Study of Creep Constitutive Model for Rock Mass Anchored by Bolts

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Abstract. In the study of high-stress deep-buried tunnels, the creep phenomenon of the surrounding rock significantly affects tunnel stability. To address this, this paper establishes a creep constitutive equation for rock masses anchored by bolts (RMAB). A comparison between numerical methods and theoretical solutions reveals a high degree of consistency between the two. The study shows that as the Ek value increases, the initial displacement of the surrounding rock grows significantly. However, once Ek reaches a certain level, the rate of displacement increase gradually decreases, and the system stabilizes. Additionally, as ηk increases, the displacement of the surrounding rock decreases significantly, enhancing the rock's energy dissipation capacity and effectively suppressing deformation. The findings of this research provide important theoretical support and reference for the design of bolted support systems in deep-buried tunnels, with practical engineering value.

Keywords: Creep constitutive equation; RMAB; Numerical methods; Theoretical solutions.

1. Introduction

With the continuous advancement of modern engineering technology, the scale and complexity of underground engineering are increasing, particularly in the excavation and support of deep-buried tunnels, where the stability of rock masses is receiving growing attention [1-3]. Under complex geological conditions and long-term loading, rock masses often exhibit creep behavior, characterized by slow deformation under sustained stress. This phenomenon significantly impacts the safety and stability of tunnels, especially in deep rock conditions, where creep has a profound effect on the deformation and mechanical behavior of surrounding rock. Therefore, in-depth research on the creep properties of rock masses and their influence on bolt support systems is crucial for optimizing underground engineering design and construction.

Bolts [4,5], as an effective support technology, are widely used in underground engineering. By transferring external support forces to the surrounding rock, bolts enhance the load-bearing capacity of the rock and improve overall stability. The interaction between bolts and rock is a complex coupling process, particularly under creep conditions, where the stress state of the bolts and their support effectiveness are significantly affected by the deformation of the surrounding rock. Therefore, establishing a creep constitutive model for bolted rock masses is a key approach to understanding this coupling relationship [6-8].

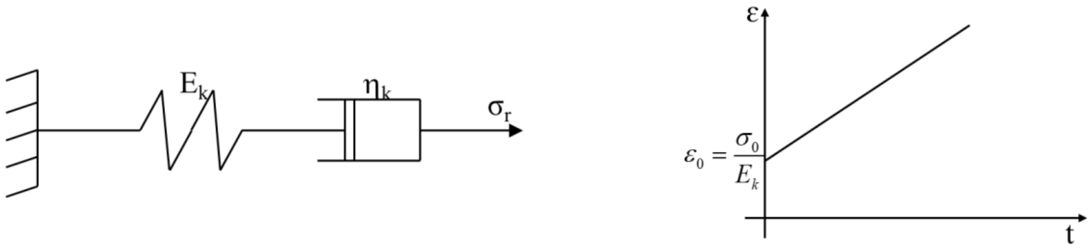
In previous research, many scholars have extensively studied the creep behavior of rock masses and proposed various creep constitutive models. These models are typically based on rheological principles and describe the time-dependent deformation characteristics of rock under stress. However, existing studies are lacking in terms of the interaction between bolts and surrounding rock, especially when considering the influence of bolts on rock creep. Since the presence of bolts can significantly alter the stress distribution and deformation mechanisms of the surrounding rock, establishing an effective creep constitutive model for bolted rock masses can more accurately reflect the complex situations encountered in actual engineering.

This study aims to establish a creep constitutive model for bolted rock masses and explore the coupling mechanism between bolts and surrounding rock. Numerical methods were used to verify the reliability of the proposed constitutive equation. The findings provide theoretical support for the design of support systems in underground engineering.

2. Problem description

2.1. Rock creep model

Maxwell is a viscoelastic body composed of a spring and a dashpot connected in series [9]. In this paper, the Maxwell body is used to simulate the creep state of rock masses (**Fig**. 1).



(a) Maxwell body (b) Creep curve

Fig. 1 Rock creep model

According to **Fig**. 1, based on the series connection, the following can be obtained:

$$\begin{cases} \sigma_r = \sigma_k = \sigma_\eta \\ \varepsilon_r = \varepsilon_k + \varepsilon_\eta \end{cases} \tag{1}$$

In the equation, σ_r is the rock stress; σ_k is the spring stress; σ_η is the dashpot stress; ε_r is the rock strain; ε_k is the spring strain; ε_η is the dashpot strain.

$$\begin{cases} \dot{\varepsilon}_k = \dfrac{\dot{\sigma}_k}{E_k} \\ \dot{\varepsilon}_\eta = \dfrac{\sigma_\eta}{\eta_k} \end{cases} \tag{2}$$

In the equation, $\dot{\varepsilon}_k$ is the derivative of the spring strain with respect to time t; $\dot{\sigma}_k$ is the derivative of the spring stress with respect to time t; E_k is the elastic modulus of the spring; $\dot{\varepsilon}_\eta$ is the derivative of the dashpot strain with respect to time t; σ_η is the stress in the dashpot; η is the viscosity coefficient of the dashpot.

