A NEW NONLINEAR VISCOELASTIC-PLASTIC SEEPAGE-CREEP CONSTITUTIVE MODEL CONSIDERING THE INFLUENCE OF CONFINING PRESSURE

by

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In this paper,thenonlinear viscoelastic-plastic creep models in one-dimensional and three-dimensional casesare established.The new nonlinear viscoelastic-plastic seepage-creep constitutive modelis addressed, considering the influence of confining pressure. Theproposed models provide the prediction ofthe creep deformation under the seepage.

Key words*: seepage-creep coupling, creep deformation, confining pressure*

Introduction

Asthemineproductionhasentered in the stageof deep mining, the roadwaylarge deformationcaused bythe creep becomes one of the important factors of the roadway instability[1-3].The seepage effect of the underground water accelerates the deformation velocity of theroadwaysurrounding rock [4-10]. The confining pressure has a great influence on the rock seepage[11-13]. The seepage-creep law of the rock under the different confining pressure is of great significance for the safe and efficient mine production.

It is shown that the creep deformation of the rock are closely related to thecongfing pressure in which they are located[14-17]. The creep behavior of the rock were reported in [18-25]. Some nonlinear and viscoplastic constitutive models wered proposed [26-28]. In the abovementioned research, however, the creep constitutive parameters of the rock mostly had been regarded as constants[29]. The nonlinear viscoelastic-plastic body (NVPB)was proposedin[30]. In view of above mentioned, we address a new nonlinear viscoelastic-plastic seepage-creep constitutive model considering the influence of the confining pressure based on the NVPBand the basic mechanical elements and models.

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The structure of the paper is as follow:insection 2, we establish a nonlinear viscoelastic-plastic creep model in one-dimensional case. In section 3, we reporta nonlinear viscoelastic-plastic creep model in three-dimensional case. In section 4, we propose the new nonlinear viscoelastic-plastic seepage -creep model.Finally, the conclusion is given in section 5.

A Nonlinear Viscoelastic-Plastic Creep Model inone-dimensional case

In order to construct,we give the model contains the Hook body, the Kelvin model, the Bingham model and theNVPB, as shown in Fig.1.

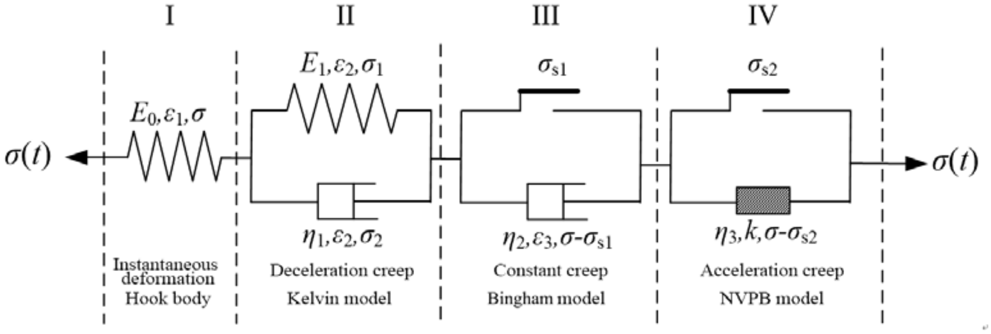

Fig.1 One-dimensional nonlinear viscoelastic-plastic creep model

The constitutive and creep equations are given as follow:

The constitutive equations

The constitutive equations underdifferent conditions are shown as follows:

(a) When $\sigma<\sigma_{s1}$, part I and part II of the model participate in the creep deformation of the rock.Then, the model state equation we have

$$\begin{cases} \sigma_1 = E_0\varepsilon_1, \\ \sigma_2 = E_1\varepsilon_2 + \eta_1\dot{\varepsilon}_2, \\ \sigma = \sigma_1 = \sigma_2, \\ \varepsilon = \varepsilon_1 + \varepsilon_2, \end{cases} \tag{1}$$

where σ is the stress and σ_1 is the stress inthe Hooke body stage, σ_2 is the stress inthe Kelvin modelstage, ε is the strain, ε_1 is the straininthe Hooke bodystage, ε_2 is the strain inthe Kelvin modelstage, E_0 is the rock elastic coefficient in the Hook body, E_1 is the rock elastic coefficient in theKelvin model, η_1 isthe rock viscosity coefficient in theKelvin model, and$\sigma_{s1}$is the stressof the long-term strength and yield strength of the rock in the Bingham model stage.

