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Study on the mechanical model of macro-mecro creep under high seepage pressure in brittle rocks

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Abstract: High seepage pressure has a great significance on creep behaviors of brittle rocks under deep underground engineering. However, the macro-mecro relationship between mecrocrack growth and macroscopic deformation under high seepage pressure during the decelerated, steady-state, accelerated creep has been rarely studied. In this study, based on the stress intensity model of crack tips with the influence of initial cracks and new wing cracks, the mechanical relationship between seepage pressure and initial cracks and new wing cracks is introduced, and the stress intensity model model of crack tips considering seepage pressure is established. Then combined with the subcritical crack law and crack-strain damage model, a macro-mecro mechanical model is proposed to explain the relationship between creep crack growth and macroscopic deformation of brittle rock considering the influence of seepage pressure. The rock behaves elasticity when the applied axial stress is smaller than the crack initiation stress, while behaves plasticity when the axial stress exceeds the crack initiation stress but is less than the rock peak strength. The theoretical creep curves subjected to step axial loading are studied under different seepage pressures, and the rationality of the proposed model is verified by experimental results. Furthermore, the creep evolution of crack length, crack growth velocity, axial strain, and axial strain rate under constant or step loading seepage pressure are discussed. The new model provides a significant theoretical basis for the evaluation of the stability of surrounding rocks in deep underground engineering under high seepage pressure.

Keywords: brittle rocks; creep; high seepage pressure; crack propagation; macro-mecro model

1 Introduction

Creep mechanics behavior of brittle rocks in deep underground engineering is of great significance for evaluating the stability of surrounding rocks in deep engineering construction and long-term operation. In addition, the surrounding rocks are often accompanied by the interference of groundwater, and thus the high seepage water pressure has an important influence on the creep mechanics characteristics of brittle rocks in deep underground. Many scholars have studied the influence of constant seepage pressure on the creep mechanical behavior through creep tests. It was found that with the increase of seepage pressure, the failure time of rock creep is accelerated[1−2]. However, under natural conditions, the seepage pressure around rocks is continuously changing. Some scholars have also tested and analyzed the creep strain evolution characteristics of rocks under constant loads and step loading seepage pressure[3−4]. Based on the above testing results, some scholars also put forward many creep theoretical models by combining the elastic, viscous and plastic creep module models, by which the influence of seepage pressure on creep strain evolution was summarized[5−7]. The above findings all involve the creep mechanical properties of macroscopic seepage pressure, but the impact of seepage pressure on creep crack propagation mechanism inside the rock has rarely been reported.

Liu et al.[8] analyzed the variation of microcracks in the creep rock under seepage pressure through electron microscope scanning. Grgic et al.[9] used acoustic emission monitoring technique to analyze the acoustic emission signals induced by crack propagation in creep rocks under seepage pressure, which indirectly reflected the crack evolution inside rocks. Xu et al.[10] proposed a stress−strain constitutive model of rock considering hydraulic−mechanic coupling effect, and numerically analyzed the intact creep strain evolution curve of rock under different seepage pressures and the creep crack extension. Zhao et al.[11] studied the influence of seepage pressure on rock's decelerated and steady-state creep crack growth behaviors by introducing pore pressure into the stress intensity factor model, and verified the reasonability of the rock creep

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First author: LI Xiao-zhao, male, born in 1987, PhD, Associate Professor, mainly engaged in rock mechanics and underground engineering research. E-mail: lixiaozhao@bucea.edu.cn crack model with Burgers creep model considering seepage pressure. Based on self-consistent theory and linear viscoelastic fracture mechanics theory, Wei et al.[12] studied the creep compliance formula of jointed rock mass under the influence of open crack, closed crack, and water pressure and discussed the influences of seepage pressure, crack density parameters and friction coefficient on the creep compliance of fractured rock mass. On the basis of the wing crack extension model, the subcritical crack growth law and the crack deformation damage model, Li et al.[13] studied the macro-microscopic mechanical model of rock creep without considering the influence of seepage pressure. However, the mechanism of microscopic crack and macroscopic deformation under the interaction of seepage pressure in the process of complete decelerated, steady-state and accelerated creep of brittle rocks cannot be explained by the current research.

In this paper, a mechanism model of crack propagation induced by effective seepage pressure is proposed. Combined with the wing crack growth model, the subcritical crack extension model and the crack strain damage model, the macro-microscopic creep models of brittle rock considering the influence of seepage pressure are established. This study provides theoretical supports for the evaluation of surrounding rock stability during the short term construction and long term operation of deep underground engineering under the influence of seepage pressure.

