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Research Article

A Nonlinear Creep Damage Model of Layered Rock under Unloading Condition

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Triaxial unloading creep tests of layered rock specimen of Jinping II hydropower station were carried out using the rock creep testing machine; thus the creep deformation curves under different confining pressures were acquired. The test results showed that, in addition to the obvious unloading creep characteristics of rock specimen, the nonlinear accelerating creep deformation emerged under the last stage confining stress condition, and the whole creep curves presented the typical rock creep three stages. On the other hand, the Burgers creep model constitutive equations under the three-dimensional stress state were also deduced. Based on the creep test data, through identifying the creep parameters using the optimized algorithm, the corresponding parameters of triaxial creep constitutive model were obtained. By comparative analysis of creep parameters, it can be concluded that creep parameters nonlinearly degraded with the decrease of confining pressure gradually. Moreover, when the load is below the long-term strength of rock, the creep parameters are only related to the unloading ratio, while in the case that the load is larger than the long-term strength of rock, the unloading creep parameters are related to both unloading ratio and creep time. According to the creep parameters under the first-stage stress level, and through introducing unloading ratio damage factor to describe the degrading rule of creep parameters on other stress levels, the method of uniformity determining the creep parameters was proposed. It was assumed that the damage degree in rock interior was relative to both unloading ratio and creep time; a nonlinear creep damage model of rock under unloading was proposed, which could better reflect the nonlinear characteristics of rock creep. The results showed that rock nonlinear creep damage model achieved perfectly consistent results with the creep test.

1. Introduction

Natural rocks in actual engineering are normally in the form of rock combination in various sizes which are cut by a variety of bedding, cracks, and joints. With remarkable nonlinear elastic, inhomogeneity, discontinuity, and anisotropy characteristics, the engineering rock masses are different from the other engineering materials [1–3].

With the rapid development of China's economy and infrastructure construction, many major engineering projects have successively started constructing in the high crustal stress and complex regional geological conditions such as the Three Gorges Project, the large-scale hydropower project group in the southwest region of Sanjiang, the West Power to East Projects, the Qinghai-Tibet Plateau Railway, and the South-to-North Water Diversion Project. The construction of these major projects will inevitably involve a large number of excavations of high and steep slopes and large-scale underground caverns. In this situation, artificial excavation unloading process will destroy the balance of the initial stress field of rock; thus engineering rock mass will be automatically adjusting the secondary stresses to reach a new stress equilibrium state, which will make a significant rock unloading relaxation phenomena occurring within a certain range. Under unloading condition, the original joints and cracks in the rock mass will be opened and expanded which will result in the instability of rock mass slope. Therefore, conducting creep mechanics characteristic tests of layered rock and researching its nonlinear constitutive model under high stress unloading conditions are of important theoretical and practical significance.

Rock will show significant aging characteristics under the long-term loads. Currently, systematic studies of the rock creep mechanical properties under loading stress path conditions have been carried out [4–7]. However, regarding the creep mechanical properties of rock with beddings and fractures under high stress unloading conditions, relevant experimental and theoretical studies are rare.

Xia et al. [8] carried out triaxial rheological tests on marble samples from Jinping hydropower station under the condition of step unloading confining pressure and constant axial pressure and obtained the stress-strain-time curves of the marble samples. According to the rheological deformation properties of marble samples under high stress unloading condition, a new rheological constitutive model was proposed based on Cristescu model and the corresponding parameters of the model were obtained based on the rheological test results. Considering the impact of unloading stress path, the proposed model can better reflect the lateral rheological deformation. Li et al. [9] conducted the triaxial unloading creep mechanics test and obtained the typical three-stage process creep deformation curve of the sandstone in Yichang area, so as to finish the research of the sandstone creep mechanical characteristics under unloading condition. Suppose the microelement destruction of rock strain in the unloading nonlinear accelerated creep phase was subject to Weibull statistical distribution; the corresponding nonlinear unloading creep model was established by introducing damage factors into viscosity coefficients. Taking green sandstone samples from Jinping hydropower station as research objective, Zhu et al. [10] performed the unloading triaxial rheological tests under step-by-step unloading confining stress and studied long-term creep properties of green sandstone under high stress unloading conditions. Considering the internal damage of materials, the damage evolution equation and nonlinear rheological model with various parameters were proposed. In the model, the creep parameters of sandstone were weakened with viscous strain gradually, so the deterioration process of the material can be reflected by unsteady creep parameters directly. Li et al. [11] carried out creep tests on deep amphibolite samples from Jinchuan mining area using multistep incremental loading and unloading method. In addition, the viscoelastoplastic model was adopted to research viscoelastoplastic creep properties of deep amphibolites, reaching the conclusion that the viscoelastoplastic model can properly describe long-term creep deformation law of samples.

