Research Article

Analysis of Shear Characteristics of Deep, Anchored Rock Mass under Creep Fatigue Loading

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To study the influence of earthquakes and engineering disturbances on the deformation of deeply buried rock masses, shear tests were carried out on anchored sandstone rock masses, anchored marble rock masses, and anchored granite rock masses under creep fatigue loading, and a new creep fatigue model was established to characterize the deformation characteristics of anchored rock masses under creep fatigue loading. The creep fatigue curves of different lithologies clearly show three stages: creep attenuation, steady-state creep, and accelerated creep. Fatigue loading can increase the creep of anchored specimens, and the lower the rock strength is, the higher the creep variable under fatigue loading is. However, for the same rock strength, with the increase in load level, the creep variable produced by creep fatigue load presents a linear downward trend. Considering the changes in the mechanical properties of the anchored rock mass under creep fatigue loading, the creep fatigue model of anchored rock masses is established by introducing a function of the fatigue shear modulus, and the accuracy and applicability of the model are verified by laboratory creep fatigue test data. The model provides a theoretical basis for the study of anchored rock mass support under low-frequency earthquakes or blasting loads.

1. Introduction

In the construction of strategic projects in large-scale deep rock masses in China, the safety and stability of underground engineering are of great importance. Complex engineering geological environments have presented many challenges in the development of underground engineering [1–3]. For example, the engineering construction of the Sichuan-Tibet railway is particularly challenging because the railway corridor is formed under the coupling effect of structural activity, geomorphic uplift, climate change, and engineering disturbance [4, 5]. The structural deformation, rock mass loosening, surface freeze-thaw, and engineering disturbance in the shallow crust along the corridor have a profound impact on the stability of the geological body, engineering geological body, engineering rock soil mass, and engineering structure body in the corridor area. The Sichuan-Tibet railway passes through complex geological structures [6–8].

Scholars in China and abroad have performed a considerable amount of research on the shear creep of rock. Liu [9, 10] took the shear creep characteristics of mica schist as a research object and discussed the variation law of the radial displacement of mica schist with time determined from the results of the indoor shear creep tests of mica schist. To study the shear creep characteristics of marble with structural planes, He et al. [11] carried out a series of shear creep tests on two kinds of marble with weak and hard structural planes. To study the influence of weak intercalation on the long-term stability of geological bodies, Yao et al. [12] proposed a new unsteady fractal differential creep (UFDC) model based on fractal derivative theory and the results of circumferential shear creep tests of weak interlayers to effectively explain the creep deformation of soft interlayers. Zhang et al. [13] carried out a series of shear creep tests of serrated structural planes under various pore water pressures to explore the influence of pore water pressure on the shear creep characteristics of rock mass discontinuities.

Additionally, experts have carried out corresponding research on the rheological properties of rocks under different conditions. Wu et al. [14] conducted shear creep tests on fractured mudstone to study the influence of normal stress and pre-cut fracture length on the shear creep characteristics of mudstone. Because most creep models cannot accurately describe the nonlinear creep behavior of mudstone, an improved time-varying creep model was proposed. Zhang et al. [15] carried out creep tests of mudstone under different loading modes and water contents and established an appropriate creep model. Zhang et al. [16] carried out shear creep tests on samples after different numbers of freeze-thaw cycles to study the influence of freeze-thaw cycling on the shear creep characteristics of rock. Chen et al. [17] carried out a series of long-term creep tests of clay rock under different confining pressures and deviatoric stresses under complex conditions of thermal-fluid-mechanical coupling. Xu et al. [18] carried out a series of shear creep tests on rocks with discontinuities to simulate the initiation and propagation of cracks under the action of continuous shear stress and normal stress. Jia et al. [19] carried out shear creep tests on structural plane faults and established a corresponding creep formula.