By substituting EQ.(2) into EQ.(1), we obtain:

$$\dot{\varepsilon}_r = \frac{\dot{\sigma}_r}{E_k} + \frac{\sigma_r}{\eta_k} \tag{3}$$

2.2. Bolt model [10]

Assuming that the stress-strain curve of the anchor rod conforms to the characteristics of an ideal elastoplastic model, the anchor rod model is simulated by combining a spring and a friction plate in series (**Fig**. 2). When $\sigma_b<\sigma_s$, the anchor rod is in an elastic state. Thus:

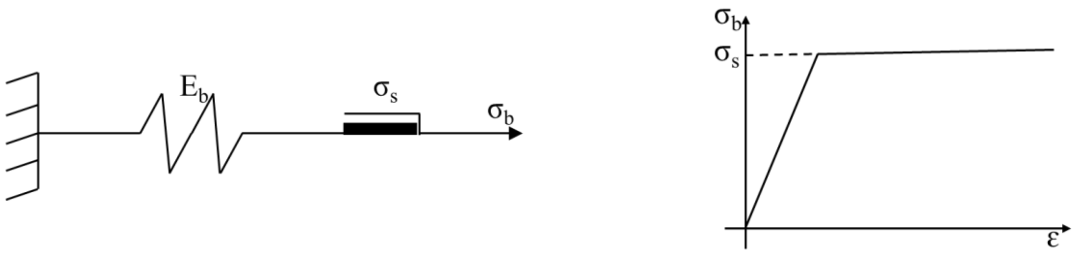
$$\sigma_b = E_b \varepsilon_b \tag{4}$$

In the formula, σ_b is the stress of the anchor rod; E_b is the elastic modulus of the bolt; ε_b is the strain of the anchor rod.

When $\sigma_b>\sigma_s$, the anchor rod enters the plastic state.

$$\sigma_b = \sigma_s \tag{5}$$

In the formula, σ_s is the stress of the anchor rod in the plastic stage.



(a) Ideal elastic-plastic model (b) Mechanical curve

Fig. 2 Bolt model

3. RMAB creep constitutive derivation

The RMAB is simulated by connecting the anchor model and the rock model in parallel to represent the stress state of RMAB (**Fig**. 3). When the stress on the anchor, $\sigma_b<\sigma_s$, both the rock and the bolt are in an elastic state (EE state). When the stress on the bolt, $\sigma_b>\sigma_s$, the bolt enters a plastic state, while the rock remains in an elastic state (EP state). Therefore, based on the stress conditions, the RMAB is divided into EE and EC states for further solution.

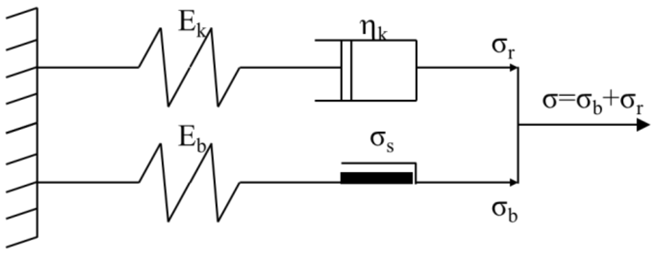


Fig. 3 RMAB model

3.1. Solution of EE

When $\sigma_b>\sigma_s$:

$$\begin{cases} \sigma = \sigma_b + \sigma_r \\ \sigma_b = \sigma_s \\ \dot{\sigma} = \dot{\sigma}_b + \dot{\sigma}_r \end{cases} \tag{6}$$

Substituting EQ.(6) into EQ.(3), we obtain:

$$E_k \eta_k \dot{\varepsilon} + E_k E_b \varepsilon = \eta_k \dot{\sigma} + E_k (\sigma - \sigma_s) \tag{7}$$

During the loading phase, the model is subjected to a tensile force of σ_0, and the initial strain is maintained by the spring connection. Therefore, when t = 0, ε_0 is:

$$\varepsilon_0 = \frac{\sigma_0}{E_k + E_b} \tag{8}$$

Substituting EQ.(8) into EQ.(7), we obtain:

$$\varepsilon = \frac{\sigma_0}{E_b} + \left(\frac{\sigma_0}{E_k + E_b} - \frac{\sigma_0}{E_b}\right) e^{-\frac{E_b t}{\eta_k}} \tag{9}$$