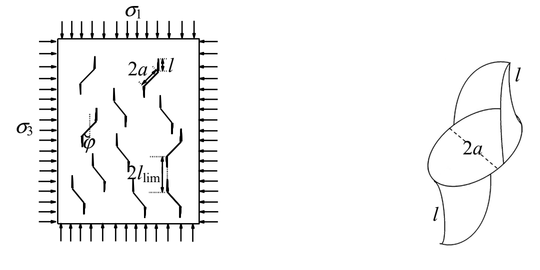
2 Theoretical model

2.1 Relationship between high seepage pressure crack propagation and stress (σ_1, σ_3)

Based on the microscopic crack propagation model, a macro-microscopic creep model of brittle rock under the action of seepage pressure is proposed. The theoretical derivation of the new model is as follows. Figure 1 presents the mechanical characteristics of crack propagation based on the wing crack model, which takes into account the influences of axial stress σ_1, confining stress $\sigma_3 = \sigma_2$, and seepage pressure P_p. Assume the creep model is an isotropic elastomer. Initial damage of brittle rock $D_\mathrm{o} = N_\mathrm{V} a^3$[15], a is the initial crack size, N_V is the number of initial cracks in rock per unit volume. The average limited length of the wing crack extension length l is $l_\mathrm{lim} = a[(3/(4\pi D_\mathrm{o}))^{1/3} - \alpha]$ [16], $\alpha = \cos\varphi$, φ is the angle between the initial crack and the axial direction, namely the initial crack angle. Considering the seepage pressure, the shear stress τ and normal stress σ_n on the initial crack surface inside the compressed rock are (Fig. 1(c)):

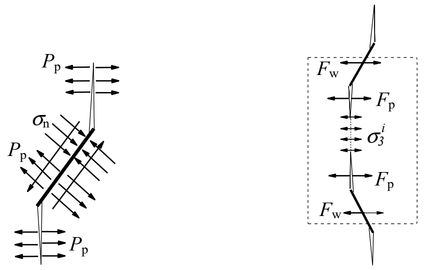
$$\tau = \frac{\sigma_3 - \sigma_1}{2}\sin 2\varphi \qquad (1)$$

$$\sigma_\mathrm{n} = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_3 - \sigma_1}{2}\cos 2\varphi - P_\mathrm{p} \qquad (2)$$



(a) Model of crack extension in brittle rock under high seepage pressure

(b) 3D force diagram of a single crack



(c) 2D force diagram of a single crack (d) Force balance between cracks

Fig. 1 Model based on wing cracks

In the theoretical calculation, the seepage pressure is assumed to be negative, otherwise it is positive. In the result analysis, for the convenience of observation, the seepage pressure is considered as positive. It is explained by Eq. (2) that the high seepage pressure triggers the stress weakening in the initial crack opening direction and promotes the initial crack surface sliding, leading to the wing crack propagate along the direction of maximum principal stress σ_1. The occurrence of high seepage pressure enhances the extension of the newly formed wing cracks. In the following section, this crack extension enhancement mechanism will be explained by introducing the wing crack surface effective seepage pressure parameter F_p into the microscopic crack extension model.

Based on the stress intensity factor at the wing crack tips[14], the seepage pressure parameter P_p is introduced, and thus an improved stress intensity factor for opening crack at the wing crack tips considering seepage pressure is expressed as follow:

$$K_{\mathrm{I}} = \frac{F_{\mathrm{w}}}{[\pi(l+\beta a)]^{\frac{3}{2}}} + \frac{2}{\pi}(\sigma_3 + \sigma_3^i)\sqrt{\pi l} \tag{3}$$

where

$$\sigma_3^i = \frac{F_{\mathrm{w}} + F_{\mathrm{p}}}{S - \pi(l+\alpha a)^2} \tag{4}$$

$$S = \pi^{1/3}\left[3/(4N_{\mathrm{V}})\right]^{2/3} \tag{5}$$

$$F_{\mathrm{w}} = (\tau + \mu\sigma_n)\pi a^2 \sin\varphi \tag{6}$$

$$F_{\mathrm{p}} = |P_{\mathrm{p}}|\left[\pi(l+\alpha a)^2 - \pi(\alpha a)^2\right] \tag{7}$$

where μ is the friction coefficient of the initial crack; β is a constant; | | marks the absolute value; S is the average area occupied by a single crack surface in a unit volume rock containing N_{V} initial cracks ($S = \pi r^{2}$, r is the radius of a sphere assigned by a single crack per unit volume, $4\pi r^3/3 = 1/N_{\mathrm{V}}$). In Fig. 1(d), F_{w} is the tensile force on initial crack surface, which is the tensile force of the wing crack caused by external load and seepage pressure; F_{p} is the introduced effective seepage pressure parameter, which is the tensile force of wing crack caused by seepage pressure; σ_3^i is the internal stress acting on two wing crack tips, and in the model, it is assumed that the projection of the initial crack surface and the wing crack surface in σ_3 direction are approximately within a circular plane, therefore, $\pi(l+\alpha a)^2$ represents the projection area formed by the initial crack surface and the wing crack surface in σ_3 direction, and $\pi(\alpha a)^2$ indicates the projected area of the initial crack surface in σ_3 direction, and $\pi(l+\alpha a)^2 - \pi(\alpha a)^2$ represents the area on the wing crack surface subjected to seepage pressure. Figure 2 presents the relationships between the seepage pressure, the normal stress on the initial crack surface, the initial crack surface tensile force F_{w} and the wing crack surface effective seepage pressure F_{p}.