The above research mainly analyzes the rock mass from the aspects of freeze-thaw cycles and structural planes. Research on the influence of fatigue loads caused by low-frequency earthquakes or blasting on the rheological properties of rock is relatively limited, while the occurrence frequency of low-frequency earthquakes in actual geotechnical engineering is relatively high, and the impact on geotechnical engineering is also important [20–22]. Earthquakes occur frequently along the Sichuan-Tibet railway, and fault and fracture zones are relatively dense. Earthquakes and engineering blasting result in both dynamic and cyclic loads that are described as low-cycle fatigue loads [23, 24]. There are many joints and fissures in the deep surrounding rock roadway, which will affect the stability of the rock mass. The rock mass needs to be supported by anchor bolt, anchor cable, or grouting. When the surrounding rock mass is excavated by blasting, it will have a certain impact on the stability of the above anchored rock mass, and the deformation and failure of the deep rock mass is mainly shear creep; therefore, this paper uses indoor test to explore the influence of blasting, excavation, and other disturbance loads on the mechanical properties and stability of anchored rock mass. Based on the above engineering background, to study the shear characteristics of deep anchored jointed rock masses under creep fatigue loading, the deformation characteristics of anchored rock masses under creep fatigue loading under different rock strengths are analyzed through laboratory tests. Based on the change in shear modulus under fatigue loading, a constitutive model reflecting creep fatigue loading is constructed, and the accuracy of the model is verified. This model can comprehensively explain the shear failure characteristics and anchoring mechanism of anchored jointed rock masses under complex stress paths and provide a reference for the study of deep rock mass disaster prevention and safety production.

2. Creep Fatigue Testing

2.1. Specimen Preparation. The test rock samples include anchored sandstone rock masses, anchored marble rock masses, and anchored granite rock masses, and the test pieces are all 100 mm × 100 mm × 100 mm cubes. The size of the test pieces conforms to the relevant provisions of the test specifications of the International Society of Rock Mechanics [25]. The steps followed to prepare the test pieces are as follows:

- (1) *Rock Block Processing.* A massive rock mass is selected, a rock cutter is used to process the rock block into a 100 mm × 100 mm × 50 mm rock mass, and a drilling machine is used to drill a hole with a diameter of 10 mm and length of 50 mm from the center of a side with dimensions of 100 mm × 100 mm (for the anchor rod).
- (2) *Rock Block Bonding.* The joints are used to bond the upper and lower plates of the rock block. A joint is made by pouring cement mortar into a cuboid of 100 mm × 100 mm × 5 mm space (the joint thickness is 5 mm). The joint mix ratio is cement : river sand : water = 1 : 1.5 : 0.8. The test materials are 42.5 ordinary silicate cement and medium-grained sand. The joint shape, size, and material distribution are checked during the test. The test block shall be bonded with cement mortar and placed in the curing box for curing for 28 d.
- (3) *Installation of the Anchor Rod.* HRB335 steel with a yield strength of 335 MPa is selected as the anchor material. A steel bar with a diameter of 6 mm is placed in the hole in the test piece. The overall length of the reinforcement is 110 mm. The exposed end of the ribbed steel bar is machined to a length of 10 mm, and 50 mm extends into the test piece, through both the upper and lower walls. Grouting is used to fill the holes and reinforce the anchor rod. The grouting material is the same as the joint material. Anchor the test piece with anchor bolt and put it into the curing box for curing for 28 d.

An anchored rock mass fabricated according to the above steps is shown in Figure 1.

The test loading system adopts the cutting equipment of the TAW-2000 triaxial testing servo apparatus of the civil engineering test center of Liaoning University of Engineering and Technology, as shown in Figure 2. It is mainly composed of a loading system, measuring system, and controller. Fully automatic control is achieved by micro-computer-controlled electrohydraulic servo valve loading and manual hydraulic loading. The host machine and the control cabinet are separate. The testing machine uses sensors to measure force, and the host machine automatically collects stress data and displacement. The resulting test curves and test results have high reliability.

2.2. Test Scheme and Steps

2.2.1. Test Scheme. Before the test, it was necessary to determine the basic mechanical parameters, such as

FIGURE 1: Test pieces. (a) Specimen model diagram. (b) Physical drawing of the specimen.

FIGURE 2: Shearing device.

compressive strength, tensile strength, and elastic modulus, of the three rock materials. The basic mechanical parameters of the three kinds of rocks were determined by uniaxial compression tests and Brazilian splitting tests [26,27], and the details are shown in Table 1. The mechanical parameters of anchored jointed rock mass are summarized in Table 2.

The basis for selecting loading parameters is as follows: according to relevant reference [28], the maximum peak velocity of underground vibration is 0.52~4.38 m/s, the frequency range is 0.01~0.1 Hz, the shear wave velocity is 2480 m/s, and the longitudinal wave velocity is 4300 m/s. Therefore, during these tests, the loading rate was set to 200 N/s, the fatigue load was set to ± 5 kN on the basis of all levels of loading, and the shear stress was set to ± 0.5 MPa. The load amplitude was 1/10~1/100 of the compressive strength. The specific test scheme is shown in Figure 3.

