

Nonlinear creep model based on shear creep test of granite

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Abstract. The creep characteristics of rock is of great significance for the study of long-term stability of engineering, so it is necessary to carry out indoor creep test and creep model of rock. First of all, in different water-bearing state and different positive pressure conditions, the granite is graded loaded to conduct indoor shear creep test. Through the test, the shear creep characteristics of granite are obtained. According to the test results, the stress-strain isochronous curve is obtained, and then the long-term strength of granite under different conditions is determined. Then, the fractional-order calculus software element is introduced, and it is connected in series with the spring element and the nonlinear viscoplastic body considering the creep acceleration start time to form a nonlinear viscoplastic creep model with fewer elements and fewer parameters. Finally, based on the shear creep test data of granite, using the nonlinear curve fitting of Origin software and Levenberg-Marquardt optimization algorithm, the parameter fitting and comparative analysis of the nonlinear creep model are carried out. The results show that the test data and the model curve have a high degree of fitting, which further explains the rationality and applicability of the established nonlinear visco-elastoplastic creep model. The research in this paper can provide certain reference significance and reference value for the study of nonlinear creep model of rock in the future.

Keywords: accelerating creep starting element; fractional calculus; nonlinear creep model; shear creep test

1. Introduction

Rock creep is an important part of rock rheological mechanics theory. A large number of engineering practices show that the long-term stability of engineering is closely related to rock creep (Wang *et al.* 2015, Discenza *et al.* 2011, Zhao *et al.* 2018, Bozzano *et al.* 2012). With the development of engineering construction, the problem of engineering stability caused by rock creep has become increasingly prominent (Song and Li 2020, Hou *et al.* 2019, Singh *et al.* 2018, Wang *et al.* 2015, Zhang *et al.* 2018). Therefore, we study the creep properties of rock has important theoretical significance and engineering application value.

Rock indoor creep test is the main means to obtain its creep characteristics, and many scholars have done a lot of research. Ding *et al.* (2019) carried out triaxial creep tests under different loading and unloading stress paths to effectively reveal the creep deformation characteristics and failure mechanism of cavern granite. Ma *et al.* (2018) conducted uniaxial compression creep tests on siltstone specimens with different dry-wet cycles to study the influence mechanism of water content change of

surrounding rock on long-term stability of deep rock mass. Huang *et al.* (2017) carried out uniaxial compression creep test on slate to study the influence of inherent anisotropy on creep characteristics. Yang *et al.* (2019) conducted triaxial creep tests on gneiss under freeze-thaw cycles, and analyzed the influence mechanism of freeze-thaw cycles on the creep characteristics of gneiss. The above research is mainly in rock triaxial or uniaxial compression creep test, rock shear creep test is less. However, the slope engineering mainly occurs shear failure along its slip surface. Therefore, we need to carry out shear creep test on rock to explore its creep characteristics.

The creep constitutive model of rock established through creep test is an important content to reveal the rheological mechanical properties of rock, and it is also the focus and hot content of the current theoretical research on rock rheological mechanics. Many researchers have carried out a lot of research in this area, and established many rheological models from the perspective of phenomenon rheology. According to the classical linear basic mechanical elements, a multi-parameter combination rheological model is established, and on this basis, a nonlinear rheological model is established by introducing nonlinear mechanical elements (Roberts *et al.* 2015, Hashiba *et al.* 2018, Fahimifar *et al.* 2015, Nadimi *et al.* 2011, Rassouli *et al.* 2018, Li and Shao 2016, Kinscher *et al.* 2020). In order to better fit the test results, some models used multiple components, which achieved good fitting results, but increased the number of parameters. Therefore, seeking a creep model that can be composed of fewer components has