The crack extension occurs when the stress intensity factor K_{I} reaches the fracture toughness K_{IC}. According to Eq. (3), the relationship between the applied stress and crack length of brittle rock under seepage pressure is

$$\sigma_1(l) = \frac{K_{\mathrm{IC}} - \sigma_3\left(A_1\pi a^2\chi + 2\sqrt{l/\pi}\right) + A_3 - A_4}{A_2\pi a^2\chi} \tag{8}$$

where

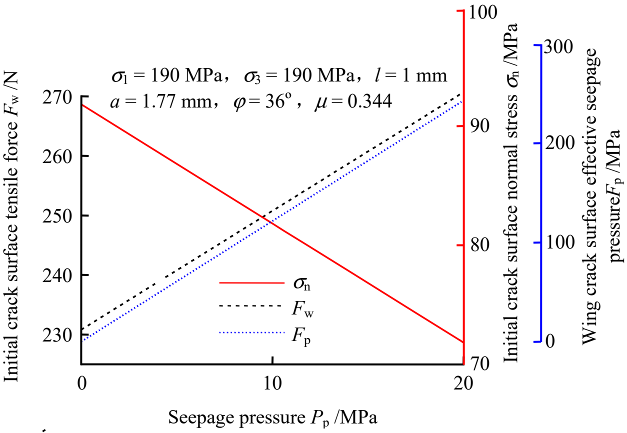


Fig. 2 Relationships between seepage pressure and normal, tensile stress on initial crack surface and effective seepage pressure on wing crack surface

$$A_1 = \left[(\sin 2\varphi + \mu + \mu\cos 2\varphi)\sin\varphi\right]/2 \tag{9}$$

$$A_2 = \left[(\mu - \mu\cos 2\varphi - \sin 2\varphi)\sin\varphi\right]/2 \tag{10}$$

$$A_3 = a^2\mu\pi\chi P_{\mathrm{p}}\sin\varphi \tag{11}$$

$$A_4 = 2F_{\mathrm{p}}\sqrt{l/\pi}[S - \pi(l+\alpha a)^2] \tag{12}$$

$$\chi = [\pi(l+\beta a)]^{-3/2} + 2\sqrt{l/\pi}[S - \pi(l+\alpha a)^2]^{-1} \tag{13}$$

It is easy to know that according to Eq. (8), the stress–crack length relationship $\sigma_1(l)$ corresponds to the stress–strain relationship, and there is a peak strength $\sigma_{1\mathrm{peak}}$[16]. The axial stress of rock crack initiation ($l = 0$) is

$$\sigma_{1\mathrm{c}} = \left[\left(\beta^{3/2}K_{\mathrm{IC}}\right)/\sqrt{a/\pi} - \sigma_3 A_1 + \mu P_{\mathrm{p}}\sin\varphi\right]/A_2 \tag{14}$$

Equations (13) and (14) give the criteria of peak stress and crack initiation stress under different confining stresses. These two critical stress values provide important references for the selection of applied constant stress values during rock creep.

2.2 Creep equation induced by high seepage pressure subcritical crack extension

By substituting Eq. (3) into the single opening rock subcritical crack extension rate and crack strength factor equation $\mathrm{d}l/\mathrm{d}t = v(K_{\mathrm{I}}/K_{\mathrm{IC}})^n$[17], the relationship between stress, crack length, crack extension rate and time can be derived:

$$l' = \frac{\mathrm{d}l}{\mathrm{d}t} = v\left[\frac{\sigma_1 A_2\pi a^2\chi + \sigma_3\left(A_1\pi a^2\chi + 2\sqrt{l/\pi}\right) - A_3 + A_4}{K_{\mathrm{IC}}}\right]^n \tag{15}$$

where v and n are the characteristic crack extension rate and stress erosion parameter, respectively, which can be obtained by subcritical crack propagation tests[17]. For crack length differential equation (Eq. (15)), the initial crack length l_o can be obtained through Eq. (8) under a given stress state ($\sigma_{1c} < \sigma_1 < \sigma_{1peak}$).

With reference to the definition of axial strain, rock damage can be expressed as[18]

$$D = 1 - \exp\left[-\varepsilon_o^{-1}\left(\varepsilon_1 - 2\gamma E^{-1}|\sigma_3|\right)\right]^m \qquad (16)$$

where D is rock damage parameter; m and ε_o are the material constants; ε_1 is axial stain; γ and E are Poisson's ratio and elasticity modulus, respectively.

The rock damage can be defined by using microscopic crack characteristics[15] as

$$D = N_V (l + a)^3 \qquad (17)$$

In combination with the rock damage defined by crack and strain, the relationship between macroscopic strain and microscopic crack length can be given as

$$\varepsilon_1 = 2E^{-1}\gamma|\sigma_3| + \varepsilon_o\left(-\ln\left[1 - D_o\left(l/a + 1\right)^3\right]\right)^{\frac{1}{m}} \qquad (18)$$

By substituting the crack limit length $l_{\lim}$ into Eq. (18), the ultimate failure strain of rock can be estimated approximately. Substituting the time-dependent crack extension $l(t)$ calculated by Eq. (15) into Eq. (18), when the applied stress is higher than the crack initiation stress σ_{1c} and less than the rock strength σ_{1peak}, the axial creep strain induced by crack extension is

$$\varepsilon_1(t) = 2E^{-1}\gamma|\sigma_3| + \varepsilon_o\left(-\ln\left[1 - D_o\left(l(t)/a + 1\right)^3\right]\right)^{\frac{1}{m}}, \quad \left(\sigma_{1c} < \sigma_1 < \sigma_{1peak}\right) \qquad (19)$$

When the axial stress is less than the crack initiation stress σ_{1c}, the creep of the rock is approximately linear elastic deformation. In addition, it can be seen from the rock compression test results[6, 19] that the seepage pressure has a more significant influence on the mechanical properties of rock in the plastic deformation stage, but less influence in the elastic stage. Therefore, when the axial stress is less than the crack initiation stress and the influence of seepage pressure on the elasticity modulus and Poisson's ratio can be neglected, the elastic deformation of the rock can be calculated by

$$\varepsilon_1 = |\sigma_1 - 2\gamma\sigma_3|/E, \qquad (0 \leqslant \sigma_1 \leqslant \sigma_{1c}) \qquad (20)$$