2.2.2. Test Procedure. The creep fatigue testing was carried out by graded loading, to approximately 20%, 40%, 60%, and 80% of the compressive strength of the specimen, i.e., 2 MPa, 4 MPa, 6 MPa, and 8 MPa. The three-dimensional stress states of rock mass are as follows: there are rightward stresses in the upper left and right directions of the specimen. There is a right stress at the lower left of the specimen; a left stress at the lower right of the specimen; and no stress in other

directions. This test is an unconfined shear test, and the relevant test steps are as follows:

- (1) *Application of Shear Stress.* The specimen is put into the shear device, and then the load is controlled at a rate of 0.5 MPa/s to the specified shear stress, which is then maintained.
- (2) *Application of Fatigue Load.* When the shear stress of each level is applied for approximately 59 h, load control is adopted, and fatigue loading is applied at a rate of 200 N/s. Before and after the fatigue loading is applied, the pressure is stabilized for a certain period, and the internal stress of the specimen is adjusted to make the conditions more accurately match those encountered in engineering practice. The test is carried out according to the above steps until the specimen is damaged.
- (3) *Reading Data.* The shear creep values are read at intervals of 5 min, 10 min, 20 min, 40 min, 1 h, 2 h, 4 h, 8 h, and 12 h during the creep attenuation and steady-state creep stages and then read every 12 h until the end of the test. During the fatigue loading stage and creep acceleration stage, the data are read every 0.5 min. The condition for the stability of the shear creep deformation of a rock mass is a creep rate increment $\leq 5 \times 10^{-4}$ mm/D [29].

FIGURE 4: Time-dependent curves of strain and stress under different rock strengths and failure specimen. (a) Anchored sandstone rock masses. (b) Anchored marble rock masses. (c) Anchored granite rock masses. (d) Failure specimen.

FIGURE 5: Fitting curve of creep at different stages.

TABLE 3: Related parameters of the fitting curve.

Rock specimen	M	N	R^2
Anchored sandstone rock masses	0.667	0.156	1
Anchored marble rock masses	0.581	0.102	0.965
Anchored granite rock masses	0.064	0.182	0.955

granite rock masses. The higher the rock strength is, the stronger its ability to resist shear deformation and the lower the instantaneous creep; consequently, the instantaneous creep intercept M is smaller. N is the slope of the fitting formula (1) and represents the initial creep rate in the steady-state phase. The larger N is, the faster the change in the initial creep in the steady-state stage is; the corresponding order is anchored granite rock masses > anchored sandstone rock masses > anchored marble rock masses. Since the change in creep during the steady-state stage is small, the deformation of a rock specimen in the steady-state stage can be quantitatively reflected by the change in N .

3.2.2. Creep Fatigue Increment. To study the influence of fatigue loading on the shear creep deformation of rock specimens at all levels of loading, the creep variables before and after the application of fatigue loads are summarized and plotted, as shown in Figure 6. The changes in creep increment during different stages before and after fatigue loading are plotted as shown in Figure 7.

The creep variables before and after fatigue at all levels of loading follow the order of anchored sandstone rock masses > anchored marble rock masses > anchored granite rock masses, which indicates that the creep variables under shear loads of different rock strengths are different. The lower the rock strength is, the larger the creep variable is, and vice versa. From the results of the creep increment before and after fatigue loading is applied at all levels, the overall creep variable decreases with increasing load level, indicating that the creep increment increases. The results show that the sensitivity of fatigue loading to shear creep decreases with the increase in load level, which is due to the increase in shear stress, leading to further compaction of the specimen and a decrease in the creep variable. Compared with the incremental change in the anchored sandstone rock masses, the incremental changes in the anchored marble rock masses and anchored granite rock masses have larger ranges, indicating that the influence of fatigue loading on the deformation of high-strength rock is more obvious than that on weak rock.

3.3. Shear Modulus. As a variable describing the inherent properties of rock, the shear modulus is often used to characterize the change in rock strength [30, 31]. To explore the effect of fatigue loading on the shear modulus of the specimen, the shear modulus change curve with time throughout the creep process is drawn, as shown in Figure 8. The shear modulus is solved by equation (2), where E is the elastic modulus, which is solved by the ratio of shear stress and longitudinal strain in the stress-strain curve, ν is the Poisson ratio, which is solved by the ratio of transverse strain

FIGURE 6: Bar chart of creep before and after fatigue loading.

