Study on mechanical damage mechanism of initial crack and water content to free face rock

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Abstract: The surrounding rock of the underground cavern at Yebatan Hydropower Station is faced with the combined action of fault cutting and rich groundwater. After the excavation of underground cavern, the relaxation deformation and the stability analysis of free face rock have always been the focus of the engineering. Based on this, this paper constructs rock specimens with different types of initial cracks and different water content, and places them in a special mold which can simulate the free face for compression testing. In this paper, the strength, deformation and failure characteristics of the rock specimens with different initial rack types and water content combinations are studied, and the sensitivity of crack types and water content to the mechanical properties of free face rock is also analyzed. The specimens with typical failure characteristics are selected for microscopic scanning to obtain the microscopic damage pattern, the relationship between the microscopic damage and the macroscopic failure of the free face rock under the action of complex factors is established. This study can provide reference for the stability analysis of surrounding rock with similar background.

Keywords: initial crack, water content, free face rock, damage mechanism

1. Introduction

The Yebatan hydropower station is located on the main stream of Jinsha River in Baiyu County, Sichuan Province and Gongjue County, Tibet Province. It is the seventh level of the 13-level development plan for the upper reaches of the Jinsha River. The underground cavern of Yebatan hydropower station is faced with the combined action of fault cutting and rich groundwater, which brings great challenges to the stability control of surrounding rock. Scholars have carried out extensive research on the adverse effect of fault cutting on surrounding rock. These studies mainly study the mechanical properties of the fault area through laboratory tests or numerical simulation methods, and put forward corresponding measures to improve the integrity of surrounding rock [1-4]. Similarly, scholars have conducted in-depth research on the influence of water on the stability rock. In these studies, laboratory tests are mainly used to study the influence of water on the instantaneous strength, long-term strength and damage development of soft and hard rock [5-9]. Previous studies mostly focused on the conventional uniaxial or triaxial mechanical properties of complete rock specimens, without considering the special stress state of the free face rock after the excavation of the cavern. However, the deformation and failure characteristics of the free face rock is a direct manifestation of whether the surrounding rock is stable, and it is also an
important basis for adopting relevant support measures. In addition, previous studies have seldom analyzed the mechanical damage mechanism of rock under the combined action of faults and water content, making the support of free face rock can only be carried out according to the relevant engineering experience, which has a certain blindness. So aiming at the characteristics of fault cutting and abundant groundwater in the underground cavern of Yebatan hydropower station, this paper constructs free face rock specimens with different types of cracks and different water contents, and conducts a systematic study on their mechanical properties.

2. Material and methods

2.1. Specimen preparation

The rock blocks used in this experiment are all taken from the Yebatan hydropower station, and the lithology is granite. In order to construct specimens with different initial cracks and water content, the following steps were performed respectively: Firstly, a number of complete cube specimens with a size of 50mm×50mm×50mm were taken out from the rock block; Secondly, the front and back surfaces of some intact rock specimens are slit. The crack is penetrating. The length of the crack \( L \) is 25 mm and the width \( W \) is 0.4 mm. The center point of the crack coincides with the center point of the specimen surface, and the angle of the crack \( \alpha \) is 0°, 45° and 90°, respectively. The other four surfaces of the specimen are not treated, and the schematic diagram and physical diagram of the crack specimen are shown in Figure 1; Finally, three specimens of the same type (complete specimens or specimens with the same crack inclination angle) are taken out and dried in an oven, as shown in Figure 2. Then, one specimen is kept dry without treatment, one specimen is taken for cooking for 10 minutes in boiling water, and one specimen is taken for cooking for 1 hour in boiling water. So far, the specimens with different initial cracks and water content are obtained, as shown in Figure 3.

