Numerical simulation on Time-dependent Behavior and Long-term Safety Analysis of Soft Rock Tunnel under Seepage Condition

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Abstract: This study investigates the time-dependent behavior of soft surrounding rocks of the Shanxi Panxiushan railroad tunnel. Based on the viscoelastic-plastic damage mechanics, the rheological problem, mechanical properties of degradation, and seepage problem of the soft rock tunnel are comprehensively considered. The time-dependent deformation and stress of the surrounding rock mass following excavation were simulated using the proposed model of finite-difference software FLAC3D. The stress distribution of the surrounding rock support and reinforcement after the excavation were obtained. The simulation results show that the rationality of the existing reinforcement scheme is verified and the final deformation stability time of the surrounding rock during the operational period is calculated. Furthermore, a novel damage-based long-term safety analysis method is proposed, providing theoretical guidance and technical support for the design and construction of soft rock tunnels. The factor of safety (FOS) of the surrounding rock during the excavation and operational period is analyzed using the proposed analysis method. These results could have reference value for the design and construction of similar soft rock tunnels.

Keywords: Soft rock tunnel, time-dependent behavior, numerical simulation, long-term safety analysis, seepage

1. Introduction
The time-dependent behavior of soft surrounding rock mass is a significant and challenging engineering problem of tunnel construction and use. Soft rock mass has the characteristics of low strength, large deformation, and manifest rheology [1]. The excavation of the soft rock tunnel buried in complex construction environments will disturb the surrounding rock and change its stress distribution, leading to deformation, fracture, and instability. Because of the mechanical properties of soft rock and high in-situ stresses during and after the excavation process of a soft rock tunnel, the deformation of the surrounding rocks, including roof subsidence, floor heaving, and sidewall shrinkage, is large [2]. Even at low stress levels, because of the rheological properties, obvious viscoelasticity can be found in the soft surrounding rock. The tunnel convergences exhibit strong time-dependent characteristics, causing stress in the rock walls continuously increasing with time [3]. Meanwhile, degradation and softening of soft rock mechanical properties occur under seepage conditions, leading to high construction risk and support costs. For tunneling in soft rock mass under seepage conditions, rock rheology, degradation of mechanical properties, and extreme disturbance during the excavation process significantly influence the stress distribution on the support system and
endanger the long-term safety of the tunnel [4–5]. It, therefore, is essential to study the time-dependent behavior and assess the long-term safety of soft rock tunnels. The significant characteristics of soft rock tunnels are reflected in the high deformation degree of the surrounding rock, large damage range, support failure, and other aspects [6–7]. Effectively analyzing and designing to control the deformation of soft rock is principal technical problems in the design and construction of soft rock tunnels. Researchers have described the time-dependent behavior in the soft surrounding rock of tunnels by conducting in-depth studies using analytical methods [8–9], empirical approaches [10], and numerical simulations [11–12]. The analytical and empirical methods are low calculation costs and can be conveniently used in the analyses of tunneling problems. However, they only apply to tunnels under single specific conditions and only consider the ultimate state of the tunnels. Linear viscoelastic models are often adopted for simulating the time-dependent behavior of the surrounding rock of tunnels, which are efficient in computation but barely satisfactory in the coupling simulations. Although there have been many studies on the time-dependent behavior of soft rheological rock tunnels, existing solutions seldom consider the coupled effect of seepage and damage in tunnels and rock rheology. Moreover, there is no proper long-term stability analysis method. Therefore, this study systematically investigates the time-dependent behavior of soft rock tunnel under seepage conditions, including deformation, stress, and damage evolution using numerical simulation with a newly developed model. This study is based on the case study of the Shanxi Panxiushan railroad tunnel. The existing reinforcement scheme is verified, and the proposed long-term safety analysis method analyzes the long-term safety.

2. Engineering Background
The Shanxi Panxiushan railroad tunnel, located between Changzhi City and Linfen City, is designed as a left-right line separated type, with approximately 40 meters between the two middle sidewalls. The total length of the right tunnel is 3,832 m, with a design elevation of 1,180.36 m at the Changzhi end (mileage K39+025), a design elevation of 1,253.75 m at the Linfen end (mileage K42+857), and a maximum buried depth of 202.48 m. The left tunnel’s total length is 3,765 m, with a design elevation of 1,179.15 m at the Changzhi end (mileage ZK39+000), a design elevation of 1,253.58 m at the Linfen end (mileage ZK42+765), and a maximum buried depth of 210.08 m. The left and right lines are both super long tunnels with a general strike of 288–266°.

