Mechanical properties and stability analysis of surrounding rock of underground cavern under various stress loading paths

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Abstract: Under the influence of geological tectonic movement and human engineering activities, the geological environment of rock mass is often very complex, and its stress state is also complex and constantly changing. During the excavation of underground caverns, the stress of surrounding rock will be redistributed, and its radial stress and tangential stress are constantly changing and adjusting. From this point of view, the excavation of underground chamber causes strong stress differentiation in surrounding rock, and the experimental study under simple stress path cannot fully reflect the actual state of rock engineering. In order to comprehensively understand the damage mechanism of rock under complex stress paths, this paper takes the granite of an underground powerhouse of a power plant as the research object, designs and carries out a variety of laboratory tests such as conventional triaxial test, unloading test and creep test, and obtains the deformation and failure characteristics of granite under different stress loading paths. Based on the laboratory results, it puts forward specific surrounding rock support recommendations. This study can provide more targeted supporting measures for surrounding rock under different stress states, which is of practical significance to maintain stability of surrounding rock in the factory area.

Keywords: stress in the surrounding rock, underground cavity, path of loading, stability of surrounding rock, mechanical properties

1. Introduction
The excavation of underground cavern will cause stress adjustment and redistribution, and the surrounding rock will break the previous equilibrium stability and be in a complex stress path. Therefore, the rock under different working conditions may be in different loading states. The stability and analysis of surrounding rock is a major technical problem in engineering, and as the underground cavern continues to move towards the complex area, this phenomenon is particularly prominent. A comprehensive study of the mechanical properties and damage mechanisms of rock masses under different stress paths is of great significance for studying the rock mechanics response of underground caverns and the stability of surrounding rocks. As for the mechanical mechanism of rocks under different stress paths, scholars have done relevant research: Wang Yanqi described the failure process of rock under uniaxial compression with CT based on image retrieval technology[1]; Xu Tao studied the theory, experiment and numerical simulation of brittle rock deformation and failure under uniaxial compression[2]; Yang Yongjie studied the damage of rock based on the triaxial compression acoustic emission test[3]; Xia Dong studied the damage and energy characteristics of saturated rock deformation...
and failure under cyclic loading and unloading[4]; Dai Bing studied the damage characteristics and energy dissipation characteristics of the rock with holes under cyclic impact loading[5]; Liu Lang conducted research on the creep test of deep saturated rock and its rheological model[6]; Han Gengyou studied the creep characteristics of thin-layered rocks under stepwise loading[7]. It can be seen that the previous research mainly carried out related experimental studies under different stress paths for different types of rocks, and rarely carried out different stress path tests for the same type of rocks. Therefore, it is impossible to have a systematic understanding of the mechanical properties of the surrounding rock of the underground cavern. Based on this, this paper takes the granite in the underground cavern of a hydropower station as the research object, combined with the loading methods that the rock mass may suffer on site, carries out conventional triaxial compression tests, cyclic loading and unloading tests, and creep tests to obtain the granite under different stress paths. According to the test results, it puts forward specific surrounding rock support recommendations. This paper can provide theoretical support for the stability analysis of underground caverns with similar backgrounds.

2. Test methods and test equipment

In order to study the mechanical properties of surrounding rock of underground cavern under different stress paths, four test schemes are designed in this paper (as shown in Table 1). It includes conventional triaxial test scheme, two loading and unloading test schemes and creep test scheme. The granite samples used in the test are taken from the excavation site of underground cavern. Through indoor processing, the specimens are made into standard cylinder specimen with size of 50mm ×100mm, which is naturally air dried, and the average density is 2.75g/cm³. MTS815 Flex Tes GT Rock Mechanics Test System is used in the test. The axial deformation is measured by axial extensometer, and the transverse deformation is measured by circumferential extensometer. The loading and measurement are automatically controlled by computer program, and the rate control is stable and accurate in the whole loading process.