Yang et al. [12] carried out creep mechanical tests of typical diabase samples from Dagangshan hydropower under the condition of constant axial pressure and unloading confining pressure. They considered that deformation of rock samples gradually transformed from elastic deformation to plastic deformation in the process of unloading confining pressure. In order to describe the nonlinear characteristics of accelerated creep, the Burgers model was improved to have variable parameters. Yang et al. [13] found that relaxation behavior existed for precracked hard rock though double-torsion experiment. And relaxation behavior tended to be more obvious under a lower unloading rate.

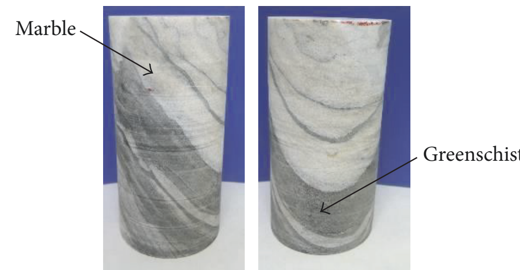

Figure 1: Typical layered rock specimen.

Taking the typical layered rock samples from Jinping II hydropower project as the study object, this paper carried out triaxial unloading creep test in the method of constant deviatoric stress and step unloading confining pressure, studied the long-term creep properties of layered rock under unloading condition, and analyzed unsteady creep parameters of rock. Based on unloading ratio and load time, the nonlinear creep damage model was established by introducing damage factors, which can describe different creep deformation stages of layered rock under unloading conditions.

2. Triaxial Unloading Confining Pressure Test

Triaxial unloading creep tests were carried out on typical marble and interbedding greenschist rocks from Jinping II hydropower station using TLW-2000 creep testing machine. It was found that the marble was hard, while the greenschist was relatively soft in the layered rock samples. Samples were processed in accordance with the standard recommended by the International Society for Rock Mechanics. Surfaces of cylindrical rock samples (ϕ50 mm × 100 mm) should be polished smooth, and typical layered rock samples are shown in Figure 1.

The laboratory should maintain constant temperature and humidity in the process of triaxial unloading confining pressure creep test. In the method of step unloading confining pressure, the deviatoric stress should be maintained at constant 60 MPa, while the confining pressure was unloaded progressively from 40 MPa till the sample was destroyed. Each level of unloading value was 5 MPa with unloading rate of 0.5 MPa/min. The axial, confining stress state should be maintained unchanged after unloading one level of confining pressure; then creep strain rate reached constant stage before unloading the next one cycles went on like this till the destruction of the specimen. The scheme of triaxial unloading creep tests is shown in Table 1.

Triaxial unloading creep test curve of layered rock samples is shown in Figure 2. Under the effect of long-term loads, the creep properties of rock samples are not significant when the confining pressure is high, while with the gradual decrease of confining pressure, creep deformations represented by decay creep, and steady creep increases accordingly. In particular, creep rate gradually tends to a constant value as time goes by. Continuing unloading confining pressure, creep

Table 1: Triaxial unloading creep test scheme.

Series	$(\sigma_1 - \sigma_3)$/MPa	σ_3/MPa	Unloading rate/(MPa/min)
Level 1	60	40	0.5
Level 2	60	35	0.5
Level 3	60	30	0.5
...	60	...	0.5
Level 7	60	10 (destroy)	0.5

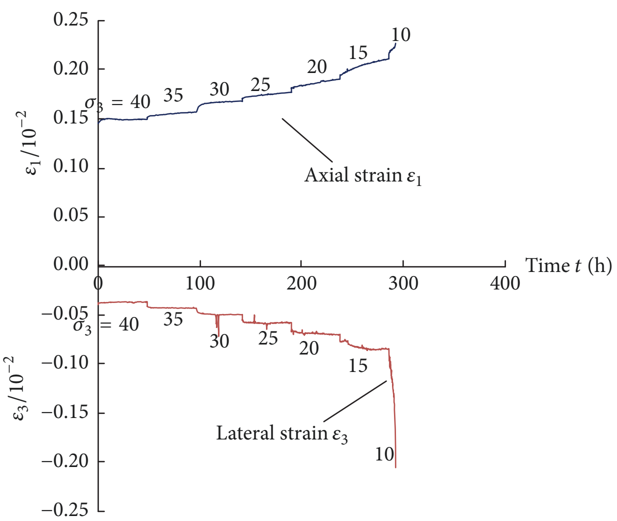

Figure 2: Triaxial unloading creep test curves of layered rock specimen.

