Optimal Support Solution of Soft Rock Roadway Based on Drucker-Prager Yield Criteria

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Abstract

Through theoretical calculation, the stress and deformation of surrounding rock can be analyzed, which can provide guidance for support design and optimization of soft rock roadway. In this paper, theoretical solutions for both the optimal support pressure and the allowable maximum displacement of surrounding rock are derived based on the Drucker-Prager (DP) yield criteria and the steady creep criterion expressed by the third invariant of deviator stress. The DP criteria with different parameters are compared and analyzed by an engineering example. Then, based on the calculation results, the effects of long-term strength, cohesion and internal friction angle of soft rock on the maximum plastic zone radius and allowable maximum displacement of roadway are discussed. The results show that the optimal support solution of soft rock roadway based on DP criteria can not only reflect the intermediate principal stress reasonably, but also can compare and discuss the influence of different DP criteria on the calculation results. The higher the long-term strength of the roadway surrounding rock is, the smaller the optimal support force is and the larger the allowable maximum displacement is. When the calculated long-term strength of soft rock can ensure that the deformation of the roadway does not exceed the allowable maximum displacement, the roadway can maintain long-term stability without support. With the increase of the cohesion or internal friction angle of soft rock, the radius of plastic zone decreases gradually, and the allowable maximum displacement is reduced by degrees. Through grouting and other means to improve the strength of surrounding rock can effectively reduce the roadway deformation and save support costs.

Keywords: Roadway; Soft Rock; Optimal Support; Drucker-Prager yield criteria; Elasto-Plastic Analysis

1. Introduction

In the process of underground roadway excavation, the stress field will redistribute around the excavation area. The redistribution of stress field leads to convergence deformation of cavities produced by excavation. The size of deformation is related to rock mass properties, in-situ stress and support condition [1-4]. It is important to analyze the distribution of stress field and displacement field of surrounding rock by theoretical calculation [5-7]. Based on the ideal elastic-plastic model, Fenner and Kastner analyzed the elastic and plastic zones of tunnels and derived Fenner formula and Kastner formula [8]. Carranza-Torres [9] proposed an elastic-plastic solution of tunnel problems using the generalized form of the Hoek-Brown failure criterion. Park and Kim [10] discussed the analytical solutions for the prediction of

displacements around a circular opening in an elastic–brittle–plastic rock mass compatible with a linear Mohr–Coulomb or a nonlinear Hoek–Brown yield criterion. Sharan [11] presented a simple exact solution for the elastic–brittle–plastic plane strain analysis of displacements around circular openings in an isotropic Hoek–Brown rock subjected to a hydrostatic in-situ stress. According to the strain-softening characteristics of rock mass, Guo et al. [12] and Pan et al. [13] established elastic strain-softening models based on different strength criteria, calculated and analyzed the deformation of roadway surrounding rock, and considered the effects of intermediate principal stress, strain softening parameters and dilatancy. Fan et al. [14] developed a mechanical model for circular tunnels based on the unified strength criterion, and determined the critical support pressure when the plastic zone and damage zone begin to occur.

For deep geotechnical engineering, some roadways will gradually transform from shallow hard rock roadway to deep soft rock roadway. Therefore, the problem of soft rock support has become a major safety problem to be solved urgently [15-17]. Soft rock has obvious creep deformation characteristics. In engineering, serious extrusion deformation will occur in all directions of roadway, which will lead to the instability and failure of surrounding rock support structure [18-21]. In the process of support design of soft rock roadway, it is generally necessary to optimize the support parameters reasonably by theoretical calculation, guide engineering design by theoretical calculation results, and reduce the uncertainty brought by engineering analogy method [22-24]. Based on the experience of tunnel engineering and rock mechanics theory, Rabcewicz [25] combined bolt and shotcrete as the main support method, and proposed the new Austrian tunneling method (NATM). At present, NATM is almost a basic method for tunnel excavation in weak and fractured surrounding rock [26-28]. However, NATM is composed of a series of qualitative principles, and there is no quantitative calculation method for the important parameters of support, such as the optimal support force of roadway and the maximum allowable displacement of surrounding rock, which makes the design and construction of support still stay in the stage of engineering experience analogy.

According to the creep mechanism of rock and the rheological control principle of soft rock, some scholars have established the optimal support calculation method of soft rock, and solved the optimal support force and the allowable maximum displacement of surrounding rock [29-31]. For example, based on the Mohr-Coulomb (MC) criterion and steady creep criterion expressed by the second invariant of deviator stress, Fan et al. [29] derived the optimal support force and the maximum allowable displacement of surrounding rock for soft rock cavern. Cui et al. [30] discussed the optimum supporting force, the maximum allowable displacement of surrounding rock and the relevant parameters of constant resistance steel frame by using the MC criterion and steady creep criterion expressed by the third invariant of deviator stress. Based on the unified strength theory and considering the effect of the intermediate principal stress and strength criterion, Zeng et al. [31] provided the theoretical solutions of the optimal support force and the maximum allowable displacement of surrounding rock under two kinds of stable creep criteria.

The instability of excavation is usually caused by the excessive concentration of stress in the rock mass near the excavation, the excessive stress of supporting components, or the change of rock deformation and strength characteristics [32-36]. And the deformation pressure of viscoelastic rock mass on underground roadway support depends on the properties of surrounding rock and rock-support interaction. Therefore, based on DP series criteria reflecting intermediate principal stress, this paper deduces the analytical solution of optimal support force and allowable maximum displacement of surrounding rock in circular roadway, and compares

different DP criteria by an engineering example, and discusses the effects of long-term strength, cohesion and internal friction angle of soft rock on the maximum plastic zone radius and allowable maximum displacement of roadway. The research results can provide theoretical guidance for the rational design and optimization of soft rock roadway support.