FIGURE 7: Creep increment curve before and after fatigue loading.

and longitudinal strain, in which the longitudinal strain is the strain in the stress-strain curve, and the transverse strain is monitored by the strain collector.

$$G = \frac{E}{2(1 + \nu)}, \quad (2)$$

where G is the shear modulus; E is the elastic modulus; and ν is the Poisson ratio.

Figure 8 shows that the shear modulus changes piecewise with time. Before the fatigue load is applied, the curve changes approximately linearly, while after the fatigue load is

FIGURE 8: Shear modulus versus time curve. (a) Anchored sandstone rock masses. (b) Anchored marble rock masses. (c) Anchored granite rock masses.

applied, the curve shows a nonlinear change trend, which is represented by a piecewise function:

$$G(t - t_m) = \begin{cases} a_1 t + b_1 & (t \leq t_m) \\ a_2 t^2 + b_2 t + c & (t > t_m) \end{cases}, \quad (3)$$

where $G_1(t - t_m)$ is the function of fatigue shear modulus; t_m is the initial moment of fatigue load application, which is 40 h; a_1 and b_1 are the coefficients of the first-order function; and a_2 , b_2 , and c are the coefficients of the quadratic function. Regression analysis of equation (3) is carried out using the data in Figure 8, as shown in Table 4.

4. Creep Fatigue Modeling

4.1. Creep Model. The creep curve of a rock mass mainly includes three stages [32, 33]. The model of a combination of elastic elements, viscoelastic elements, and viscoplastic elements in series is often used to describe the creep attenuation and steady-state creep stages [34]. The rheological properties of Nishihara model under low stress conditions are also more comprehensive, which can better describe the attenuation and stability stage of rock creep, and have relaxation characteristics. The rheological properties of Nishihara model are closer to those of the actual rock mass [35]. The creep model is shown in Figure 9 [36, 37].

TABLE 4: Related parameters of fitting curve.

Rock specimen	Load level	First-order function			Quadratic function			
		a_1	b_1	R_1^2	a_2	b_2	C	R_2^2
Anchored sandstone rock masses	1	0.02	-0.09	0.94	-0.02	1.60	-40.69	0.98
	2	0.03	0.39	0.97	-0.02	2.03	-48.55	0.90
	3	0.06	0.13	0.93	-0.02	1.95	-44.03	0.90
Anchored marble rock masses	1	0.01	0.01	0.93	-0.02	1.72	-41.91	0.80
	2	0.01	0.13	0.98	-0.01	1.25	-29.96	0.95
	3	0.01	0.24	0.99	-0.01	1.29	-31.10	0.94
Anchored granite rock masses	1	0.01	0.01	0.93	-0.01	1.46	-34.14	0.94
	2	0.01	0.16	0.99	-0.02	1.61	-36.34	0.89
	3	0.01	0.22	0.98	-0.02	2.27	-50.00	0.98

FIGURE 9: Shear creep model.

FIGURE 10: Model of body E.

In Figure 9, G_0 is the instantaneous shear modulus, G_1 is the viscoelastic shear modulus, and η_1 and η_2 are the viscosity coefficients, which indicate that the speed of the rheological change is stable. The smaller the value of a viscosity coefficient is, the shorter the time to reach stability. τ_s is the yield shear stress or long-term shear strength; τ_0 is the shear stress.

Considering the actual stress of the rock mass, the model was modified as follows:

- (1) The above analysis shows that the creep attenuation stage has obvious nonlinear characteristics and that the Kelvin model cannot describe the creep attenuation stage of rock. Considering the time correlation of the viscosity coefficient in the Kelvin model, assuming that the coefficient satisfies the power function relationship with time in the creep process, the nonlinear Kelvin viscoelastic model is established.
- (2) To satisfy the shear rheological properties of specimens under fatigue loading, a modified nonlinear Kelvin model is obtained by introducing the fatigue shear modulus function $G_1(t - t_m)$.
- (3) When the stress level imposed by the creep test is higher than the long-term strength, body B plays a role. The steady-state stage can be described as a stable creep stage, but the unstable creep stage and accelerated creep stage cannot be well described. This problem can be solved by connecting a nonlinear rheological element E with the time factor in series.