Therefore, combining the approximated linear elastic equation (Eq. (19)) before crack extension and the nonlinear creep equation (Eq. (20)) after crack extension, the complete creep evolution equation of rock can be written as

$$\varepsilon_1(t) = \begin{cases} |\sigma_1 - 2\gamma\sigma_3|/E, & (0 \leqslant \sigma_1 \leqslant \sigma_{1c}) \\ 2E^{-1}\gamma|\sigma_3| + \varepsilon_o\left(-\ln\left[1 - D_o\left(l(t)/a + 1\right)^3\right]\right)^{\frac{1}{m}}, & \\ & \left(\sigma_{1c} < \sigma_1 < \sigma_{1peak}\right) \end{cases} \qquad (21)$$

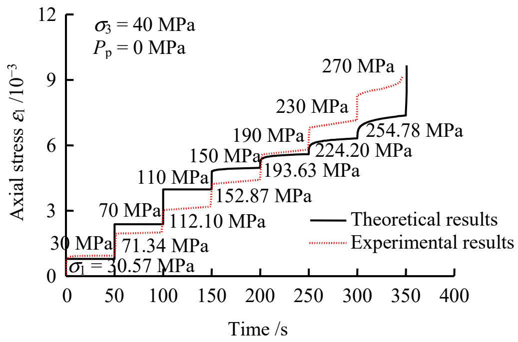
It is worth noting that this study focuses on the effect of seepage pressure on the creep behavior of brittle rock after crack initiation ($\sigma_{1c} < \sigma_1 < \sigma_{1peak}$).

3 Results and discussion

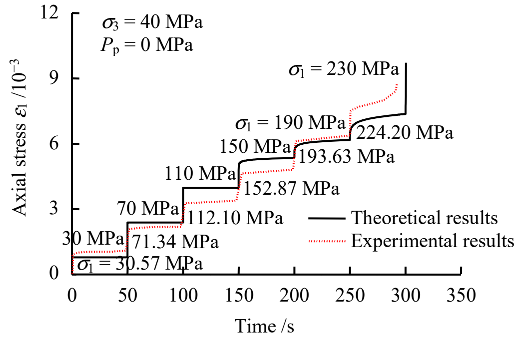
3.1 Theoretical model validation

In this paper, parameters of deep buried sandstone were selected by references[6, 20–22]. The elasticity modulus of 25.03 GPa and Poisson's ratio of 0.13 were determined by conventional triaxial compression tests. The rock fracture toughness was measured by three point bending test, K_{IC} = 0.69 MPa • m$^{1/2}$. The rock initial damage D_o = 0.059 was estimated by SEM test. The stress erosion index n = 20; characteristic crack extension rate $v = 8\times10^{-18}$, seepage saturation n = 16, $v = 1.7\times10^{-13}$ were determined by rock subcritical crack propagation tests. However, it is difficult to accurately determine the initial crack friction coefficient, initial crack size and angle through physical tests. In this study, by comparing the strain–time creep evolution curve of rock obtained by theoretical analysis and indoor tests, the relevant parameters are determined through trial calculation, including the initial crack friction coefficient μ = 0.344, initial crack size a = 1.77 mm, initial crack angle $\varphi = 36^{\circ}$, rock material constants m = 2, ε_o = 1/58 and β = 0.29. These parameters can be determined through previous experience and the specific model parameter selection has been reported elsewhere[16].

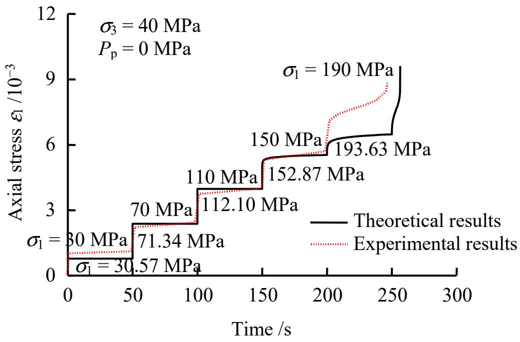
Based on Eq. (14), when the confining stress σ_3 = 40 MPa, the crack initiation stress without seepage pressure can be calculated. Therefore, when the step loading axial stress is 30 MPa or 70 MPa, the creep of rock is characterized by elastic strain, which corresponds to the deformation of the first stage in the creep evolution equation (Eq. (21)) $(0<\sigma_1<\sigma_{1\mathrm{c}})$; When the axial stress gradually increases to 110 MPa, the creep of the rock presents nonlinear characteristics, which corresponds to the deformation in the second stage of Eq. (21) $(\sigma_{1\mathrm{c}}<\sigma_1<\sigma_{1\mathrm{peak}})$. The comparison between the theoretical predictions and experimental results of sandstone creep under step loading axial stress is illustrated in Fig. 3 when the seepage pressure is 0, 1 and 10 MPa, respectively.