2. Drucker-Prager Yield Criteria

The yield surface of MC yield criterion is an irregular hexagonal pyramid in three-dimensional stress space. To eliminate the singularity of the yield surface on the cone top and the ridgeline, Drucker and Prager proposed a smooth conical yield surface that is inscribed in the MC yield criterion hexagonal pyramid [37]. According to the relative positional relationship between the DP yield criterion and the Mohr-Coulomb yield criterion on the π plane, the DP yield criteria are derived [38]. The DP yield criteria can be given by

$$\alpha I_1 + \sqrt{J_2} = k \tag{1}$$

where the parameters α and k are related to the cohesion c and the internal friction angle φ of the surrounding rock. According to the matching relationship with the MC criterion, the corresponding parameter expressions are shown in Table 1. I_1 is the first invariant of stress tensor, $I_1=\sigma_1+\sigma_2+\sigma_3$; J_2 is the second invariant of stress deviator, $J_2=[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]/6$, and σ_1, σ_2, and σ_3 are the large, medium and small principal stresses of the surrounding rock, respectively.

The expression of DP criterion under plane strain condition is as follows

$$\sigma_1 = M\sigma_3 + N \tag{2}$$

where $M = \frac{1+3\alpha}{1-3\alpha}$, $N = \frac{2k}{1-3\alpha}$. Because the internal friction angle φ is always greater than 0, $\alpha \neq 0$ and $M \neq 1$.

Table 1: Parameter expressions of Drucker–Prager yield criteria.

Serial number	Criterion types	α	k
DP1	The MC criterion based with external corner circumscribed, a circle yield criterion	$\frac{2\sin\varphi}{\sqrt{3}(3-\sin\varphi)}$	$\frac{6c\cos\varphi}{\sqrt{3}(3-\sin\varphi)}$
DP2	The MC criterion based with inner corner circumscribed, a circle yield criterion	$\frac{2\sin\varphi}{\sqrt{3}(3+\sin\varphi)}$	$\frac{6c\cos\varphi}{\sqrt{3}(3+\sin\varphi)}$
DP3	The MC criterion based with matching circles, for plain strain problems with associated flow rules	$\frac{\sin\varphi}{\sqrt{3}\sqrt{3+\sin^2\varphi}}$	$\frac{3c\cos\varphi}{\sqrt{3}\sqrt{3+\sin^2\varphi}}$
DP4	The MC criterion based with equivalent area, a circle yield criterion	$\frac{2\sqrt{3}\sin\varphi}{\sqrt{2\sqrt{3}\pi\ (9-\sin^2\varphi)}}$	$\frac{6\sqrt{3}c\cos\varphi}{\sqrt{2\sqrt{3}\pi\ (9-\sin^2\varphi)}}$
DP5	The MC criterion based with matching circles, for plain strain problems with non-associated flow rules	$\frac{\sin\varphi}{3}$	$c\cos\varphi$

3. Optimum Support Calculation of Roadway

3.1 Basic assumptions

In order to carry out the elastic-plastic analysis of surrounding rock, the following assumptions are made:

(1) The cross-section of the roadway is in circular and the length is infinite. So it can be simplified as a plane strain problem.

(2) Surrounding rock of the roadway is a continuous, homogeneous, and isotropic elastic-plastic material.

(3) Ignoring the effects of the surrounding rock weight on the yield, the original rock stress can be simplified as a uniform stress distribution. The roadway is under the conditions of uniform in-situ stress and support force.

3.2 Elastic-plastic analysis

Taking the circular roadway under the combined action of uniform in-situ stress p_0 and uniform support force p_i shown in Figure 1 as an example, the elastic-plastic stresses of surrounding rock during excavation are solved in this section. In Figure 1, r_i is the excavation radius of roadway, R is the radius of plastic zone of surrounding rock, u_0 is the displacement of roadway wall, and σ_r and σ_θ are the radial and tangential stresses respectively.

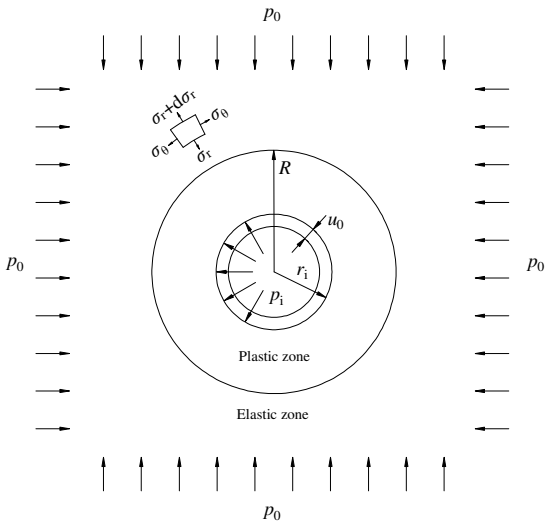


Figure 1 Elastic-plastic analysis model of circular roadway [31]

In the plastic zone of the surrounding rock, the tangential stress σ_θ and the radial stress σ_r are the maximum and minimum principal stresses, respectively. Equation (2) can be written as

$$\sigma_\theta = M\sigma_r + N \tag{3}$$

The differential equation of equilibrium for the axisymmetric problem can be expressed as

$$\frac{\mathrm{d}\sigma_r}{\mathrm{d}r}+\frac{\sigma_r-\sigma_\theta}{r}=0 \tag{4}$$

where r is the radius of calculation area of circular roadway.

By taking the stress at the inner wall of roadway as the boundary condition, the stress field distribution in plastic zone are obtained as follows [12, 13]

$$\left.\begin{aligned}\sigma_r^{\mathrm{p}}&=(p_i+\frac{N}{M-1})(\frac{r}{r_i})^{M-1}-\frac{N}{M-1}\\ \sigma_\theta^{\mathrm{p}}&=M(p_i+\frac{N}{M-1})(\frac{r}{r_i})^{M-1}-\frac{N}{M-1}\end{aligned}\right\} \tag{5}$$

where p_{i} is the support force, r_{i} is the radius of roadway, σ_r^{p} and $\sigma_\theta^{\mathrm{p}}$ are the radial stress and tangential stress in plastic zone respectively.