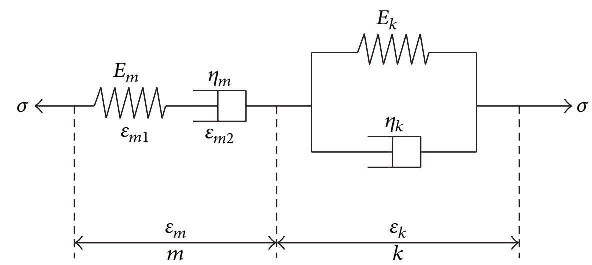

Figure 3: Burgers rheological model under one-dimensional stress state.

deformation of rock samples is increasingly apparent. When confining pressure reaches the last stage of 10 MPa, the creep curves present the typical three-stage characteristics in rock creep and finally go to nonlinear accelerated creep till failure.

3. Burgers Creep Model and Parameters

From triaxial unloading creep test results, we can see that rock samples produce instantaneous deformation immediately. When the confining pressure is in the range of 15~40 MPa, the creep increase rate value gradually decreases and eventually maintains a constant creep rate as the time goes on. According to presented rheological characteristic, the Burgers creep constitutive model was adopted to fit test results and to analyze identified creep parameters [14].

Burgers creep constitutive model is composed of the Maxwell model and Kelvin model in series, and the creep element model under the one-dimensional stress conditions is shown in Figure 3. Burgers creep constitutive model is a viscoelastic model. In Figure 3, σ and ε are the total stress and total strain of creep model, respectively; σ_m, σ_k, ε_1 and ε_2 are corresponding stress and strain of Maxwell and Kelvin model, respectively; ε_{m1} and ε_{m2} are, respectively, the corresponding elastic strain and viscous strain in Maxwell model; E_m, E_k, η_m, η_k are elasticity and viscosity parameters of rock material; t is creep deformation time.

Under the effect of long-term loads, the corresponding state equation of Burgers creep constitutive model is

$$\begin{aligned} \sigma_m &= E_m \varepsilon_{m1} \\ \sigma_m &= \eta_m \dot{\varepsilon}_{m2} \\ \sigma_k &= E_k \varepsilon_k + \eta_k \dot{\varepsilon}_k \\ \sigma &= \sigma_m = \sigma_k \\ \varepsilon &= \varepsilon_{m1} + \varepsilon_{m2} + \varepsilon_k . \end{aligned} \tag{1}$$

The constitutive equation of total stress and total strain can be obtained by eliminating equation subscript of (1) as

$$\begin{aligned} &\eta_m \eta_k \ddot{\sigma} + \left(E_m \eta_k + E_m \eta_m + E_k \eta_m\right) \dot{\sigma} + E_m E_k \sigma \\ &\quad = E_m \eta_m \eta_k \ddot{\varepsilon} + E_m E_k \eta_m \dot{\varepsilon}. \end{aligned} \tag{2}$$

By conducting Laplace transformation and corresponding inverse transformation for (2), the creep equation of total strain can be deduced:

$$\varepsilon = \frac{\sigma}{E_m} + \frac{\sigma}{\eta_m} t + \frac{\sigma}{E_k}\left(1 - e^{-(E_k/\eta_k)t}\right). \tag{3}$$

The first and second derivatives with regard to time t are carried out at, respectively, left side and right side of; then it can obtain

$$\dot{\varepsilon} = \frac{\sigma}{\eta_m} + \frac{\sigma}{\eta_k} e^{-(E_k/\eta_k)t} \tag{4}$$

$$\ddot{\varepsilon} = -\frac{\sigma E_k}{(\eta_k)^2} e^{-(E_k/\eta_k)t}. \tag{5}$$

From (3)~(5), it can be concluded that $\ddot{\varepsilon}$ is smaller than 0 while $\dot{\varepsilon}$ is greater than 0. After the long-term constant

Table 2: Creep parameters of rock under different confining pressures.