(a) Without seepage pressure



(b) Seepage pressure 1 MPa



(c) Seepage pressure 10 MPa

Fig. 3 Comparison of theoretical and experimental creep curves under step axial loading

The theoretical results are comparable to the experimental results[6] with similar variation trends, which verifies the rationality of the macro-micro mechanical model of rock creep under seepage pressure. The differences between theoretical and experimental results may be due to: ① The model in this paper cannot simulate the random distribution of microscopic cracks, but assumes the initial crack size and angle in the rock are constants by an averaging method. ②The model does not consider the influence of water–rock chemical interaction on mechanical parameters of brittle rock. ③It is impossible to guarantee that the value of step loading axial stresses in the theoretical results are exactly the same as that in the experimental results. ④Errors can also be introduced into the model because of inappropriate parameter selection.

3.2 Creep characteristics of brittle rock under constant seepage pressure

Figure 4 shows the evolution curves of crack length, crack extension rate, axial strain and axial strain rate during complete creep process under constant axial stress, confining stress and seepage pressure. Both crack length and axial strain experience three stages of deceleration, steady state and acceleration, which can be explained by the change of crack extension rate and axial strain rate. It can be seen that the evolution trends of crack length and strain over time are similar, which also stems from the proportional relationship between crack length and strain in Eq. (18). Figure 5 illustrates the evolution of effective seepage pressure on the newly formed wing crack surface during rock creep under different seepage pressures. It is easy to find that the effective seepage pressure increases with time and rises sharply in the later stage. This phenomenon also indicates that in the accelerated creep stage, the damage of internal crack is aggravated, leading to the accelerated increase of the contact area between water and internal crack surface, which in turn leads to the accelerated rock failure. Since the creep failure time of rock varies greatly under different seepage pressures, the time axis in Fig. 5 is in the form of logarithmic coordinates to present the effective seepage pressure evolution curves in a unified graph.

Figure 6 demonstrates the influence of different seepage pressures on the evolution of crack length, crack extension

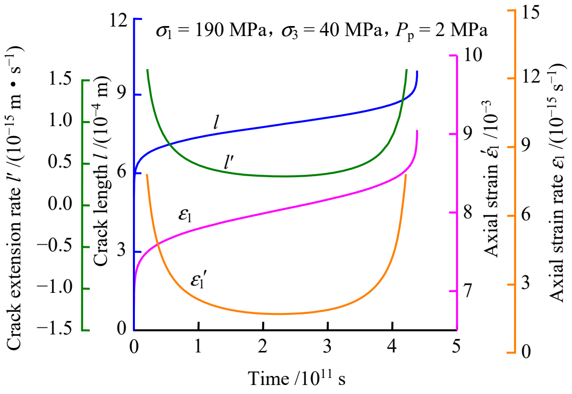


Fig. 4 Evolution of crack length, crack growth velocity, axial strain, and axial strain rate under constant loading and seepage pressure during complete creep

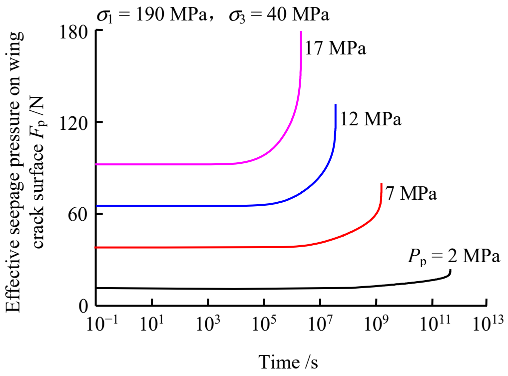
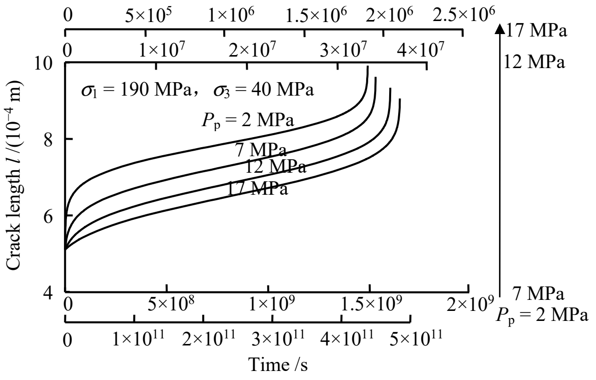


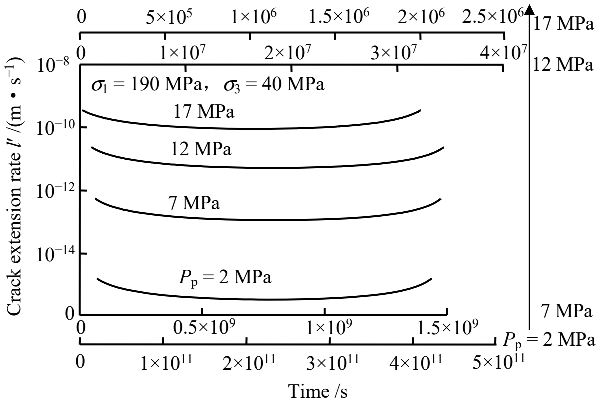
Fig. 5 Evolution of effective seepage pressure on wing crack surface during rock creep

rate, axial strain and axial strain rate during complete rock creep. With the increase of seepage pressure, the creep failure time of rock decreases. Correspondingly, the steady state creep crack extension rate and axial strain rate of rock increase continuously. In Fig. 6(c), the variable between different seepage pressures is 5 MPa, which has a significant impact on the magnitude of rock creep failure time. As a result, the influence of different seepage pressures on rock creep strain at the same time cannot be accurately identified. For better explanation, Figure 7 presents the influence of seepage pressure with a variable of 1 MPa in the complete creep failure curve. It can be observed that with the increase of seepage pressure or decrease of effective confining stress P_e, the axial strain at the same time increases continuously, which is consistent with previous research results[10].

