Study on mechanical properties and damage evolution characteristics of granite under different stress paths

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Abstract. In order to study the strength and damage characteristics of surrounding rocks of the first high-level radioactive waste repository in Beishan, Gansu Province, China, uniaxial compression, uniaxial cyclic loading and unloading, and triaxial cyclic loading and unloading of deep granite at the depth of 450~480m of BS15 borehole in Beishan preferred area were performed on MTS815 rock mechanics experimental equipment and acoustic emission monitoring system. The test results show that: (1) the cyclic loading and unloading process causes continuous damage in the specimen, and the peak stress and elasticity of granite under uniaxial cyclic loading and unloading decrease by 8.10% and 5.01% respectively, compared with the uniaxial loading test; (2) the confining pressure effect restrains the formation of internal damage in the rock, comparing to uniaxial cyclic loading and unloading, peak stress and modulus of elasticity under triaxial loading and unloading increased by 42.11% and 13.80%. (3) under different stress paths, the number of cyclic loading and unloading increased, the damage variable increased, and the damage degree of rock increased. The damage evolution rate under triaxial condition is slower than that under uniaxial condition, and the damage evolution process in yield and post-peak stage is less severe than that under uniaxial condition.

1. Introduction

During the construction and operation of underground projects, affected by excavation support and geological tectonic movement, the rock will be subjected to different degrees of loading and unloading cycles. During the process of loading and unloading the rock, the mechanical properties of the rock changed to some extent, showing the fatigue damage characteristics of the rock. Fatigue damage characteristics are one of the important mechanical properties of rock materials, which have a significant impact on the long-term operation and safety of tunnels and underground projects [1-2].

Granite has the characteristics of good stability and low permeability, so it is often used as an ideal surrounding rock for high-level underground storage. Research on the mechanical properties of granite has been relatively sufficient. According to Huang Runqiu’s [3] unloading test of rock specimens, it is found that during the unloading process of granite, the rebound in the direction of unloading is strong, the brittle failure characteristics are obvious, and the tensile characteristics are strong after failure. By carrying out indoor experiments, Xu Xichang [4] studied the variation of the main mechanical parameters of granite at different temperatures (20 ~ 600 °C) through laboratory tests. It is found that
75 °C and 200 °C are the threshold temperatures of granite elastic modulus and uniaxial compressive strength; Liu Quansheng [5] conducted a tri-axial compressive creep experiment on the Sanxia granite at high temperature, and fitted the empirical formula of the mechanical model of the granite and its cohesiveness with temperature and time; Studying the damage evolution process of rock failure is of great significance for maintaining the long-term operation of underground structures [7-8]. Wang Feiyun [9] studied the acoustic emission characteristics and damage evolution mechanism of granite brittle and ductile failure processes, and found that there are few serious damage areas in the brittle fracture granite and the distribution is concentrated. The direction of crack development in the damage zone is single. The ductile damage internal damage zone is mostly distributed throughout the sample, and the cracks in the damage zone mainly develop along two mutually orthogonal directions; Chen Liang [10] combined with the acoustic emission detection system, found that the damage evolution of granite under compressive stress begins with the generation and expansion of micro-cracks. It has developed rapidly in the stage of destruction and post-peak, and proposed empirical formulas related to granite permeability and damage and confining pressure.

At present, research on the mechanical properties and damage under the conventional mechanical experiments of granite has been sufficient, but discussions are still insufficient regarding the mechanical properties and damage evolution of granite under cyclic loading and unloading and the influence of different stress paths on the related properties[11-12]. Therefore, based on indoor uniaxial compression, uniaxial cyclic loading and unloading and three-axis cyclic loading and unloading experiments, the mechanical properties and damage evolution process of granite under different stress paths are studied and discussed in depth.

2. Test Result Analysis
The full stress-strain curve of granite under uniaxial compressive stress path shows obvious periodic characteristics, namely initial compaction phase, elastic deformation phase, elastoplastic deformation phase and post-peak phase. The rock is affected by natural geological structure, excavation, transportation and other factors, so there is a certain initial damage inside the laboratory rock sample [10]. Under the action of axial pressure, the natural damage of internal cracks and holes is closed. Under the condition of small stress change, the granite undergoes a large volume compression. The elastic-stage stress-strain curve is a straight line at this time, and the rock deformation conforms to Hooke's law, and the stress increment is proportional to the strain increment. After the yield stress, the granite enters the elastoplastic deformation stage. At this stage, the stress growth is slower but the strain increases rapidly. The granite specimen thus enters the “expansion phase” and gradually reaches the peak stress intensity $\sigma_p=183.60 \text{ MPa}$ until the rock breaks. The full stress-strain curve of granite damage shows that the residual strength after damage is $\sigma_r=162.04 \text{ MPa}$, which reaches 88.26% of the peak stress intensity, which indicates that the granite still maintains good compressive bearing capacity after the damage.