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become the goal pursued by many researchers of rock rheological constitutive model. With the development of fractional calculus research (Qu *et al.* 2019, Sumelka *et al.* 2020, Sun *et al.* 2020, Zhou and Zhang 2020), some researchers try to apply the fractional calculus theory to the study of creep model. Yin *et al.* (2007) proposed a soft element based on fractional calculus theory to describe the rheological properties of geotechnical materials between ideal solid and ideal fluid. The physical meaning expressed by this element is clear, which provides an idea and way for using fewer elements to construct the creep model. Sun and Zhang (2007) used Kelvin model with fractional derivative to simulate the creep law of soft soil. Zhang *et al.* (2011) proposed an accelerated creep starting element and connected it in series with Burgers model to establish a new nonlinear viscoelastic-plastic creep model of rock. Song *et al.* (2012) proposed a four-element nonlinear visco-elastoplastic rheological model with fractional calculus software components. Xu *et al.* (2015) proposed an improved nishihara creep model by using fractional-order clay pot and nonlinear viscoplastic body model. Ding *et al.* (2015) constructed the constitutive relation of Abel clay pot based on damage, and obtained the fractional rheological constitutive model of salt rock. He *et al.* (2016) established the unsteady creep constitutive model based on fractional derivative. He *et al.* (2016) constructed the fractional order volumetric strain-axial strain relationship of rock under uniaxial and triaxial compression, relaxation and creep conditions. Wang *et al.* (2018) deduced the nonlinear creep constitutive equation of coal under three-dimensional stress conditions.

The above studies have achieved good results in the construction of rock creep model, but most of them are directly replacing the Newton body element with the fractional order software element, and there may still be many model parameters. In order to construct a creep model with fewer elements and fewer parameters, based on the shear creep test of granite, this paper attempts to establish a nonlinear creep model that only includes Hooke element, fractional-order software element and accelerated creep starting element. Then, the creep test results are fitted with this model to verify the rationality and applicability of the model constructed in this paper.

2. Shear creep test of granite

2.1 Lithological characteristics

The Bangpu mining area in Tibet is located in the middle reaches of the Lhasa valley of the Yarlung Zangbo River at the southwest foot of the Tanggula Mountains (Wang *et al.* 2011). The mountains in the area are stacked and the valleys are vertical and horizontal. The terrain is generally high in the east and low in the west, and the terrain is undulating. The general altitude is between 4426 and 5341 m, and the relative height difference is about 915 m. The slope is large, and the altitude is high, and the relative height difference is large, which belongs to the deep cutting area of high mountains. The granite in the mining area is mainly distributed in the middle of the open-pit

slope, which is an acidic intrusive rock in the overall structure. The surrounding rock in contact with the granite is gray-black andesite volcanic breccia. The contact surface tends to be north, partial to south, and the dip angle is $70^\circ \sim 80^\circ$.

The rock samples are collected from Bangpu Mo-Cu polymetallic mine in Tibet. They are gray-white granite, porphyritic structure and massive structure. The main mineral components are feldspar, quartz and biotite. The crystal of rock sample is uniform and coarse, and the micro-fractures are extremely developed.

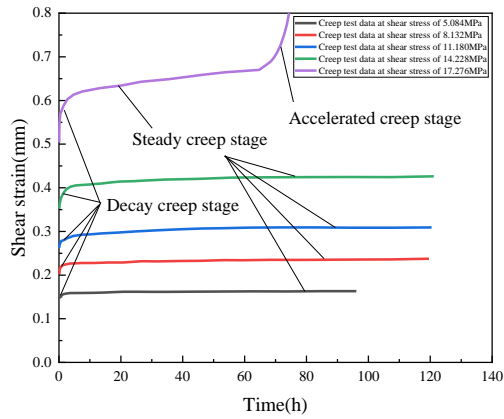
2.2 Test survey

Shear creep test using JQ200 rock shear rheometer, the instrument consists of three parts: the host, the console, the regulator system (Wang *et al.* 2014a, Wang *et al.* 2014b). The whole system is easy to install, debug and operate. During the test, the rock sample was installed between the upper and lower shear boxes, and the load was applied to the upper shear box through vertical and horizontal jacks. 3 rows of rigid rollers are arranged between the upper shear box and the base so that the upper shear box can move freely. Rigid balls are arranged between the vertical pressure transmission plate and the vertical pressure head to ensure uniform stress of the specimen. At the same time, two displacement monitoring points are set on the surface of the upper shear box, and the average value of the two monitoring points is taken as the displacement of rock shear creep.