| Test scheme              | Specimen number | Diameter (mm) | Height (mm) | Quality (g)  | Density (g/cm³) | Initial stress σ₁/MPa | σ₃/MPa |
|-------------------------|-----------------|---------------|-------------|--------------|-----------------|-----------------------|-------|
| Conventional triaxial test |                |               |             |              |                 |                       |       |
|                         | CL-1            | 50.80         | 100.61      | 562.85       | 2.76            | 0.5                   |       |
|                         | CL-2            | 50.79         | 100.49      | 556.94       | 2.74            | 1                     |       |
|                         | CL-3            | 50.83         | 100.76      | 564.13       | 2.76            | 3                     |       |
|                         | CL-4            | 50.79         | 100.48      | 559.54       | 2.75            | 5                     |       |
|                         | CL-5            | 50.85         | 100.62      | 563.65       | 2.76            | 10                    |       |
|                         | CL-6            | 50.77         | 100.18      | 558.51       | 2.75            | 20                    |       |
|                         | CL-7            | 50.69         | 100.14      | 553.51       | 2.74            | 30                    |       |
|                         | CL-8            | 50.85         | 99.45       | 554.92       | 2.75            | 40                    |       |
| Unloading test (increasing axial pressure and relieving confining pressure) | LU-1 | 50.63 | 100.12 | 551.53 | 2.74 | 5 | |
|                         | LU-2            | 50.86         | 100.53      | 564.90       | 2.77            | 10                    |       |
|                         | LU-3            | 50.73         | 100.44      | 556.32       | 2.74            | 20                    |       |
|                         | LU-4            | 50.83         | 100.71      | 564.27       | 2.76            | 30                    |       |
|                         | LU-5            | 50.87         | 100.61      | 567.05       | 2.77            | 40                    |       |
| Unloading test (stabilizing axial pressure and relieving confining pressure) | UU-1 | 50.83 | 100.60 | 561.09 | 2.75 | 5 | Limit of strength ratio of triaxial test |
|                         | UU-2            | 50.86         | 100.70      | 556.71       | 2.72            | 10                    |       |
|                         | UU-3            | 50.76         | 99.99       | 555.21       | 2.74            | 20                    |       |
|                         | UU-4            | 50.82         | 100.51      | 560.25       | 2.75            | 30                    |       |
|                         | UU-5            | 50.74         | 100.26      | 556.77       | 2.75            | 40                    |       |
| Creep test              | RB-1            | 50.96         | 100.62      | 568.86       | 2.77            | 10                    |       |
The specific loading methods of the four experimental schemes are as follows.

(1) For conventional triaxial compression test: 1) Increase $\sigma_3$ to a predetermined value at a rate of 6MPa/min; 2) Apply $\sigma_1$ at a rate of 20kN/min; 3) At the end of the elastic stage, the axial load is applied at the rate of 0.02 mm / min of transverse deformation, and after the peak load, the axial load is applied at the rate of 0.04 mm / min until the residual deformation stage. (2) For unloading test (increasing axial pressure and relieving confining pressure): 1) Apply the confining pressure to the initial condition; 2) Apply the axial pressure to the initial condition; 3) The increase rate of $\sigma_1$ is 6MPa/min, and the decrease rate of $\sigma_3$ is 2MPa/min; 4) Once the specimen is damaged, stop unloading the confining pressure $\sigma_3$, and keep the confining pressure unchanged, while continuing to apply the axial stress until the stress difference $\sigma_1-\sigma_3$ does not decrease with the increase of the axial strain, and the test ends. (3) For unloading test (stabilizing axial pressure and relieving confining pressure): 1) Apply the confining pressure to the initial condition; 2) Apply the axial pressure to the initial condition; 3) $\sigma_1$ remains unchanged, and the reduction rate of $\sigma_3$ is 2MPa/min; 4) Once the specimen is damaged, stop unloading the confining pressure $\sigma_3$ and keep the confining pressure unchanged until the end of the test. (4) For creep test: Carry out grading loading for a period of time at 70%, 80%, and 90% of the expected strength of the triaxial test. If the specimen is not damaged, continue to load at 100%, 110%, or 120% of the expected strength for a period of time until the specimen is damaged.

3. Test results

3.1. Triaxial loading test

Figure 1 shows the stress-strain curve of conventional triaxial test granite under different confining pressures, $\varepsilon_1$ represents axial strain, $\varepsilon_3$ represents lateral strain, and $\varepsilon_v$ represents volumetric strain. It can be seen from Figure 1 that as the confining pressure $\sigma_3$ increases, the compressive strength $\sigma_1$ of the rock also becomes stronger. The confining pressure is a key factor affecting the compressive strength of the rock. The rock exhibits obvious elastic and brittle characteristics. Even if the confining pressure reaches 40MPa, it still shows brittle failure characteristics. The confining pressure required for brittle-ductile transition is very high. Figure 2 shows the failure mode of rock sample in conventional triaxial compression test. The failure degree of rock sample under high confining pressure is stronger than that under low confining pressure. Generally, the failure of rock sample is mainly inclined section. It can be seen that the failure of rock sample under compression is mainly shear failure, and it also has tensile fracture characteristics. At the same time, with the increase of confining pressure, the shape of inclined section is clearer. The relationship between compressive strength and confining pressure is shown in Figure 3. It can be seen that the triaxial compressive strength increases with the confining pressure. The cohesion value of the rock is 29.08MPa, and the internal friction angle is 50.84°.