Assuming that the radial stress at the interface between elastic zone and plastic zone of surrounding rock is $\sigma_r^{\mathrm{e\text{-}p}}$, based on thick-walled cylinder theory [12], the stress field distribution in elastic zone can be obtained as follows

$$\left.\begin{aligned}\sigma_r^{\mathrm{e}}&=p_0-(p_0-\sigma_r^{\mathrm{e\text{-}p}})\frac{R^2}{r^2}\\ \sigma_\theta^{\mathrm{e}}&=p_0+(p_0-\sigma_r^{\mathrm{e\text{-}p}})\frac{R^2}{r^2}\end{aligned}\right\} \tag{6}$$

where p_0 is the uniform in-situ stress, R is the radius of plastic zone, σ_r^{e} and $\sigma_\theta^{\mathrm{e}}$ are the radial stress and tangential stress in elastic zone respectively, E and v are elastic modulus and Poisson's ratio of surrounding rock respectively.

Since the stress at the elastic-plastic interface of surrounding rock is continuous, the expressions of radial stress at the elastic-plastic interface and the radius of plastic zone can be obtained as follows

$$\sigma_r^{\mathrm{e\text{-}p}}=\frac{2p_0-N}{M+1} \tag{7}$$

$$R=r_i\left(\frac{\sigma_r^{\mathrm{e\text{-}p}}+\frac{N}{M-1}}{p_i+\frac{N}{M-1}}\right)^{\frac{1}{M-1}} \tag{8}$$

By substituting Equation (7) into Equation (6), the stress solutions in elastic zone are obtained as follows

$$\left.\begin{aligned}\sigma_r^{\mathrm{e}} &= p_0 - \frac{(M-1)p_0+N}{M+1}\left(\frac{\frac{2p_0-N}{M+1}+\frac{N}{M-1}}{p_i+\frac{N}{M-1}}\right)^{\frac{2}{M-1}}\left(\frac{r_i}{r}\right)^2 \\ \sigma_\theta^{\mathrm{e}} &= p_0 + \frac{(M-1)p_0+N}{M+1}\left(\frac{\frac{2p_0-N}{M+1}+\frac{N}{M-1}}{p_i+\frac{N}{M-1}}\right)^{\frac{2}{M-1}}\left(\frac{r_i}{r}\right)^2\end{aligned}\right\} \tag{9}$$

During the excavation of roadway, the support force of surrounding rock is 0, and the initial plastic zone radius can be calculated by Equation (8). The initial plastic zone radius R_0 is expressed as follows

$$R_0 = r_i\left[1+\frac{(M-1)(2p_0-N)}{(M+1)N}\right]^{\frac{1}{M-1}} \tag{10}$$

In the support stage, the elastic stress solution at the elastic-plastic interface can be obtained by substituting Equation (10) with Equation (9). The radial and tangential stresses at the elastic-plastic interface are as follows

$$\left.\begin{aligned}\sigma_r^{\mathrm{e}}\big|_{r=R_0} &= p_0 - \frac{(M-1)p_0+N}{M+1}\left[\frac{N}{(M-1)p_i+N}\right]^{\frac{2}{M-1}} \\ \sigma_\theta^{\mathrm{e}}\big|_{r=R_0} &= p_0 + \frac{(M-1)p_0+N}{M+1}\left[\frac{N}{(M-1)p_i+N}\right]^{\frac{2}{M-1}}\end{aligned}\right\} \tag{11}$$

For the plane strain problem, the Z-direction strain is 0, so the intermediate principal stress σ_z can be derived by Hooke's law as follows

$$\sigma_z = \nu(\sigma_\theta + \sigma_r) \tag{12}$$

The following equation can be obtained by ordering the principal stresses at the elastic-plastic interface:

$$\sigma_1=\sigma_\theta^{\mathrm{e}}\big|_{r=R_0},\ \sigma_2=\sigma_z^{\mathrm{e}}\big|_{r=R_0},\ \sigma_3=\sigma_r^{\mathrm{e}}\big|_{r=R_0} \tag{13}$$

Then, combined with equations (11), (12) and (13), the average principal stress σ_m can be obtained as follows

$$\sigma_m = \frac{\sigma_1+\sigma_2+\sigma_3}{3} = \frac{2(1+\nu)}{3}p_0 \tag{14}$$

3.3 Optimal support solution

Creep is a special form of elastic-plastic deformation of rock, which is a phenomenon that the strain increases with time under the condition of keeping the stress constant. For example, soft rock or hard rock under high stress usually has obvious creep characteristics, and shows serious extrusion deformation from all directions of underground engineering, which often leads to instability and failure of support [39, 40]. Therefore, this kind of rock can be considered as an

elastic-plastic material with rheological properties. The typical creep curve of rock mainly includes three stages: temporary creep (AB), stable creep (BC) and accelerated creep (CD), as shown in Figure 2.

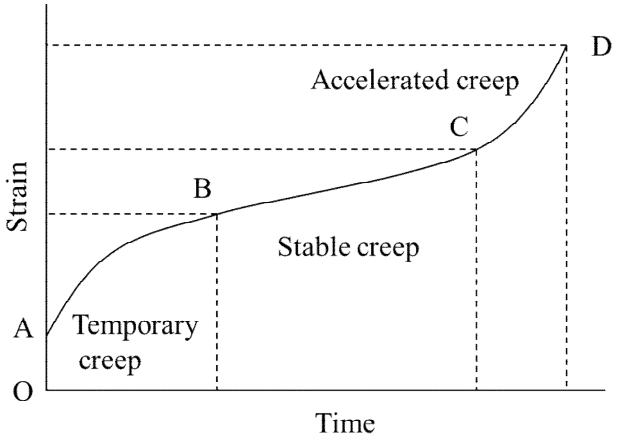


Figure 2 Typical creep curve of rock

A large number of engineering practices show that the excessive harmful deformation is the main reason for the instability of underground engineering. The establishment and application of creep model is one of the core contents in the study of deformation characteristics of soft rock. The expression of the steady creep criterion expressed by the third invariant of deviator stress is as follows [30]

$$\sqrt[3]{\frac{27}{2}J_3} \le \sigma_L \tag{15}$$

$$J_3 = (\sigma_1 - \sigma_{\mathrm{m}})(\sigma_2 - \sigma_{\mathrm{m}})(\sigma_3 - \sigma_{\mathrm{m}}) \tag{16}$$

where σ_{L} is the long-term strength of rock, J_3 is the third invariant of deviator stress.