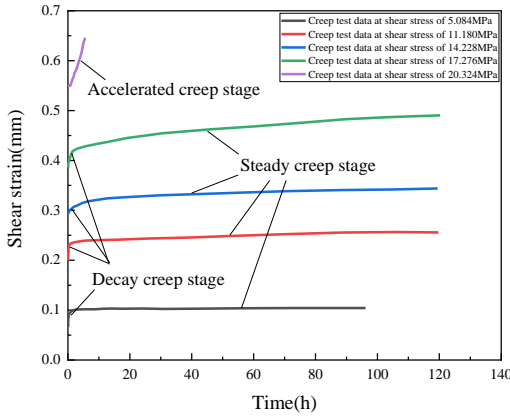
After high precision cutting and grinding, the rock sample is processed into 50mm×100mm standard specimen. The specimen is loaded step by step. In the test, a constant normal stress is applied to the specimen to stabilize for more than 24 hours, and then the shear stress is applied from low to high step by step. During the test, when the displacement within 24 hours is less than 0.001 mm, it is considered that the deformation is relatively stable, and the next shear stress can be applied, so as to continue until the specimen is destroyed.

2.3 Experiment results and analysis

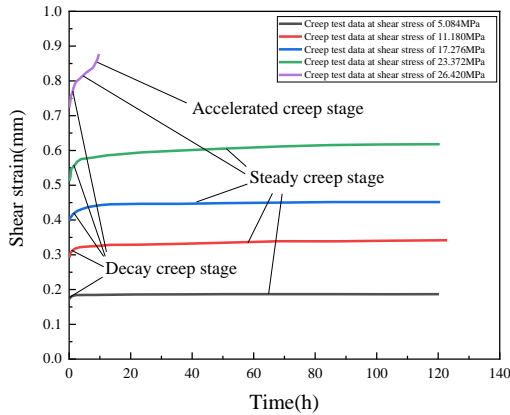
Before the shear creep test of granite, the conventional test is carried out. The density of granite is 2.945 g/cm³. According to the slope situation of the mining area described above, we select the dip angle of 75° and the relative height difference of 700 m and 297 m, respectively. Through calculation, the normal stress they bear is 5.229 MPa and 2.216 MPa, respectively. Then the direct shear test of saturated granite under normal stress of 2.216 MPa, through the test shows that the shear strength is 17.276 MPa, We use this as the maximum shear stress of this rock sample, and then to each stage difference 3.048 MPa to determine the shear stress at all levels. For dry rock samples with normal stress of 2.216 MPa and saturated and dry rock samples with normal stress of 5.229 MPa, based on the classification of saturated granite load with normal stress of 2.216 MPa, the shear stress at all levels of each rock sample is determined by the difference of 3.048 MPa or its multiple.



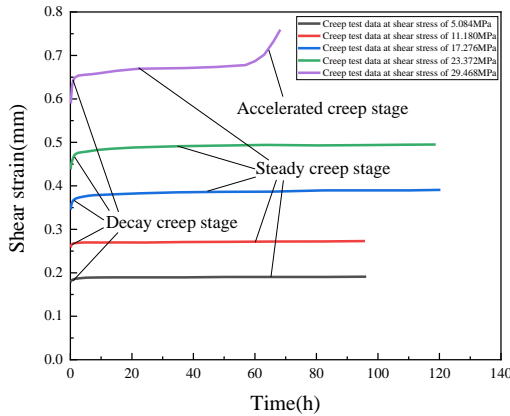
(a) Normal stress 2.216 MPa saturated granite



(b) Normal stress 2.216 MPa dry granite



(c) Normal stress 5.229 MPa saturated granite



(d) Normal stress 5.229 MPa dry granite

Fig. 1 Shear creep test curve of granite

In order to analyze the creep deformation under different shear stresses more clearly, the Boltzmann superposition principle was used to process the shear creep test data of granites. The test results are shown in Fig. 1.

According to the above shear creep test curve of granite, we can know:

1) In the moment of applying shear stress at all levels, granite generates instantaneous elastic deformation, indicating that granite has elastic characteristics.

2) When the shear stress is small, the creep process of granite only has the decay creep stage, and the creep curve quickly tends to be horizontal. With the gradual increase of shear stress, the decay creep stage and the steady creep stage are obvious. When the shear stress increases to a certain value, the three stages of complete creep of granite will appear.