3.2. Solution of EC

When $\sigma_b<\sigma_s$:

$$\begin{cases} \sigma = \sigma_b + \sigma_r \\ \sigma_b = \sigma_s \\ \dot{\sigma} = \dot{\sigma}_b + \dot{\sigma}_r \end{cases} \tag{10}$$

Substituting EQ.(10) into EQ.(3), we obtain:

$$E_k \eta_k \dot{\varepsilon} + E_k E_b \varepsilon = \eta_k \dot{\sigma} + E_k (\sigma - \sigma_s) \tag{11}$$

During the loading phase, the model is subjected to a tensile force of σ_0. When t = 0, ε_0 is:

$$\varepsilon_0 = \frac{\sigma_0 - \sigma_s}{E_k} \tag{12}$$

Substituting EQ.(12) into EQ.(11), we obtain:

$$\varepsilon = \frac{\sigma_0 - \sigma_s}{E_b} + \left(\frac{\sigma_0 - \sigma_s}{E_k} - \frac{\sigma_0 - \sigma_s}{E_b}\right) e^{-\frac{E_b t}{\eta_k}} \tag{13}$$

To sum up, the RMAB creep constitutive equation is:

$$\varepsilon = \begin{cases} \frac{\sigma_0}{E_b} + \left(\frac{\sigma_0}{E_k + E_b} - \frac{\sigma_0}{E_b}\right) e^{-\frac{E_b t}{\eta_k}}, \sigma_0 < \sigma_s \\ \frac{\sigma_0 - \sigma_s}{E_b} + \left(\frac{\sigma_0 - \sigma_s}{E_k} - \frac{\sigma_0 - \sigma_s}{E_b}\right) e^{-\frac{E_b t}{\eta_k}}, \sigma_0 > \sigma_s \end{cases} \tag{14}$$

4. Theoretical verification

4.1. Model establishment

The numerical software ABAQUS is used to verify EQ.(12) and EQ.(13). The numerical model is shown in **Fig**. 4. The model length is 100m, and the excavation radius of the tunnel is 5m. A vertical stress P_0=20 MPa is applied to the top of the model, and normal constraints are applied to the left, right, and bottom boundaries. The parameters of the surrounding rock and anchor bolt are shown in **Table** 1, with E_k set to 37.48MPa, η_k set to 2200MPa, σ_s as 400MPa, and E_b as 330GPa.

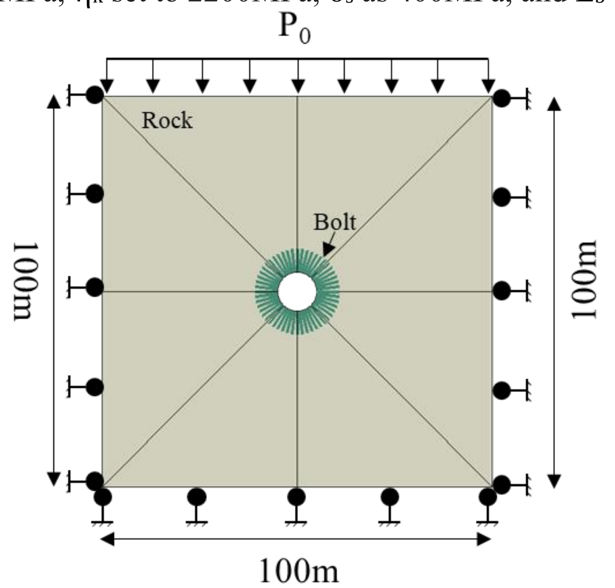


Fig. 4 RMAB model

Table 1. RMAB Parameters

	E_k	η_k	σ_s	E_b
Rock	624MPa	2200MPa	-	-
Bolt	-	-	400MPa	424MPa

4.2. Verification results

By comparing the numerical solutions with the theoretical solutions, the displacement of the surrounding rock shows a consistent trend over time. Specifically, in the early stage ($0 < t < 50$), the difference between the numerical and theoretical solutions is relatively small, with a maximum error of no more than 1.0%. For instance, at t = 10, the numerical solution is 7.94 mm, while the theoretical solution is 7.86 mm. As time progresses, the error increases somewhat, but it remains within an acceptable range. At t = 150, the numerical solution is 27.81 mm, and the theoretical solution is 27.53 mm, resulting in an error of approximately 2%. Overall, there is a high degree of agreement between the numerical and theoretical solutions, confirming the accuracy and reliability of the proposed theoretical model.