(a) Schematic diagram of crack specimen  (b) Physical diagram of crack specimen

Figure 1. the schematic diagram and physical diagram of the crack specimen

Figure 2. Oven  Figure 3. Complete and crack specimens with different water content

The specimens in Figure 3 are numbered as follows: 1-1, 1-2, 1-3... 4-1, 4-2, 4-3. The Arabic numerals on the left side of the number represent the specimen type, "1" represents the complete specimen, and "2-4" represents the specimen with the inclination angle of 0°, 45° and 90° respectively. The Arabic numerals on the right side represent the cooking time in boiling water. "1" means that the specimen will not be cooked. "2, 3" represent the cooking
time are 10 minutes and 1 hour, respectively. For example, the specimen numbered 2-2 represents a specimen with a crack inclination angle of 0° that has been cooked in water for 10 minutes.

2.2. Test method
In order to study the mechanical properties of the free face rock, a kind of mold with lateral restraint is specially designed. The material of the mold is 45# steel, and the volume of the internal cavity of the mold is 56mm (long side, as the free face) × 51mm (wide side) × 46mm (high side, to prevent the indenter from contacting the mold). Through the screw and shim, the placed specimen is in contact with the three sides of the mold, so as to realize the lateral restraint of the specimen. The mold can ensure that only one surface of the specimen is a free surface during the compression test, and the remaining surfaces are all restrained. The specimen is placed in the mold as shown in Figure 4.

Figure 4. The mold which can simulate the force characteristics of the free face rock

A microcomputer controlled electro-hydraulic servo universal testing machine is used in the experiment, the maximum load of the testing machine is 600kN, which has the characteristics of high precision and sensitive response. In order to take into account the test accuracy and the data collection time, the loading method includes two ways, that is, displacement control and stress control. The initial compaction stage is the displacement control method, and the loading rate is 0.05mm/s; when the load reaches at 3kN, the loading mode is automatically switched to stress control, and the loading rate is 2kN/s.

3. Results

3.1. Water content and analysis
By weighing the mass of each specimen after drying and cooking, the water content of each specimen is obtained, as shown in Figure 5.

Figure 5. Water content of each specimen

It can be seen from Figure 5 that the water content of different types of specimens has the following laws: for the same type of test piece, the moisture content of cooking in water for 1 hour is always greater than that of cooking in water for 10 minutes; when the cooking time of the specimen is 10 minutes, the water content of the complete and cracked specimens with inclination angles of 0°, 45° and 90° gradually increase; when the cooking time of the specimen is 1 hour, the water content of the complete and cracked specimens with inclination
angles of 0°, 45° and 90° first increase and then decrease; when the cooking time is the same, the water content of the cracked specimen is significantly higher than that of the complete specimen. Therefore, the water content of cracked granite should be paid special attention in water environment.

3.2. Characteristics of stress-strain curve
In the test, it is found that the stress-strain curve of the specimen can be roughly divided into two types, in which the complete specimen corresponds to one type of stress-strain curve, and the cracked specimen corresponds to another type of stress-strain curve. Here, 1-2 specimen and 3-3 specimen are taken as representatives to explain. It can be seen from Figure 6 that the stress-strain curve of the complete specimen under different water content is basically similar to that under conventional uniaxial compression. There are also compaction stage, linear elastic stage, microcrack propagation stage, inelastic deformation failure stage and post peak stage, which will not be changed due to the existence of lateral constraints; for the cracked specimen, in addition to the above stages, there is an obvious stress drop phenomenon in the microcrack propagation stage, that is, the stress will decrease briefly and then continue to increase. And it is found that when the stress drop occurs in the crack specimen, there will be a loud sound in the compression process, which may be due to the compaction of the prefabricated crack under the action of axial pressure, and the friction sliding occurs. Combining with the shape of the specimen after failure, it can be considered that the compaction of the prefabricated cracks has a strong correlation with the occurrence of stress drop. At the same time, the apparent degree of stress drop has an obvious relationship with the inclination angle of the prefabricated cracks. Generally speaking, as the inclination angle of the prefabricated crack increases, the stress drop phenomenon weakens, but it has little correlation with the water content of each specimen.