3) Under the same conditions, the rheological effect of saturated granite is more significant. For example, under the action of 2.216 MPa normal stress and 17.276 MPa shear stress, the saturated granite presents a complete three-stage rheological, while the dry granite only appears the first two stages of rheological, and does not reach the accelerated stage of rheological. In addition, under the same normal stress and shear stress, the shear displacement of saturated granite is larger than that of dry granite at the same time, which indicates that the internal damage and deterioration of granite occur after saturated, weakening the mechanical properties of granite, and the rheological effect is more significant.

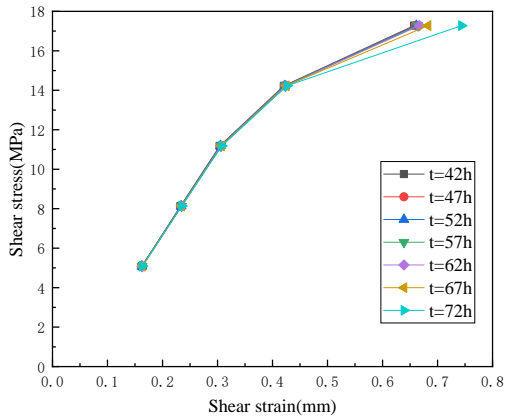
4) In the same water-bearing state, the rheological effect of granite under smaller normal stress is more significant, and granite under larger normal stress can withstand more levels of shear stress load, and the shear stress required in the acceleration stage is also larger. As shown in Fig. 1 (a), under the normal stress of 2.216 MPa, the saturated granite enters the accelerated creep stage when the shear stress of 17.276 MPa is applied. In Fig. 1 (c), under the normal stress of 5.229 MPa, when the shear stress of 17.276 MPa is applied, the granite only appears the first two stages of rheology, and when the shear stress of 26.420 MPa is applied, all the three stages of rheology appear. This shows that the applied normal stress increases the friction between granite crystals or mineral particles, so that the shear rheological failure is not easy to occur.

2.4 Long-term strength of granite

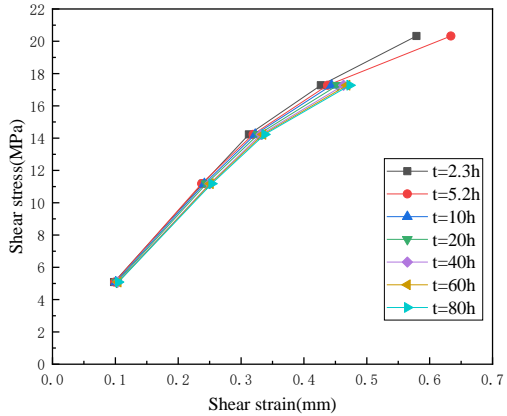
The long-term strength of rock is an important parameter to evaluate the engineering stability. At present, the stress-strain isochronous curve method is widely used to determine the long-term strength of rock (Zhang *et al.* 2011). The stress-strain isochronous curve of granite is obtained by processing the shear creep test curve of granite, as shown in Fig. 2.

According to the stress-strain isochronous curve of granite, we can know:

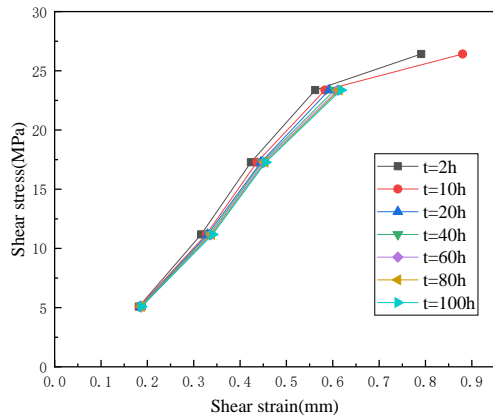
1) The stress-strain isochronous curves of both saturated and dry granites are a broken line cluster. When the shear stress is small, the stress-strain isochronous curves are approximately a cluster of straight lines. The creep properties of granites are linear viscoelastic.



