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Characteristics of Pre-peak Mechanical Damage and Energy Evolution of Typical Hard-rock in Diversion Tunnel under Cyclic Loading-Unloading

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ABSTRACT

An in-depth understanding of the pre-peak mechanical damage and energy-evolution characteristics of typical hard-rock in a diversion tunnel under cyclic load is of great significance to promote the safe and efficient construction of the diversion tunnel and the stability of surrounding rock. To study the pre-peak mechanical characteristics and the competition mechanism between energy storage and energy dissipation of typical hard-rock in a diversion tunnel under cyclic loading-unloading, combined with the internal drilling and blasting excavation of the actual engineering rock mass and the external vehicle cyclic load environment of the diversion tunnel, the cyclic loading-unloading tests of typical granite and tuff in diversion tunnel were carried out. Based on the analysis principle of mechanics and energy, the strain variables, modulus variables, energy variables and damage variables of granite and tuff under cyclic loading-unloading test were defined. The cyclic mechanical properties and energy-evolution characteristics of granite and tuff under pre-peak load were analyzed. The competition mechanism between pre-peak energy storage and pre-peak energy dissipation of granite and tuff and the evolution law of strain damage variable and energy damage variable were revealed. The selection principle of rock sample size and the limitation of the test scheme were further discussed. The study of the damage evolution of rocks close to failure (pre-peak stage) under cyclic load is helpful to better understand the damage and failure mechanism of rocks in practical engineering problems.

Keywords: Diversion tunnel, Cyclic loading-unloading, Granite/Tuff, Blasting cyclic load, Energy evolution.

INTRODUCTION

The construction of diversion tunnels can create favorable conditions for city emergency backup water supply, farmland irrigation, river network ecological water replenishment and flood control and drainage. However, the diversion tunnels have a long route and underpass a variety of buildings (expressways, … etc.). The dimensions and surrounding-rock properties of the main tunnel, branch tunnel, water-distribution tunnel and inspection tunnel are very different and the site conditions and surrounding environment of each construction face are complicated (Wu and Wang, 2011). Under the initial influence of complex geological structures and natural occurrence conditions, periodic cyclic external loads, such as earthquakes, blasting and vehicles, have extremely adverse effects on the surrounding-rock stability of the tunnel (Hu et al., 2023; Cui and Ma, 2021; Yuan and Wang, 2021). The mechanical-damage properties and energy-evolution process of rock under cyclic load are different from those under static load and this makes the study of damage evolution of rocks close to failure (pre-peak stage) under cyclic loading helpful to better understand the damage and failure mechanisms of rocks in practical engineering problems (Song et al., 2016). Therefore, the experimental study on a cyclic dynamic load of typical rock in a diversion tunnel is of great significance in obtaining the relevant dynamic parameters of rock mass in a diversion tunnel.

At present, many scholars have carried out dynamic cyclic-loading tests on all kinds of rock. In the aspect of mechanical damage under cyclic load, Lin et al. (2022) studied the stress-strain behavior, damage variable and dissipated energy in the process of deformation and failure of salt rock under cyclic load and obtained the damage characteristics and energy change of triaxial failure of salt rock. Li et al. (2023) systematically studied the blasting-failure mechanism of rock mass and the cumulative damage evolution effect of cyclic-blasting load under different ground-stress conditions through theoretical analysis, laboratory tests and numerical analysis. Xu et al. (2021) analyzed the change law of meso-fatigue damage crack number and energy of rock joints under cyclic shear loading and revealed the evolution process of rock rhythmic meso-fatigue failure and the characteristics of particle distribution. Liu et al. (2016) introduced the damage variable based on energy dissipation, calculated the damage-evolution equations of two typical rocks under cyclic loading and established the damage constitutive model of rock under cyclic loading. Shen et al. (2020) carried out cyclic loading-unloading tests of sandstone under different stress paths, analyzed the variation rules of cyclic mechanical properties and acoustic emission signals of samples, described the evolution characteristics of residual strain and elastic modulus and revealed the evolution mechanism of cyclic damage.