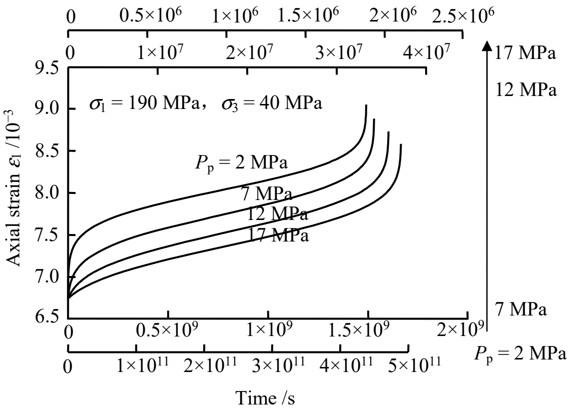
Figure 8 plots the relation curves between seepage pressure and rock creep failure time under different confining stresses and axial stresses. It reveals that the creep



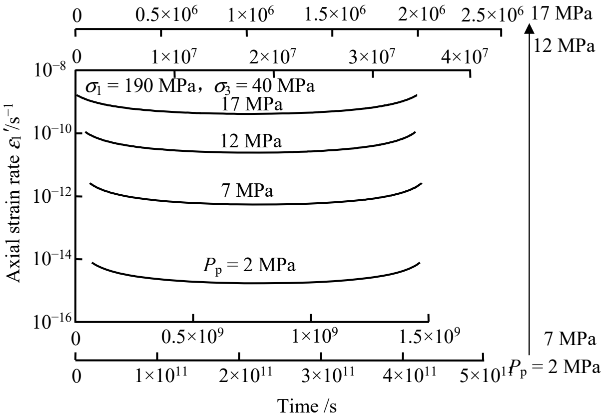
(a) Crack length



(b) Crack extension rate



(c) Axial strain



(d) Axial strain rate

Fig. 6 Effects of seepage pressure on complete creep evolution

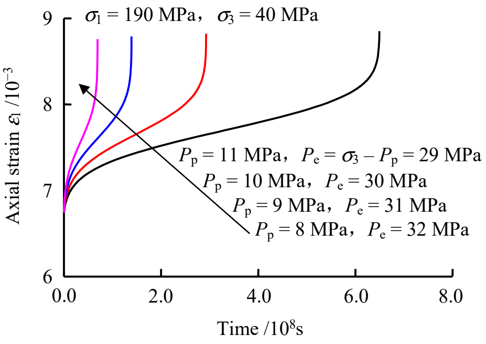
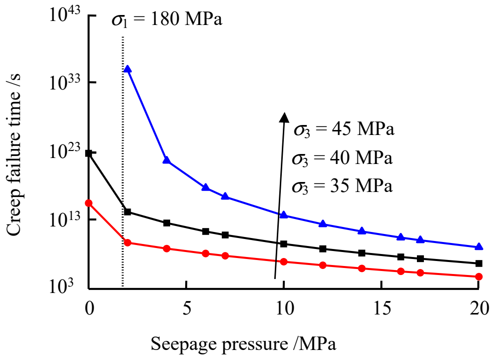
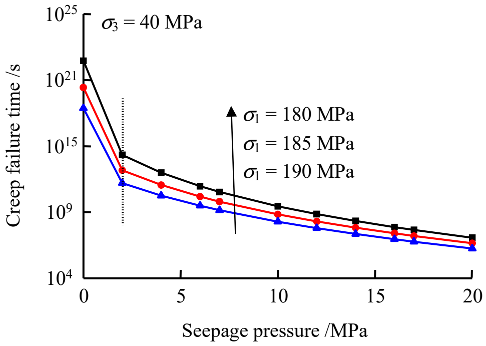


Fig. 7 Effects of seepage pressure P_p or effective confining pressure P_e on creep behaviors of brittle rocks



(a) Effect of confining stress



(b) Effect of axial stress

Fig. 8 Relationship between seepage pressure and creep failure time under different confining pressures or axial stresses

failure time decreases with the increase of seepage pressure. Under the same seepage pressure, the creep failure time increases with the increase of confining stress or the decrease of axial stress. In addition, when the confining stress or axial stress produces the same stress increment of 5 MPa, the confining stress has a greater influence on creep failure time than that of axial stress, indicating that the sensitivity of confining stress to rock creep failure is more obvious than that of axial stress. As can be seen from Fig. 8(a), when the confining stress is 45 MPa and the seepage pressure is 0 MPa, there is no data available in the creep failure time. The reason is that under current stress state, the creep failure time of rock is infinite, meaning that rock failure will not occur.

3.3 Creep characteristics of brittle rock with step loading seepage pressure

In the previous section, the influence of constant seepage pressure on rock creep behavior was presented. However, in deep underground environment, with the interference of external factors such as construction, the seepage pressure in rock may change continuously. In this section, the influence of step loading seepage pressure on the creep evolution will be discussed.