The nonlinear characteristics of the acceleration element are particularly obvious. The accelerated creep stage of rock is the nonlinear acceleration change of rock. Using this element can better characterize the acceleration stage of rock. The model of body E is shown in Figure 10 [38, 39], where G_2 and n are model parameters, γ is the

shear strain, t_2 is the start time of the acceleration stage, and t_3 is the end time of the acceleration stage.

$$\gamma = \begin{cases} 0 & (t \leq t_2) \\ \frac{\tau_0}{G_2} \left\{ 1 - \exp \left[- \left(\frac{t - t_2}{t_3 - t_2} \right)^n \right] \right\} & (t > t_2) \end{cases}, \quad (4)$$

4.2. Creep Fatigue Model. The creep fatigue model is shown in Figure 11 [40]. The corresponding creep equations are obtained as follows.

In this figure, λ is a constant, and $G_1(t - t_m)$ is a function of the viscoelastic fatigue shear modulus varying with time.

The total shear creep strain γ satisfies [41, 42]

$$\gamma = \gamma_H + \gamma_K + \gamma_B + \gamma_E, \quad (5)$$

where γ_H is the elastic shear strain; γ_K is the viscoelastic shear strain; γ_B is the viscoplastic shear strain; and γ_E is the nonlinear shear strain.

- (1) The creep equation of the elastic element is

$$\gamma_H = \frac{\tau_0}{G_0}. \quad (6)$$

- (2) The creep equation of the elastic viscous element is

$$\gamma_K = \frac{\tau_0}{G_1(t - t_m)} \left[1 - \exp \left(- \frac{G_1(t - t_m)}{\eta_1 \lambda} t^\lambda \right) \right]. \quad (7)$$

- (3) The creep equation of viscoplastic components is

$$\gamma_B = \frac{\tau_0 - \tau_s}{\eta_2} t. \quad (8)$$

- (4) The creep equation of acceleration element is

FIGURE 11: Creep fatigue model.

$$\gamma_E = \frac{\tau_0}{G_2} \left\{ 1 - \exp \left[- \left(\frac{t - t_2}{t_3 - t_2} \right)^n \right] \right\}. \quad (9)$$

$$\gamma = \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1(t-t_m)} \left[1 - \exp \left(- \frac{G_1(t-t_m)}{\eta_1\lambda} t^\lambda \right) \right]. \quad (10)$$

The creep equation at different stages is as follows:

- (1) When the shear stress level is less than the long-term strength, the creep equation is as follows:

- (2) When the shear stress level is higher than the long-term strength but creep has not reached the acceleration stage, the creep equation is as follows:

$$\gamma = \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1(t-t_m)} \left[1 - \exp \left(- \frac{G_1(t-t_m)}{\eta_1\lambda} t^\lambda \right) \right] + \frac{\tau_0 - \tau_s}{\eta_2} t. \quad (11)$$

- (3) When the shear stress level is higher than the long-term strength and the creep reaches the acceleration stage, the creep equation is as follows:

$$\gamma = \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1(t-t_m)} \left[1 - \exp \left(- \frac{G_1(t-t_m)}{\eta_1\lambda} t^\lambda \right) \right] + \frac{\tau_0 - \tau_s}{\eta_2} t + \frac{\tau_0}{G_2} \left\{ 1 - \exp \left[- \left(\frac{t - t_2}{t_3 - t_2} \right)^n \right] \right\}. \quad (12)$$

In conclusion, the shear creep equation under fatigue loading is as follows [43, 44]:

$$\gamma = \begin{cases} \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1(t-t_m)} \left[1 - \exp \left(- \frac{G_1(t-t_m)}{\eta_1\lambda} t^\lambda \right) \right] & (\tau_0 \leq \tau_s) \\ \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1(t-t_m)} \left[1 - \exp \left(- \frac{G_1(t-t_m)}{\eta_1\lambda} t^\lambda \right) \right] + \frac{\tau_0 - \tau_s}{\eta_2} t & (\tau_0 > \tau_s, t \leq t_2) \\ \frac{\tau_0}{G_0} + \frac{\tau_0}{G_1(t-t_m)} \left[1 - \exp \left(- \frac{G_1(t-t_m)}{\eta_1\lambda} t^\lambda \right) \right] + \frac{\tau_0 - \tau_s}{\eta_2} t + \frac{\tau_0}{G_2} \left\{ 1 - \exp \left[- \left(\frac{t - t_2}{t_3 - t_2} \right)^n \right] \right\} & (\tau_0 > \tau_s, t > t_2) \end{cases} \quad (13)$$

5. Model Validation

To solve the relevant parameters of the creep equation, combined with the creep test data, the mathematical optimization software 1stOpt is used; based on the quasi-Newton method and general global optimization method [45, 46], the solution method of equation (13) is given under different conditions, as shown in Table 5.

