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Coupled temperature-hydrologic-mechanical (THM) model of rock mass subject to low-temperature freeze-thaw cycles and its application to underground caverns in cold regions

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Abstract. Under low temperature and freeze-thaw cycles, the water in the rock microcracks experiences phase change and volume expansion, which cause the increase of frost heaving force of microcracks and have great influence on the stability of surrounding rock. Based on continuum mechanics, thermodynamics, fluid mechanics and damage mechanics, coupled Temperature-Hydrologic-Mechanical model of rock mass was established under low temperature and freeze-thaw cycles. The tests take into account the influence of the volume strain on temperature field and seepage field of rock mass, the effect of temperature gradient and seepage pressure on the stress field of rock mass, and the effect of the frost heaving force and freeze-thaw cycles on the stability of surrounding rock and lining structure. The frost heaving process in underground caverns was analyzed with regard to an underground project in Xinjiang using finite element method. The variation law of frost heaving force is studied for surrounding rock of underground caverns subject to low temperature and freeze-thaw cycles. The deformation and mechanical characteristics of lining structure experiencing different freeze-thaw cycles are analyzed and discussed. The results indicate the maximum frost stress of surrounding rock of underground caverns is up to 1.6MPa during freezing, and with the temperature rise the frost stress gradually dissipates.

Key words. Cold regions of underground caverns, low temperature and freeze-thaw cycles, thm coupled model, frost heaving force, horizontal displacement.

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1. Introduction

The frost heave of surrounding rock involves interactional multi-field coupling of rock temperature field, hydrological field, mechanical field and freeze-thaw damage in cold regions of underground caverns. THM coupled model of rock mass frost heave under the conditions of low temperature and freeze-thaw cycles has been a research focus[1]. For general engineering rock mass in cold regions, the fracture of frost heaving crack determines the stability of the rock mass. Therefore, the key problems to be solved in the study of rock frost heave during freeze-thaw cycles include the frost heaving force of the rock mass, the dissipation mechanism, the multiple freeze-thaw strength damage and the stability evaluation [2].

A large number of engineering studies show that in the process of freezing, besides the volume expansion of the original water, the moisture migrates continually, accumulates at the freezing front and crystallizes into ice lens, which also significantly contributes to the generation of frost heaving rock mass [3]. K. Takeda and other scholars have conducted systematic analysis on the mechanism of water and heat transfer [4], developed multiple water-heat coupling calculation models[5-6], and verified the validity of the models. A series of research results have been achieved by investigating the frost heaving characteristics and freeze-thaw deterioration rule of underground caverns under the coupled effect of THM [7-9]. However, a majority of studies have focused on the coupling of multiple fields of high temperature rock mass with abundant research results. In contrast, there has been no systematic study on the multiple fields coupling of rock mass subject to low temperature and freeze-thaw. Moreover, the available research did not take into account either the frost heaving force dissipation or the effect of low temperature and freeze-thaw cycles on the mechanical characteristics of the surrounding rock and the stability of the lining structure.

The model takes into account the influence of the volume strain on temperature field and seepage field of rock mass, the effect of temperature gradient and seepage pressure on the stress field of rock mass. According to the underground engineering in cold area, the frost heaving process of underground caverns was analyzed by using finite element method. The present research focused on the frost heaving force variation law of surrounding rock of underground caverns subject to low temperature and freeze-thaw cycles. The influence of the freeze-thaw cycles and strain on the stability of lining structure of surrounding rock was discussed. The deformation and mechanical characteristics of lining structure under different freeze-thaw cycles were studies. The present study provides theoretical basis for the design and construction of lining structure and the stability analysis of the surrounding rock in the underground caves in cold regions.

2. Control equation THM coupling

2.1. Control equation of temperature field

Under the THM three-field coupled conditions, the previous research sheds light on the control equation of temperature field in the surrounding rock [10]. The temperature field includes two parts: the temperature field of the surrounding rock, which is in stable equilibrium before the cavern excavation; and the environment temperature field after the cavern excavation, which is changed by the ventilation measures. In the calculation and analysis, the change of the geotherm and temperature field of the cavity environment should be considered fully so as to solve the actual temperature field of the surrounding rock. The influence by volume deformation of the surrounding rock on the temperature field must be considered in the calculation[11]. The control equation of temperature field can be obtained as follows:

$$C_e \frac{\partial T}{\partial t} + \nabla\left[-\lambda_e \nabla T\right] + \left[\left(v_w \nabla\right)\left(\rho c T\right)_w\right] + \left(1-n\right) T \gamma \frac{\partial \varepsilon_v}{\partial t} = Q_e \tag{1}$$

where $\gamma = 2\mu + 3\lambda\beta_s$; C_e is the heat capacity of the rock under equivalent volume; λ_e is the coefficient of thermal conductivity of the rock mass; v_w is the seepage velocity of water; μ and λ are the Lam? constants; β_s is the linear thermal expansion coefficient of the rock mass; ε_v is the body strain of the rock mass; Q_e is the heat generated or consumed by the heat conduction in the rock mass.

2.2. Hydrologic equation of the surrounding rock

According to the published study, the control equation of the hydrologic field of the surrounding rock under THM coupling conditions can be obtained as:

$$\begin{gathered}\theta_w \beta_w \rho_{w0} \tfrac{\partial p_w}{\partial t} - \theta_w \alpha \rho_{w0} \tfrac{\partial T}{\partial t} + \left(\rho_w - \rho_i\right) n \tfrac{\partial \chi}{\partial t} + \\ \nabla\left[-\tfrac{\rho_w k_w}{\mu_w}\left(\nabla p_w + \rho_w g_j\right) - \rho_w\left(SP_0 - D_T\right)\nabla T\right] + \left(\tfrac{\theta_w}{n}\rho_w + \tfrac{\theta_i}{n}\rho_i\right)\tfrac{\partial \varepsilon_v}{\partial t} = \rho_w \boldsymbol{q}_w\end{gathered} \tag{2}$$

where θ_w and θ_i are the water volume and ice volume, respectively; β_w is the pressure coefficient of water; ρ_{w0} is the initial density; α is the thermal expansion coefficient of water; ρ_w and ρ_i are water density and ice density, respectively; n is the porosity; $\chi$is the volume fraction of unfrozen water. $\chi$is 0 when the temperature is higher than the ice/water phase change point; k_w is the permeability coefficient of water; μ_w is the coefficient of dynamic viscosity of water; SP_0 is the segregated potential; D_T is the water diffusion rate subject to the temperature difference.

2.3. Control equation of stress in the surrounding rock

According to the principle of Terzaghi effective stress, the total stress increment of the rock mass under the low temperature can be expressed as:

$$\sigma_{ij} = \sigma'_{ij} - (\alpha_w p_w + \alpha_i p_i)\delta_{ij} \tag{3}$$

where σ_{ij} is the total strain tensor; σ'_{ij} is the effective strain tensor; p_w and p_i are the pore water pressure and the pore ice pressure, respectively; α_w and α_i are the incremental effective strain coefficient, respectively; δ_{ij} is the Kronecker symbol.

3. Engineering applications

3.1. The related engineering project and on-site conditions

The underground engineering project in Xinjiang is part of a major project of the provincial highway, where the climate condition is harsh and the geological condition is complicated. The freezing period is up to 6 months per year. The average thickness of the frozen layer amounts to 3˜5m with the maximum of 8m. The annual average temperature is 1.4, the average temperature of the coldest month (January) is -9.6, and in the hottest month (July) it is 9. The change of temperature is obvious in the vertical direction, e.g. the temperature drops by 0.94 when the height rises approximately every 100m. In order to ensure the stability of the surrounding rock, the surrounding rock is supported by the initial support and the secondary lining structure of the concrete, as shown in Figure 1. Given the large temperature difference in the area, particular attention should be paid to the stability of surrounding rock of underground caverns and the mechanical properties of lining structure. The analysis is carried out based on the local historical data and -30˜+50temperature cycles are adopted to simulate the periodical process of frost weathering. The structure mechanical and deformation characteristics of underground caverns are presented for different number of freeze-thaw cycles. The influences of low temperature and freeze-thaw cycles on the mechanical characteristics of the surrounding rock mass are investigated and the stability of the structure is determined quantitively.

3.2. Finite element model and its parameters and boundary conditions

The influence of environmental temperature on the surrounding rock mainly occurs at certain depth of the hole of underground caverns. Considering the typical temperature difference in the region, -30℃∼+50℃ temperature cycles are adopted to simulate the frost weathering. The specific calculation model is shown in Figure 1.