![Figure 1. Stress-strain curve of the test](image-url)
3.2. Unloading test

The excavation of underground cavern will release the stress or accumulated energy of surrounding rock. In essence, it is a process of stress redistribution due to unloading of rock mass in one direction. Such unloading behavior often reduces the confining pressure of rock mass, and stress redistribution may cause different degrees of stress concentration behavior of rock mass in another direction. Based on this, this paper designed unloading test (increasing axial pressure and relieving confining pressure) and unloading test (stabilizing axial pressure and relieving confining pressure) respectively corresponding to the obvious stress concentration and no obvious stress concentration caused by unloading after the on-site cavern excavation. The two working conditions are expected to provide more comprehensive theoretical guidance for the stability analysis of the surrounding rock of the cavern.

3.2.1. Unloading test (increasing axial pressure and relieving confining pressure). Figure 4 shows the results of the unloading test. It can be seen that when the rock reaches the peak strength, the stress difference (σ1-σ3) will decrease slightly, then slowly increase, and then slowly decrease until it fails. This is because after the rock reaches its peak, due to the existence of the confining pressure, the rock has a process of compacting and increasing its strength. Later, as the rock continued to expand, the rock eventually broke down. It can also be seen from the figure that as the initial confining pressure increases, the compressive strength (σ1-σ3) of the rock will increase. So the confining pressure can also enhance the compressive strength of the rock under such a scheme.

The failure mode of the rock specimen is shown in Figure 5. It can be seen from the figure that under this test condition, the rock has a relatively strong expansion along the unloading direction, and the failure of the rock has strong tensile fracture characteristics, but with the confining pressure increased, shear failure is dominant.
The relationship between compressive strength and confining pressure is shown in Figure 6. The cohesion is 21.97 MPa and the internal friction angle is 52.32°. It can be seen that the triaxial compressive strength increases with the confining pressure, which is consistent with the conventional triaxial compression test.

3.2.2. Unloading test (stabilizing axial pressure and relieving confining pressure). The test results are shown in Figure 7. It can be seen that when the rock reaches its peak strength, the stress difference ($\sigma_1 - \sigma_3$) will basically remain unchanged as the strain increases, and then slowly decrease until it fails. This is because when the rock reaches the peak strength, due to the existence of the confining pressure, the rock has a compacting process, and finally the rock is damaged due to the expansion of the rock.

The failure morphology of the rock sample is shown in Figure 8. It can be seen that it is similar to section 3.2.1, that is, the rock has a relatively strong expansion along the unloading direction, and the failure of the rock has strong tensile fracture characteristics, but with the confining pressure increased, shear failure is dominant. Therefore, under the two unloading schemes, the specimens have similar failure laws.
The relationship between compressive strength and confining pressure is shown in Figure 9. The cohesion is 31.96 MPa and the internal friction angle is 46.00°. It can be seen that the triaxial compressive strength increases with the confining pressure, which is consistent with the conventional triaxial compression test as well.

For the on-site surrounding rock mass, the peak strength of the rock is always the focus of the project. Therefore, it is necessary to make a comparative analysis of the peak strength of the rock in the above three test schemes. Through comparison, it can be found that under the same confining pressure, the strength ($\sigma_1-\sigma_3$) of conventional triaxial compression (CL), unloading test (increasing axial pressure and relieving confining pressure, LU), unloading test (stabilizing axial pressure and relieving confining pressure, UU) decreases in sequence. Taking a confining pressure of 40 MPa as an example to show, as shown in Figure 10, the others have similar rules, which will not be repeated.

Figure 8. Failure shape of the specimens

Figure 9. Relationship between compressive strength and confining pressure

Figure 10. Comparison curve of three schemes under the same confining pressure
3.3. Creep test
The test results are shown in Figure 11.

![Creep curve](image)

(a) Axial creep curve                      (b) Transverse creep curve

**Figure 11. Creep curve**

It can be seen from Figure 11 that with the increase of stress level, the axial deformation of the specimen transits from stable creep to unstable creep, and finally the accelerated creep stage occurs, and the specimen is destroyed. In addition, different from the axial creep deformation, there is no obvious stable creep zone in the transverse creep deformation, but under the action of axial stress, the deformation changes from the initial creep stage to the creep stage with non-zero creep rate. The same as the axial creep deformation, the transverse creep deformation appears the accelerated creep stage after the steady creep stage under the last stress, and the specimen is destroyed. The creep failure mode of granite is shown in Figure 12. At this time, the rock failure is dominated by shear failure. Rock has obvious expansion characteristics during creep failure, and the expansion characteristics are more obvious than the conventional triaxial compression test under the same confining pressure, and the degree of rock failure is also stronger.