Confining pressure/MPa	G_m/GPa	K/GPa	η_m/(GPa·d)	G_k/GPa	η_k/(GPa·d)	R^2
			Axial Burgers creep model parameters (deviatoric stress 60 MPa)			
40	23.86	36.46	4.56×10^3	5.53×10^2	35.28	0.952
35	20.50	33.71	1.60×10^3	1.10×10^3	89.63	0.991
30	19.20	30.40	1.02×10^3	2.42×10^2	30.29	0.989
25	16.72	29.23	8.19×10^2	1.29×10^3	160.28	0.991
20	14.99	27.73	5.54×10^2	4.33×10^2	2.24	0.987
15	13.35	25.06	4.32×10^2	1.90×10^2	150.55	0.996
			Lateral Burgers creep model parameters (deviatoric stress 60 MPa)			
40	18.32	27.47	1.21×10^3	5.98×10^3	368.21	0.941
35	16.03	24.04	6.09×10^2	7.71×10^2	65.21	0.968
30	14.25	21.37	5.37×10^2	3.15×10^3	399.31	0.934
25	12.09	18.14	4.17×10^2	2.45×10^3	325.40	0.908
20	9.71	14.57	2.33×10^2	5.46×10^2	28.24	0.913
15	8.43	12.65	1.29×10^2	3.24×10^2	256.73	0.903

loads σ are applied to the model, deformations including instantaneous elastic deformation and creep deformation occur, and as time goes on, creep rate gradually decreases and finally maintained a constant value. Therefore, Burgers creep constitutive model can describe the instantaneous elastic deformation, attenuation creep deformation, and steady creep deformation well.

Assuming that the rock specimen is a continuous and uniform material, the total strain of Burgers creep constitutive model under the three-dimensional stress condition can be expressed as

$$\varepsilon_{ij} = \varepsilon_{ij}^{m1} + \varepsilon_{ij}^{m2} + \varepsilon_{ij}^{k}. \tag{6}$$

Under the three-dimensional stress condition, the internal stress tensor of rock specimen can be decomposed into the spherical stress tensor σ_m and deviatoric stress tensor S_{ij}. δ_{ij} is Kronecker function, which can be expressed as below:

$$\begin{aligned} \sigma_m &= \frac{1}{3}\left(\sigma_1 + \sigma_2 + \sigma_3\right) = \frac{1}{3}\sigma_{kk} \\ S_{ij} &= \sigma_{ij} - \delta_{ij}\sigma_m = \sigma_{ij} - \frac{1}{3}\delta_{ij}\sigma_{kk}. \end{aligned} \tag{7}$$

Under the three-dimensional stress condition, the deviator strain tensor of Burgers creep constitutive model can be expressed as

$$e_{ij} = \frac{S_{ij}}{2G_m} + \left(\frac{S_{ij}}{2\eta_m}\right)t + \frac{S_{ij}}{2G_k}\left(1 - e^{-(G_k/\eta_k)t}\right). \tag{8}$$

Based on the generalized Hook's law, and considering the spherical strain tensor, the constitutive equation of Burgers creep model under the three-dimensional stress condition is deduced as below:

$$\begin{aligned} \varepsilon_{ij} = {} & \frac{S_{ij}}{2G_m} + \frac{1}{3K}\sigma_m\delta_{ij} + \left(\frac{S_{ij}}{2\eta_m}\right)t \\ & + \frac{S_{ij}}{2G_k}\left(1 - e^{-(G_k/\eta_k)t}\right), \end{aligned} \tag{9}$$

where

$$\begin{aligned} K &= \frac{E_m}{3\left(1 - 2\mu\right)} \\ G_m &= \frac{E_m}{2\left(1 + \mu\right)} \\ G_k &= \frac{E_k}{2\left(1 + \mu\right)}, \end{aligned} \tag{10}$$

where K is the bulk modulus, G_m and G_k are shear modulus, and μ is Poisson's ratio coefficient.

Under the conventional triaxial creep test conditions ($\sigma_2 = \sigma_3$), the axial strain in (9) can be expressed as

$$\begin{aligned} \varepsilon_{11}(t) = {} & \frac{\sigma_1 - \sigma_3}{3G_m} + \frac{\sigma_1 + 2\sigma_3}{9K} + \left(\frac{\sigma_1 - \sigma_3}{3\eta_m}\right)t \\ & + \frac{\sigma_1 - \sigma_3}{3G_k}\left(1 - e^{-(G_k/\eta_k)t}\right) \end{aligned} \tag{11}$$

According to the constitutive equation of Burgers creep model under the three-dimensional stress condition, the parameters of creep constitutive model are identified using the least squares method after optimization search; thus the corresponding parameters of the three-dimensional Burgers creep model can be obtained, as shown in Table 2.

