Experimental Research on the Rheology Slip Damage Mechanical Properties of Sandstone under the Dynamic Loading

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Abstract. The soft sandstone is taken as samples, and the RLW-2000M triaxial rheological testing machine is used as the main equipment to test the axial stress-strain, the axial rheological deformation in this paper. The axial strain is selected as damage variables, the damage degree expression is derived, and the effect of each factor on damage degree is studied. Research results show that axial deformation increases with the passage of time, and the hysteresis curve change from sparse to dense under the action of the dynamic loading. The axial deformation increase with the increase of the dynamic loading amplitude, and it increases with the decrease of frequency. The damage degree of specimen tends to be stable after mutation and increases with the increase of the dynamic loading amplitude. The research results will provide the scientific basis for us to disclose the rule of rheology-damage evolution of sandstone under the action of dynamic loading.

Keywords. Frequency of dynamic loading, the amplitude of dynamic loading, rheological curve, rheological damage.

1. Introduction
Dynamic loads, such as earthquake, explosion and vibration, accelerate the rheological damage of soft rock, resulting in rheological damage to soft rock and soil and causing serious geological disasters [1-2]. The process of the generation, development and connection of micro-cracks and micro-defects in the internal structure of weak rock mass is its failure process. However, the theory of damage mechanics regards the materials as a continuum containing various micro-defects and studies these micro-defects and the evolution of material damage [3-4]. In recent years, the research on the failure mechanism of weak rock and soil rheological deformation based on the theory of damage mechanics has become the frontier research direction of rock and soil mechanics.

The relationship between the number of acoustic emission events and loading time is constructed based on the Weibull distribution by means of the uniaxial rheological and acoustic emission test of salt rocks, and then obtained the evolutionary relationship of damage variables [5]. Some researchers carried out Hopkinson pressure bar tests on granite samples with circular and square holes under different axial prestatic load and the same impact dynamic load respectively, and obtained the characteristic parameters of granite samples such as relaxation time T2 spectrum curve, nuclear magnetic porosity and nuclear magnetic resonance image [6]. The influencing factors of seismic
fracture damage degree of landslide rock mass under the action of strong earthquake from the perspective of dynamics analyzed based on the fatigue test [7]. Based on the classification of creep strain, some scholars put forward the test method of viscoelastoplastic strain separation creep [8]. The time-dependent characteristics of soft rock have a significant influence on practical engineering, a Burger-deterioration rheological model is presented and applied to an engineering example (Ureshino Tunnel Line 1, Nagasaki, Japan) to illustrate the delayed deformation that has occurred since its completion in November 1992 [9]. A three-stage damage equation based on strain energy is established in the viscoplastic zone, and a nonlinear elastic-viscoplastic rheological damage model is established to explain the three-mode creep response of hard rock [10]. This paper selects soft sandstone as the research object, using RLW-2000M triaxial rheological testing machine to study the dynamic rheological damage characteristics, soft rock engineering characteristics and deformation failure mechanism of soft rock mass under dynamic load. It is of great theoretical and practical significance to prevent and control the geological disasters of geotechnical engineering and ensure the safety of key infrastructure projects in China.

2. The Programme and Process of Experiment

2.1. The Programme of Experiment

The sample was a cylinder serving as a 50 mm×100 mm fine-grained sandstone, belonging to a land-based fine-grained clastic sedimentary rock with a particle size of 0.1~0.5 mm, mainly composed of quartz, feldspar, flint and white mica.

During the test, the confining pressure was kept constant at 10 MPa and the dynamic load was loaded with sinusoidal changes until the sample was damaged. According to the test results, the influence of dynamic load amplitude and dynamic load frequency on the axial rheological characteristic curve, axial stress-strain curve, axial rheological deformation, and hysteretic loop curve of axial rheological deformation of sandstone samples were studied and analyzed. The axial strain was selected as the damage variable, the expression of damage degree was deduced, and the influence characteristics of various factors on the damage degree were studied.

