Numerical Simulation of Soft Rock Creep Behavior under Coupling Influence of Temperature and Stress

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Abstract: In order to investigate the deformation law of deep surrounding rock under the coupling influence of temperature, cracks and stress. We take the temperature, initial damage and confining pressure into consideration to simulate the deformation of deep surrounding rocks after mining. The numerical simulation of the creep characteristics of deep tunnel can be summed up as follows: a) the increase of temperature makes the strength decrease and the increase deformation of rock mass; b) With the increase of confining pressure, the anti-deformation ability of rock mass is enhanced and the failure mode of rock mass changes from brittle failure to plastic failure; c) The existence of cracks reduces the strength of rocks and intensifies the deformation of rocks; d) the stress in the tunnel mainly concentrates on the tip of the initial cracks and the existence of defects aggravates the deformation inside the tunnel.

1. Introduction

A large quantity of engineering practice proved that after a certain period of excavation, from weeks to months, the roof of the roadway will deform and crack, which seriously affects mineral mining and workers' safety. Especially for soft rock mass and tunnel excavation in deep engineering, the deformation with time is more serious. Many scholars have studied the creep characteristics of rock, Chen[1] et al investigated the creep characteristics of Beishan granite under the separated influence of temperature and stress; Rybacki [2] et al investigated the creep characteristics of shale under the coupling influence of temperature and confining pressure. Heap [3] have carried out tri-axial creep tests at different temperatures (20 °C, 75°C) for three types of sandstone in different areas to study the effect of temperature on the creep behavior of sandstone, which found the increase of temperature led to the acceleration of the propagation and evolution rate of internal cracks. Mishra [4] et al carried out single and tri-axial creep tests on coal seam shale to investigate time-aging creep characteristics of coal seam shale. Liu [5] et al carried out tri-axial creep tests on clay rocks at different confining pressures to investigate the effects of deviatoric stress on creep velocity, creep strain and permeability of clay rock; Brantuf [6] et al studied the effect of initial damage (porosity, cracks) on the creep rate of sandstone and found that the larger the initial damage is, the faster the creep rate is.

We take the deep tunnel in 1000m as a sample and the size of tunnel is shown in Fig.1. According to Saint-Venant's principle, the stress in the vicinity of the roadway has no effect on the strata beyond it. So we just consider the influence of stress and temperature around the tunnel.
2. Model Parameter
The tunnel simulated in this paper is a deep tunnel 1000m underground and the surrounding rock of the stratum where the roadway located is engineering soft rock. The parameters of soft rock is shown in Table 1.

| Type       | Peak Stress (MPa) | Peak Strain (×10^{-3}) | Poisson’s ratio | Elasticity Modulus (GPa) |
|------------|-------------------|-------------------------|-----------------|--------------------------|
| Soft Rock  | 4.232             | 5.916                   | 0.25            | 1.632                    |

Based on the measured stress data of crust in China, the vertical and horizontal in-situ stresses of 1000 meters are about 30MPa and 24MPa\(^7\). The creep equations embedded in ABAQUS software are mainly divided into two categories, which are Power-law model and Hyperbolic-sine law model. The Power-law model is further divided into Time hardening form and Strain hardening form. Power-law model can be well applied to creep phenomenon in engineering. Therefore, the power-law model based on time hardening was selected as the creep equation for creep numerical simulation in this paper.

3. Numerical Simulation of Temperature Field in Deep Soft Rock Tunnel
The temperature field is set in the tunnel to set temperature boundary conditions, which is used to simulate the thermal stress caused by the temperature change inside the surrounding rock of deep tunnel. The initial temperature is set to 20°C, and the surrounding rock temperature of the roadway is 40°C and 60°C, respectively. The influence of temperature on the creep characteristics of deep soft rock is explained by simulating the internal stress distribution and deformation of surrounding rock after temperature rise. The stress distribution and deformation of deep soft rock roadway surrounding rock after temperature change are shown in Fig.2 and Fig.3.
The distribution of thermal stress inside the surrounding rock of the roadway under different temperature conditions are shown in Fig. 2 and Fig. 3, respectively. As can be seen from Fig. 2 and Fig. 3, the maximum stress inside the surrounding rock of deep roadway reach 7.711e-1 MPa when the temperature inside the roadway rises to 40℃, whereas the maximum thermal stress in the surrounding rock of the roadway increases to 1.266 MPa when the temperature rises to 60℃. It can be seen from the simulation results that the internal stress of surrounding rock increases with the increase of temperature. At the same time, the influence of thermal stress is relatively small, only near the heat source will produce a large thermal stress, while in the range far away from the heat source, the thermal stress caused by the temperature decreases.

4. Numerical Simulation of Creep Characteristics of Deep Soft Rock Roadway

In order to verify the influence of cracks in the surrounding rock on the creep characteristics of surrounding rock, the original defects were prefabricated in the tunnel to explore the influence of cracks in the tunnel on the internal stress distribution and deformation of the surrounding rock. The load is applied to the surrounding rock of the roadway. In order to prevent the calculation from not converging due to the load, the load is applied step by step. The creep behavior of surrounding rock is simulated when the load of surrounding rock reaches the predetermined load. The creep time is set as 8.64e5s to simulate the creep situation of surrounding rock within ten days. The simulation is based on the assumption of uniform load distribution and isotropic properties of surrounding rock, and ignores the influence of unequal pore distribution in rock mass.
Fig. 4 Numerical Simulation of Surrounding Rock under Different Temperature and Confining Pressure

The distribution of stress and creep of surrounding rock under different temperature and confining pressure supporting conditions is shown in Fig. 4. As can be seen from the Fig.4 that the stress distribution in the surrounding rock is mainly concentrated at the roof and the junction between the side wall and the bottom of the roadway, the creep deformation in the tunnel mainly concentrates on the roof of the tunnel and the stress concentration position. Especially in the roadway bottom and side wall junction, there is a large stress concentration due to the shape. As can be seen from Fig. 4a-d,
under the same supporting conditions, the stress distribution inside the surrounding rock and the creep strain of surrounding rock have no obvious change with the increase of temperature. In Fig. 4a and Fig. 4c, it can be found that the maximum stress inside the surrounding rock under the two working conditions is the same, and only the minimum stress position is different.

According to the comparison between Fig. 4i and Fig. 4g, it can be found that the existence of cracks changes the distribution of stress inside surrounding rock of roadway. The stress in the surrounding rock is transferred to the crack tip, and the stress in the surrounding rock is increased accordingly. The maximum stress in the surrounding rock with fracture increases to 3.709e1MPa which increases by 37.3% compared with the condition without crack defect. As can be seen from Figure 4j, the cracks inside the surrounding rock of the roadway increased the creep strain of surrounding rock from 3.069e-2 to 5.579e-2, It can be inferred that the cracks in the surrounding rock accelerate the deformation and failure of the surrounding rock, and the failure of the roadway surrounding rock occurs first from the defect position.

5. Conclusions
1) The increase of temperature weakens the strength and enhances the deformation of rock mass. The increase of confining pressure enhances the anti-deformation ability of rock mass. The failure mode of rock mass changes from brittle failure to plastic failure with the influence of confining pressure.
2) The stress in the tunnel mainly concentrates on the tip of the defect when there is an initial cracks in the tunnel and the existence of initial cracks aggravates the deformation inside the tunnel. The stress and deformation in the surrounding rock are obviously reduced after supporting measures are applied to the surrounding rock.

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