By substituting Equation (13) and (14) into Equation (15) and making both sides of the equation equal, the optimum support force of roadway is obtained as follows

$$p_{i-\min} = \frac{N}{M-1}\left[\frac{1}{3}\sqrt{\frac{\sigma_L^3}{(1-2\nu)p_0} + (1-2\nu)^2 p_0^2}\left[\frac{N}{M-1} + \left(\frac{M-1}{M+1}\right)p_0\right]^{-1}\right]^{-\frac{M-1}{2}} - \frac{N}{M-1} \tag{17}$$

It is the optimal support state when the roadway support force p_i is equal to the optimum support force $p_{i-\min}$. In this case, the radius of plastic zone is

$$R_{\max} = r_i\left[\left(\frac{2p_0 - N}{M+1} + \frac{N}{M-1}\right)\left(p_{i-\min} + \frac{N}{M-1}\right)^{-1}\right]^{\frac{1}{M-1}} \tag{18}$$

where $R_{\max}$ is the maximum radius of plastic zone.

Based on thick-walled cylinder theory, the displacement in elastic zone is

$$u^{e}=\frac{1+\nu}{E}(p_0-\sigma_r^{e\text{-}p})\frac{R^2}{r} \tag{19}$$

At the elastic-plastic interface, $r=R$, and the displacement of surrounding rock at the elastic-plastic interface is

$$u^{e\text{-}p}=\frac{(1+\nu)R}{E}(p_0-\sigma_r^{e\text{-}p}) \tag{20}$$

In the optimum support condition, the initial elastic displacement at the elastic-plastic interface is as follows

$$u_0^{e}=\frac{(1+\nu)R_{max}}{E}\frac{(M-1)p_0+N}{M+1} \tag{21}$$

The creep modulus of rock can be obtained by laboratory rheological test. By replacing the elastic modulus E of Equation (21) with the creep modulus E_c, the creep displacement at the elastic-plastic interface can be obtained as follows

$$u^{c}=\frac{(1+\nu)R_{max}}{E_c}\frac{(M-1)p_0+N}{M+1} \tag{22}$$

The displacement of plastic zone is composed of initial elastic displacement and stable creep displacement. According to Equation (21) and Equation (22), the stable displacement of roadway can be calculated as follows

$$\nabla u=u^{c}-u_0^{e}=\frac{(1+\nu)R_{max}[(M-1)p_0+N]}{M+1}\left(\frac{E-E_c}{E\cdot E_c}\right) \tag{23}$$

Taking $u|_{r=R_{max}}=\nabla u$ as the displacement boundary condition, the displacement of roadway wall at the optimum support condition is obtained as

$$u_{0-max}=\frac{R_{max}}{r_i}\nabla u=\frac{(1+\nu)R_{max}^2[(M-1)p_0+N]}{(M+1)r_i}\left(\frac{E-E_c}{E\cdot E_c}\right) \tag{24}$$

It can be seen that different DP yield criteria correspond to different parameters M and N. By substituting Equation (17) into Equation (18) to obtain the maximum radius of plastic zone R_{max}, and then substituting Equation (18) into Equation (24), the allowable maximum displacement at the roadway wall can be obtained.

4 Example Studies and Discussion

4.1 Roadway parameters

The Beizao Coal Mine is located in Longkou City, Shandong Province, China, which is a typical soft rock mine with complex geological conditions, especially with the continuous extension of mining level, roadway deformation problem is very prominent. Taking the soft rock roadway in the Beizao Coal Mine as an engineering example, the effects of DP criterion

and mechanical parameters of surrounding rock on roadway support are analyzed. The geometric and mechanical parameters of the roadway are shown in Table 2. The yieldable U-shaped steel ribs are used to support the roadway, and the in-situ measured roadway wall displacement is 18.7mm.

Table 2: Geometrical and mechanical parameters

Symbol	Description	Value
r_i/m	Excavation radius	2.0
p_0/MPa	In-situ stress	5.6
E/MPa	Elastic modulus	1500
E_c/MPa	Creep modulus	400
v	Poisson's ratio	0.24
c/MPa	Cohesion	0.71
φ/°	Internal friction angle	23.6
σ_c/MPa	Uniaxial compressive strength	29.0
σ_L/MPa	Long-term strength	6.38

4.2 The effect of yield criteria

The calculation results of optimal support force, maximum plastic zone radius and allowable maximum displacement of surrounding rock under different DP criteria are shown in Table 3.

Table 3: Calculation results of different DP yield criteria

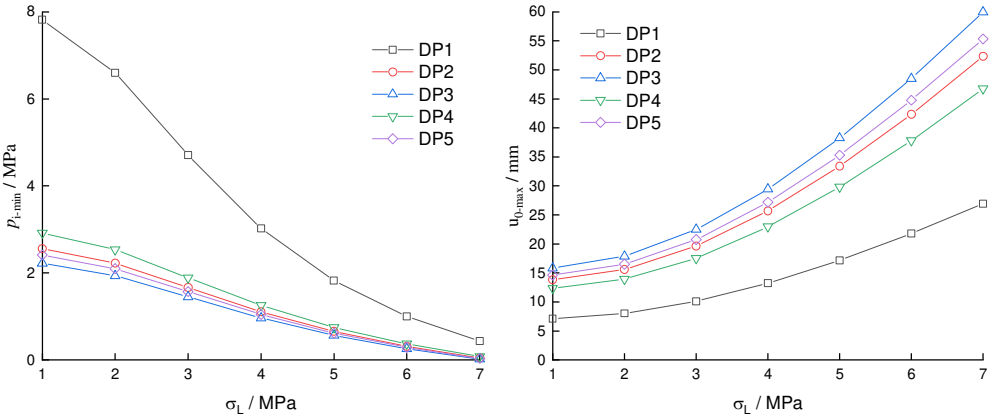
Serial number	$p_{i\text{-}min}$/MPa	R_{max}/m	$u_{0\text{-}max}$/mm
DP1	0.76	2.33	23.69
DP2	0.20	3.71	46.03
DP3	0.16	4.06	52.72
DP4	0.25	3.43	41.10
DP5	0.18	3.85	48.66