In order to determine the maximum loading peak of the test, the full stress-strain curve of sandstone was first tested, and the peak strength of the sample was about 242 kN when it was destroyed. In order to ensure that sandstone could be destroyed after a certain rheological time, 70% of the peak strength of sandstone triaxial compression was taken as the reference basis for setting the maximum axial load. Four-stage axial load intervals are set respectively F1-2=70~120 kN, F3-4=90~140 kN, F5-6=110~160 kN, F7-8=130~180 kN. Four levels of dynamic load frequency are set from low to high. Considering the wide variation range of axial load at each level, the frequency should not be set higher. Through experimental exploration, the four levels of frequency are set as 0.008 Hz, 0.01 Hz, 0.02 Hz and 0.005 Hz respectively based on the actual conditions of the test equipment. The main parameters of the test scheme are shown in table 1.

| The sample numbering | Number of test | Frequency f (Hz) | The range of dynamic load F (kN) | The sample numbering | Number of test | Frequency f (Hz) | The range of dynamic load F (kN) |
|----------------------|---------------|-----------------|---------------------------------|----------------------|---------------|-----------------|---------------------------------|
| 1                    | 1             | 0.008           | 70-120                          | 3                    | 9             | 0.02            | 90-140                          |
| 2                    | 2             | 90-140          | 90-140                          | 10                   | 10            | 0.02            | 70-120                          |
| 3                    | 3             | 110-160         | 110-160                         | 11                   | 11            | 13              | 110-160                         |
| 4                    | 4             | 130-180         | 130-180                         | 12                   | 12            | 13              | 130-180                         |
| 5                    | 5             | 70-120          | 70-120                          | 13                   | 13            | 13              | 70-120                          |
| 6                    | 6             | 90-140          | 90-140                          | 14                   | 14            | 0.05            | 90-140                          |
| 7                    | 7             | 110-160         | 110-160                         | 15                   | 15            | 110-160         | 110-160                         |
| 8                    | 8             | 130-180         | 130-180                         | 16                   | 16            | 130-180         | 130-180                         |
2.2. The Process of Experiment
RLW-2000M triaxial rheological testing machine was used in the experiment. The test equipment can complete the dynamic triaxial rheological tests of various rocks under dynamic load. The software part of the device is controlled by the test software running under the Windows system, which can automatically record data during the test and display the corresponding relationship between variables in the form of images (such as deformation-time, load-time, strain-time, stress-strain, etc.).

3. Analysis of Test Results

3.1. Axial Rheological Deformation Curves of Each Sample
The sample is generally shear failure, and the cracks in the graph and the ring direction show a certain Angle, and there are several main cracks on the surface of the sample. The samples taken after saturation, under loading and after failure are shown in figures 1-3 respectively.

Figure 1. Saturated sample. Figure 2. The computer controls the process by which the sample is being loaded. Figure 3. The shape of the sample after damage.

The relation curve of axial rheological deformation of each sample with time under sinusoidal dynamic load is shown in figure 4.

![Axial Deformation-time Relation Curves](image)

**Figure 4.** Axial deformation-time relation curve of the specimen.
It can be seen from figure 4 that: the sample undergoes a short-term decelerating rheological transformation under the first, second and third stages of dynamic load to reach a steady state and enter a stable-state rheological phase. Under the action of the last stage of dynamic load, the rheology of the samples shows obvious acceleration phase, and the samples are destroyed. The deformation of the sample under the first three stages of dynamic loads is small and grows slowly, while the deformation increment of the sample under the fourth stage of dynamic load is significantly larger than that of the first three stages of stages.