In the aspect of energy evolution under cyclic load, to study the energy distribution characteristics of rock and its response to confining pressure, Luo et al. (2023) analyzed the pre-peak input strain energy, pre-peak elastic strain energy and pre-peak dissipated strain energy of rock under triaxial cyclic compression and confirmed the linear energy storage and dissipation law in the process of triaxial cyclic compression. He et al. (2023) studied the fracture evolution and macroscopic and microscopic energy evolution of round-hole rock specimens under stress gradient and constant stress and quantified the energy-storage and energy-dissipation capacity of rock. Considering the law of linear energy-dissipation under uniaxial cyclic compression, Gong et al. (2022) proposed a rock damage-characterization method including compression energy dissipation coefficient and established brittle rock damage variables based on compression-energy dissipation coefficient and input strain energy. To study the influence of the thermal effect on the energy dissipation of rock during dynamic cyclic loading, Shu et al. (2019) carried out cyclic impact loading experiments on heat-treated rocks and analyzed the correlation among energy dissipation, energy-dissipation rate, impact times, cumulative energy per unit volume, failure mode and temperature. To explore the relationship between the energy-dissipation process and shear-expansion deformation in the process of rock damage and failure, Zhang et al. (2018) took gneissic granite in the diversion tunnel of a hydropower station in southern Xinjiang as the research object, carried out incremental cyclic loading-unloading tests of rock under different confining pressure and revealed the variation law between energy-dissipation rate and shear-expansion angle.

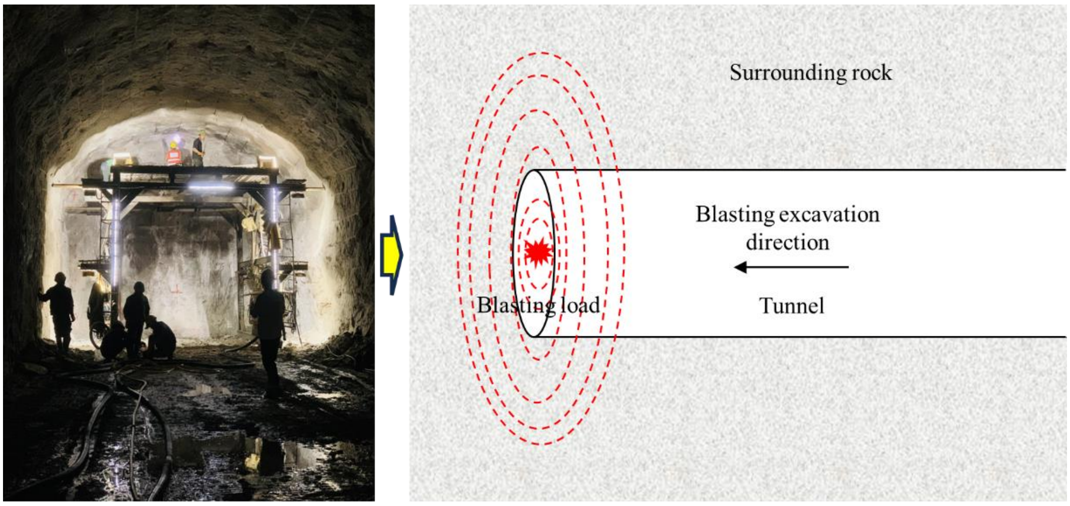
It is undeniable that the above research results play an important role in the development of rock mechanics and engineering technology. However, most of the above studies lack practical engineering background and most of the research results are at the theoretical level, which does not have targeted engineering guidance. At the same time, the research on the pre-peak mechanical damage law and energy-evolution characteristics of hard rock under cyclic loading-unloading is not deep enough. In particular, the competition mechanism between different energies of rocks under cyclic loading-unloading has not been fully concerned and deeply revealed. There is also a lack of research and discussion on the evolution law of strain-damage variables and energy-damage variables. In view of this, combined with the internal drilling and blasting excavation of the actual engineering rock mass and the external vehicle cyclic load environment of the diversion tunnel, the cyclic loading-unloading tests were carried out on the typical hard rock (granite and tuff) of the diversion tunnel. The typical pre-peak cycle mechanical properties and energy-evolution characteristics of granite and tuff were analyzed and the evolution law of cyclic mechanics and the competition mechanism between energy storage and energy dissipation were revealed. Also, the evolution law of strain-damage variable and energy-damage variable was revealed.

TEST OVERVIEW AND METHODOLOGY

Engineering Background

The surrounding rocks of a diversion tunnel in Zhejiang are mainly granite and tuff, which are hard rocks with good engineering geological conditions and the surrounding rocks of the tunnel are mainly type II ~ III surrounding rocks.

Blasting Cyclic Load: Tunnel excavation was mainly done by drilling and blasting, noting that cyclic blasting excavation undoubtedly had a negative impact on the surrounding rock to a certain extent. Therefore, it is necessary to consider the effect of blasting cyclic load on the surrounding rock of the diversion tunnel. The schematic diagram of the blasting cyclic load of the diversion tunnel is shown in Figure 1.