It can be seen that the optimal support force, maximum radius of plastic zone and allowable maximum displacement calculated by different DP criteria are different. The optimal supporting force obtained by DP1 criterion is the largest, while that by DP3 criterion is the smallest. The optimum support force of DP3 criterion is only 21% of DP1 criterion. The effect of intermediate principal stress σ_2 on surrounding rock strength is equal to the minimum principal stress σ_3 according in DP1 criterion, which will exaggerate the influence of intermediate principal stress. Therefore, the maximum plastic zone radius and allowable maximum displacement obtained by DP1 criterion are the smallest of DP series criteria. The maximum plastic zone radius calculated by DP3 criterion is 1.74 times of DP1 criterion, and the allowable maximum displacement is 2.23 times of DP1 criterion. This means that DP1 criterion and DP3 criterion are the upper and lower limits of DP series criteria respectively. When DP criteria are used for elastic-plastic analysis of roadway surrounding rock, the appropriate DP yield criterion should be selected according to the actual engineering background and the mechanical parameters of surrounding rock.

4.3 The effect of long-term strength

Figure 3 shows the variation rule of optimal support force and allowable maximum displacement under different long-term strength. It can be seen that the larger the long-term strength is, the smaller the optimal support force is and the larger the allowable maximum displacement is. In other words, the greater the long-term strength of surrounding rock is, the more stable the roadway is. From Figure 3a, it can be seen that the overall performance of the

optimal support force is DP1 > DP4 > DP2 > DP5 > DP3. With the increase of the long-term strength of surrounding rock, the optimal support forces calculated by different DP criteria are closer and closer, which will eventually completely coincide and achieve the ideal state without support. The reason for this change is that the larger the long-term strength of rock mass is, the smaller the plastic zone of roadway is, which leads to the weakening of the effect of yield criterion. As can be seen from Figure 3b, the allowable maximum displacement is DP3 > DP5 > DP2 > DP4 > DP1. The results of DP3 criterion are relatively conservative. Using DP3 criterion in roadway support design can improve the safety, but it will increase the support cost.



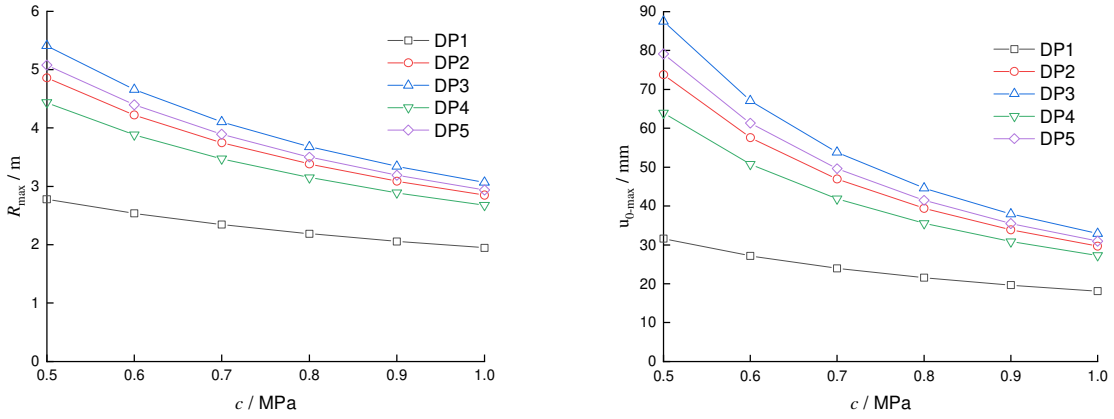
(a) optimal support force (b) allowable maximum displacement

Figure 3 Effect of long-term strength on support

4.4 The effect of strength parameters

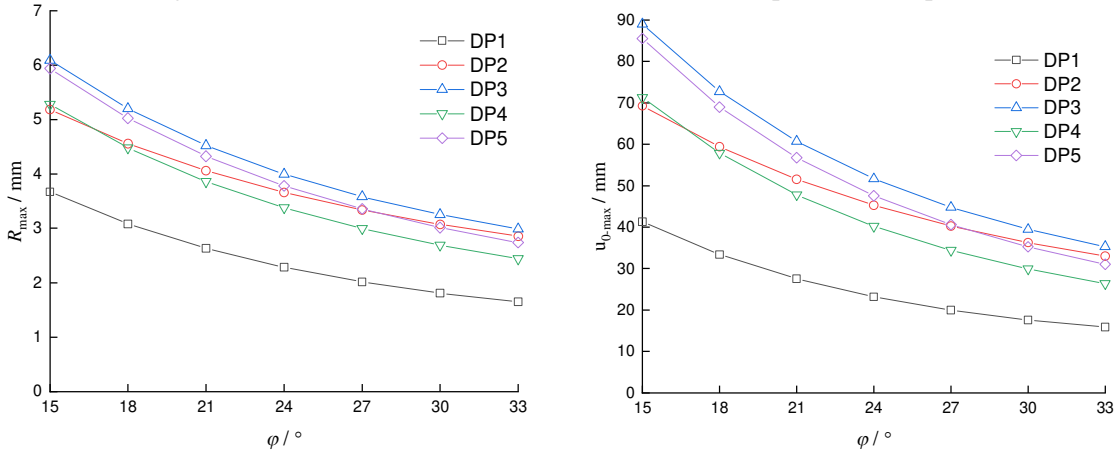
Figure 4 and Figure 5 show the variation of maximum plastic zone radius and allowable maximum displacement under different cohesion and internal friction angles, respectively. It can be seen that the influence trend of cohesion and internal friction angle on roadway deformation is roughly the same, that is, with the increase of cohesion or internal friction angle, the radius of maximum plastic zone is smaller and smaller, and the allowable maximum displacement is also gradually reduced. The reason for this change is that the increase of cohesion or internal friction angle increases the bearing capacity of rock mass, thus reducing the failure range and restraining plastic deformation of surrounding rock.

