Energy Evolution Mechanism and Confining Pressure Effect of Granite under Triaxial Loading-Unloading Cycles

WANG Hao$^{1,2}$, MIAO Sheng-jun$^{1,2}$

$^1$School of civil and environmental engineering, University of Science and Technology Beijing, Beijing 100083, China
$^2$Key Laboratory of High-Efficient Mining and Safety of Metal Mines (Ministry of Education of China)
E-mail: wanghai@126.com

Abstract. Rock mass undergoes some deformational failure under the action of external loads, a process known to be associated with energy dissipation and release. A triaxial loading-unloading cycle test was conducted on granite in order to investigate the energy evolution pattern of rock mass under the action of external loads. The study results demonstrated: (1) The stress peaks increased by 50% and 22% respectively and the pre-peak weakening became more apparent in the ascending process of the confining pressure from 10MPa to 30MPa; the area enclosed by the hysteresis loop corresponding to 30MPa diminished by nearly 60% than that corresponding to 10MPa, indicating a higher confining pressure prohibits rock mass from plastic deformation and shifts strain toward elastic deformation. (2) In the vicinity of the strength limit, the slope of dissipation energy increased to 1.6 from the original 0.7 and the dissipation energy grew at an accelerating rate, demonstrating stronger propagation and convergence of internal cracks. (3) At a pressure of 70% of the stress peak, the elastic energy of the granite accounted for 88% of its peak value, suggesting the rock mechanical energy from the outside mostly changes into the elastic energy inside the rock, with little energy loss. (4) Prior to test specimen failure, the axial bearing capacity dropped with a decreasing confining pressure in an essentially linear way, and the existence of confirming pressure played a role in stabilizing the axial bearing capacity.

1. Introduction
During the excavation process, rock mass undergoes some deformational failure to be associated with energy evolution. Failure of rock mass has become an important hot issue in geotechnical engineering field. The nature of rock material failure is destabilization rupture driven by energy. Now in the geotechnical engineering field, more and more people analyze the failure process of rock from the perspective of energy [1]. The failure process of rock is usually coupled with energy input, accumulation, dissipation and release, attributing to complex energy exchange [2]. Energy of rock is input into the rock in the form of external mechanical energy and is stored in rock in the form of elastic energy [2-3]. In the vicinity of the strength limit under the action of external loads, the elastic energy is released so as to generate kinetic energy, followed by causing rock fragmentation. Since it is difficult to see the micro-variation inside rock during failure process, to analyze the process from the perspective of energy is very effective and closer to the nature reason of failure [1][4][5]. Many experts and scholars have conducted some researches on the characteristics of rock failure. Zhang et al. pointed that the energy evolution process of rock reflects the failure process in the microcosmic, revealing the failure law of rocks [6]. Zhang et al. pointed that within the quasi-state loading range, the
less the loading rate is, the larger the dissipation energy will be [7]. Basically, the loading rate has no influence on the elastic energy evolution. Peng et al. showed that under low confining pressure and uniaxial compression, the elasticity modulus of coal rock rises with the decrease in cyclic stress [8]. The elasticity modulus does not present such feature under high confining pressure. Yang et al., You et al. have conducted regular triaxial compression test on marble and siltstone, finding that the energy absorbed by rock mass presents the same linear relation with confining pressure [9-10]. Fu et al. studied the rock failure process under different stress paths in virtue of acoustic emission monitoring technology [11]. Based on the triaxial compression test on granite, Pan et al. found out that with the decrease in axial stress, crack inside samples increases in a linear way [12]. Zhao et al. pointed that the decrease in rock strength is due to energy dissipation which is easy to cause rock catastrophe phenomenon [13].

The excavation process of rock mass is usually coupled with energy input, accumulation, dissipation and release. The deformational failure and reinforced supporting process of loaded rock is also a process where energy transfers and evolves. Considering differences in energy input way and rate, rock structure, geological environment and other factors, rock energy evolution has different expression forms. Also, ways of rock deformational failure change accordingly. In order to observe, explain and solve some puzzles in rock engineering, it is necessary to firstly study the energy status of rock under different stress statuses, including the amount of accumulated elastic energy and dissipation energy and their proportion in total input energy. Besides, it is necessary to study the characteristics of energy evolution of loaded rock with different lithology and under different confining pressures. On the basis of triaxial cyclic loading and unloading test on three varieties of rocks respectively, the paper gets the cyclic loading and unloading curve, energy evolution and distribution law as well as the confining pressure effect. Research results are of great significance to studying the failure mechanism of rock.