The shear creep model under fatigue loading can be obtained by introducing the relevant parameters in Table 4 into equation (13). Firstly, 1stOpt software is used to identify the parameters in equation (13) of creep fatigue model. Secondly, bring the solved parameters into the creep fatigue model to obtain the equation describing the relationship between rock stress-strain and time. Finally, by giving time to the creep fatigue equation, the corresponding theoretical

TABLE 5: Summary of model parameters.

Specimen	Shear stress (MPa)	G_0 (GPa)	G_1 (GPa)	η_1 (GPa·h)	η_2 (GPa·h)	λ	G_2 (GPa)	n	R^2
Anchored sandstone rock masses	2	1.47	23.41	11.54	0.21	0.74	—	—	0.978
	4	1.22	20.17	10.13	1.42	0.82	—	—	0.976
	6	0.99	18.52	9.77	0.63	0.91	—	—	0.964
	6.5	0.86	15.44	8.12	0.77	0.21	10.04	0.58	0.951
Anchored marble rock masses	2	0.73	14.97	7.46	0.84	0.44	—	—	0.981
	4	2.31	34.22	16.52	1.09	0.56	—	—	0.972
	6	2.14	30.56	12.44	1.54	0.84	—	—	0.966
	6.4	1.98	28.94	10.12	0.13	0.11	15.43	0.66	0.944
Anchored granite rock masses	2	1.87	25.10	9.81	0.15	0.37	—	—	0.974
	4	1.74	24.13	9.54	3.11	0.59	—	—	0.951
	6	0.44	47.18	19.46	2.56	0.87	—	—	0.948
	6.6	1.12	45.69	18.57	1.69	0.14	22.16	0.74	0.936

FIGURE 12: Continued.

FIGURE 12: Comparisons between the experimental data and theoretical curves. (a) Anchored sandstone rock masses. (b) Anchored marble rock masses. (c) Anchored granite rock masses.

displacement value can be obtained. To verify the accuracy of the model, comparison diagrams between the test data and the theoretical curves are drawn, as shown in Figure 12.

The theoretical curves can accurately describe the creep test results and can better describe the resulting fatigue curves. The attenuation stage, stability stage, fatigue stage, and acceleration stage all meet the requirements. Generally, the fitting coefficient is higher than 0.93, indicating that the fitting degree is good, which indicates that the model can accurately reflect the shear mechanical characteristics of anchored rock masses under creep fatigue loading.

6. Conclusion

In this paper, through the shear testing of anchored rock masses with different rock strengths under creep fatigue loading, the influence law of fatigue loading on shear creep is explored:

- (1) The creep fatigue tests under different rock strengths exhibit typical creep mechanical properties, instantaneous creep, attenuation creep, steady-state creep, and accelerated creep. With increasing specimen strength, the unstable creep stage appears earlier. The creep variable increases with increasing load level under different rock strengths; the creep variable values exhibit the order of anchored sandstone rock masses > anchored marble rock masses > anchored granite rock masses.
- (2) By applying fatigue loading during shear creep tests, the resulting creep curve fluctuates to a certain extent; with the increase and decrease in stress, the strain fluctuates, and the fluctuation in strain occurs after the change in stress, which indicates that the change in shear strain lags behind the change in

shear stress. The creep increment under fatigue loading presents a decreasing trend with progression of the creep stages, and the sensitivity of fatigue loading to shear creep decreases with the increase in load level.

- (3) Considering the influence of fatigue loading on the model parameters, the fatigue shear modulus function is introduced into the Kelvin model and constructed a creep fatigue model. The accuracy of the model is verified by comparing the test data with the theoretical curve, which provides the basis for the support of the surrounding rock cavern under low-frequency seismic loading.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The authors declare that this paper has been presented as preprint in Research Square.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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