The geological report revealed that the surrounding rock of the tunnel is mainly composed of arkose, sandy mudstone, and argillaceous siltstone. The soft rock, mostly weak sandstone and mudstone, accounts for more than 72% of the total surrounding rock. The average thickness of the strongly weathered rock stratum is 4.3 m, with a thickness ranging from 2.0–6.4 m. The joint fissures are mostly weathering types with high fracture density and relatively broken rock mass. The weathering fissures of the weakly weathered rock stratum are often combined on the structural fissures. Moreover, abundant underground water stored in the stratum leads to poor surrounding rock quality. Therefore, the surrounding rock is classified as grade III and grade IV.

3. Model Setup and Parameters Selection
In this section, FLAC3D is used to establish the calculation model of the tunnel surrounding rock. The viscoelastic-plastic damage mechanics is considered to conduct the nonlinear numerical simulation calculation of the time-dependent behavior of the soft rock tunnel under seepage conditions, and the calculation parameters are determined based on the geological report. The soft rock section of the Shanxi Panxiushan railroad tunnel under the seepage conditions is considered in this study. The buried depth of the tunnel is 200 m. Because the scale of the tunnel cross-section is far less than its longitudinal length, under the action of in-situ stress, the displacement in the longitudinal direction is small enough to be neglected, and only the lateral displacement will be considered. Therefore, mechanical analysis of the tunnel can be simplified by setting the length along the axis direction of the tunnel as a small value.
The influence scope of the tunnel excavation radius is considered in the modeling, and thus, the research scope of the calculation model is calculated as follows: the length of the x-coordinate direction (horizontally in the plane of the tunnel cross-section) is taken as 150 m ($x = 0$–150 m); the length of the y-coordinate direction (longitudinally of the tunnel) is taken as 5 m ($y = 0$–5 m); and the depth of the z-coordinate direction (vertically in the plane of the tunnel cross-section) is taken as 100 m ($z = -100$–0 m). The width of the tunnel face is 10 m and the total height is 7.7 m, with a radius of 5.6 m for the roof. For minimizing boundary effects and ensuring the accuracy of the calculation, a domain more than 10 times the span of the tunnel is discretized, and the refined element sizes and aspect ratios are adopted near the excavation boundary and gradually increase outwards. The calculation model uses the displacement boundary condition, while the ground stress of cover rocks is applied at the top boundary. Figure 1 shows the finite-difference grid adopted for the calculation model. The upper stratum in blue represents grade IV rock mass, whereas the lower stratum in green is in grade III. The part in red is the tunnel face of excavation. The original water head is zero at the interface of the upper and lower stratum ($z = -30$ m). Darcy’s law is used in the analysis. At a high stress level, the water pressure causes the microcracks in the rock to expand and produce the initial action of damage. Meanwhile, permeability changes rapidly, leading to a continuous accumulation of damage. Therefore, the mechanical parameters of the rock deteriorate with it. In this study, the damage variable of rock is defined as

$$D = \begin{cases} \exp \left\{ - \frac{\left( \varepsilon_i - \varepsilon_{\text{thr}} \right)}{\varepsilon_0} \right\} & \varepsilon_i > \varepsilon_{\text{thr}} \\ 0 & \varepsilon_i \leq \varepsilon_{\text{thr}} \end{cases}$$

(1)

where $\varepsilon_i$ is the axial strain, $\varepsilon_0$ and $m$ are parameters of the Weibull distribution, and $\varepsilon_{\text{thr}}$ is a threshold strain of damage evolution.

When under complex stress conditions, plastic deformation will occur in rock materials. Assuming that the material is isotropic, plastic behavior follows the Mohr-Coulomb criterion, and thus, the plastic strain can be obtained. The viscoelastic-plastic damage constitutive relationship of the soft rock is defined as

$$\varepsilon_{ij} = \frac{2G_1}{G_1} \varepsilon_{ij} + \frac{2G_2}{G_2} \left[ 1 - \exp \left( - \frac{G_2}{\eta} \right) \right] + \varepsilon_{ij}^p,$$

(2)

$$\tilde{S} = \frac{S}{1 - D}$$

(3)

where $\varepsilon$ is the deviatoric strain, $G_1$, $G_2$ represent the shear modulus, $\tilde{S}$ is the effective deviatoric stress with damage effects, $\eta$ is the viscosity, and $\varepsilon_{ij}^p$ is an additional plastic strain to the model.