Taking DP1 criterion as an example, when the cohesion increases from 0.5 MPa to 1.0 MPa, the radius of plastic zone decreases from 2.78 m to 1.95 m, which reduces by nearly 30%. The allowable maximum displacement was reduced by 43% from 31.58 mm to 18.10 mm. When the internal friction angle increases from 15 to 33 degrees, the radius of plastic zone decreases from 3.67 m to 1.65 m, and it decreases by 55%. The allowable maximum displacement is reduced from 41.30 mm to 15.86 mm, which reduces by 62%. It can be seen that the strength parameters of rock mass have great influence on roadway support. The mechanical properties of engineering surrounding rock should be fully considered in support design. For example, the strength of surrounding rock can be improved by grouting, which can effectively reduce the deformation of roadway.



(a) plastic zone radius (b) allowable maximum displacement

Figure 4 Effect of cohesion on radius and maximum displacement of plastic zone



(a) plastic zone radius (b) allowable maximum displacement

Figure 5 Effect of internal friction angle on radius and maximum displacement of plastic zone

5 Conclusion

(1) An analytical solution of optimal support force and allowable maximum displacement of surrounding rock for circular roadway based on DP series criteria is proposed. The proposed optimal support solution can not only reflect the intermediate principal stress reasonably, but also can compare and discuss the influence of different DP criteria on the calculation results. The analytical solution can also provide theoretical guidance for engineering practice.

(2) The long-term strength of roadway surrounding rock has a significant impact on the optimal support force and the allowable maximum displacement. The higher the long-term strength of roadway surrounding rock is, the smaller the optimal support force is and the larger the allowable maximum displacement is. When the calculated long-term strength of soft rock can ensure that the deformation of the roadway does not exceed the allowable maximum displacement, the roadway can maintain long-term stability without support.

(3) The influence of surrounding rock parameters on roadway support and deformation is also significant. With the increase of cohesion or internal friction angle, the radius of plastic zone of surrounding rock becomes smaller and smaller, and the allowable maximum displacement also decreases gradually. Through grouting and other means to improve the strength of surrounding rock, can effectively reduce the deformation of roadway.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Data Availability

The experimental data used to support the findings of this study are included within the article.

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Figures

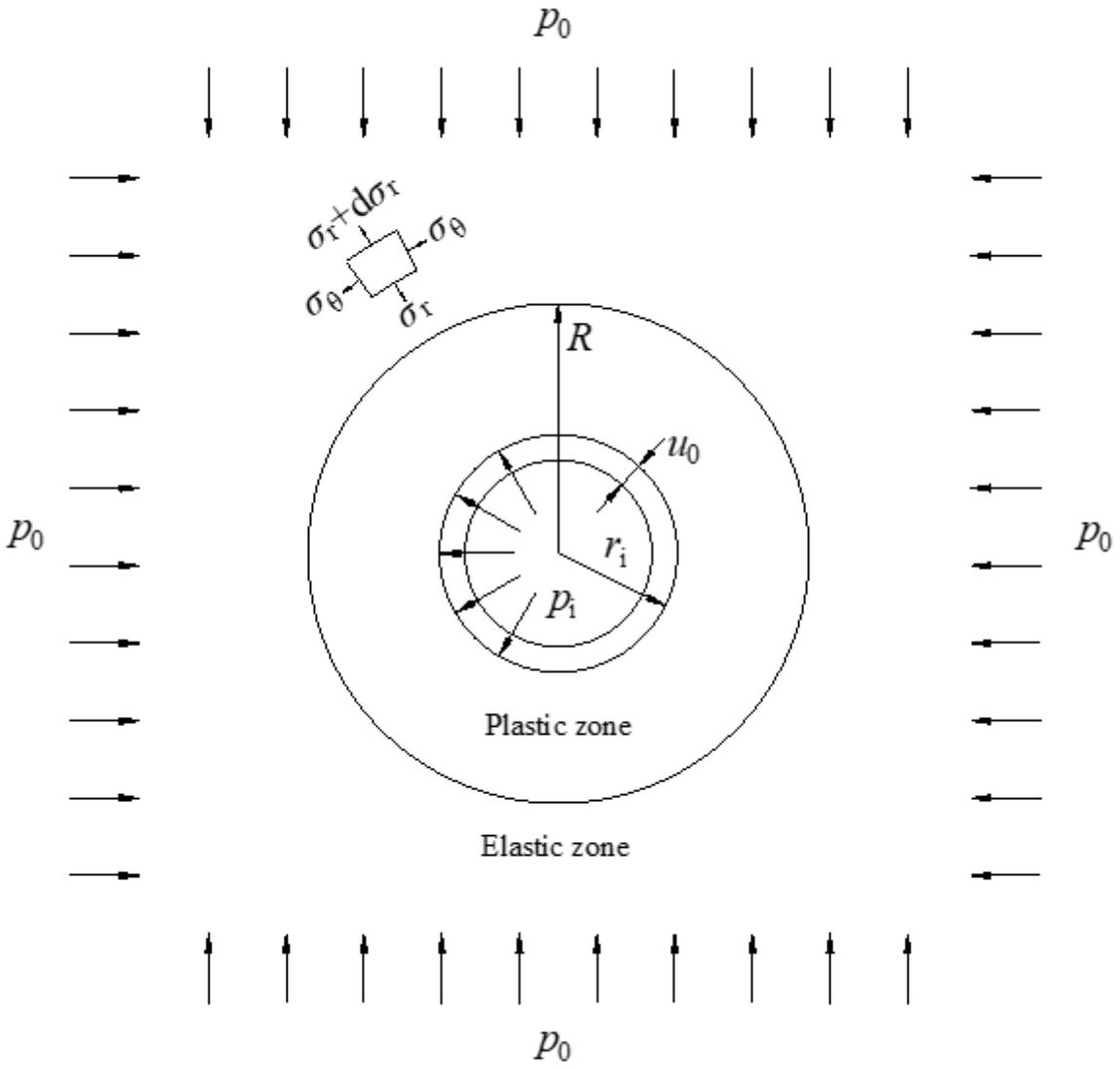


Figure 1

Elastic-plastic analysis model of circular roadway [31]