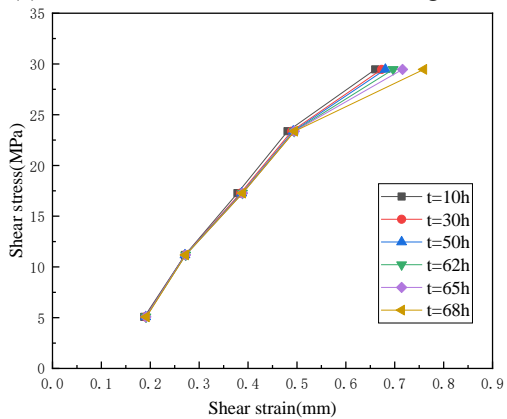
(a) Normal stress 2.216 MPa saturated granite



(b) Normal stress 2.216 MPa dry granite



(c) Normal stress 5.229 MPa saturated granite



(d) Normal stress 5.229 MPa dry granite

Fig. 2 The stress-strain isochronous curve of granite

2) With the increase of shear stress, the stress-strain isochronous curve is obviously nonlinear, and the curve gradually deviates from the straight line. The creep characteristics of granite show nonlinear viscoplasticity.

3) There is a turning point in the stress-strain isochronous curve of granite from linear to nonlinear, and the shear stress corresponding to this turning point is the long-term strength of granite. It can be seen from the above figure that the long-term strength of saturated and dry granite under positive stress of 2.216 MPa is 15.3 MPa and 18.5 MPa, respectively, and that of saturated and dry granite under positive stress of 5.229 MPa is 24.3 MPa and 27.4 MPa, respectively.

3. Establishment of nonlinear viscoelastic-plastic creep model

3.1 Creep element based on fractional calculus

Calculus is usually called derivative and integral of positive integer order, while fractional calculus is a mathematical problem to study the properties and applications of differential and integral operators of any order. Fractional calculus has a variety of definitions. This paper uses the Riemann-Liouville theory (Yin *et al.* 2007, Ma 2017) and defines the β -order integral of function $f(t)$ as:

$$\frac{d^{-\beta} f(t)}{dt^{-\beta}} = {}_0D_t^{-\beta} f(t) = \int_0^t \frac{(t-\tau)^{\beta-1}}{\Gamma(\beta)} f(\tau) d\tau \quad (1)$$

Fractional differential is defined as:

$$\frac{d^{\beta} f(t)}{dt^{\beta}} = {}_0D_t^{\beta} f(t) = \frac{d^n}{dt^n} [{}_0D_t^{-(n-\beta)} f(t)] \quad (2)$$

In Formulas (1) and (2), $\beta > 0$ and $n-1 < \beta \leq n$ (n is a positive integer); $\Gamma(\beta)$ is a gamma function defined as:

$$\Gamma(\beta) = \int_0^{\infty} e^{-t} t^{\beta-1} dt \quad (\text{Re}(\beta) > 0) \quad (3)$$

The Laplace transform of the fractional calculus is:

$$\left. \begin{aligned} L[{}_0D_t^{-\beta} f(t), p] &= p^{-\beta} \bar{f}(p) \quad (\beta > 0) \\ L[{}_0D_t^{\beta} f(t), p] &= p^{\beta} \bar{f}(p) \\ (f(t) \text{ Integrable near by } t=0, \quad 0 \leq \beta \leq 1) \end{aligned} \right\} \quad (4)$$

where $\bar{f}(p)$ is the Laplace transform of $f(t)$.

The stress-strain relationship described by the fractional calculus is:

$$\sigma(t) = \xi \frac{d^{\beta} \varepsilon(t)}{dt^{\beta}} \quad (5)$$

Obviously, when $\beta=0$, it is the stress-strain relationship of ideal solid, and when $\beta=1$, it is the stress-strain relationship of ideal fluid. Therefore, when $0 < \beta < 1$, the state of matter between ideal solid and ideal fluid can be

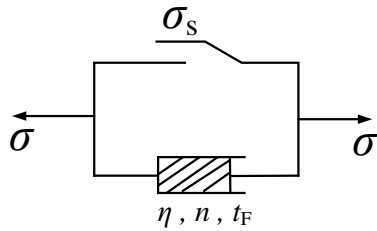


Fig. 3 Accelerating creep starting element

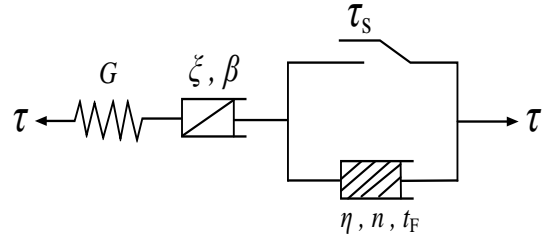


Fig. 4 Schematic diagram of nonlinear viscoelastic-plastic creep model of rock

described. Yin *et al.* (2007) called mechanical elements satisfying Formula (5) soft elements. The soft element is actually a two-parameter element containing ξ and β , which can better reflect the nonlinear gradual process of rheological problems.