![Stress-strain curve under uniaxial loading](image)

Fig.1 Stress-strain curve under uniaxial loading

The single-axis and three-axis cyclic loading and unloading test is performed on the peak stress $\sigma_p=183.60 \text{ MPa}$ based on the uniaxial test. The peak stress is unloaded at about 20%, 40%, 60%, 80%,
and 100%, and the corresponding axial pressures $F=75\text{kN}$, $150\text{kN}$, $225\text{kN}$, $300\text{kN}$, $375\text{kN}$, etc. are taken as the force-controlled unloading point to the rock loading process. The lateral confining pressure of the tri-axial test is $10\text{ MPa}$, and the axial pressure-time and stress-strain curves of the whole process are shown in Figures 2 and 3.

According to the uniaxial loading and unloading axial force-time relationship curve, during the first four loading and unloading processes, the granite gradually enters the yield stage from the elastic phase. For the fifth loading process, the predetermined target axial stress is $375\text{kN}$, but the rock yields fatigue appears after the loading stress reaches about $300\text{kN}$. At this point, the increase rate of force decreases, the curve begins to slow down, gradually reaches the peak stress, and is unloaded at the peak stress. For the tri-axial cyclic loading and unloading test, the lateral confining pressure $\sigma_3=10\text{ MPa}$, the unloading point and the test scheme are the same as the uniaxial cyclic loading and unloading. According to the axial force-time relationship curve, under the influence of confining pressure, the strength of granite increases under the condition of tri-axial test, and the number of loading and unloading cycles increases. After 6 cycles of loading and unloading, the granite showed obvious yield characteristics. For the seventh loading process, the predetermined target axial stress is $525\text{kN}$, but the rock will fatigue yield after the loading stress reaches about $420\text{kN}$.

At the initial stage of loading, the internal damage of the rock is small, and the internal fissure structure remains basically the same, so the plastic strain after unloading is basically 0. The second-stage loading stress-strain curve basically coincides with the first-stage curve under low pressure; As the axial stress increases, the internal damage of the granite is restored, and the joints, cracks, etc. are closed to some extent under the action of axial pressure; After the axial pressure is further increased, new damage begins to occur inside the rock, and the crack continues to grow and expand. After entering the unloading process, due to the elastic recovery of the rock itself, the crack is filled with loose debris, and the tightness of the rock interior is relatively increased.

Under the different stress paths of uniaxial compression, uniaxial cyclic loading and unloading and three-axis cyclic loading and unloading, the peak stress of granite specimens are $183.60\text{MPa}$, $168.70\text{MPa}$ and $239.74\text{MPa}$, respectively, and the elastic moduli are $49.84\text{GPa}$, $47.34\text{GPa}$ and $53.93\text{GPa}$, respectively. Compared with the granite specimen under uniaxial compression, the peak stress and elastic modulus of the specimen under the uniaxial cyclic loading and unloading test conditions
decreased by 8.10% and 5.01%, respectively. This is due to the fact that during the first four cycles of loading and unloading of granite specimens, a certain number of pores and cracks are generated due to cyclic loading and unloading fatigue. At this time, a higher degree of damage has been generated inside the initial state, so the peak stress and elastic modulus of the rock are relatively lower; Compared with the granite specimens, under the condition of tri-axial cyclic loading and unloading, the peak stress of the specimen increased by 30.63% and 42.11%, respectively, and the elastic modulus increased by 8.21% and 13.80%, respectively, showing obvious confining pressure effect. Under the pressure of 10MPa, the crystal cohesive force of the rock increases, the particle points are close to each other, the crystal lattice is not easy to be destroyed. The development of internal damage of rock is inhibited, and the strength of rock increases while the deformation changes from brittle deformation to ductile deformation, and the plastic deformation ability is improved.

![Fig.4 Peak stress and Modulus of elasticity comparison under different stress paths](image)

3. Damage Evolution Analysis

3.1 Energy-based Damage Variables

According to the definition of the damage variable, the change of the elastic modulus can generally be used to calculate the damage variable of the rock [13].

\[
D = 1 - \frac{\bar{E}}{E}
\]

where \(E\) is a non-damaged elastic modulus and \(\bar{E}\) is a damage elastic modulus.