Engineering site Schematic diagram of blasting excavation

Figure (1): Schematic diagram of the blasting cyclic load of the diversion tunnel

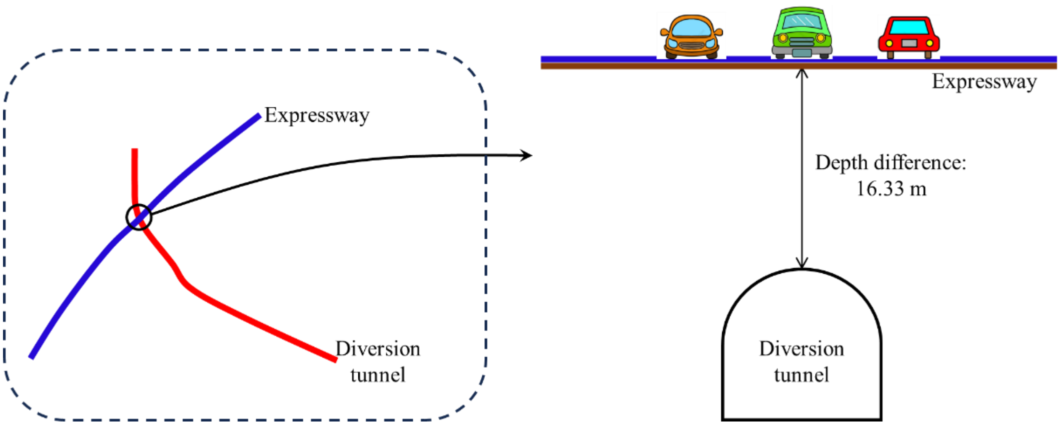


Figure (2): Schematic diagram of the vehicle cyclic load of the diversion tunnel

Vehicle Cyclic Load: A certain section of the tunnel passes through the highway and the angle of intersection between the two is 75°. The relative depth difference between the top of the tunnel excavation and the foundation top of the highway is about 16.33m. So, it is necessary to consider the effect of vehicle cyclic load on the surrounding rock of the diversion tunnel. The schematic diagram of the vehicle cyclic load of the diversion tunnel is shown in Figure 2.

Preparation Method of Rock Samples

The raw materials used in the test were granite and tuff from the diversion tunnel passing through the expressway. The original rock materials in the field were processed into rock samples with a size of *Φ* 55 mm × *h* 110 mm through the processes of on-site coring, laboratory cutting and end-face polishing. According to the regulations of GB/T 23561-2009 and GB/T 50266-2013, the diameter of the standard rock sample should be 48~56 mm, the ratio of height to diameter of the rock sample should be 2.0~2.5 and the non-parallelism error between the two ends of the specimen is guaranteed to be less than 0.05mm. The rock samples used in the test all met the standard rock samples required in the standard specification. The specific process of rock-sample preparation is shown in Figure 3. It should be noted that to ensure the accuracy of the test results, the number of tested samples for each rock material was not less than 5.

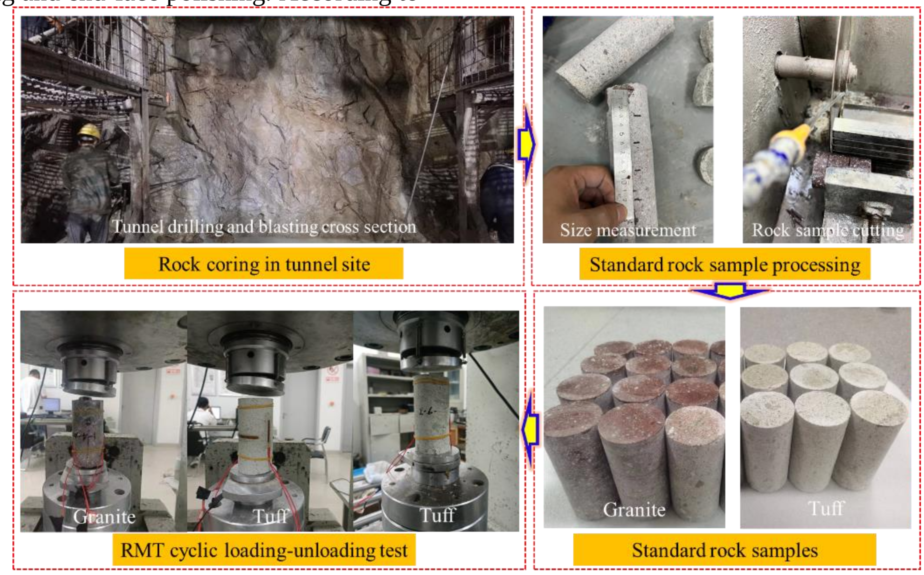


Figure (3): Preparation process of rock samples

Cyclic Loading-Unloading Method

By using the RMT-150B electro-hydraulic servo rock mechanics test system (Figure 4), the cyclic compression tests of granite and tuff specimens with a size of *Φ* 55 mm × *h* 110 mm were carried out under uniaxial conditions by controlling the loading method (the loading-unloading rate was 2 kN/s and the increased amplitude of each loading was 20 kN). The maximum loading force set by the test was 400 kN. Combined with the relevant research methods (Xu et al., 2022), the cyclic loading-unloading method and results are shown in Figure 5 and Table 1.