When the stress is constant, the element will describe the creep phenomenon, the fractional integral on both sides of Equation (5), according to the Riemann-Liouville fractional calculus operator theory, the creep equation of soft element is:

$$\varepsilon(t) = \frac{\sigma}{\xi} \frac{t^\beta}{\Gamma(1+\beta)} \quad (0 \leq \beta \leq 1) \quad (6)$$

3.2 Accelerated creep startup component

According to the shear creep test of granite, the accelerated creep will occur when the stress of rock exceeds a certain stress threshold. The NVPB element proposed by Xu *et al.* (2006) considers the accelerated creep law of rock when the stress level is higher than the accelerated creep stress threshold. The results of various rock creep tests also show that the starting time of accelerated creep is different, and the selection of the starting time of accelerated creep will inevitably affect the determination of creep model parameters. Therefore, based on the NVPB element, Zhang *et al.* (2011) proposed a nonlinear viscoplastic creep element (NAVPB) with accelerated creep start time, as shown in Fig. 3.

Nonlinear viscoplastic creep element (NAVPB) satisfies the following equation:

$$\varepsilon = \begin{cases} 0 & (\sigma \leq \sigma_s) \\ \frac{\sigma - \sigma_s}{\eta} H(t - t_F) & (\sigma > \sigma_s) \end{cases} \quad (7)$$

Where, operator a satisfies the following equation:

$$H(t) = \begin{cases} 0 & (t \leq 0) \\ t^n & (t > 0) \end{cases} \quad (8)$$

In the formula, σ is the stress threshold, η is the plastic parameter, n is the rheological index, t_F is the accelerated creep start time.

3.3 Nonlinear viscoelasto-plastic creep model

It can be seen from the shear creep test results of granite that when the shear stress is less than the stress threshold of

accelerated creep, the rock produces instantaneous elastic strain, attenuation creep and steady creep. At this time, the spring element in series with the fractional order soft element can be used to describe the characteristics of rock creep. When the shear stress exceeds the stress threshold of accelerated creep, the rock will eventually enter the nonlinear accelerated creep stage at a certain time point after experiencing the first two stages of creep deformation. At this time, the nonlinear viscoplastic creep element (NAVPB) can be combined with the spring element and the software element in series to form a four-element creep model. Compared with most existing creep models, the model is simple in form, less in elements and less in parameters. It can also describe the characteristics of each stage of rock creep, and has certain advantages. The model is shown in Fig. 4.

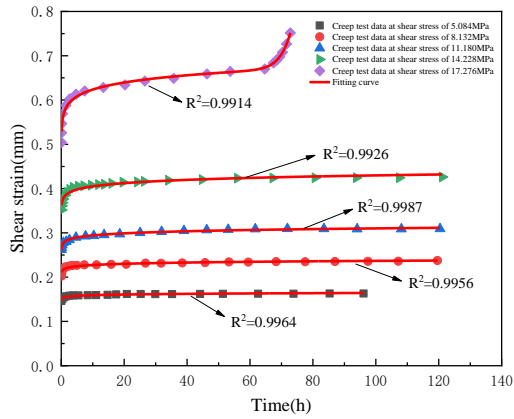
The model shown in Figure 4 satisfies the following relationship:

$$\varepsilon = \frac{\tau}{G} + \frac{\tau}{\xi} \frac{t^\beta}{\Gamma(\beta+1)} \quad (\tau \leq \tau_s) \quad (9)$$

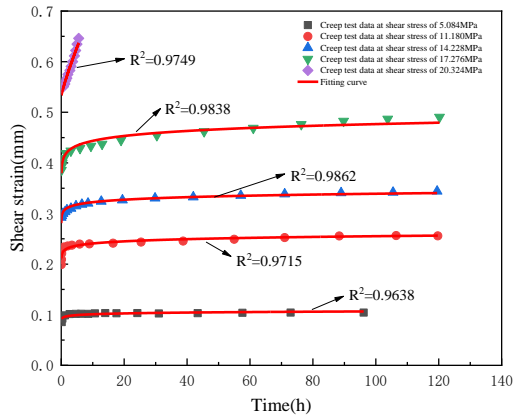
$$\varepsilon = \frac{\tau}{G} + \frac{\tau}{\xi} \frac{t^\beta}{\Gamma(\beta+1)} + \frac{\tau - \tau_s}{\eta} H(t - t_F) \quad (\tau > \tau_s) \quad (10)$$