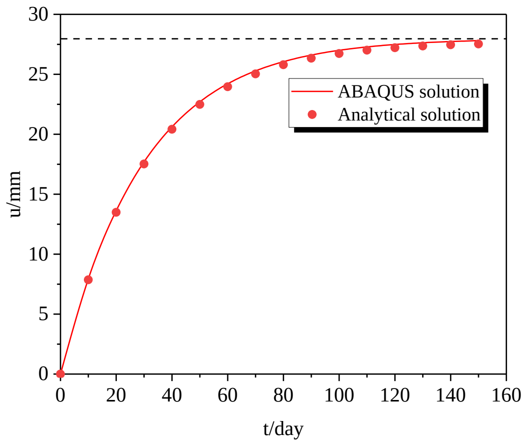


Fig. 5 Verification of Numerical and Theoretical Solutions

5. Parameter analysis

5.1. Effect of Ek

As shown in **Fig**. 6, the displacement of the surrounding rock increases as the E_k value rises from 0.4 times to 1.4 times its initial value. Specifically, when E_k increases from 0.4 to 0.8 times, the displacement rises significantly, from 24.21 mm to 27.49 mm. However, as E_k continues to increase, the rate of displacement growth gradually decreases. For instance, when E_k increases from 1.2 to 1.4 times, the displacement only increases by 0.044 mm. Quantitative analysis shows that the initial increase in E_k has a notable effect on displacement, but after reaching a certain value, the displacement tends to stabilize, indicating that the system is approaching a steady state. This trend reflects the diminishing marginal effect of E_k on displacement.

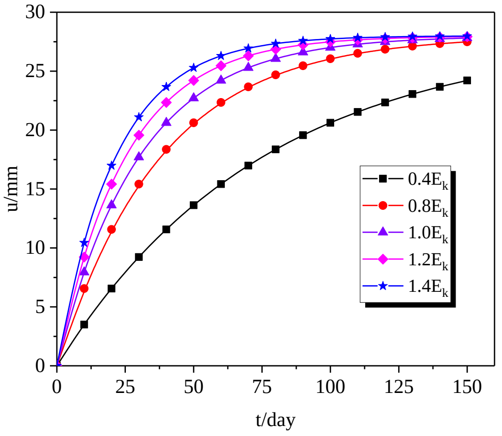


Fig. 6 The Effect of E_k on Displacement

5.2. Influence of ηk

According to **Fig**. 7, as the viscosity coefficient (η_k) increases from 0.4 to 1.4 times, the displacement of the surrounding rock gradually decreases. Specifically, when η_k increases from 0.4 to 0.8 times, the displacement slightly decreases from 28.0 mm to 27.95 mm. As η_k continues to increase, the reduction in displacement accelerates, with the displacement dropping to 27.21 mm at 1.4η_k. Quantitative analysis shows that increasing the viscosity coefficient effectively enhances the energy dissipation capacity of the surrounding rock, inhibiting excessive deformation. This indicates that increasing η_k improves the rheological performance of the surrounding rock, helping to control displacement and enhance tunnel stability.

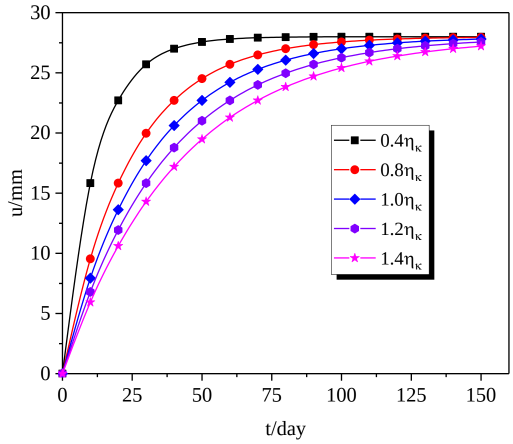


Fig. 7 Influence of η_k on displacement

6. Conclusions

In high-prestress deep-buried tunnels, the creep effect of rock has a significant impact on the stability of surrounding rock and support design. In this study, a creep constitutive equation for anchored rock mass was established, and its accuracy and reliability were verified through numerical methods and theoretical comparison.

(1) The analysis of different E_k values revealed that an increase in E_k significantly affects the displacement of the surrounding rock. In the early stages, as the E_k value increases, the displacement grows rapidly; however, when the E_k value reaches a certain level, the displacement increment gradually decreases, indicating that the system tends to stabilize. This result highlights the critical role of E_k in the stability of surrounding rock.

(2) As the viscosity coefficient increases, the displacement of the surrounding rock decreases significantly, indicating that increasing η_k can effectively enhance the energy dissipation capacity of

the surrounding rock and suppress deformation. This further confirms the effectiveness of anchor support in improving the mechanical behavior of the surrounding rock.

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