![Figure 6. Typical stress-strain curves of complete and cracked specimens](image)

3.3. Strength characteristics
The compressive strength of each specimen is shown in Figure 7.

![Figure 7. Relationship between strength and water content of specimen](image)

It can be seen from Figure 7 that the strength of each specimen is between 92.212 MPa and 221.64 MPa, which is generally greater than the conventional uniaxial compression
strength. This is due to the existence of lateral restraint, which makes the specimen subject to similar confining pressure on several surfaces except the free surface. For the complete specimen and the cracked specimen with different dip angles, the strength decreases with the increase of water content. Compared with dry specimen, the strength of the same type of specimen is reduced after cooking in boiling water for different times, that is: 13.23% (1-2), 30.17% (1-3); 9.34% (2-2), 48.98% (2-3). It can be seen that, compared with the dry specimen, the maximum ratio of strength reduction is 50.92% (4-3), and the lowest ratio of strength reduction is 9.34% (2-2), indicating that when the crack angle of the specimen is 90°, the long-time water environment can have a significant impact on the strength of the specimen; when the crack angle of the specimen is 0°, the short-time water environment cannot have a significant impact on the strength of the specimen, however, if the specimen is exposed to a water environment for a long time, the strength of the specimen will still be greatly reduced. For the complete specimen or crack specimen with the inclination angle is 45°, the strength reduction is relatively low when they are in the water environment for a long time. In conclusion, for the excavation and support of free face in the field water environment, we should pay attention to the rock strength at the fault with gentle and steep dip angle.

3.4. Deformation and failure characteristics
It is found that the axial deformation of the specimen in the compression process has obvious stages, which can be roughly divided into the following two processes: 1. when the specimen does not reach its peak strength, the deformation of the specimen is not significantly different from that of the conventional uniaxial compression, and the deformation increases slowly; 2. when the specimen reaches its peak strength, the specimen is destroyed instantaneously. At this time, the specimen shows obvious compression shape, and the height of the specimen is only slightly higher than that of the mold. That is to say, the axial deformation of the specimen at the peak stage is abrupt, and the typical comparison between the height of the specimen after failure and the height of the mold is shown in Figure 8.

Figure 8. Comparison between the height of specimen after failure and the mold
The reason for this phenomenon is that: the mold provides lateral restraint on the specimen, the transverse deformation of the specimen in the pre-peak compression stage is restricted to a certain extent, which also makes the axial deformation of the specimen not obvious. However, it does not mean that the development of micro-damages inside the specimen is delayed. On the contrary, since the deformation is suppressed at this time, the energy accumulated inside the specimen cannot be effectively released, so the energy accumulated inside the specimen is more than that under conventional uniaxial compression, which can promote the rapid development of micro-damage in the pre-peak stage, the specimen is fully affected by the pressure head, and the larger fragments of the granite gradually transform into smaller fragments, or even into broken grains. When these smaller fragments or granules can no longer bear the load, they will deform and gush out toward the free surface, and the accumulated energy will be released, resulting in a sudden change in the axial deformation of
the specimen. This test phenomenon is similar to the mechanism of rock burst in the working face. When the energy inside the rock accumulates to a certain extent, the broken rock mass gushes out towards the free face. Therefore, for the support of free face, it may be an attempt to increase the deformation space of constraint surface and reduce the deformation space of free face. In addition, the deformation and failure of free face hard rock is suddenly, so timely support is particularly important. The failure mode of the specimen can further reveal the mechanical damage mechanism. Figure 9 shows the final failure mode of each specimen.

![Figure 9. Ultimate failure mode of specimen](image)

It can be seen from Figure 9 that the final failure form of the specimen has different characteristics, mainly in the following aspects. (1) For the same type of specimen, the degree of fragmentation of the specimen is negatively correlated with the moisture content, that is, as the moisture content increases, the degree of fragmentation of the specimen is lower. This is due to the intrusion of water, which softens the granite to a certain extent, weakens its brittleness and increases its plasticity. (2) At similar water content, the final fragmentation of the complete specimen is the most severe. This is because there is no crack, the free face rock will not consume part of the energy due to the closure of the crack, as other cracked specimens do. And the specimen accumulates more energy, which can promote the development and expansion of microcracks better, so the specimen is broken more thoroughly.
in the end. (3) For the crack specimens with inclination angles of 0° and 45°, the
macro-controlling cracks that finally lead to the failure of the specimens are all developed
from the tip of the prefabricated crack; and for the crack specimens with an inclination angle
of 90°, the failure morphology of the specimen has little correlation with the prefabricated
crack. It can be longitudinal split failure (such as +1) or laminar failure (such as +3).