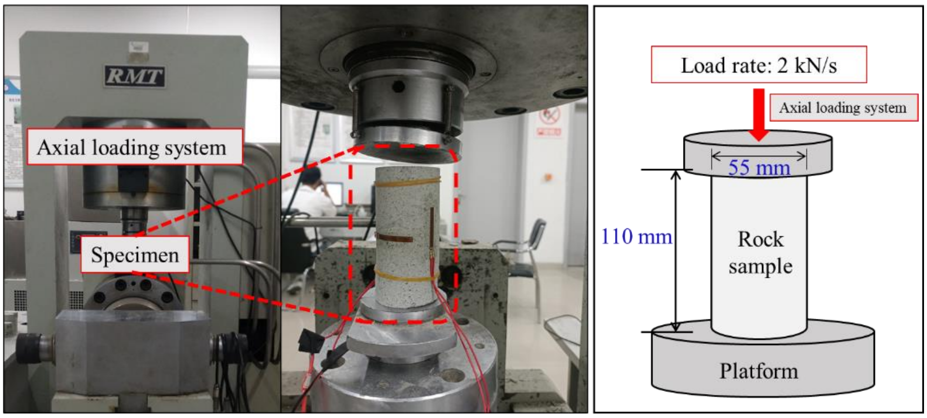


Figure (4): RMT-150B rock mechanics test system

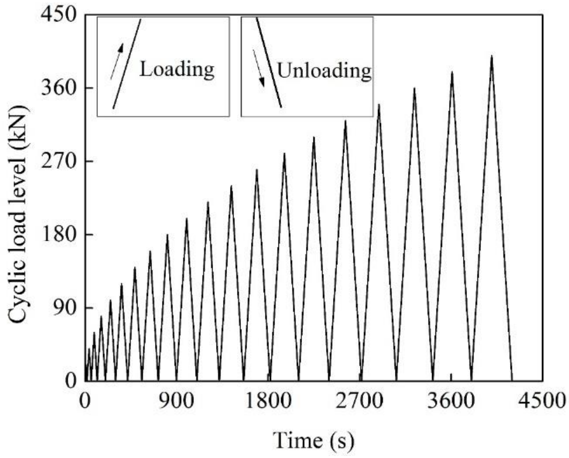
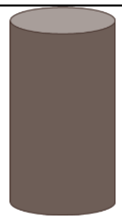
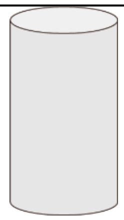


Figure (5): Cyclic loading-unloading method (Xu et al., 2022)

Table 1. Cyclic loading-unloading method and results of granite and tuff

Rock type	**Test method**		**Load lower limit value (kN)**	**Load upper limit value (kN)**	**Number of cycles *n***
 Granite	Loading-unloading rate	2 kN/s	0	20	20
			0	40	
	Loading mode	Slope	0	60	
			0	80	
	Increased amplitude	20 kN	......	......	
			0	400	
 Tuff	loading-unloading rate	2 kN/s	0	20	13
			0	40	
	Loading mode	Slope	0	60	
			0	80	
	Increased amplitude	20 kN	......	......	
			0	260	

Calculation and Analysis Principles of Mechanics and Energy

Under the action of external cyclic load, the essence of rock material damage depends on the change of internal stress and strain states caused by the input of external energy. Before the failure and instability, the stress and strain are in dynamic equilibrium in the process of damage accumulation, accompanied by the accumulation and dissipation of energy. Therefore, the pre-peak mechanical damage and energy-evolution characteristics of rock under cyclic loading-unloading can be analyzed from the aspects of strain, modulus and energy. According to the principle of energy calculation, the variation characteristics of stress and strain are taken into account in the energy evolution. Combined with the above research and calculation principles (Yang et al., 2022), taking the stress-strain curve under the 5th cycle as an example, the calculation and analysis principles of strain, modulus and energy of granite and tuff under cyclic-compression test are shown in Table 2 and Figures 6 and 7.

In a cyclic loading-unloading process, rock samples inevitably undergo irreversible deformation (plastic deformation or residual strain) and reversible deformation (elastic deformation) because of their elastic-plastic characteristics and show the lag effect of strain recovery, which leads to the accumulation and dissipation of input energy in the loading process and the release and dissipation of elastic energy in the unloading process. The irreversible deformation also leads to the difference between the loading deformation modulus and the unloading deformation modulus.