4. Determination of creep model parameters

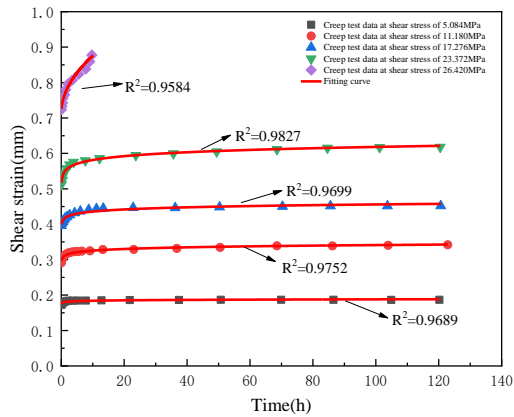
Firstly, the creep test results of granite in saturated state under normal stress of 2.216 MPa under various shear stresses are fitted and analyzed to determine the model parameters in this case. Under the action of shear stress of 5.084 MPa-14.228 MPa, since the shear stress level does not exceed the stress threshold of accelerated creep, the creep process of rock is only the first two stages, namely the decay creep stage and the steady creep stage. At this time, Eq. (9) is used for the fitting analysis of the creep model. When the shear stress is 17.276 MPa, because the applied shear stress exceeds the stress threshold of accelerated creep, the rock undergoes a complete three-stage creep. From the creep test curve, it can be seen that at the 67th hour, the creep rate of rock changes significantly, before the creep rate is small, after this moment, the creep rate of rock increases sharply. Therefore, it can be considered that the accelerated creep start time is $t_F=67h$, and the fitting analysis of the creep model is carried out by Equation (10). Using the nonlinear curve fitting of Origin software,



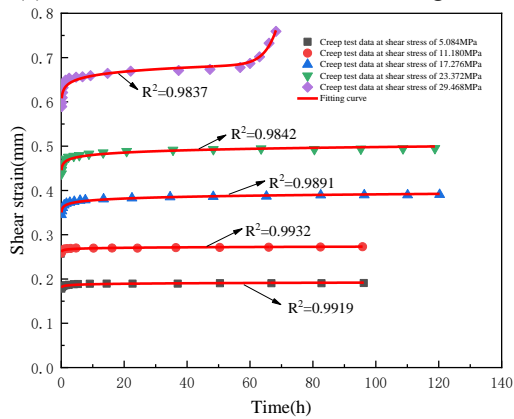
(a) Normal stress 2.216 MPa saturated granite



(b) Normal stress 2.216 MPa dry granite



(c) Normal stress 5.229 MPa saturated granite



(d) Normal stress 5.229 MPa dry granite

Fig. 5 Test data and fitting curve

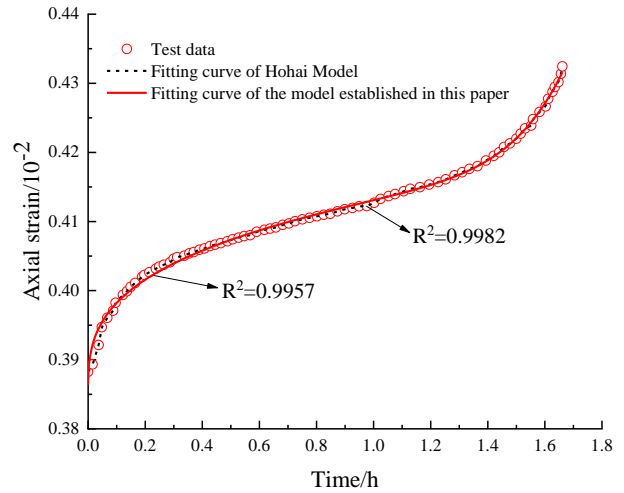


Fig. 6 Creep test data and fitting curve of greenschist

Formula (9) and Formula (10) are compiled into the custom function relationship, and the Levenberg-Marquardt optimization algorithm is used to fit and analyze the creep test data of granite under different shear stress levels. All shear creep test data of granite are fitted and analyzed by the same method. The fitting curve is shown in Fig.5. The creep model parameters are obtained by fitting, as shown in Table 1 and Table 2.