3.2. The Axial Dynamic Stress-Strain Curve of the Sample at Each Stage
When the specimen is under the action of the first, second and third stage of dynamic load, the initial several hysteresis curves are relatively loose. And with the continuous function of dynamic load, the hysteresis curve gradually became denser. It shows that specimen enters the stable-state rheological stage after a short period of deceleration rheology, the strain rate of specimen diminishes, but the hysteresis curve has been offset in the direction of the strain increase, reflects the specimen strain is gradually increasing, the irreversible plastic strain also gradually accumulates. The loading period and unloading period of each hysteretic curve in each stage of the sample don't coincide but form a closed ring. It reflects the obvious elastic-plastic characteristics of the sandstone sample during the test. When the samples are about to fail under the fourth dynamic load, the hysteretic curves of the samples gradually become sparse from dense, and the strain of the last few hysteretic curves increases significantly under the circumstance that the stress changes little, which indicates that the samples have begun to appear the stage of accelerating rheology. With the increase of the dynamic load range, the area enclosed by the hysteresis curve of each stage tends to increase, and the dissipation of energy gradually increases. As result, the damnification of specimen also accumulates constantly.

The axial dynamic stress-strain curves of the sample1-4 at each stage are shown in figures 5-8.

Figure 5. The axial stress-strain curve in different stages of specimen 1.
Figure 6. The axial stress-strain curve in different stages of specimen 2.

Figure 7. The axial stress-strain curve in different stages of specimen 3.
4. Study on Characteristics of Dynamic Rheological Damage

4.1. The Selection of Damage Variable

If sandstone specimens are under the action of cyclic loading, the deformation also is cyclical change. Assuming that the damage evolution process of sample in each cycle of the damage is constant, we can study cyclic loading time limit stress of the sample development evolution of damage state based on this assumption. under the action of cyclic loading, the limit stress of specimen damage status of the development evolution means the damage evolution process of the sandstone samples. The specific damage degree formula of sandstone is deduced as follows:

One dimensional damage constitutive equation of sandstone:

\[
1 - D = \frac{\sigma}{Ee}
\]  
(1)

Take the derivative of both sides with respect to \( \varepsilon \):

\[
dD = \frac{\sigma}{Ee^2} d\varepsilon
\]  
(2)

\( \varepsilon \) is the strain corresponding to the upper limit stress of cyclic load in the first week, when the sample is not damaged; \( \varepsilon' \) is the strain corresponding to the upper limit stress of cyclic load in the last week, when the sample is completely damaged. Integrate both sides of equation (2) to get:

\[
\int_{0}^{D} dD = \frac{\sigma}{E} \int_{\varepsilon_0}^{\varepsilon'} \frac{1}{\varepsilon} d\varepsilon
\]  
(3)

\[
D = \frac{\sigma}{E} \left( \frac{1}{\varepsilon_0} - \frac{1}{\varepsilon} \right) + C
\]  
(4)

Substitute the initial conditions \( D = 0 \) when \( \varepsilon = \varepsilon_0 \), \( D = 1 \) when \( \varepsilon = \varepsilon' \) into equation (4), and get:
\[ D = \frac{\varepsilon - \varepsilon_0}{\varepsilon' - \varepsilon_0} \times \frac{\varepsilon'}{\varepsilon} \]  

4.2. Effect of Dynamic Load Frequency on Damage Degree
The curve of the variation of the sample's damage variable with time can be obtained after processing the test data. Figures 9-12 show the relation curve of the sample damage degree with time under different dynamic load frequencies.

![Figure 9](image1.png)  
**Figure 9.** The damage degree change curve of sample 1 at 0.008Hz.

![Figure 10](image2.png)  
**Figure 10.** The damage degree change curve of sample 2 at 0.01Hz.

![Figure 11](image3.png)  
**Figure 11.** The damage degree change curve of sample 3 at 0.02Hz.

![Figure 12](image4.png)  
**Figure 12.** The damage degree change curve of sample 4 at 0.05Hz.