Figure 1. Illustration of the calculation model
Using geological conditions and construction design combined with the viscoelastic-plastic damage theory, the parameters of rock mechanical properties and permeability are determined and listed in Table 1, and Table 2 shows the calculation parameters of rheological damage properties. From the design, Figure 2 shows the bolts/lining combined support system. The diameter of the bolt is 22 mm, 3 m long, and an interval of 1 m between every two bolts. For the roof and sidewall, the lining support is C25 concrete with a thickness of 200 mm and reinforced by an 8 mm steel network. The lining of the floor is 400 mm C30 concrete with reinforcement. The bulk density of the reinforced concrete is taken as 25 kN/m$^3$. The elastic modulus is 28 GPa for C25 concrete and 30 GPa for C30 concrete.

### Table 1. Mechanical properties of the surrounding rock

| Rock classification | Density (kg/m$^3$) | Bulk modulus $K$ (GPa) | Shear modulus $G_1$ (GPa) | Cohesion $c$ (MPa) | Friction angle ($^\circ$) | Permeability coefficient $k$ (cm/s) |
|---------------------|--------------------|------------------------|---------------------------|------------------|------------------------|----------------------------------|
| III                 | 2.500              | 2.85                   | 1.63                      | 1.35             | 40                     | $4 \times 10^{-5}$               |
| IV                  | 2.420              | 1.76                   | 0.68                      | 0.65             | 33                     | $6 \times 10^{-4}$               |

### Table 2. The parameters of rheological damage properties of the surrounding rock

| Rock classification | Shear modulus $G_2$ (GPa) | Viscosity (GPa·d) | $\theta$ | $m$ | $\theta_{th}$ |
|---------------------|----------------------------|------------------|---------|-----|---------------|
| III                 | 16.1                       | 88               | $4 \times 10^{-3}$ | 0.5 | $1 \times 10^{-3}$ |
| IV                  | 14.3                       | 18.3             | $5 \times 10^{-3}$ | 0.4 | $8 \times 10^{-4}$ |

4. **Time-dependent Behavior of Surrounding Rock**

According to the above model, the calculated parameters of the rock mass and support system, FLAC3D is used for the calculation and analysis of the time-dependent behavior of surrounding rock under seepage conditions. Numerical simulation steps have been performed based on actual construction sequences to achieve realistic modeling results of the tunnel.

In the excavation stage, elasto-plastic analysis is adopted at the beginning of numerical computing, considering two conditions with and without seepage in the tunnel. The bolts of the support system are modeled as cable, while the lining is modeled as beam elements. Taking the results from the mechanical-seepage coupled elasto-plastic analysis as the initial state, the time-dependent behavior during excavation, fully considering the influence of seepage in the entire process, was simulated by running the viscoelastic-plastic damage model for 30 years to match the tunnel response as observed through monitoring. The results are obtained and then analyzed in the following subsections.

4.1. **Analysis of the displacement and stress field**
In the excavation stage, both with and without seepage conditions are considered and compared. Table 3 lists the short-term ultimate displacement and stress in the surrounding rock of the tunnel. The influence of seepage leads to larger values of the total displacement and major principal stress, whereas its influence on the minor principal stress is inapparent. The seepage in the tunnel could increase the possibility of failure. Thus, the results considering the seepage condition are taken as the initial state of the subsequent calculation.

**Table 3.** The ultimate displacement and principal stress under seepage and without seepage conditions

| Condition                  | Total displacement | Major principal stress | Minor principal stress |
|---------------------------|--------------------|------------------------|------------------------|
| Seepage condition         | 11.90 mm           | −18.40 MPa             | 0.16 MPa               |
| Without seepage condition | 10.66 mm           | −18.06 MPa             | 0.18 MPa               |

Based on the proposed model and considering the rheological properties and damage evolution of the tunnel under the seepage condition, long-term behavior during the working period of the tunnel is obtained. Figures 3–5 show the calculation results of the displacement around the tunnel. The figures show the obvious deformation of the tunnel surrounding rock. Under the action of excavation and rheology, the tunnel displacement develops toward the free face. The maximum horizontal displacement is 14.55 mm, the maximum vertical displacement is 20.76 mm, and the maximum total rheological displacement is 20.77 mm, which occurs at the position of the tunnel crown. The rheological displacement of the tunnel is dominated by vertical displacement, which is 1.4 times of the lateral displacement.

Figure 6 shows that the maximum value of the major principal stress is −12.65 MPa (the negative value represents compression). Figure 7 illustrates the distribution of the minor principal stress, which has a maximum value of 0.70 MPa. The tensile stress area is mainly located on the tunnel floor and midpoint of the tunnel sidewalls, which could lead to failure.