By focusing on the cavity entrance of the site, the present study calculates and analyzes the frost heaving force and the stability of the surrounding rock mass. The distance from the area under study to the entrance is 35 m. According to elastic mechanics, the model can be characterized by a plane strain problem. As shown in

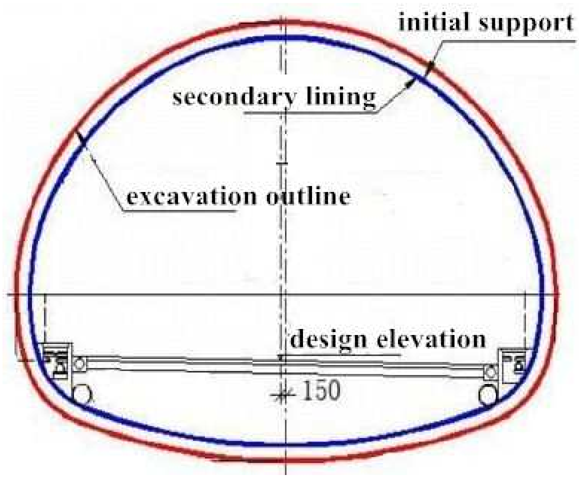

Fig. 1. The schematic sectional view of the underground caverns and the finite element model

Figure 1, AB and CD are axisymmetric boundaries. The horizontal displacement is zero, so is the vertical displacement DE. The mechanical parameters of surrounding rock and lining structure are shown in Table 1. Given the small embedded depth of underground caverns and according to the geo-mechanical test records, the ground stress in this region is mainly gravity stress, and the tectonic stress is small. Therefore, in the finite element calculation, the gravity stress is mainly considered to simulate the process of surrounding rock mass excavation and support. The mechanical properties of the lining structure and its internal stress were obtained after analysis on the deformation characteristics of caverns under different freeze-thaw cycles.

Table 1. Mechanical parameters of the surrounding rock and lining structure

Material	Density /(kgm^{-3})	Elastic modulus/Gpa	Poisson's ratio	Uniaxial compressive strength/MPa	Modulus of deformation/GPa	Porosity
Weathering andesite	2350	2.8	0.23	31.0	0.35	0.73
Lining concrete	2500	29.5	0.2	31.5	11.8	0.29

3.3. Results and discussion

When the environment temperature of underground caverns is lower than 0, the surrounding rock and lining structure will gradually form a series of freeze circles. With the decrease of temperature, the freeze range and depth increases, and the frost heaving force also increases. However, as the temperature rises, the decrease of frost heaving force gradually slows down and even stops. Figure 2 shows the frost heaving force distribution of surrounding rock mass under low temperature and freeze-thaw cycles. It can be noted that, throughout the freeze (November-march), the frost heaving force always exists. The results also show the change trend of frost heaving force over time. From November, the frost heaving force begins to appear. As the freeze continues, the temperature continues to decline and the frozen depth increases. The maximum frost heaving force in the freeze period is 1.6 MPa, and its position is in the arch foot of the surrounding rock. In March of the next year, the frost heaving force begins to decrease gradually. As the temperature rises, the freeze range decreases gradually and the frost heaving force dissipates gradually. In April, the maximum frost heaving force of surrounding rock is 0.36 MPa, which is in the position of the arch foot of the surrounding rock. The frost heaving force decreases by 77.5% compared to its value in the freeze period. The phenomenon shows that the frost heaving force gradually dissipates with the increase of temperature.

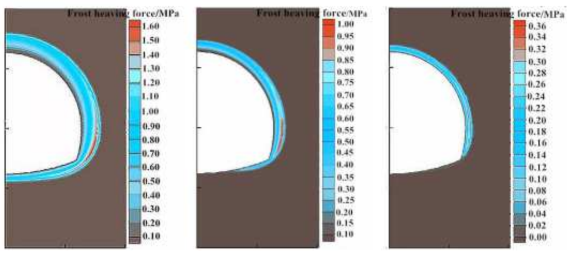

Fig. 2. Size and distribution of surrounding rock frost heaving force in different times

For the underground caverns in cold regions, the frost heaving force caused by low temperature and freeze-thaw cycles damages the surrounding rock and lining structure, which influences the stability of caverns. Figure 3 shows the horizontal displacement of surrounding rock after 0, 50 and 100 freeze-thaw cycles, which indicates that the horizontal displacement of surrounding rock appears in the wall after different numbers of freeze-thaw cycles. The maximum horizontal displacements are 1.3 mm, 2.4 mm and 2.8mm after 0, 50 and 100 freeze-thaw cycles, respectively. The biggest increase of displacement is 115.4%. The comparison among the horizontal displacements after different numbers of freeze-thaw cycles suggests that the freeze-thaw cycles have evident influence on the displacement of surrounding rock.