2. Energy calculating method

The deformational failure process of rock is usually associated with energy dissipation and release. Considering that the release of dissipation energy features irreversibility and that of elastic energy features reversibility, we have investigated the elastic energy and dissipation energy of rock during deformational failure process. According to the Energy Conservation Law [14-15]:

\[ W = E_e + E_d \]

Figure 1. Loading and unloading stress-strain curves of rock at stress of \( \sigma' \)

3. Test process
3.1. Sample preparation
Sample is granite which is from the Lingbao Mine of Henan Province. The average longitudinal wave velocity of samples is 4,015m/s, the porosity is 1.19%, the dynamic elasticity modulus is 43.60GPa and the average density is 2.561g/cm³. There are many original interstices inside samples. Samples are processed into Φ50mm×100mm standard cylinder in lab. Two ends of samples are repeatedly polished using sandpaper to make the surface flatness lower than 0.05mm. The flatness between top and bottom surface is controlled to be lower than 0.2mm.

3.2. Test method and equipment
Choose the granite samples for triaxial loading and unloading test at confining pressure of 10MPa, 20MPa, 30MPa respectively. Use TYP-500 triaxial compression tester to add the confining pressure to target value and than add axial pressure. The confining pressure of each sample is loaded to 50% of peak limit and unloaded to 0MPa, followed by being increased by 30MPa for each time. The loading rate in early stage is 0.1mm/min. When the confining pressure is loaded to residual phase, the loading rate is rose to 0.03mm/min in order to get the post-peak curve. PCI-2 acoustic emission monitoring system is used during whole process to monitor and record data needed.

4. Rock energy evolution and analysis under triaxial loading and unloading cycle test

4.1. Triaxial cyclic loading and unloading failure characteristics
The cyclic loading and unloading stress-strain curve and failure modes of samples are got after test. As shown in Figure 4, the external envelope mode in the cyclic loading and unloading stress-strain curve, similar with regular loading curve, can be divided into four phases, namely compaction phase, elastic phase, weakening phase and failure phase. The stress peaks of granite are 120MPa, 180MPa and 220MPa respectively at confining pressures of 10MPa, 20MPa and 30MPa. Therefore, when confining pressure increases, the stress peaks increase by 50% and 22% respectively. According to the stress-strain curve under the same confining pressure, increase in stress and strain presents nonlinear relation. The curve appears concave, indicating that the larger the strain is, the faster the increase speed of stress will be. According to Figure 2, 3, 4, hysteresis loop of sample deformation curve under cyclic loading effect shrinks gradually. The area enclosed by the hysteresis loop corresponding to 30MPa diminished by nearly 60% than that corresponding to 10MPa, indicating that a higher confining pressure prohibits rock mass from plastic deformation and shifts strain toward elastic deformation. Besides, prior to conducting axial stress, higher confining pressure makes natural interspace close more tight inside rock, which verifies that the higher confining pressure can improve compressive strength. After collecting and comparing fracted samples tested in lab, it is founded that there are more rock fragments under 10MPa and most fragments concentrate around the main fault line. Fault line of samples under 20MPa appears obvious shear plane and the fracture plane is not smooth, with loose rock seen. Fault line of rock samples under 30MPa is not obvious and presents curve shape. With increase in confining pressure, main fault line number decreases gradually, showing that confining pressure increase enhances the integrity of rock.

![Figure 2](image_url)

*Figure 2. The cyclic loading and unloading stress-strain curves and failure modes of granite H-4 under 10MPa confining pressure*
Figure 3. The cyclic loading and unloading stress-strain curves and failure modes of granite H-42 under 20MPa confining pressure

Figure 4. The cyclic loading and unloading stress-strain curves and failure modes of granite H-59 under 30MPa confining pressure

4.2. Energy evolution pattern during triaxial cyclic loading and unloading process
According to loading and unloading curve from Figure2 to Figure4, the elastic energy density and dissipation energy density of granite under different loading levels are calculated using mathematics integral formula, seen in Figure5.