The constitutive equations is written as

$$\sigma(t) + \frac{\eta_1}{E_0 + E_1}\dot{\sigma} = \frac{E_0E_1}{E_0 + E_1}\varepsilon + \frac{E_0\eta_1}{E_0 + E_1}\dot{\varepsilon}. \tag{2}$$

(b) When $\sigma_{s1} \le \sigma<\sigma_{s2}$, the three parts(I, II and III) of the model participate in the creep deformation of the rock.Then, the model state equation we obtain

$$\begin{cases} \sigma_1 = E_0\varepsilon_1, \\ \sigma_2 = E_1\varepsilon_2 + \eta_1\dot{\varepsilon}_2, \\ \sigma_3 - \sigma_{s1} = \eta_2\dot{\varepsilon}_3, \\ \sigma = \sigma_1 = \sigma_2 = \sigma_3, \\ \varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3, \end{cases} \tag{3}$$

where σ_3 is the stress inthe Bingham modelstage, and ε_3 is the strain inthe Bingham modelstage, σ_{s2}isthe stress of the long-term strength and yield strength of the rock in the NVPB stage,and$\sigma_{s1}<\sigma_{s2}$.

The constitutive equations is written as

$$\ddot{\varepsilon}+\frac{E_2}{\eta_1}\dot{\varepsilon}=\frac{1}{E_0}\ddot{\sigma}+\frac{E_1\eta_2+E_0\eta_2+E_0\eta_1}{E_0\eta_1\eta_2}\dot{\sigma}+\frac{E_1}{\eta_1\eta_2}(\sigma-\sigma_{s1}), \tag{4}$$

where η_2 is therock viscosity coefficient in theBingham model.

(c)When $\sigma \geq \sigma_{s2}$, the four parts of the model participate in the creep deformation of the rock. Then, the model state equation we get

$$\begin{cases}\sigma_1=E_0\varepsilon_1,\\ \sigma_2=E_1\varepsilon_2+\eta_1\dot{\varepsilon}_2,\\ \sigma_3-\sigma_{s1}=\eta_2\dot{\varepsilon}_3,\\ \sigma_4-\sigma_{s2}=\dfrac{\eta_3\dot{\varepsilon}_4}{kt^{k-1}},\\ \sigma=\sigma_1=\sigma_2=\sigma_3=\sigma_4,\\ \varepsilon=\varepsilon_1+\varepsilon_2+\varepsilon_3+\varepsilon_4,\end{cases} \tag{5}$$

where σ_4 is the stress in the NVPB stage, and the ε_4 is the strain inthe NVPBstage.

Theconstitutive equation can be expressed as

$$\begin{aligned}&\ddot{\varepsilon}+\frac{E_1}{\eta_1}\dot{\varepsilon}=\frac{\ddot{\sigma}}{E_0}+(\frac{1}{\eta_2}+\frac{1}{\eta_3}kt^{k-1}+\frac{1}{\eta_1}+\frac{E_1}{E_0\eta_1})\dot{\sigma}+\frac{E_1}{\eta_1\eta_2}(\sigma-\sigma_{s1})\\ &+[\frac{1}{\eta_3}k(k-1)t^{k-2}+\frac{E_1}{\eta_1\eta_2}kt^{k-1}1](\sigma-\sigma_{s2}).\end{aligned} \tag{6}$$

The creep equations

The creep equations under different conditions are shown as follows:

(a) when$\sigma<\sigma_{s1}$, $\sigma(t)=\sigma_0$, the creep equation is written as

$$\varepsilon(t)=\frac{\sigma_0}{E_0}+\frac{\sigma_0}{E_1}(1-e^{-\frac{E_1}{\eta_1}t}), \tag{7}$$

where$\sigma(t)$and$\sigma_0$are the stresses on the rock, and t is the time.

Derivating both sides of Eq. (7) yields that

$$\dot{\varepsilon}=\frac{\sigma_0}{\eta_1}e^{-\frac{E_1}{\eta_1}t}. \tag{8}$$

From Eq. (8), it can be seen that the creep deformation rate gradually decreases with time, and finally goes to zero.