The maximum and the minimum principal stresses distribution of the lining after 0, 50 and 100 freeze-thaw cycles are calculated, and the results are presented in Figures 4 and 5. It can be seen that the maximum and minimum principal stresses appear in the arch foot of the lining structure. This position is the same as the position of the frost heaving force of surrounding rock. After 0, 50 and 100 freeze-thaw cycles, it can be seen that the stress of lining structure increases significantly with the increase of freeze-thaw cycles. Taking the maximum principal stress of the lining structure as an example, the maximum stress of the lining structure is 1.0MPa, 1.25MPa and 1.6MPa after different freeze-thaw cycles. It appears in the position of the arch foot, and the maximum increase is 60%, as shown in Figure 4. Taking the minimum principal stress of the lining structure as an example, the

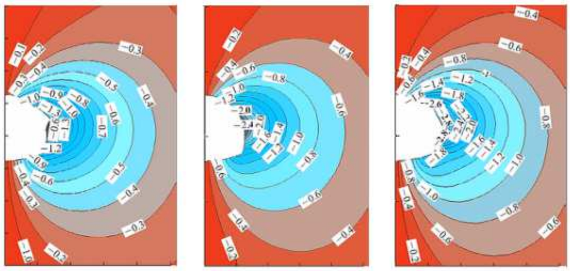

Fig. 3. Horizontal displacement of surrounding rocks after different numbers of freeze-thaw cycles

maximum stress of the position of the arch foot is 2.39MPa, 3.27MPa and 4.18MPa after different freeze-thaw times, with an increase of 74.9%, as shown in Figure 5. The results suggest that the low temperature and freeze- thaw cycles have great influence on the stress of the lining structure.

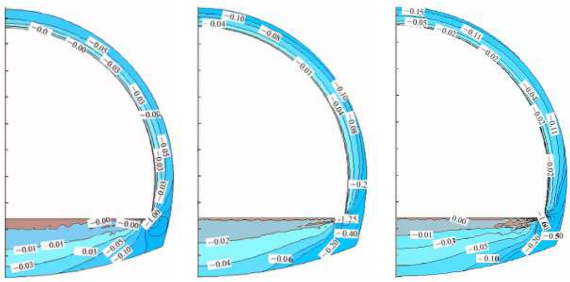

Fig. 4. Distribution of maximum principal stress in the lining after different freeze-thaw cycles

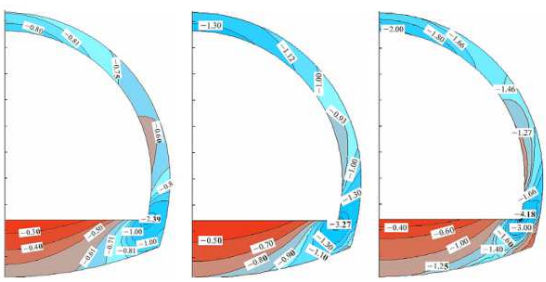

Fig. 5. Distribution of minimum principal stress in the lining after different freeze-thaw cycles

4. Conclusions

The result indicates that, without any thermal insulation measures in underground caverns under low temperature and freeze-thaw environment (-30 to +50), the maximum frost heaving force in freeze period of surrounding rock is 1.6MPa, and it occurs in February. As the temperature rises, the final frost heaving force of surrounding rock is 0.36MPa and it occurs in April. This is a decrease of 77.5% compared to the freeze period. The results show that the frost heaving force dissipates gradually with the temperature rise.

The maximum compressive stress of lining structure of surrounding rock is 2.39MPa, 3.27MPa and 4.18MPa after 0, 50 and 100 freeze-thaw cycles, respectively. The increase is up to 74.9%. This shows that low temperature and freeze-thaw cycles have greater influence on the mechanics and deformation of lining structure of surrounding rock mass. Therefore, thermal insulation layer is significant to the stability of cavern in the design of underground caverns in cold areas.

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