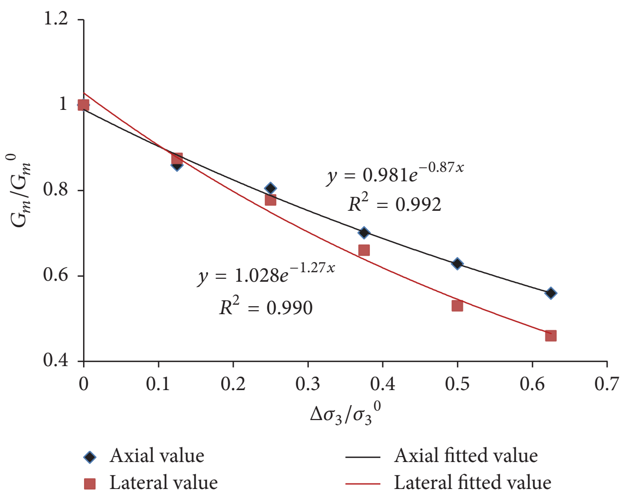

FIGURE 4: Correlation between shear modulus G_m and unloading ratio.

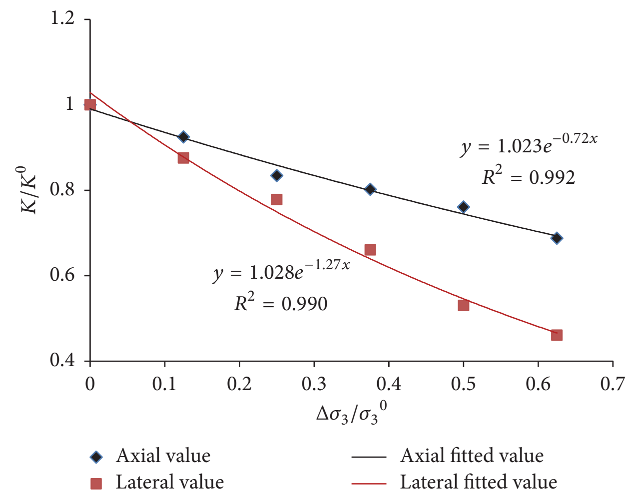

FIGURE 5: Correlation between bulk modulus K and unloading ratio.

4. Nonlinear Unloading Creep Damage Model and Parameters

Usually, creep mechanical parameters of rock under long-term loading conditions are considered to be constant.

Table 2 shows that, with the increase of unloading value $\Delta\sigma_3$ (the difference between initial confining pressure and the confining pressure after unloading), the internal damage of rock specimen gradually increased; accordingly the creep parameters show a more significant nonstationary rule, in which the regularity between the shear modulus G_m and unloading value and the regularity between viscosity parameter η_m and unloading value are relative more significant. In the model, $\Delta\sigma_3/\sigma_3^0$, which is the ratio of unloading value and initial confining pressure, and G_m/G_m^0, K/K^0, η_m/η_m^0, which are the ratios of parameters under different unloading confining pressures and parameters under initial confining pressure, were adopted. Based on the analysis of these parameters, the nonstationary rule of creep parameters upon the variation of unloading value can be obtained.

In Figures 4–6, it can be seen that the shear modulus G_m, bulk modulus K, and viscosity coefficient η_m present nonlinear deterioration with the increase of the unloading ratio under the high stress unloading conditions. It can be concluded that when loads are smaller than the long-term strength of rock samples, unloading creep deformation parameters are gradually weakening with the increase of unloading ratio. When loads are greater than the long-term strength of rock samples, the rock deformation will enter the nonlinear accelerated creep stage. Over time the internal damage of the rock will rapidly increase to the ultimate destruction. Therefore, under such condition, the unloading creep parameters are related to not only relative unloading ratio, but also creep time. Generally, the parameters will present variation of nonlinearly accelerated deterioration with the increase of relatively unloading ratio and creep time.