(b)When$\sigma_{s1}\leq\sigma<\sigma_{s2}$, $\sigma(t)=\sigma_0$, the creep equation is written as

$$\varepsilon(t)=\frac{\sigma_0}{E_0}+\frac{\sigma_0}{E_1}(1-e^{-\frac{E_1}{\eta_1}t})+\frac{\sigma_0-\sigma_{s1}}{\eta_2}t. \tag{9}$$

Derivating both sides of Eq.(9) yields that

$$\dot{\varepsilon}=\frac{\sigma_0}{\eta_1}e^{-\frac{E_1}{\eta_1}t}+\frac{\sigma_0-\sigma_{s1}}{\eta_2}. \tag{10}$$

From Eq. (10), it can be seen that the creep deformation rate gradually decreases with the time, and eventually tends to be a constant. Combined with Eq. (9), it is known that Eq.(10) canbe represented as the instantaneous, deceleration and constant velocity in the process of the rock creep deformation.

(c)When $\sigma \geq \sigma_{s2}$, $\sigma(t) = \sigma_0$, the creep equation is written as

$$\varepsilon(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1}(1 - e^{-\frac{E_1}{\eta_1}t}) + \frac{\sigma_0 - \sigma_{s1}}{\eta_2}t + \frac{\sigma_0 - \sigma_{s2}}{\eta_3}t^k, \tag{11}$$

where$k$is the rheological coefficient of the rock.

Similarly, derivating both sides of Eq.(13) yields that

$$\dot{\varepsilon} = \frac{\sigma_0}{\eta_1}e^{-\frac{E_1}{\eta_1}t} + \frac{\sigma_0 - \sigma_{s1}}{\eta_2} + \frac{\sigma_0 - \sigma_{s2}}{\eta_3}kt^{k-1}. \tag{12}$$

In order to express the whole process of the rock creep deformation,k must be more than 1in Eq. (12). When k>1, the creep of the rock increases with time andthedeformation rate of the rock increases gradually, too.

In summary, the creep equation of the one-dimensional nonlinear viscoelastic-plasticcreep model of the rock can be expressed as follows:

(a) when $\sigma_0 < \sigma_{s1}$, we get

$$\varepsilon(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1}(1 - e^{-\frac{E_1}{\eta_1}t}); \tag{13}$$

(b)when $\sigma_{s1} \leq \sigma_0 < \sigma_{s2}$, we have

$$\varepsilon(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1}(1 - e^{-\frac{E_1}{\eta_1}t}) + \frac{\sigma_0 - \sigma_{s1}}{\eta_2}t; \tag{14}$$

(c)when $\sigma_0 \geq \sigma_{s2}$, we give

$$\varepsilon(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1}(1 - e^{-\frac{E_1}{\eta_1}t}) + \frac{\sigma_0 - \sigma_{s1}}{\eta_2}t + \frac{\sigma_0 - \sigma_{s2}}{\eta_3}t^k. \tag{15}$$

The extendedof rock three-dimensional nonlinear viscoelastic-plastic creep model

From the result in Eqs.(13), (14) and (15),we give the extended of the rock nonlinear viscoelastic plastic creep model in the three-dimensional case.For any points in the rock, the stress state can be decomposed into two parts:the stress ball tensor and the stress deviatorictensor, as shown in Eq.(16). The stress ball tensor only alter the volume deformation of the element. The stress deviatoric tensor causes the change ofthe unit shape plastic deformation.

$$\sigma_{ij} = \sigma_m \delta_{ij} + S_{ij}, \tag{16}$$

where σ_{ij} is stress tensor, $\sigma_m \delta_{ij}$ is the stress ball tensor, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$, σ_1 is the maximum principal stress, σ_2 is the middle principal stress, σ_3 is the minimum principal stress, δ_{ij} is the Kronecher symbol, and S_{ij} isthe stress deviatoric tensor.

In the same way, the strain ball tensor and strain deviatoric tensor at this point can be written as

$$\varepsilon_{ij} = \varepsilon_m \delta_{ij} + e_{ij}, \tag{17}$$

where ε_{ij} is the strain tensor, $\varepsilon_m \delta_{ij}$ is the strain ball tensor, $\varepsilon_m = (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)/3$, $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are the principal strain, and e_{ij} isthe straindeviatoric tensor.

