, [K]
t – time, [s]

Greek Symbol

ρ – density of water, [kgm^{-3}]

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