As can be seen from figure 9 to figure 12, the damage degree of each sample increases gradually with the increase of time. The damage degree of each sample does not increase greatly under the action of the first-stage graded load, which is because the sample has a process of being compacted gradually at the beginning stage, and the damage degree of the sample is still small. After increasing the range of dynamic load, the damage degree of each sample will have an abrupt mutation and then tend to be stable. The rate of change of the damage degree also has a process of attenuation and then stability, which is similar to the deformation curve of the sample. With the continuous increase of dynamic load, the damage performance of the sample becomes more and more obvious. When the dynamic stress level reaches and exceeds the yield stress of the sample, the damage of the sample accelerates and increases until the sample is destroyed.

5. Conclusion
The rheological behavior of soft sandstone under the action of graded dynamic load is the same as that under the action of static load, and the features of rheological curve accord with the three stages of rheological evolution. With the stepwise loading of dynamic load, the rheological deformation of the sample tends to increase. With the accumulation of deformation, the deformation increment of the
sample under the fourth-stage dynamic load significantly increases compared with the first three stages, until the accelerated rheological damage occurs.

(2) During the loading process of the sample, the loading and unloading periods of each hysteretic curve do not coincide and form a closed ring. The shape of the hysteretic curve is roughly inclined and flat. The hysteretic curve area of each stage of the sample under dynamic load has a tendency to be enlarged with the increase of dynamic load amplitude. When the sample is loaded to be destroyed, the hysteresis curve of the sample gradually becomes sparse from dense.

(3) When the operating range of dynamic load is constant, as the frequency of dynamic load increases, the number of vibrations under dynamic load increases in the same time to consume more energy and the samples tend to become denser, resulting in increased axial deformation of the sample. The radial deformation increment tends to decrease with increasing frequency, which is contrary to the trend of increasing with the increase of dynamic load amplitude.

(4) After increasing the range of dynamic load, the damage degree of the sample will be abruptly mutated and then tend to be stable. With the increase of the dynamic load, the damage performance of the sample becomes more obvious. When the dynamic stress level reaches and exceeds the yield stress of the sample, the damage of the sample accelerates and increases until the sample is destroyed.

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References
[1] Hu H and Zheng X 2013 Experimental research on dynamic rheological characteristics of marine deposit soft soil under different frequencies of dynamic loading Rock and Soil Mechanics 34 9-13.
[2] Zhang C 2016 The stress-strain-permeability behaviour of clay rock during damage and compaction Journal of Rock Mechanics and Geotechnical Engineering (01) 16-26.
[3] Cai Y and Cao P 2016 A non-stationary model for rock creep considering damage based on Burgers model Rock and Soil Mechanics 37 369-374.
[4] Xie L, Zhao G and Meng X 2013 Research on excess stress constitutive model of rock under impact load Chinese Journal of Rock Mechanics and Engineering 32 2772-2781.
[5] Ding J, Zhou H and Chen Q 2015 Characters of rheological damage and constitutive model of salt rock Rock and Soil Mechanics 36 769-776.
[6] Li X, Weng L, Xie X and Wu Q 2015 Study on the degradation of hard rock with a preexisting opening under static-dynamic loadings using nuclear magnetic resonance technique Chinese Journal of Rock Mechanics and Engineering 34 1985-1993.
[7] Luo J, Pei X, Huang R and Du Y 2015 Influencing factors for damage degree of shattered landslide rock mass under high seismic action Geot. Eng. 37 1105-1114.
[8] Zhao Y, Tang J, Fu C, Wan W, Wang W and Luo S 2016 Rheological test of separation between viscoelastic-plastic strains and creep damage model Chinese Journal of Rock Mechanics and Engineering 35 1297-1308.
[9] Guan Z, Jiang Y, Tanabashi Y and Huang H 2008 A new rheological model and its application in mountain tunnelling. Tunnel and Underground Space Technology Chinese Journal of Rock Mechanics and Engineering 23 292-299.
[10] Hu B, Yang S and Xu P 2018 A nonlinear rheological damage model of hard rock J. Cent. South Univ. 25 1665-1677.