Figure 5. The elastic and dissipation energy densities curves of granite with its stress change

Theoretically, the confining pressure of hydrostatic stress status is the start point of research. Actually, the energy inside rock mass suffers some changes during the process from the beginning of loading to hydrostatic balance status, yet, the value of these changes is small compared with energy change during rock failure process. Therefore, the energy change during this phase is excluded from consideration in the test. The test only takes into account the axial action of tester on samples. Figure5 shows that during the triaxial cyclic loading and unloading process, with the increase in axial stress, the elastic energy density curve of three samples is basically similar with dissipation energy density curve, analyzed taking H-42 as an example. The elastic energy density of sample under confining pressure of 100MPa is 85KJ/m3, and that rises to 130 KJ/m3 under confining pressure of 140MPa and to 190 KJ/m3 under confining pressure of 175MPa. As seen from image that dissipation energy curve increase is basically the same as elastic energy curve, with both increasing in an approximate power exponent form. In Figure5, since the axial stress is implemented, the elastic energy curve is basically above the elastic energy curve. Differences between two numerical values become larger and larger prior to stress peak, indicating that rock is mainly under energy accumulation prior to
stress peak. From the other perspective, the reason that curve increases in an approximate power exponent form and curvature appears small to big is that there are too many interspace cracks inside rock in early stage. Inside particles are squeezed mutually after compaction and energy conversion ratio increases. With increase in loading, samples gradually reach the energy storage strength limit. In the vicinity of the strength limit, the slope of dissipation energy increased to 1.6 from the original 0.7, rising by 128% or so. The growth rate keeps rising, demonstrating stronger propagation and convergence of internal cracks. Also, the inside structure is under change under action of cyclic loads. As shown in diagram, the dissipation energy density of sample H-4 suddenly boosts in the fourth cycle because that a large amount of energy is consumed due to pre-peak failure, which is basically consistent with the research results of Dai Bing.

4.3. Energy distribution law during triaxial cyclic loading and unloading process
Figure 6 is the curve of proportion of elastic energy and dissipation energy of granite in total input energy under different confining pressures with stress peak intensity ratio change. The curve reflects the energy distribution law during triaxial cyclic loading and unloading process. During the triaxial cyclic loading and unloading process, a part of mechanical energy implemented by machine is released in the form of dissipation energy and another part is transferred into elastic energy to be stored inside the rock. In energy ratio curve, elastic energy takes up 0.7-0.9, much higher than that of dissipation energy, demonstrating that most mechanical energy from the outside are transferred into elastic energy and only 10%-30% of mechanical energy are transferred into other dissipation energy. In the ascending process of peak intensity ratio from 0.2 to 0.7, the proportion of elastic energy of H-42 in input energy rises with the increase in loads and, at the peak intensity of 0.7, the proportion reaches the peak of 0.88 while proportion of dissipation energy reaches the lowest point of 0.12 (H-59 presents similar image). That indicates that prior to stress peak, stress change impacts energy evolution process, revealing the distribution law of energy inside rock. According to the curve of H-4 granite, the proportion of elastic energy of the fourth cyclic rock lowers greatly and that of dissipation energy rises greatly because that the samples have lost bearing capacity due to failure before the fourth cycles, demonstrating that large amount of energy will be consumed during failure process which takes up a large proportion of energy consumption. Based on above analysis, value of confining pressure can obviously affect the energy distribution inside rock. The larger the confining pressure is, the larger the elastic energy it transfers will be and the easier that rock burst will occur during excavation.

![Figure 6](image_url)

Figure 6. The evolution law of granite elastic and dissipation energy account for the proportion of total input energy with the ratio of peak intensity change

5. Confining pressure effect of rock energy evolution
5.1. Rock energy evolution under unloading confining pressure test
According to the rock inside energy evolution and distribution law got from the triaxial cyclic loading failure test, energy change during unloading process has different stress path from that during loading process. The mechanical properties of the two processes are different in nature. The unloading confining pressure test of granite studies the impact of unloading confining pressure on rock strength and deformation characteristics with axial stress unchangeable. Test operators load a
certain stress (about 85% of peak strength, ensure that samples will not be damaged) in axial under confining pressure of 10MPa, 15MPa, 20MPa, 25 MPa and 30MPa respectively and lower confining pressure after making axial stress unchangeable using triaxial tester, until samples are damaged.