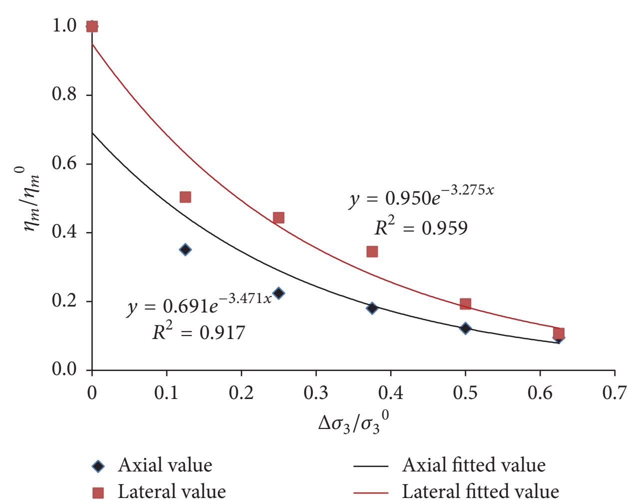

FIGURE 6: Correlation between viscosity coefficient η_m and unloading ratio.

When $\sigma < \sigma_\infty$, the evolution equation of damage parameter upon unloading ratio is expressed as

$$D = 1 - \left(a * e^{b*(\Delta\sigma_3/\sigma_3^0)}\right)^{-1}. \tag{12}$$

When $\sigma \geq \sigma_\infty$, the evolution equation of damage parameter upon unloading ratio and creep time is expressed as

$$\overline{D} = 1 - \left(a * e^{b*(\Delta\sigma_3/\sigma_3^0 + t^n)}\right)^{-1}, \tag{13}$$

where $\Delta\sigma_3$ is unloading value, σ_3^0 is initial confining pressure, t is creep time, and a, b, and n are damage parameters.

Based on Hoek-Brown criterion, it can be judged whether rock creep stress reaches its long-term strength with the definition of long-term parameters m_∞ and s_∞; thus the equation is

$$F = \sigma_1 - \sigma_3 - \sqrt{m_\infty \sigma_c \sigma_3 + s_\infty \sigma_c^2}, \tag{14}$$

Table 3: Unified creep parameters of rock specimen under different confining pressures.

G_m/GPa	K/GPa	η_m/(GPa·d)	G_k/GPa	η_k/(GPa·d)
Axial Burgers creep model unified parameters (deviatoric stress 60 MPa)				
$23.86\times(1-D_1)$	$36.46\times(1-D_2)$	$4.56\times10^3\times(1-D_3)$	6.35×10^2	78.04
Lateral Burgers creep model unified parameters (deviatoric stress 60 MPa)				
$18.32\times(1-D_1)$	$27.47\times(1-D_2)$	$1.21\times10^3\times(1-D_3)$	2.20×10^3	240.52

where σ_1 and σ_3 are, respectively, the maximum and minimum principal stress when failure occurs, σ_c is uniaxial compressive strength of intact rock, m_∞ reflects the macroscopic mechanical parameters of rock, and s_∞ reflects the crushing degree of rock.

By introducing (12) and (13) into (9), we can obtain nonlinear unloading creep damage constitutive equation:

$$\begin{aligned}\varepsilon_{ij} &= \frac{S_{ij}}{2G_m(1-D_1)} + \frac{1}{3K(1-D_2)}\sigma_m\delta_{ij} + \left(\frac{S_{ij}}{2\eta_m(1-D_3)}\right)t + \frac{S_{ij}}{2G_k}\left(1-e^{-(G_k/\eta_k)t}\right) \quad (F<0)\\ \varepsilon_{ij} &= \frac{S_{ij}}{2G_m(1-D_1)} + \frac{1}{3K(1-D_2)}\sigma_m\delta_{ij} + \left(\frac{S_{ij}}{2\eta_m(1-\overline{D})}\right)t + \frac{S_{ij}}{2G_k}\left(1-e^{-(G_k/\eta_k)t}\right) \quad (F\geq 0);\end{aligned} \tag{15}$$

when $\sigma_2 = \sigma_3$, axial strain of nonlinear creep model can be expressed as

$$\begin{aligned}\varepsilon_{11}(t) &= \frac{\sigma_1-\sigma_3}{3G_m(1-D_1)} + \frac{\sigma_1+2\sigma_3}{9K(1-D_2)} + \left(\frac{\sigma_1-\sigma_3}{3\eta_m(1-D_3)}\right)t + \frac{\sigma_1-\sigma_3}{3G_k}\left(1-e^{-(G_k/\eta_k)t}\right) \quad (F<0)\\ \varepsilon_{11}(t) &= \frac{\sigma_1-\sigma_3}{3G_m(1-D_1)} + \frac{\sigma_1+2\sigma_3}{9K(1-D_2)} + \left(\frac{\sigma_1-\sigma_3}{3\eta_m(1-\overline{D})}\right)t + \frac{\sigma_1-\sigma_3}{3G_k}\left(1-e^{-(G_k/\eta_k)t}\right) \quad (F\geq 0).\end{aligned} \tag{16}$$