It can be seen from Fig. 5, Table 1 and Table 2 that the creep model constructed in this paper can well fit the shear creep test data of granite, indicating that the model can accurately reflect the creep characteristics of granite. In order to further verify the rationality and applicability of the model, the model is used to nonlinearly fit the creep test data of greenschist made by Xu *et al.* (2006). The fitting results are shown in Fig. 6 and Table 3. It can be seen that the creep model constructed in this paper and the Hohai Model proposed by Xu *et al.* (2006) can well fit the experimental data. Moreover, the model constructed in this paper is simple in form and has fewer parameters, and can accurately reflect the creep characteristics of rocks. It also further illustrates the rationality and applicability of the model established in this paper.

5. Conclusions

We obtained the shear creep characteristics of granite through experiments. On this basis, a simple creep model with fewer elements is established by using fractional order software elements and accelerated creep starting elements. Finally, the nonlinear curve fitting of creep test datas is carried out by Origin software to determine the model parameters. The main conclusions of this paper are as follows:

Through the shear creep tests of saturated and dry granite, it can be seen that the rheological effect of saturated granite is more significant, and the size of positive stress also affects the rheological effect of granite, which has important guiding significance for the study of long-term stability of slope.

Table 1 Identification results of creep parameters under normal stress of 2.216 MPa

Moisture condition	Shearing stress/MPa	G/MPa	ξ /MPa·mm ⁻¹ ·h ^{β}	β	η /MPa·mm ⁻¹ ·h	n	R ²
Saturated state	5.084	163.078	41.666	0.017	4.858×10 ⁴⁰	22.178	0.9964
	8.132	166.495	48.537	0.022			0.9956
	11.180	170.731	53.126	0.029			0.9987
	14.228	173.643	48.272	0.032			0.9926
	17.276	180.537	36.969	0.043			0.9914
Aridity	5.084	167.359	79.291	0.033	1.013×10 ⁴⁰	22.016	0.9638
	11.180	168.326	70.747	0.034			0.9715
	14.228	169.683	64.878	0.029			0.9862
	17.276	171.493	56.465	0.039			0.9838
	20.324	38.237	883.468	0.858			0.9749

Table 2 Identification results of creep parameters under normal stress of 5.229 MPa

Moisture condition	Shearing stress/MPa	G/MPa	ξ /MPa·mm ⁻¹ ·h ^{β}	β	η /MPa·mm ⁻¹ ·h	n	R ²
Saturated state	5.084	165.407	34.236	0.011	1.002×10 ⁴⁰	22.027	0.9689
	11.180	166.384	46.559	0.025			0.9752
	17.276	167.206	55.881	0.025			0.9699
	23.372	168.539	58.315	0.034			0.9827
	26.420	37.091	579.791	0.501			0.9584
Aridity	5.084	166.436	33.208	0.011	5.949×10 ³⁴	18.179	0.9919
	11.180	167.042	56.481	0.008			0.9932
	17.276	168.953	66.546	0.021			0.9891
	23.372	168.864	72.841	0.022			0.9842
	29.468	99.999	89.547	0.036			0.9837

Table 3 Parameters of models

Creep model	E/MPa	E ₁ /MPa	E ₂ /MPa	ξ /MPa·h ^{β}	β	η_1 /MPa·h	η_2 /MPa·h	η_3 /MPa·h	n	R ²
Hohai Model	25.8	238.4	32.3	—	—	0.87	11	694.4	12.673	0.9982
Model in this paper	25.9	—	—	3965.2	0.32	—	—	9.33×10 ⁴	9.546	0.9957

- Most of the existing creep models have many elements and parameters. Based on the fractional order software element and accelerated creep starting element, this paper innovatively constructs a simple creep model with fewer elements, and the model can also describe the characteristics of rock creep stages.

- The model established in this paper is used to nonlinearly fit the creep test datas of granite in this paper and the creep test datas in the literature. The fitting curve is in good agreement with the test datas, indicating the rationality and applicability of the established model.

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