Referring to the one-dimensional Hooke's law, it is assumed that the strain ball tensor and the strain deviatoric tensor are only related to the stress ball tensor and the stress deviatoric tensor, respectively. FromEqs. (16) and (17), the three-dimensional Hooke's law expression can be given as follow:

$$\begin{cases} \sigma_m = 3K\varepsilon_m, \\ S_{ij} = 2Ge_{ij}, \end{cases} \tag{18}$$

where $K = E/3(1-2\mu)$ is the bulk modulus of the rock, $G = E/2(1+\mu)$ is the shear modulus of the rock, μ is the poisson's ratio.

Substituting the Eqs. (18) and (17) into(13), (14) and (15), the three-dimensional nonlinear viscoelastic-plastic creep equation can be expressed as follows:

(a) when $S_{11} < \sigma_{s1}$, we have

$$\varepsilon_{ij} = \frac{\sigma_m}{3K} + \frac{S_{11}}{2G_0} + \frac{S_{11}}{2G_1}(1 - e^{-\frac{G_1}{\eta_1}t}) ; \tag{19}$$

where $S_{11} = \sigma_x - \sigma_m$, σ_x is the partial stress in x-axis direction, G_0 is the shear modulus of the rock in Hook body stage, and G_1 is the shear modulus of the rock in theKelvin modelstage,

(b)when $\sigma_{s1} \le S_{11} < \sigma_{s2}$, we get

$$\varepsilon_{ij} = \frac{\sigma_m}{3K} + \frac{S_{11}}{2G_0} + \frac{S_{11}}{2G_1}(1 - e^{-\frac{G_1}{\eta_1}t}) + \frac{S_{11} - \sigma_{s1}}{\eta_2}t ; \tag{20}$$

where η_2 is the rock viscosity coefficient in theBingham model.

(c) when $S_{11} \ge \sigma_{s2}$, we obtain

$$\varepsilon_{ij} = \frac{\sigma_m}{3K} + \frac{S_{11}}{2G_0} + \frac{(S_{ij})_0}{2G_1}(1 - e^{-\frac{G_1}{\eta_1}t}) + \frac{S_{11} - \sigma_{s1}}{\eta_2}t + \frac{S_{11} - \sigma_{s2}}{\eta_3}t^k ; \tag{21}$$

where η_3 is the rock viscosity coefficient in theNVPB model.

When $\sigma_2 = \sigma_3$, we obtain from Eqs.(19), (20) and (21) that

$$\begin{cases} \sigma_m = \dfrac{\sigma_{kk}}{3} = \dfrac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \dfrac{\sigma_1 + 2\sigma_3}{3}, \\ S_{11} = \sigma_1 - \sigma_m = \dfrac{2(\sigma_1 - \sigma_3)}{3}, \end{cases} \tag{22}$$

where $\sigma_{kk} = \sigma_1 + \sigma_2 + \sigma_3$.

Substituting Eq. (22) into Eq. (19), (20) and (21), the three-dimensional nonlinear viscoelastic-plastic creep model of the rock in the equal confining pressure in the case of tri-axial compression can be represented as follows:

(a) when $\sigma_1 - \sigma_3 < \sigma_{s1}$, we arrive

$$\varepsilon(t) = \frac{\sigma_1 + 2\sigma_3}{9K} + \frac{\sigma_1 - \sigma_3}{3G_0} + \frac{\sigma_1 - \sigma_3}{3G_1}(1 - e^{-\frac{G_1}{\eta_1}t}) ; \tag{23}$$

(b)when $S_{11} < \sigma_{s1}$, we get

$$\varepsilon(t) = \frac{\sigma_1 + 2\sigma_3}{9K} + \frac{\sigma_1 - \sigma_3}{3G_0} + \frac{\sigma_1 - \sigma_3}{3G_1}(1 - e^{-\frac{G_1}{\eta_1}t}) + \frac{2(\sigma_1 - \sigma_3) - \sigma_{s1}}{6\eta_2}t ; \tag{24}$$