According to the parameter characteristics and calculation principles of strain, modulus and energy (Figures 6 and 7), in the aspect of deformation-behavior characteristics, the loading strain, cumulative residual strain, elastic strain and unclosed degree were mainly analyzed. In the aspect of modulus-behavior characteristics, the loading deformation modulus and unloading deformation modulus were mainly analyzed. In the aspect of energy-behavior characteristics, the input-energy density, elastic-energy density, dissipation-energy density and cumulative dissipation-energy density were analyzed.

Table 2. Definition of main variables under cyclic loading-unloading

Variable type		Variable name	Formula	Definition
Strain-ε	ε_L	Loading strain	ε_{Li}	The strain at the upper limit of the *i*-th cyclic loading.
	ε_R	Cumulative residual strain	ε_{Ri}	The strain at the lower limit of the *i*-th cyclic unloading.
	ε_E	Elastic strain	$\varepsilon_{Ei} = \varepsilon_{Li} - \varepsilon_{Ri}$	The reversible strain in the *i*-th cyclic loading-unloading process.
	$\Delta\varepsilon$	Unclosed degree	$\Delta\varepsilon_i = \varepsilon_{Ri} - \varepsilon_{Oi}$	The irreversible strain caused by material damage during the *i*-th cyclic loading- unloading process.
Modulus-E_S /GPa	E_L	Loading deformation modulus	$E_{Li} = \dfrac{\sigma_{Ai} - \sigma_{Oi}}{\varepsilon_{Ai} - \varepsilon_{Oi}}$	The secant modulus between the lower loading limit and the upper loading limit during the *i*-th cyclic loading.
	E_U	Unloading deformation modulus	$E_{Ui} = \dfrac{\sigma_{Ai} - \sigma_{Bi}}{\varepsilon_{Ai} - \varepsilon_{Bi}}$	The secant modulus between the lower unloading limit and the upper unloading limit during the *i*-th cyclic unloading.
Energy density-U /(MJ•m^{-3})	U_I	Input energy density	$U_{Ii} = \int_{\varepsilon_{Oi}}^{\varepsilon_{Ai}} \sigma_{LPi} d\varepsilon_i$	The energy density inputted during the *i*-th cyclic loading.
	U_E	Elastic energy density	$U_{Ei} = \int_{\varepsilon_{Bi}}^{\varepsilon_{Ai}} \sigma_{UPi} d\varepsilon_i$	The energy density released during the *i*-th cyclic unloading.
	U_D	Dissipation energy density	$U_{Di} = U_{Ii} - U_{Ei}$	The energy density dissipated due to material damage during the *i*-th cyclic loading-unloading process.
	U_{CD}	Cumulative dissipation energy density	$U_{CD} = \sum_{i=1}^{i=n} U_{Di}$	The dissipated energy density in the previous *n*-th cyclic loading-unloading process.
Related variables	σ_O	Loading lower limit stress	σ_{Oi}	The initial stress during the *i*-th cyclic loading.
	σ_A	Loading/Unloading upper limit stress	σ_{Ai}	The maximum stress in the *i*-th cyclic loading-unloading process.
	σ_B	Unloading lower limit stress	σ_{Bi}	The minimum stress during the *i*-th cyclic unloading.
	ε_O	Loading lower limit strain	ε_{Oi}	The initial strain during the *i*-th cyclic loading.

	ε_A	Loading/Unloading upper limit strain	ε_{Ai}	The maximum strain in the *i*-th cyclic loading-unloading process.
	ε_B	Unloading lower limit strain	ε_{Bi}	The minimum strain during the *i*-th cyclic unloading.
	σ_{LP}	Loading process stress	σ_{LPi}	The stress during the *i*-th cyclic loading.
	σ_{UP}	Unloading process stress	σ_{UPi}	The stress during the *i*-th cyclic unloading.