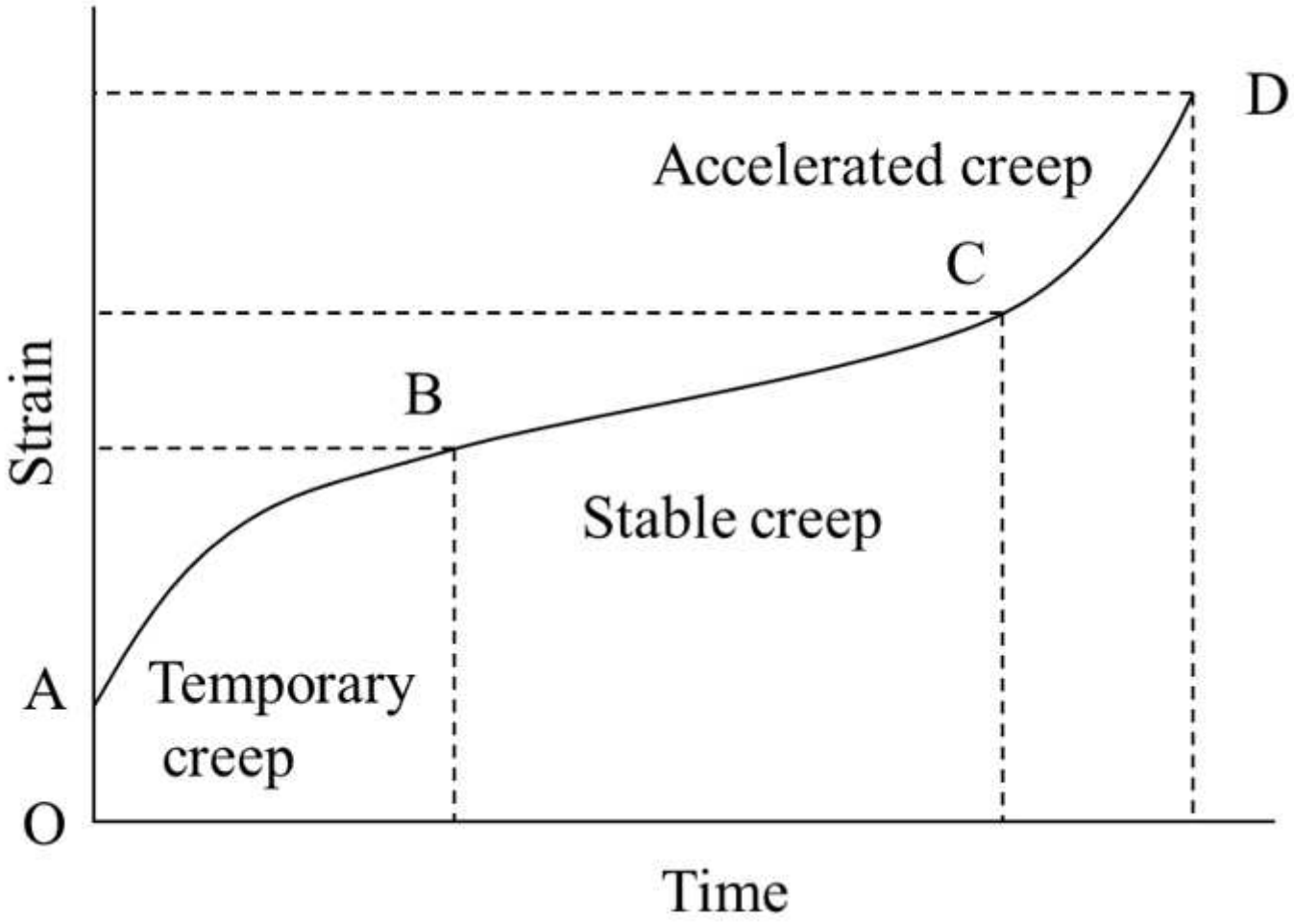
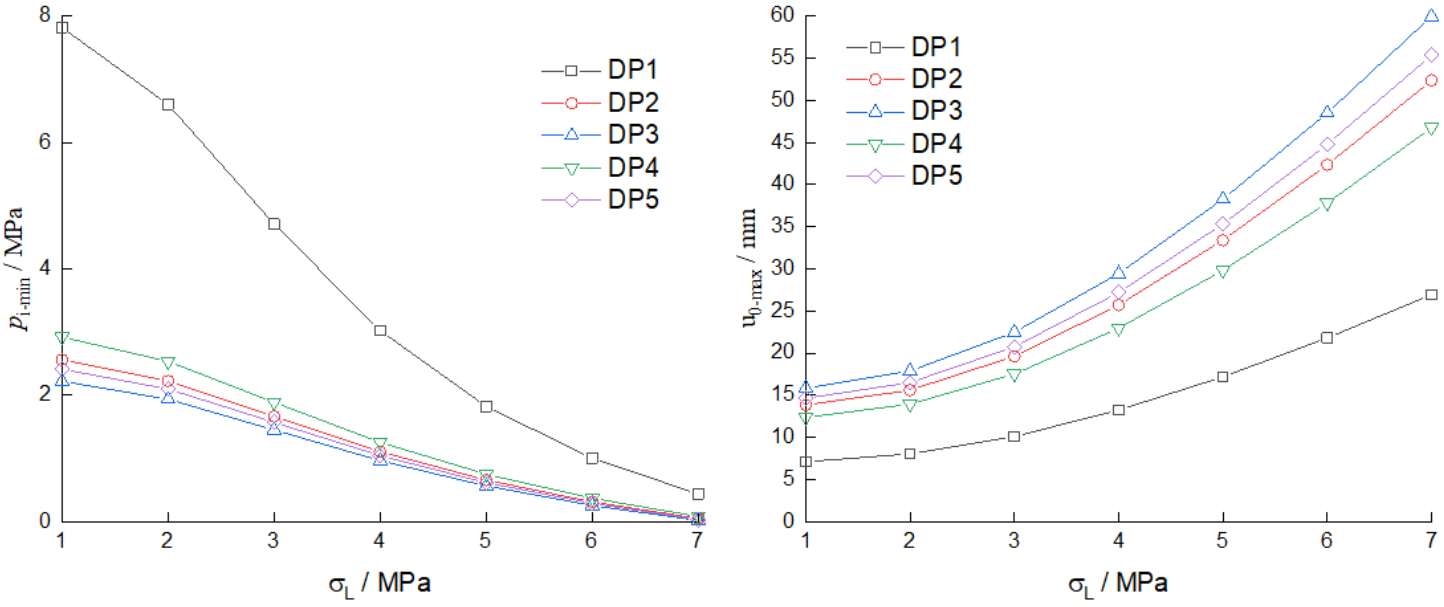