(c)when $S_{11} < \sigma_{s1}$, we have

$$\begin{aligned} \varepsilon(t) = &\frac{\sigma_1 + 2\sigma_3}{9K} + \frac{\sigma_1 - \sigma_3}{3G_0} + \frac{\sigma_1 - \sigma_3}{3G_1}(1 - e^{-\frac{G_1}{\eta_1}t}) \\ &+ \frac{2(\sigma_1 - \sigma_3) - \sigma_{s1}}{6\eta_2}t + \frac{2(\sigma_1 - \sigma_3) - \sigma_{s2}}{6\eta_3}t^k. \end{aligned} \tag{25}$$

The New Nonlinear Viscoelastic-Plastic Seepage -Creep Model

In the seepage-creep process of the rock, the effect of external loads is shared by the water in the porous medium and the medium skeleton. The former is the pore water pressure and the latter is the effective stress. With the aid ofTerzaghi stress principle

$$\sigma' = \sigma - ap_0. \tag{26}$$

where σ' is the effective stress,$\sigma$is the confining pressure,a is the Biot parameter, 0 <a< 1,and p_0 is the osmotic pressure.We obtain the followings:

(a) when $\sigma_1 - \sigma_3 < \sigma_{s2}$, we get

$$\begin{aligned} \sigma_1' &= \sigma_1 - ap_0, \\ \sigma_3' &= \sigma_3 - ap_0, \end{aligned} \tag{27}$$

where σ_1' is the maximum effective principal stress, and σ_3' is the minimum effective principal stress.

(b) when $\sigma_1 - \sigma_3 \geq \sigma_{s2}$, we have

$$\begin{aligned} \sigma_1' &= \sigma_1 - a_1 p_0, \\ \sigma_3' &= \sigma_3 - ap_0. \end{aligned} \tag{28}$$

where$a$ and a_1 are theBiot parameters.

Substituting Eqs. (27) into (23), (24), and Substituting Eqs. (28) into (25), the three-dimensional nonlinear viscoelastic-plastic creep equation of the rock considering seepage under different confining pressure can be written asfollows:

(1)when $\sigma_1 - \sigma_3 < \sigma_{s1}$, we obtain

$$\varepsilon(t) = \frac{\sigma_1 + 2\sigma_3 - 3ap_0}{9K} + \frac{\sigma_1 - \sigma_3}{3G_0} + \frac{\sigma_1 - \sigma_3}{3G_1}(1 - e^{-\frac{G_1}{\eta_1}t}); \tag{29}$$

(2)when $\sigma_{s1} \leq \sigma_1 - \sigma_3 < \sigma_{s2}$, we have

$$\varepsilon(t) = \frac{\sigma_1 + 2\sigma_3 - 3ap_0}{9K} + \frac{\sigma_1 - \sigma_3}{3G_0} + \frac{\sigma_1 - \sigma_3}{3G_1}(1 - e^{-\frac{G_1}{\eta_1}t}) + \frac{2(\sigma_1 - \sigma_3) - \sigma_{s1}}{6\eta_2}t; \tag{30}$$

(3)when $\sigma_1 - \sigma_3 \geq \sigma_{s2}$, we give

$$\begin{aligned} \varepsilon(t) = {} & \frac{\sigma_1 + 2\sigma_3 - 3ap_0}{9K} + \frac{\sigma_1 - \sigma_3}{3G_0} + \frac{\sigma_1 - \sigma_3}{3G_1}(1 - e^{-\frac{G_1}{\eta_1}t}) + \frac{2(\sigma_1 - \sigma_3) - \sigma_{s1}}{6\eta_2}t \\ & + \frac{2[(\sigma_1 - \sigma_3) - (a_1 - a)p_0] - \sigma_{s2}}{6\eta_3}t^k. \end{aligned} \tag{31}$$

Conclusions

In our work, a nonlinear viscoelastic-plastic creep model in one-dimensional and three-dimensionalcase was proposed. The new nonlinear viscoelastic-plastic seepage-creep constitutive model with the seepageunder the different confining pressure wasaddressed.The proposed new constitutive model can be used easily in predicting the large deformation of roadway under the different confining pressure.The results also can present a theory for evaluating the roadway long-term stability and the support design reliability in the deep underground engineering.

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Nomenclature

		Greek symbols		
k	-rheological coefficient of the rock,[-]	σ'	- effective stress, [kgm^{-2}]
t	-time,[s]	σ	- confining pressure,[kgm^{-2}]
a	-biot parameter, [-]		
K	-bulk modulus,[kgm^{-2}]		
G	-shear modulus,[kgm^{-2}]		

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