![Figure 3. The horizontal displacement contour of the tunnel](image-url)
Figure 4. The vertical displacement contour of the tunnel

Figure 5. The total displacement contour of the tunnel

Figure 6. The distribution of the major principal stress
4.2. The influence of the damage evolution

This section discusses the effect of damage evolution in the surrounding rock. As mentioned above, the largest deformation and stress could occur at the midpoint of the crown and sidewall, respectively. Considering the symmetry of the tunnel deformation, the midpoints of the tunnel crown and sidewall of the left line are selected as the representative point. Figures 8 and 9 show the total rheological displacement of the representative points in 30 years after tunnel excavation, considering the condition with and without damage evolution.

Figure 8 shows that at the beginning of the excavation, the total displacement of the crown under the two conditions are both in a value of 11.90 mm. When the damage evolution is considered, the convergence value of displacement is 25.94 mm, which remained stable for 23 years after excavation. The increment of rheological displacement is 14.04 mm, accounting for 54.16% of the total displacement. Without considering damage evolution, the convergence value of displacement is 20.72 mm, which remained stable for 16 years after excavation. The increment of rheological displacement is 8.82 mm, accounting for 42.57% of the total displacement. The slopes of the two lines show that the increasing rate of displacement with damage is faster than without damage. Moreover, a larger convergence displacement and a later stable state occur under the condition with damage.

Similarly, Figure 9 analyzes and compares the total displacement of the sidewall under the two conditions. With damage evolution, the convergence value of displacement is 21.27 mm, which remained stable for 19 years after excavation. The increment of rheological displacement is 13.68 mm, accounting for 64.31% of the total displacement, whereas without damage evolution, the convergence value of displacement is 15.94 mm, which remained stable for 14 years after excavation. The increment of rheological displacement is 8.35 mm, accounting for 52.38% of the total displacement. Likewise, a larger convergence displacement and a later stable state occur under the condition with damage.
Figure 8. Comparison of the total displacement at the midpoint of the tunnel crown

Figure 9. Comparison of the total displacement at the midpoint of the sidewall

5. Long-term Safety Analysis of Tunnel

In geotechnical engineering, both engineering practice and relevant research show that failure and instability might not occur immediately after the excavation. The stress and deformation of geomaterial gradually change with time, and this process often continues for a long time. In the process of tunnel construction, because of the redistribution of stress in underground rock mass caused by tunnel excavation, the surrounding rock is usually damaged. With the extension of time, the damaging effect accumulates, which could eventually lead to creep deformation and failure of the surrounding rock. The existing stability analysis methods for the surrounding rock cannot evaluate the long-term stability of rock accurately because the relationship between the damage degree and long-term strength is ignored. Given the above shortcomings, based on the Drucker-Prager criterion and introduced damage mechanics, we present a long-term stability and safety analysis method of rock mass based on long-term damage degree and develop the fish code in FLAC3D. In this method, the factor of safety (FOS) of long-term stability smaller than 1.0 represents the occurrence of failure, greater than 1.0 represents a safe condition, while the value of 1.0 is a critical state.

Using the calculation model in section 3 and the proposed viscoelastic-plastic model and coupled damage and seepage conditions, the distribution of the long-term FOS value is obtained via the rheological calculation during and after the tunnel excavation for 30 years (Figure 10). The FOS is greater than 1.0 and reveals that the surrounding rock is safe. Moreover, the FOS tends to be smaller near the excavation boundary and gradually increases outwards. However, a value approaching 1.0 can be found in the area near the midpoint of the tunnel sidewalls and on the floor, indicating potential failure at these positions. More attention should be paid to these areas during construction and use.

Figure 10. The factor of safety of the long-term stability of the tunnel
6. Conclusion
In tunnels excavated in soft rock mass, deformation around the tunnel could gradually develop with time because of the time-dependent or creep behavior of the rock mass. This study calculated the numerical solutions for double-lined tunnels that simultaneously consider the rheology of soft rock under seepage conditions and damage evolution in the surrounding rock. Based on the numerical simulation of the time-dependent behavior of the soft rock tunnel using a damage-based long-term stability analysis method, the long-term stability analysis were performed, and the long-term FOS was obtained. The main results of study are as follows:

(1) Based on the simulation results, the deformation of the tunnel surrounding rock is large around the tunnel face and develops toward the free face. The maximum total displacement occurs in the middle of the tunnel crown and is dominated by vertical displacement.

(2) The tensile stress area can be found after the calculation. It is mainly located on the floor and midpoint of the tunnel sidewalls, which could lead to the failure of the surrounding rock.

(3) When considering the effect of damage evolution on soft rock, the increasing rate of displacement with damage is faster than without damage. Under the damage condition, a larger convergence displacement and a later stable state are obtained.

(4) In this study, the long-term FOS value is greater than 1.0 and the corresponding area is in a safety condition. A value of FOS approaching 1.0 can be found near the midpoint of the tunnel sidewalls, which could lead to failure because of rheological effects.

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