3.5. Microstructure analysis
The macro-mechanical properties of the free face rock are the concentrated reflection of its
micro-features. In order to further study the mechanical damage mechanism of the free face
rock, the fracture morphology of the specimen after failure is scanned by electron microscope,
and the representative image is selected for description, as shown in Figure 10.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image10.png}
\caption{A typical scanning electron microscope image of the fracture of the
specimen.}
\end{figure}

It can be seen from Figure 10 that the failure of granite under micromorphology can be
summarized into the following two types. (1) The cementation between the minerals is
weakened, and shear cracks appear. At this time, the failure type can be regarded as
intergranular failure along the mineral cementation surface, as indicated by the number “1” in
the figure, and occupies a large proportion in the figure. The intergranular fracture of the
mineral bonding surface often makes the specimen appear to be granular, which is consistent
with the experimental phenomenon in this paper. (2) Microcracks may also be formed in
different mineral grains, and transgranular fracture may occur if these microcracks are further
developed, as indicated by the numbers “2” and “3” in the figure. Transgranular fracture often
leads to brittle failure. In this paper, because of the existence of lateral restraint, a large range
of intergranular fracture occurs between mineral particles, which makes the fracture
morphology of the specimen more broken than that under conventional uniaxial compression.

It can also be seen from Figure 10 that the contact boundary between different mineral
particles is relatively clear. Except for the part shown by number “1” where a large range of
shear failure occurs, the characteristics of brittle fracture is obvious, the other parts have
good mineral cementation, high density, flat connection between mineral particles, and no
obvious uplift or depression. These characteristics enable different mineral particles to
conduct and spread the force effectively when the granite is subjected to external force, and
avoid the formation of multiple local stress concentration states. Therefore, the strength of
granite is higher under the lateral restraint. In addition, due to the existence of lateral
constraint, the natural joints in granite may be closed to a certain extent, which will not
further crack and penetrate under the action of external force. Therefore, compared with
conventional uniaxial compression, the failure along natural joint plane (i.e. transgranular
fracture) of free face rock is weakened, while the intergranular fracture between mineral
particles is strengthened. It is found in the underground cavern of Yebatan Hydropower
Station that when the free face rock is damaged by spalling, the contact part between spalling
block and original rock often presents granular shape, which is consistent with the fracture micro morphology revealed in Figure 10.

4. Conclusion
The main conclusions of this paper are as follows.
(1) The stress-strain curve of the complete specimen under different water content is basically similar to that under conventional uniaxial compression. For the cracked specimen, there is an obvious stress drop phenomenon in the microcrack propagation stage, which has an obvious relationship with the inclination angle of the prefabricated cracks.
(2) When the complete specimen and the cracked specimen with different dip angles are in water for a long time, their strength decreases have great differences.
(3) Due to the existence of lateral restraint, the axial deformation of specimen is abrupt when it reaches the peak strength, and the broken rock mass has the phenomenon of gushing out.
(4) The degree of fragmentation of the specimen is negatively correlated with the moisture content, that is, as the moisture content increases, the degree of fragmentation of the specimen is lower. For the crack specimens with inclination angles of 0° and 45°, the macro-controlling cracks that finally lead to the failure of the specimens are all developed from the tip of the prefabricated crack; and for the crack specimens with an inclination angle of 90°, the failure morphology of the specimen has little correlation with the prefabricated crack.
(5) SEM shows that there is a large range of intergranular fracture between mineral particles, which makes the fracture morphology of the specimen more broken than that under conventional uniaxial compression.

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