This is a method for defining damage variables based on the strain equivalence hypothesis, which produces changes in the elastic modulus of the material before and after the damage. However, the "elastic modulus method" based on the strain equivalence hypothesis is essentially a method for describing elastic damage. For this granite loading test, compared with the initial non-damage elastic modulus, the damage elastic modulus increases with the increase of stress after cyclic loading and unloading. Therefore, it is not suitable for the calculation of granite damage variables under cyclic loading and unloading conditions.

Figure 7 is a typical granite cyclic loading and unloading hysteresis loop diagram. Due to the high strength of the granite, it is loaded again after unloading, and the loading line basically passes through the previous cycle unloading point. It is known from the law of conservation of energy that the total energy does not change during a complete loading and unloading test. On the premise of ignoring the energy loss caused by the test system, assuming that the total work of the load is \(U_0\), the internal elastic potential energy of the rock sample is \(U_e\), and the damage dissipated energy is \(U_d\). According to the mechanical law, the elastic potential energy can be completely released during the unloading process, which can be approximated named as the work \(U_b\) made by the load during unloading. So that:

\[
U_0 = U_e + U_d = U_b + U_d
\]
The energy in a certain loading and unloading process is analyzed. As shown in Fig. 7, the loading path is from point O to point A. At this stage, the applied load is continuously increased, the deformation of the rock is also increasing. The external force performs positive work on the test piece; the unloading path is from point A to point B. At this stage, the external load is continuously reduced until the predetermined minimum load is reached again, and the external load performs negative work. Therefore, the damage dissipative energy $U_d$ and the elastic potential energy $U_e$ can be obtained by the stress-strain curve [14-17] line. During the loading process, the integral area of the stress-strain curve is the total strain energy, and the integral area of the stress-strain curve in the unloading process is the elastic potential energy $U_e$. The difference between these two areas is the damage dissipation energy $U_d$ [14-16].

![Fig.5 Cyclic loading and unloading hysteresis loops of typical granite](image)

According to the energy mechanism analysis of the damage process, the damage variables of the rock under each cycle are calculated as follows:

$$D(i) = \frac{U_d(i)}{U_d}$$

(3)

Then, after the end of the i-th loading and unloading cycle, the rock cumulative damage variable $D$ can be expressed as

$$D = \sum D(i) = \frac{\sum U_d(i)}{U_d}$$

(4)

3.2 Study on Evolution Process of Granite Damage

According to the above method, the stress-strain curve and damage evolution process of granite failure under different stress paths are calculated and analyzed. The research on granite damage under uniaxial compression is relatively sufficient. Therefore, this paper mainly studies the damage evolution process of granite under single and tri-axial loading and unloading paths. The calculation results of the damage variables are shown in Table 1.

| Number of cycles | Uniaxial | | | Three axis | | |
|---|---|---|---|---|---|---|
| | $U_0$ (kJ·m$^{-3}$) | $U_e$ (kJ·m$^{-3}$) | $U_d$ (kJ·m$^{-3}$) | $D$ | $U_0$ (kJ·m$^{-3}$) | $U_e$ (kJ·m$^{-3}$) | $U_d$ (kJ·m$^{-3}$) | $D$ |
| 1 | 16.64 | 14.11 | 2.53 | 0.014 | 14.63 | 13.19 | 1.44 | 0.004 |
| 2 | 53.29 | 48.10 | 5.19 | 0.042 | 53.61 | 49.59 | 4.02 | 0.016 |
| 3 | 112.31 | 101.30 | 11.01 | 0.102 | 117.27 | 110.05 | 7.22 | 0.037 |
| 4 | 199.58 | 178.57 | 21.01 | 0.217 | 209.73 | 194.01 | 15.72 | 0.083 |
| 5 | 265.46 | 240.33 | 25.13 | 0.355 | 299.56 | 275.99 | 23.57 | 0.152 |
| 6 | 273.22 | 235.29 | 37.93 | 0.562 | 570.55 | 529.37 | 41.18 | 0.273 |
According to the theory of energy dissipation, if the rock is not loaded under the initial state, and the dissipated energy is 0, the initial damage of the rock can be defined as 0. It can be seen from Table 1 that the degree of damage of the rock during the whole process of loading and unloading increases with the number of cycles of loading and unloading, and it can be seen that in the first several loading and unloading cycles, since the load applied to the test piece is small, the loading and unloading process is accompanied by the compaction, closure and new crack of the primary crack, but the amount is extremely small, so the degree of rock damage is low; As the maximum load level of cyclic loading and unloading continues to increase, new cracks are generated inside the rock and penetrated each other. The degree of rock damage begins to increase until the peak stress rock reaches the post-peak stage dominated by plastic deformation. At this point, the increase rate of rock damage increased dramatically until the rock was completely destroyed.