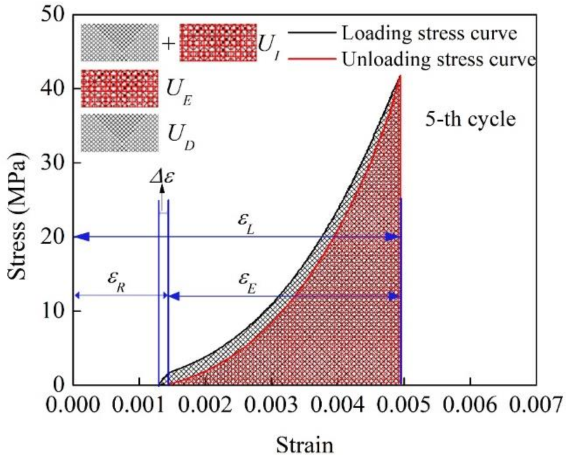


Figure (6): Calculation and analysis principles of strain and energy (Yang et al., 2022)

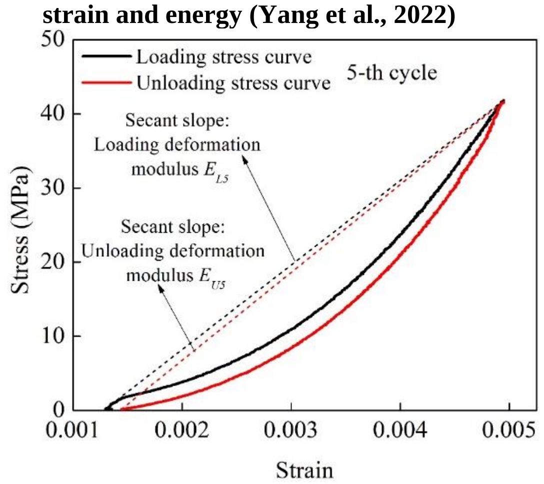


Figure (7): Calculation and analysis principle of modulus (Yang et al., 2022)

RESULTS AND ANALYSIS

Pre-peak Stress-Strain Curves

The stress-strain curves of granite and tuff under cyclic-compression test are shown in Figure 8. It can be seen from Figure 8 that the stress-strain curves of granite and tuff were very stable under the cyclic-compression test and both loading curves and unloading curves were concave. Through local magnification, it can be found that the stress-strain curves of granite and tuff showed the evolution characteristics from "sparse" to "dense" and then to "sparse". To some extent, this reflected the initial plastic-compaction effect and late cumulative-damage effect of granite and tuff in the process of cyclic-compression test. The formation mechanism of the above phenomena can be further analyzed as follows:

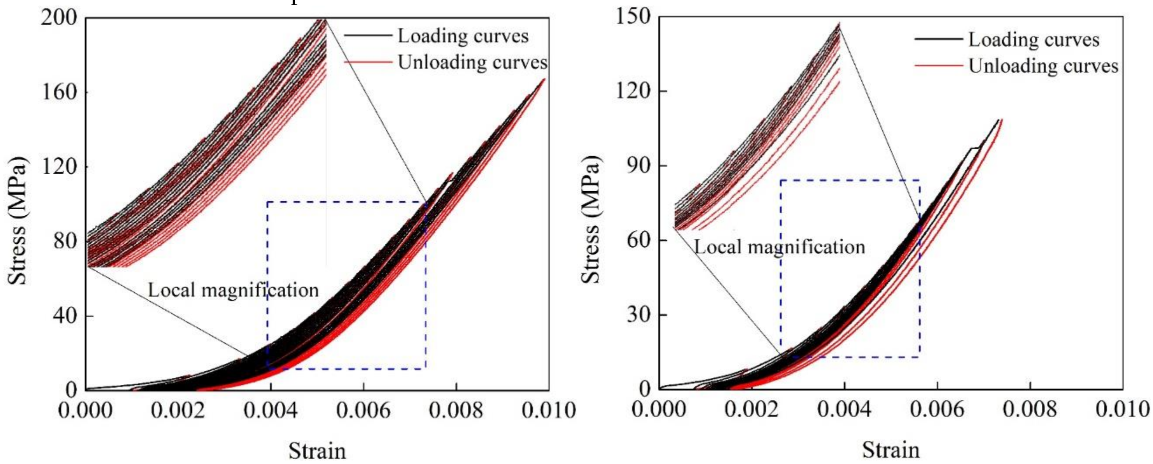
(1) Rock samples belong to elastic-plastic materials and their elastic characteristics are dominant, which highlights the elastic-brittle characteristics of rock samples as a whole. In essence, elastic deformation and plastic deformation inevitably occur in each cyclic loading-unloading process, which inevitably leads to the non-coincidence of loading-stress curve and unloading-stress curve under each cyclic loading-unloading. The pre-peak plastic deformation of rock samples is mainly caused by the compaction of initial pores and the propagation of damaged cracks.

(2) The compaction of initial pores mainly occurs in the early stage of cyclic loading-unloading. At this stage, the degree of non-coincidence between the loading-stress curve and the unloading-stress curve increases due to the plastic-compaction effect and the stress-strain curves show sparse characteristics.

(3) The nearly complete linear elastic deformation mainly occurs in the middle stage of cyclic loading-unloading. At this stage, the degree of non-coincidence between the loading-stress curve and the unloading-stress curve decreases due to the elastic-deformation effect and the stress-strain curves show dense characteristics.