Normally, creep tests of rock under long-term loading conditions are conducted on a single sample by the method of step loading. Due to different stresses for each grade, creep mechanical properties of rock under different stresses are different; thus the creep parameters identified as all stress levels are also different [15–17]. Reasonable selection of creep mechanical parameters is of great practical significance. At present, the method of taking the mean value of parameters is often used in the engineering application [18]. However, the test and the fitting results show that, due to the different unloading quantity, the parameters of the model will have a large difference under the same deviatoric stress (Table 2). For the Burgers model, the shear modulus G_m and bulk modulus K represent the instantaneous deformation of rock. The viscosity coefficient η_m represents the final creep rate of rock. η_k/G_k represents the time to enter the second creep stage. Considering that the instantaneous deformation of the rock and the final creep rate are the most concerned parameters in the engineering, therefore, the variation rule of G_m, K, and η_m with the unloading value is considered in this paper, while the variation characteristics of shear modulus G_k and the viscosity coefficient η_k are ignored. G_k and η_k are selected based on the average value of all creep parameters. Unified Burgers creep parameters of rock under different confining pressures are shown in Table 3. D_1, D_2, and D_3 are damage factors of corresponding creep parameters caused by unloading ratio, which are shown in (17).

The equations of damage factors (D_1, D_2, and D_3) are as follows:

$$\begin{aligned}D_1 &= 1-\left(1.019 * e^{0.87*(\Delta\sigma_3/\sigma_3^0)}\right)^{-1}\\ D_2 &= 1-\left(0.978 * e^{0.72*(\Delta\sigma_3/\sigma_3^0)}\right)^{-1}\\ D_3 &= 1-\left(1.167 * e^{4.50*(\Delta\sigma_3/\sigma_3^0)}\right)^{-1}.\end{aligned} \tag{17}$$

Using constitutive (16) under the condition of $F<0$, the fitting curve has been made under unloading condition based on unified parameters in Table 3. Tests curve and the fitting result are shown in Figure 7. It can be seen from Figure 7 that the fitting result of damage creep model is better and can reflect unloading creep trend of layered rock; however at some stress levels, there is a certain deviation between fitting curve and the experimental values. This is because the parameters G_k and η_k are selected based on all levels of arithmetic mean value, in which, the deviation is small and does not affect the overall creep deformation law. At the last stress level, the stress has exceeded the long-term strength of rock ($F>0$); the nonlinear accelerated creep phenomenon occurs, which leads to the destruction eventually. In addition, the internal damage is not only related to unloading ratio, but also related to the creep time. Therefore it is necessary to fit with constitutive (16) under the condition of $F<0$. The fitting result between nonlinear accelerated creep test and model is shown in Figure 8.

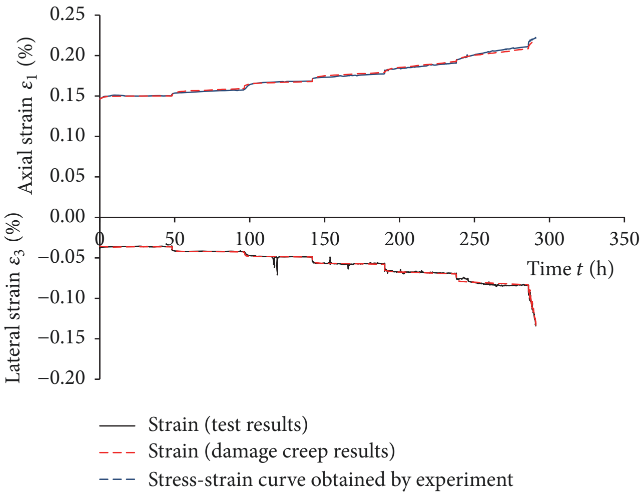

FIGURE 7: Correlation between damage creep constitutive model and unloading creep test curve.