|   | 7  | 8  | 9  | 10 | 11 | 12 | 13 |
|---|----|----|----|----|----|----|----|
|   | 272.85 | 205.39 | 45.27 | 1 | 314.6 | 232.9 | 226.18 |
|   | 227.58 | 34.86 | 1 | 357.83 | 208.48 | 198.24 | 189.96 |
|   | 45.27 | 0.809 | / | 357.83 | 37.27 | 27.94 | 22.56 |
|   | 0.809 | 591.29 | / | 304.81 | 24.42 | 27.94 | 1 |
|   | 591.29 | 332.12 | / | 47.42 | 24.42 | 27.94 | 1 |
|   | 332.12 | 35.71 | / | 0.852 | 0.852 | 0.852 | 0.852 |
|   | 35.71 | 53.36 | / | 0.781 | 0.781 | 0.781 | 0.781 |
|   | 53.36 | 0.429 | / | 0.533 | 0.533 | 0.533 | 0.533 |

In order to compare the proportion of dissipated energy to total energy in different stages, introduce dimensionless parameters:

$$K_d = \frac{U_d}{W}$$  \hspace{1cm} (5)

Where Kd is the energy dissipation ratio. By calculating this parameter, it can be used to analyze the distribution law of the dissipative energy in the total energy as the loading and unloading process proceeds.

It can be seen from Fig. 7 that the rock under the first cyclic loading is in the compaction stage. At this time, the work done by the external force on the granite is mainly converted into the elastic-plastic...
deformation energy of the micro-cracked compaction. Therefore, the dissipative energy is relatively high at this time; the rock dissipative energy is basically in a stable state when entering the linear elastic phase, and only accounts for 5%~10% of the total energy. It can be seen that most of the external force work is converted into elastic potential energy, and is released during the unloading process; After entering the yielding stage, new cracks are continuously generated inside the granite and expand and penetrate each other. The proportion of dissipated energy gradually increases; when the peak stress is exceeded, the specimen begins to gradually enter the state of failure, and the energy dissipation ratio increases rapidly.

Compared with the single-axis cyclic loading and unloading and the three-axis cyclic loading and unloading, it can be found that under the influence of confining pressure, the process of damage development under the tri-axial cyclic loading and unloading test conditions is slower. Under the condition of single-axis cyclic loading and unloading, the specimens begin to yield and reach the peak stress after 5 loading and unloading cycles, and then enter the post-peak residual phase; Under the condition of tri-axial cyclic loading and unloading, the test piece needs to enter the yielding stage after 7 cycles of loading and unloading, and the peak stress is 42.11% higher than that in the uniaxial state. It can be seen that the confining pressure has a significant inhibitory effect on the occurrence of internal cracks and the development of damage. In addition, as can be seen from Figures 6 and 7, whether the damage variable or the dissipative energy ratio, after the peak stress, the growth rate of the granite specimen under the uniaxial state is significantly higher than the tri-axial state. This again proves that confining pressure has an inhibitory effect on the production of damage.

4. Conclusion

1) The peak stresses of Beishan granite under three different stress paths are 183.60MPa, 168.70MPa and 239.74MPa, respectively, and the elastic moduli are 49.84GPa, 47.34GPa and 53.93GPa, respectively. Compared with the uniaxial compression condition, the peak stress and elastic modulus of the specimen decreased by 8.10% and 5.01% respectively under the condition of uniaxial cyclic loading and unloading test. Compared with the uniaxial cyclic loading and unloading test conditions, under the condition of tri-axial cyclic loading and unloading, the peak stress of the specimen increased by 30.63% and 42.11%, respectively, and the elastic modulus increased by 8.21% and 13.80%, respectively. The confining pressure effect was obvious.

2) Under the conditions of single-axis and three-axis cyclic loading and unloading, the research on the evolution of damage process based on energy mechanism shows that the damage variable increases with the number of cycles and stress. Compared with the single axis, the damage evolution rate is slower in the tri-axial state and the damage evolution process in the yield and post-peak stages is not as strong as the single axis; The proportion of dissipated energy in the compaction phase is reduced, but as the peak value of the load increases, the rock enters the elastic phase, and the energy dissipation ratio tends to be stable. When the peak stress is reached, the energy dissipation ratio is continuously increased, and the dissipation energy of the uniaxial loading and unloading cycle test increases more rapidly at this stage.

3) Under the influence of confining pressure effect, the development of rock damage is inhibited. Under the same load, the damage variable under the three-axis state is lower than that of the single axis; At the same time, the energy dissipation is relatively.

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