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

by

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In this paper, the non-linear viscoelastic-plastic creep models in 1-D and 3-D casesare established. The new non-linear viscoelastic-plastic seepage-creep constitutive models addressed, considering the influence of confining pressure. The proposed models provide the prediction of the creep deformation under the seepage.

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

Introduction

As the mine production has entered in the stage of deep mining, the roadway large deformation caused by the 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 the roadway surrounding 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 the confining pressure in which they are located [14-17]. The creep behavior of the rock were reported in [18-25]. Some non-linear and viscoplastic constitutive models were proposed [26-28]. In the aforementioned research, however, the creep constitutive parameters of the rock mostly had been regarded as constants [29]. The non-linear viscoelastic-plastic body (NVPB) was proposed in [30]. In view of aforementioned, we address a new non-linear viscoelastic-plastic seepage-creep constitutive model considering the influence of the confining pressure based on the NVP band the basic mechanical elements and models.

A non-linear viscoelastic-plastic creep model in 1-D case

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

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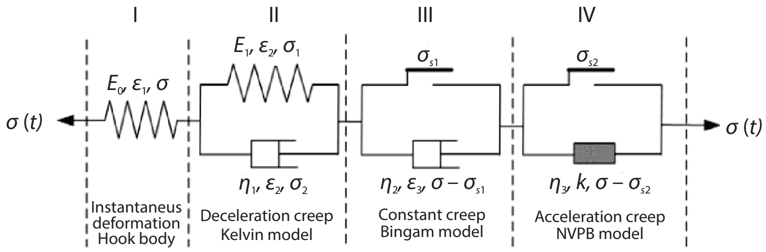

Figure 1. The 1-D non-linear viscoelastic-plastic creep model

The constitutive equations

The constitutive equations under different conditions are shown:

(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 – the stress in the Hooke body stage, σ_2 – the stress in the Kelvin modelstage, ε – the strain, ε_1 – the strain in the Hooke bodystage, ε_2 – the strain in the Kelvin modelstage, E_0 – the rock elastic coefficient in the Hook body, E_1 – the rock elastic coefficient in the Kelvin model, η_1 – the rock viscosity coefficient in the Kelvin model, and σ_{sl} – the stress of the long-term strength and yield strength of the rock in the Bingham model stage.

The constitutive equations is written:

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

(b) When $\sigma_{sl} \le \sigma < \sigma_{s2}$, 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 in the Bingham model stage, and ε_3 – the strain in the Bingham model stage, σ_{s2} – the stress of the long-term strength and yield strength of the rock in the NVPB stage, and $\sigma_{sl} < \sigma_{s2}$.

The constitutive equation:

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

where η_2 is the rock viscosity coefficient in the Bingham model.

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

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

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

The constitutive equation can be expressed:

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

The creep equations

The creep equations under different conditions:

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

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

where $\sigma(t)$ and σ_0 are the stresses on the rock, and t is the time.

Derivating both sides of eq. (7):

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

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

(b)When $\sigma_{s1} \le \sigma < \sigma_{s2}$, $\sigma(t) = \sigma_0$, the creep equation:

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

Derivating both sides of eq. (9) yields:

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

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) can be represented as the instantaneous, deceleration and constant velocity in the process of the rock creep deformation.

(c) When $\sigma \ge \sigma_{s2}$, $\sigma(t) = \sigma_0$, the creep equation:

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

where k is the arheological coefficient of the rock.

Similarly, derivating both sides of eq. (13):

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

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

In summary, the creep equation of the 1-D non-linear viscoelastic-plastic creep model of the rock can be expressed:

(a) when $\sigma_0 < \sigma_{s1}$:

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

(b) when $\sigma_{s1} < \sigma_0 < \sigma_{s2}$:

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

(c) when $\sigma_0 \geq \sigma_{s2}$:

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

The extended of rock 3-D non-linear viscoelastic-plastic creep model

From the result in eqs. (13)-(15), we give the extended of the rock non-linear viscoelastic plastic creep model in the 3-D case. For any points in the rock, the stress state can be decomposed into two parts: the stress ball tensor and the stress deviatoric tensor, 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, $\sigma_m\delta_{ij}$ – the stress ball tensor, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$, σ_1 – the maximum principal stress, σ_2 – the middle principal stress, σ_3 – the minimum principal stress, δ_{ij} – the Kronecher symbol, and S_{ij} – the stress deviatoric tensor.

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

$$\varepsilon_{ij}=\varepsilon_m\delta_{ij}+\mathrm{e}_{ij} \tag{17}$$

where ε_{ij} is the strain tensor, $\varepsilon_m\delta_{ij}$ – 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} – the strain deviatoric tensor.

Referring to the 1-D 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. From eqs. (16) and (17), the 3-D Hooke's law expression can be given:

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

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

Substituting the eqs. (18) and (17) into (13-15). The 3-D non-linear viscoelastic-plastic creep equation can be expressed:

(a) when $S_{11} < \sigma_{s1}$:

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

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

(b) when $\sigma_{s1} \leq S_{11} < \sigma_{s2}$:

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

where η_2 is the rock viscosity coefficient in the Bingham model.

(c) when $S_{11} \geq \sigma_{s2}$:

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

where η_3 is the rock viscosity coefficient in the NVPB model.

When $\sigma_2 = \sigma_2$, we obtain from eqs. (19)-(21):

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

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

Substituting eq. (22) into eqs. (19)-(21), the 3-D non-linear viscoelastic-plastic creep model of the rock in the equal confining pressure in the case of tri-axial compression can be represented:

(a) when $\sigma_1 - \sigma_3 < \sigma_{s1}$:

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

(b) when $S_{11} < \sigma_{s1}$:

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

(c) when $S_{11} < \sigma_{s1}$:

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

$$+ \frac{2(\sigma_1-\sigma_3)-\sigma_{s1}}{6\eta_2}t + \frac{2(\sigma_1-\sigma_3)-\sigma_{s2}}{6\eta_3}t^k \tag{25}$$

The new non-linear 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 of Terzaghi stress principle

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

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

(a) when $\sigma_1 - \sigma_3 < \sigma_{s1}$, 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' – the minimum effective principal stress.

(b) when $\sigma_1 - \sigma_3 \geq \sigma_{s1}$, 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 the Biot parameters.

Substituting eqs. (27) into (23), (24), and substituting eqs. (28) into (25), the 3-D non-linear viscoelastic-plastic creep equation of the rock considering seepage under different confining pressure can be written:

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

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

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

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

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

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

Conclusion

In our work, a non-linear viscoelastic-plastic creep model in 1-D and 3-D case was proposed. The new non-linear viscoelastic-plastic seepage-creep constitutive model with the seepage under the different confining pressure was addressed. 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

a – biot parameter, [–]
G – shear modulus, [kgm^{-2}]
K – bulk modulus, [kgm^{-2}]
k – rheological coefficient of the rock, [–]
t – time, [s]

Greek symbols

σ' – effective stress, [kgm^{-2}]
σ – confining pressure, [kgm^{-2}]

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