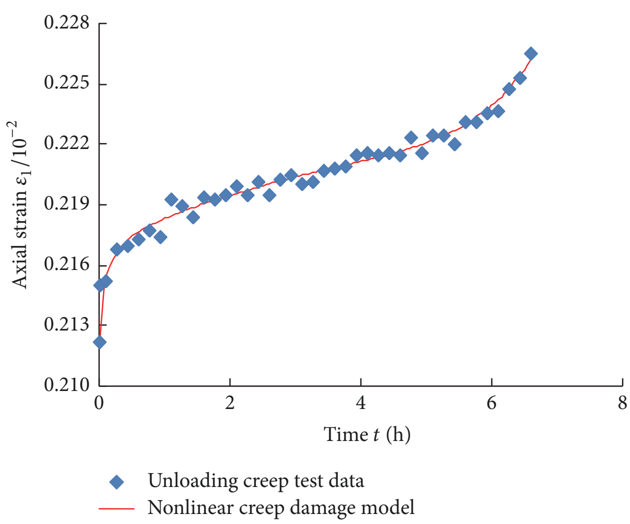

FIGURE 8: Correlation between nonlinear damage creep model and accelerative state creep test curve.

When $F > 0$, the damage factor of η_m, D is replaced by $\overline{D}_3$ in Table 3. The nonlinear damage (13) of creep parameter based on unloading ratio and creep time is expressed as

$$\overline{D} = 1 - \left(117.21 * e^{(2.41\times10^{-20})*(\Delta\sigma_3/\sigma_3^0 + t^{23.26})}\right)^{-1}. \quad (18)$$

From Figure 8, it can be seen that the nonlinear damage creep model can well reflect three stages of layered rock creep under unloading conditions. It can describe the nonlinear characteristics of rock accelerated creep phase and achieve preferable fitting effect.

5. Conclusions

(1) Triaxial unloading creep tests of layered rock specimen of Jinping II hydropower station were carried out using rock creep testing machine, and the creep deformation curves under different unloading confining pressures were acquired. The test results showed that, in addition to obvious unloading creep characteristics of rock specimen, the phenomena of nonlinear accelerated creep deformation occurred when the confining pressure was unloaded to the final stage. In general, the creep curves presented the typical three-stage characteristics of rock creep deformation.

(2) Based on long-term creep characteristics of layered rock, the Burgers creep constitutive model was used for the fitting analysis of experimental curve. The creep model constitutive equation under the three-dimensional stress state was deduced. Corresponding parameters of creep constitutive model were identified using the least squares method after optimization search, so as to obtain the corresponding parameters of three-dimensional Burgers creep model.

(3) Under the high stress unloading conditions, shear modulus G_m, bulk modulus K, and viscosity coefficient η_m of layered rock samples presented nonlinear deterioration with the increase of the unloading ratio, showing a significant nonstationary law. When loads were smaller than the long-term strength of rock samples, the unloading creep deformation parameters were gradually weakening with the increase of unloading ratio. When loads were larger than the long-term strength of rock samples, the unloading creep deformation parameters were not only related to unloading ratio, but also related to creep time. To be specific, the parameters will present nonlinear accelerated deterioration with the increase of unloading ratio and creep time.

(4) Creep parameters G_m, K, and η_m were in good correlation with relative unloading ratio. Based on the creep parameters corresponding to the first stress level, weakening laws of creep parameters at other levels can be described by introducing the damage factors according to the variation of unloading ratio. The parameter-taking method was obtained, by which the unloading creep characteristics were described through a set of parameters and damage evolution equation based on unloading ratio.

(5) Based on the 3D Burgers creep model, when loads were smaller than the long-term strength of rock samples, the damage evolution equation associated with unloading ratio was introduced; when loads are larger than the long-term strength of rock samples, damage evolution equation associated both with unloading ratio and creep time was introduced. A nonlinear creep damage model of rock under unloading was proposed, which can both reflect the creep properties under step loading condition and describe the nonlinear characteristics in rock accelerated creep phase. The test curves were fitted using the proposed nonlinear unloading creep damage model. The results showed that rock nonlinear creep damage model can well reflect the typical three stages of unloading creep rule of layered rock and achieve preferable fitting effect.

Conflicts of Interest

There are no conflicts of interest related to this paper.

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