Figure 9 shows the evolution of rock crack length, crack extension rate, axial strain and axial strain rate under constant axial stress, confining stress and step loading seepage pressure. Initial seepage pressure P_{p1} is 2 MPa, each level of the seepage pressure increment ΔP_p is 2 MPa and lasts for 50 h. The crack length and axial strain both experience multiple stages of decelerated increase until the last stage of seepage pressure when they go through accelerated increase. At this moment the rock also breaks down. The evolution curves of crack extension rate and axial strain rate clearly explain the variation of crack length and step loading axial strain change rate. The minimum crack extension rate or axial strain rate of rock increase with the increase of the step loading seepage pressure. This find agrees well previous research results[3−4].

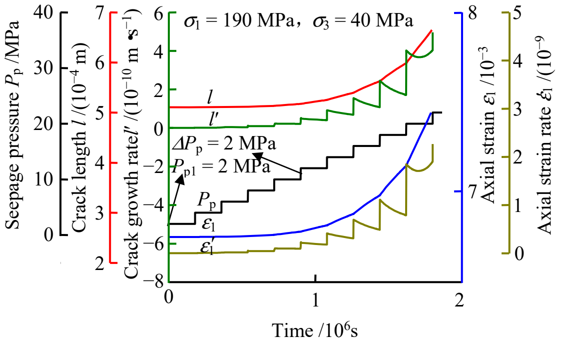
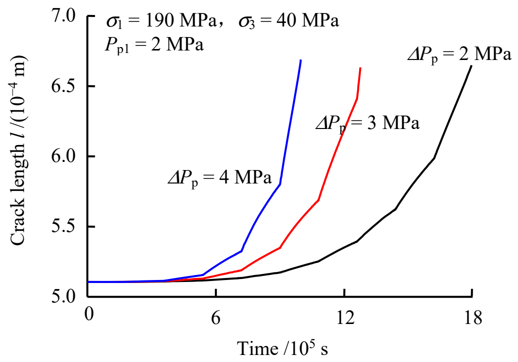
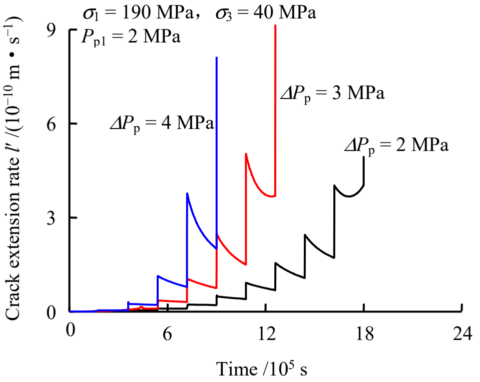


Fig. 9 Evolution of crack length, crack growth rate, axial strain, and axial strain rate under constant loading and step seepage pressure during rock creep

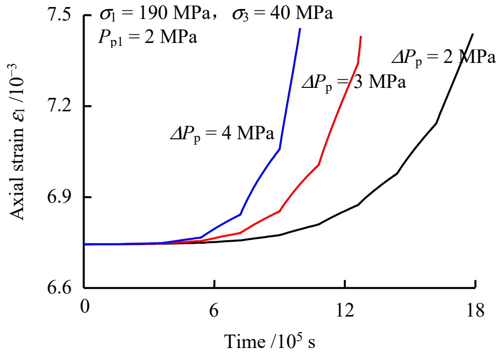
Figure 10 shows the evolution curves of rock crack length, crack extension rate, axial strain and axial strain rate under different step loading seepage pressures increment ΔP_p. With the increase of seepage pressure increment, the number of graded steps of rock creep failure declines and the rock creep failure time also decreases.



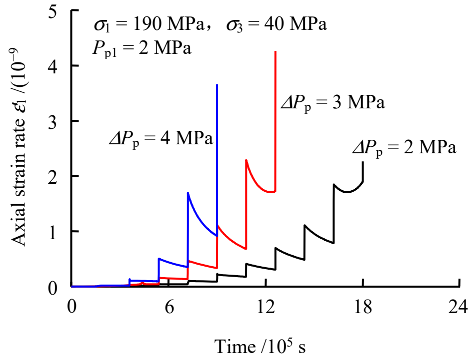
(a) Crack length



(b) Crack extension rate



(c) Axial strain



(d) Axial strain rate

Fig. 10 Effects of step loading seepage pressure on creep evolution

Meanwhile, the crack length, crack extension rate axial strain and axial strain rate of rock at the given time all increase continuously.

4 Conclusions

Based on fracture damage mechanics theory, a macro-microscopic creep mechanical model of brittle rock is established considering the effect of seepage pressure. The effects of seepage pressure on crack length, crack extension rate, effective seepage pressure, strain and strain rate of brittle rock are explained in detail. The main conclusions can be drawn as follow:

(1) With the increase of seepage pressure, the normal stress on the initial crack surface decreases linearly, whereas the tensile force on the initial crack surface and the effective seepage pressure on the newly generated wing crack surface increase linearly.

(2) Under constant seepage pressure, the creep failure time of rock decreases with the increase of seepage pressure. Moreover, the steady-state creep crack extension rate, axial strain and axial strain rate all exhibit continuous increase. Under the same seepage pressure, the creep failure time increases with the increase of confining stress or the decrease of axial stress. The influence of confining stress on the magnitude of rock creep failure time is greater than that of axial stress, indicating that the sensitivity of confining stress on rock creep failure is more obvious compared with axial stress. The effective seepage pressure increases along with the creep evolution, and the effective seepage pressure witnesses an accelerated increase during the creep acceleration stage.