(4) The propagation of damage cracks mainly occurs in the later stage of cyclic loading-unloading. At this stage, the degree of non-coincidence between the loading-stress curve and the unloading-stress curve increases due to the cumulative-damage effect and the stress-strain curves show sparse characteristics.

Therefore, the pre-peak stress-strain curves of rock samples under cyclic loading-unloading showed the evolution characteristics from "sparse" to "dense" and then to "sparse".



(a) Granite **(b) Tuff**

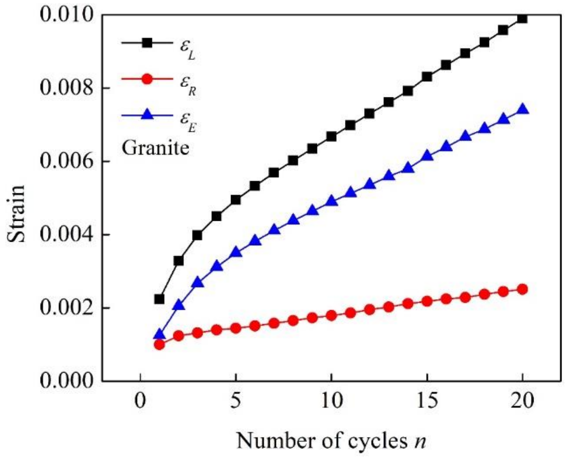
Figure (8): Stress-strain curves of granite and tuff under cyclic loading-unloading

Pre-peak Deformation Characteristics

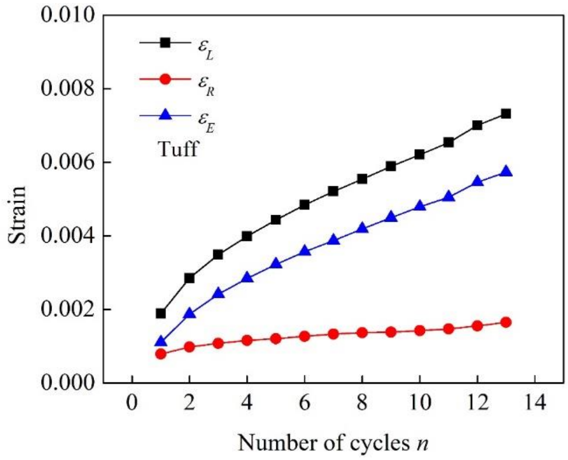
The deformation behavior of granite and tuff under the cyclic-compression test is shown in Figure 9. It can be seen from Figure 9 that the deformation-behavior characteristics of granite and tuff under cyclic-compression test were basically the same, which were shown as follows: With the synchronous increase of the number of cycles and load level, the loading strain, cumulative residual strain and elastic strain all showed the evolution characteristics of increasing and the increase of each cycle was larger in the 1st to 3rd cycles and the linear growth trend was shown in the 4th to 20th cycles as a whole. It can be found that in the whole cycle, the loading strain was greater than the elastic strain and the elastic strain was greater than the cumulative residual strain. The above showed that the elastic strain played a dominant role in the loading strain, which highlighted the elastic brittleness of rock samples. At the same time, on the whole, with the synchronous increase of the number of cycles and the load level, the unclosed degree as a whole showed the evolution characteristics of "first rapid decrease, then fluctuation stability", especially in the 1st cycle, which fully showed that the structure of rock samples became denser due to the compaction effect under cyclic load and the plastic deformation of rock samples gradually changed to elastic deformation with the increase of the number of cycles, but there was always plastic deformation. To some extent, it reflected the plastic-deformation characteristics of granite and tuff. It can be further concluded that due to the existence of plastic deformation, when the cumulative plastic deformation reaches the limit plastic deformation that the rock sample can bear, the rock sample is bound to be damaged.