Figure 2

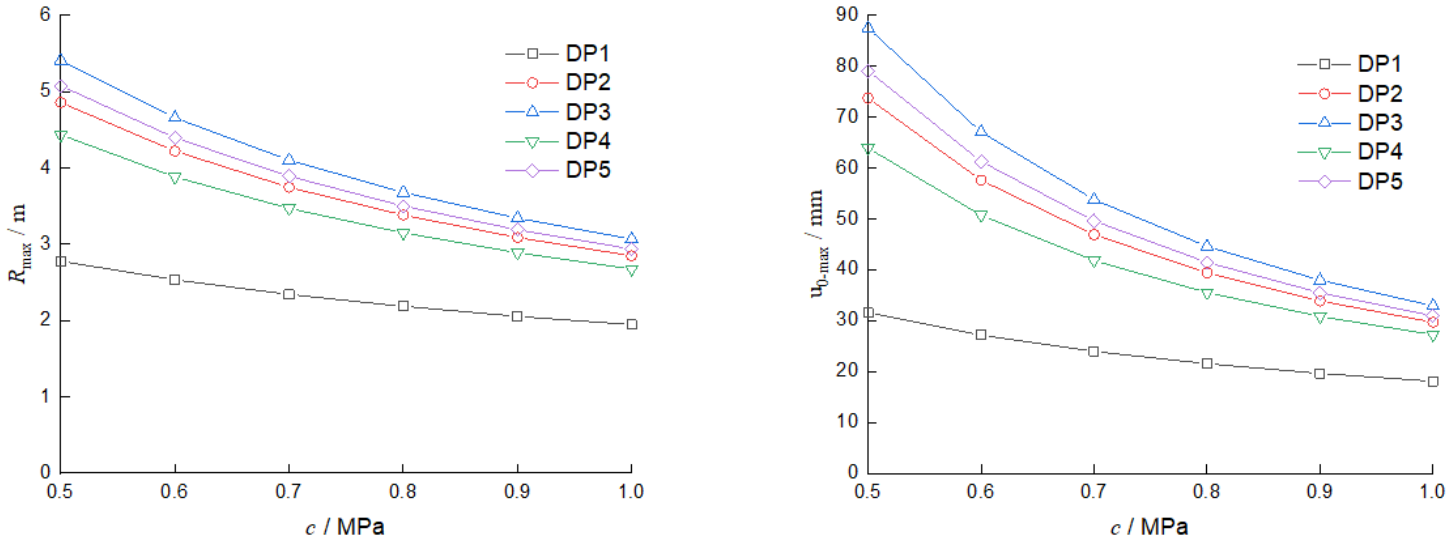
Typical creep curve of rock



(a) optimal support force (b) allowable maximum displacement

Figure 3

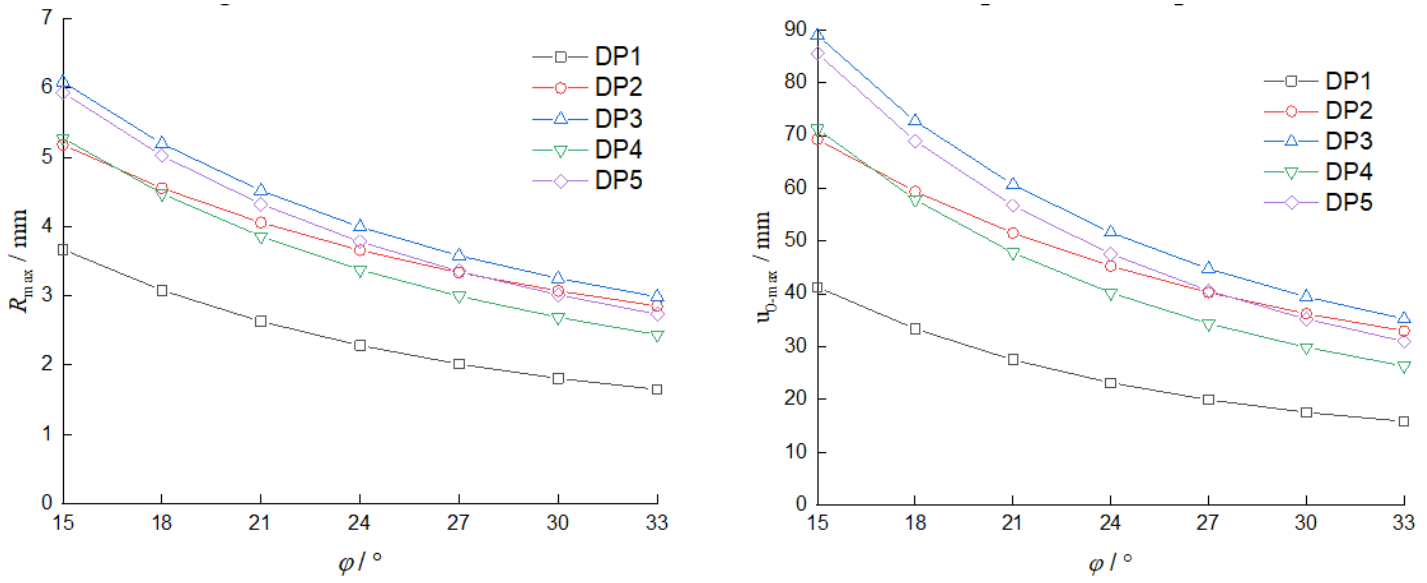
Effect of long-term strength on support



(a) plastic zone radius (b) allowable maximum displacement

Figure 4

Effect of cohesion on radius and maximum displacement of plastic zone



(a) plastic zone radius (b) allowable maximum displacement

Figure 5

Effect of internal friction angle on radius and maximum displacement of plastic zone