(3) Under step loading seepage pressure, the crack length and axial strain go through several stages of decelerated increase until the last stage of seepage pressure when both crack length and axial strain increase dramatically and the rock is broken at the same time. With the increase of the step loading seepage pressure increment, the minimum crack extension rate or axial strain rate increase, while the number of rock creep failure steps and time decrease continuously. Correspondingly, the crack length, axial strain, crack extension rate and axial strain rate of rock at the given time increase continuously.

References

[1] CAO Ya-jun, WANG Wei, XU Wei-ya, et al. Permeability

evolution of low-permeability rocks in triaxial creep tests[J]. Chinese Journal of Rock Mechanics and Engineering, 2015, 34(Suppl.2): 3822−3829.

[2] SHE Cheng-xue, CUI Xuan. Influence of high pore water pressure on creep properties of rock[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(8): 1603−1609.

[3] YAN Yan, WANG En-zhi, WANG Si-jing, et al. Study of seepage-rheology coupling experiment of rocks[J]. Rock and Soil Mechanics, 2010, 31(7): 2095−2103.

[4] YANG Hong-wei, XU Jiang, NIE Wen, et al. Experimental study on creep of rocks under step loading of seepage pressure[J]. Chinese Journal of Geotechnical Engineering, 2015, 37(9): 1613−1619.

[5] SHEN Rong-xi, LIU Chang-wu, LIU Xiao-fei. Triaxial rheology characteristics and model of carbonaceous shale in pressure water[J]. Chinese Journal of Geotechnical Engineering, 2010, 32(7): 1031−1034.

[6] JIANG Hai-fei, LIU Dong-yan, HUANG Wei, et al. Influence of high pore water pressure on creep properties of rock under high confining pressure[J]. Journal of China Coal Society, 2014, 39(7): 1248−1256.

[7] YI H Y, ZHOU H W, WANG R, et al. On the relationship between creep strain and permeability of granite: experiment and model investigation[J]. Energies, 2018, 11: 2859.

[8] LIU L, XU W Y, WANG H L, et al. Permeability evolution of granite gneiss during triaxial creep tests[J]. Rock Mechanics and Rock Engineering, 2016, 49(9): 3455−3462.

[9] GRGIC D, AMITRANO D. Creep of a porous rock and associated acoustic emission under different hydrous conditions[J]. Journal of Geophysical Research, 2009, 114: B10201.

[10] XU T, ZHOU G, HEAP M J, et al. The modeling of time-dependent deformation and fracturing of brittle rocks under varying confining and pore pressures[J]. Rock Mechanics and Rock Engineering, 2018, 51: 3241−3263.

[11] ZHAO Y L, WANG Y X, WANG W J, et al. Modeling of rheological fracture behavior of rock cracks subjected to hydraulic pressure and far field stresses[J]. Theoretical and Applied Fracture Mechanics, 2019, 101: 59−66.

[12] WEI Li-de, XU Wei-ya, YANG Song-lin, et al. Analysis of creep compliance of jointed rocks with consideration of the influence of water pressure in saturated cracks[J]. Journal of Hohai University (Natural Sciences), 2003, 31(5): 564−568.

[13] LI Xiao-zhao, SHAO Zhu-shan. Macro-micro mechanical model for progressive and creep failure of brittle rock[J]. Chinese Journal of Geotechnical Engineering, 2016, 38(8): 1391−1398.

[14] ASHBY M F, SAMMIS C G. The damage mechanics of brittle solids in compression[J]. Pure and Applied Geophysics, 1990, 133(3): 489−521.

[15] BUDIANSKY B, O’CONNEL R J. Elastic moduli of a cracked solid[J]. International Journal of Solids and Structures, 1976, 12: 81−97.

[16] LI Xiao-zhao, SHAO Zhu-shan, QI Cheng-zhi. Study on effects of crack damage and confining pressure on shear fracture band in rocks[J]. Rock and Soil Mechanics, 2019, 40(11): 4249−4258.

[17] ATKINSON B K. Subcritical crack growth in geological materials[J]. Journal of Geophysical Research, 1984, 89(6): 4077−4114.

[18] CHEN Zhong-hui, FU Yu-fang, TANG Chun-an. Confining pressure effect on acoustic emissions in rock failure[J]. Chinese Journal of Rock Mechanics and Engineering, 1997, 16(1): 65−70.

[19] PENG Jun, RONG Guan, ZHOU Chuang-bing, et al. Experimental study of effect of water pressure on progressive failure process of rocks under compression[J]. Rock and Soil Mechanics, 2013, 34(4): 941−946.

[20] WANG Jun-bao, LIU Xin-rong, LIU Jun, et al. Mechanical properties of sandstone and an improved Duncan-Chang constitutive model[J]. Chinese Journal of Rock Mechanics and Engineering, 2016, 35(12): 2388−2397.

[21] LI Bin, HUANG Da, MA Wen-zhu. Study on the fracturing behavior of sandstone influenced by bedding plane[J]. Rock and Soil Mechanics, 2020, 41(3): 858−868.

[22] LIU Xin-rong, LIU Jun, LI Dong-liang, et al. Unloading mechanical properties and constitutive model of sandstone under different pore pressures and initial unloading levels[J]. Journal of China Coal Society, 2017, 42(10): 2592−2600.