At confining pressure of 10MPa, 15 MPa, 20MPa, 25 MP and 30MPa, the axial pressure loads of samples are added to 180MPa, 200 MPa, 210MPa, 250MPa and 255 MPa successively and loading stops, so as to ensure the axial stress unchangeable. Meanwhile, the confining pressure is gradually unloaded. As shown in Figure 7 (b), (c), (d), as confining pressure decreases evenly by 5MPa, the axial loads lower gradually and transverse stress enlarges gradually until rocks are damaged, showing that confining pressure improves the compressive strength of rock, effectively restricts the transverse crack and deformation as well improves the integrity of rock.
In the initial stage of unloading confining pressure, the transverse deformation of rock samples does not increase greatly and transverse stress presents a linear relation with confining pressure. The three change curves of transverse stress at confining pressure of 10MPa, 15MPa and 20MPa are basically in a line and two curves with confining pressure of 25MPa and 30MPa present similar deformation process, proving that initial deformation is under elastic deformation phase. With continuous decrease in confining pressure, transverse deformation increases to some extents and features plastic failure. Five deformation curves in Figure 8 shows that the larger the initial value of confining pressure is, the larger the confining value during plastic failure will be. That is to say, samples failure occurs not during the process that confining pressure is totally removed but during unloading process.

![Graph](image)

**Figure 7.** Stress-strain curves of rock samples under axial unloading at different confining pressures

**Figure 8.** The confining pressure curves with transverse strain change of rock samples

Axial stress-confining pressure change curve of granite is shown in Figure 9. In the initial stage of unloading confining pressure, the axial stress descends with confining pressure decrease, yet the descending extent is relatively slow. After confining pressure descends for a while, axial bearing capacity of samples will gradually lower to the axial stress value loaded by instrument. Then samples are damaged and axial bearing capacity curve plunges rapidly. The process demonstrates that the axial bearing capacity dropped with a decreasing confining pressure in an essentially linear way, and the existence of confirming pressure played a role in stabilizing the axial bearing capacity. Also, optimization support is proven to be of vital importance to engineering project.

With axial displacement unchangeable, the energy to cause rock failure is elastic deformation energy stored inside rocks during the failure process of rock specimen under triaxial unloading process of confining pressure and there is no action from other external forces. Under triaxial stress state, when stress at a direction falls suddenly, rock failure will occur even thought the rock is under low stress state. However, due to low stress, energy value absorbed during rock failure is less. The process...
focuses on elastic energy release. If rock mass lacks effective support, energy released by protolith will be transferred into kinetic energy to crack rocks, leading to striking rock burst.

![Figure 9](image)

**Figure 9.** Variation curves of axial stress and confining pressure of granite

### 6. Conclusion

On the basis of research and analysis of energy evolution mechanism and confining pressure effect of granite under triaxial cyclic loading and unloading, the paper draws the following conclusions:

1. As for the stress-strain curve of rock, the increase in confining pressure affects the change during pre-peak phase to some extents. In the ascending process of the confining pressure from 10MPa to 30MPa, the stress peaks increased by 50% and 22% respectively and the pre-peak weakening became more apparent; the area enclosed by the hysteresis loop corresponding to 30MPa diminished by nearly 60% than that corresponding to 10MPa, indicating a higher confining pressure prohibits rock mass from plastic deformation and shifts strain toward elastic deformation. In the post-peak phase, the larger the confining pressure is, the gentler the decrease curve will be.

2. Pre-peak phase of rock focuses on energy accumulation. The proportion of elastic energy in input energy increases with the increase in loads. In the vicinity of the strength limit, the slope of dissipation energy increased to 1.6 from the original 0.7, rising by 128% or so. At the peak intensity, the elastic energy proportion reaches the peak and the dissipation energy proportion reaches the lowest point, showing that energy evolution begins to change before loads reach the peak intensity. Prior to failure, the dissipation energy grew at an accelerating rate, demonstrating stronger propagation and convergence of internal cracks.

In energy ratio curve, elastic energy takes up 0.7-0.9, much higher than that of dissipation energy, demonstrating that most mechanical energy from the outside are transferred into elastic energy and only 10%-30% of mechanical energy are transferred into other dissipation energy. Prior to stress peak, stress change impacts energy evolution process, revealing the distribution law of energy inside rock. Under triaxial stress state, the axial bearing capacity dropped with a decreasing confining pressure in an essentially linear way, and the existence of confirming pressure played a role in stabilizing the axial bearing capacity. When the stress at a certain direction plunges, energy inside rock is released quickly and elastic energy transfers into kinetic energy to crack rocks, leading rock mass failure. Therefore, in actual engineering, it is essential to conduct effective pre-supporting measures on rock masses so as to get rid of potential safety risks.

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