![Creep failure mode of specimen](image)

**Figure 12. Creep failure mode of specimen**

4. Significance of test results to surrounding rock stability
(1) The stress-strain relationship of the specimen presents obvious elastic and brittle characteristics. For example, even if the confining pressure reaches 40MPa in the conventional triaxial compression test, the specimen still exhibits obvious brittle failure characteristics, and the confining pressure required for brittle-ductile transition is very high. For such surrounding rock, brittle failure is easy to occur during the excavation of the project. For example, under the high stress environment, rock burst, fragmentation, peeling and other damages are easy to occur. The process of stress adjustment may be violent. Therefore, attention should be paid to the control of the surrounding pressure stability during the excavation period of the underground cavern. Appropriate support measures should be taken after surrounding rock excavation, especially the strength of initial support should be strengthened to ensure construction safety.
(2) Through two kinds of unloading tests, it can be known that the compressive strength of the rock increases with the confining pressure, so no matter whether the unloading behavior of underground caverns after excavation will produce obvious stress concentration phenomenon, in order to ensure the stability of surrounding rock, appropriate supporting measures should be taken quickly after excavation, so as to make up for the confining pressure loss of rock at
excavation face, making the strength of the rock as high as possible. Generally speaking, flexible supporting measures such as bolts, shotcrete with nets, and anchor cables can better adapt to the coordinated deformation of the rock, which is beneficial to the stability control of this kind of hard surrounding rock. (3) Creep makes the final failure form of surrounding rock more severe, so the small rock mass should be effectively supported in the possible creep failure area.

By observing the test process of the specimen under different loads, the following two phenomena are obtained. Firstly, confining pressure plays an important role in the failure pattern of the specimen. It is shown in all three groups of tests that the shear failure trend of the specimen becomes more obvious with the increase of confining pressure. Secondly, when the specimen is damaged, it is often accompanied by a large sound, and the more thoroughly the specimen is broken, the greater the sound, and the brittle ejection phenomenon is obvious.

5. Engineering practice
In the project implementation stage, through a comprehensive analysis of the surrounding rock of the underground cavern, and combined with the rock mass characteristics under different stress paths revealed by the test, targeted excavation and support design are carried out for the engineering, which is mainly reflected in the following aspects.

(1) In terms of support design scheme, flexible support measures such as "hanging-net grouting concrete + anchor bolt + anchor cable" are generally adopted, which can better adapt to the adjustment process of in-situ stress. In order to limit the shallow damage caused by excavation unloading, the steel fiber concrete with good initial spray flexibility and the combination of prestressed bolt and mortar bolt with cushion plate are adopted to provide support resistance for surrounding rock in time and actively, improving the shear strength of weak structural plane and sliding plane, and ensuring that the bolt and surrounding rock act together to form an overall force. In order to reduce the plastic zone development and deep deformation of surrounding rock caused by rock creep, prestressed anchor cable is adopted. Therefore, there is a complete support system from shallow layer to deep layer.

(2) In terms of on-site construction measures, phased excavation and phased support measures are adopted to gradually release the in-situ stress, such as advance support before excavation and phased support from shallow to deep after excavation. At the same time, according to the spatial gradualness of in-situ stress adjustment, the principle of "breaking the whole into parts and releasing by zones" is adopted for excavation. In the excavation process, the principles of “first hole, second wall” and “thin layered excavation” should be adhered to. The excavation span of the underground cavern involved in the test is 28.5m, and the excavation height is 14.5m at present. According to the monitoring instrument, the surrounding rock of the project is generally in a good stable state. The measured curve of typical multipoint displacement meter is shown in Figure 13. It can be seen that the overall deformation is mostly within 2cm, and the deformation of some fault structural planes is slightly larger, where local strengthening support is carried out. At the same time, the dynamic design is carried out according to the stress adjustment state of surrounding rock during excavation.

![Figure 13. Measured curve of Multipoint Displacement Meter on typical section of the project](image-url)
6. Conclusion
The main conclusions of this paper are as follows.

(1) For conventional triaxial compression, the peak strength of the specimen increases with the increase of confining pressure, and the failure degree of the specimen under high confining pressure is stronger than that under low confining pressure. Generally speaking, the failure of rock is mainly inclined section. Under the two unloading conditions, the peak strength of the specimen increases with the increase of confining pressure as well, and the failure mode of the specimen gradually transits from tensile failure to shear failure with the increase of confining pressure.

(2) Under the same confining pressure, the strength (σ1-σ3) of conventional triaxial compression, unloading test (increasing axial pressure and relieving confining pressure), unloading test (stabilizing axial pressure and relieving confining pressure) decreases in sequence.

(3) Granite has obvious expansion characteristics during creep failure, and the expansion characteristics are more obvious than the conventional triaxial compression test under the same confining pressure, and the degree of rock failure is also stronger.

(4) For the brittle and hard surrounding rock such as granite, special attention should be paid to the timely follow-up of the initial support, making up for the confining pressure loss of the rock at the excavation face quickly, keeping the strength of the rock as high as possible, which is conducive to maintaining the stability of the surrounding rock.

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