Pre-peak Modulus Characteristics

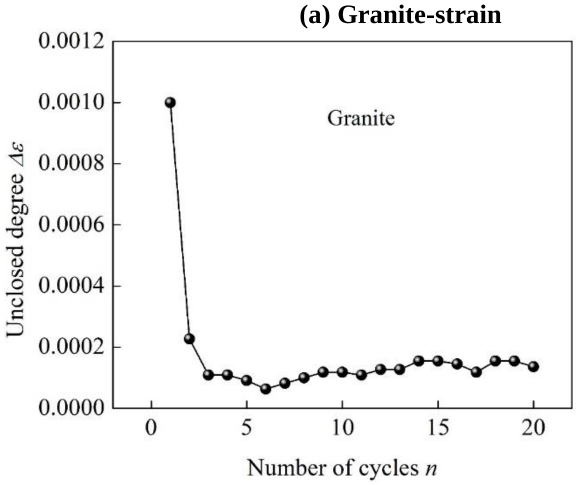
The modulus behavior of granite and tuff under cyclic-compression test is shown in Figure 10. It can be seen from Figure 10 that the modulus-behavior characteristics of granite and tuff under cyclic-compression test are basically the same, which are shown as follows: With the synchronous increase of the number of cycles and load level, both loading deformation modulus and unloading deformation modulus showed increasing evolution characteristics. However, the increasing amplitude of the deformation modulus showed a decreasing evolution characteristic, which showed that the rock samples had slight plastic deformation damage in each cycle, but there was no serious structural damage resulting in the decrease of the deformation modulus. It is worth noting that in the whole cyclic-compression process, the unloading deformation modulus was slightly smaller than the loading deformation modulus, combined with the above deformation-behavior characteristics, where the main reason for this phenomenon is the existence of plastic deformation in each cycle, which leads to the unclosed degree. It can be found that the difference between loading deformation modulus and unloading deformation modulus was the largest during the 1st to 3rd cycles, indicating that the initial compaction-plasticity characteristics of rock samples were obvious. In the process of the 4th to 10th cycles, the difference between the loading-deformation-modulus and the unloading-deformation modulus was the smallest and the deformation modulus curve was similar to a straight line, indicating that the linear elastic characteristics of rock samples were obvious. During the 11th to 20th cycles, the difference between loading deformation modulus and unloading deformation modulus increased and the nonlinear characteristic of the deformation-modulus curve was enhanced, indicating that the plastic-damage characteristics of rock samples were increased.



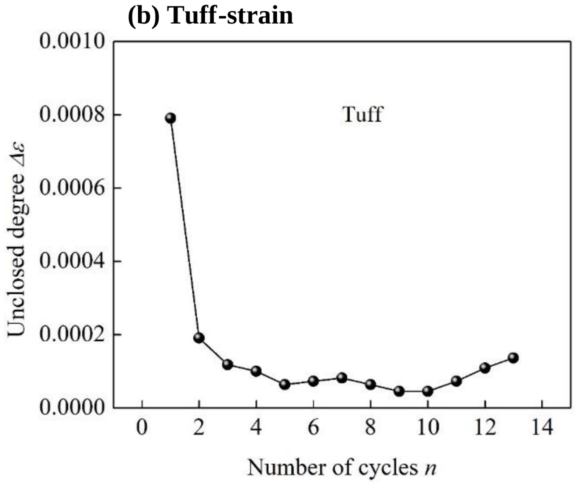
(a) Granite-strain



(b) Tuff-strain

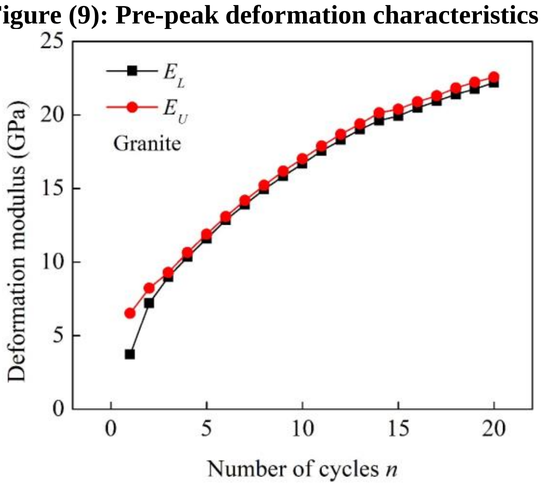


(c) Granite-unclosed degree

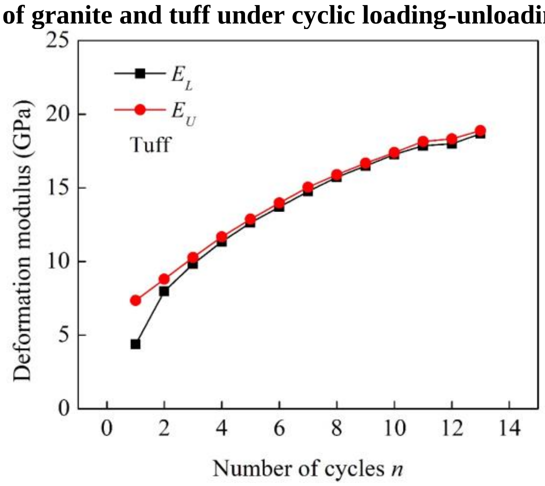


(d) Tuff-unclosed degree

Figure (9): Pre-peak deformation characteristics of granite and tuff under cyclic loading-unloading

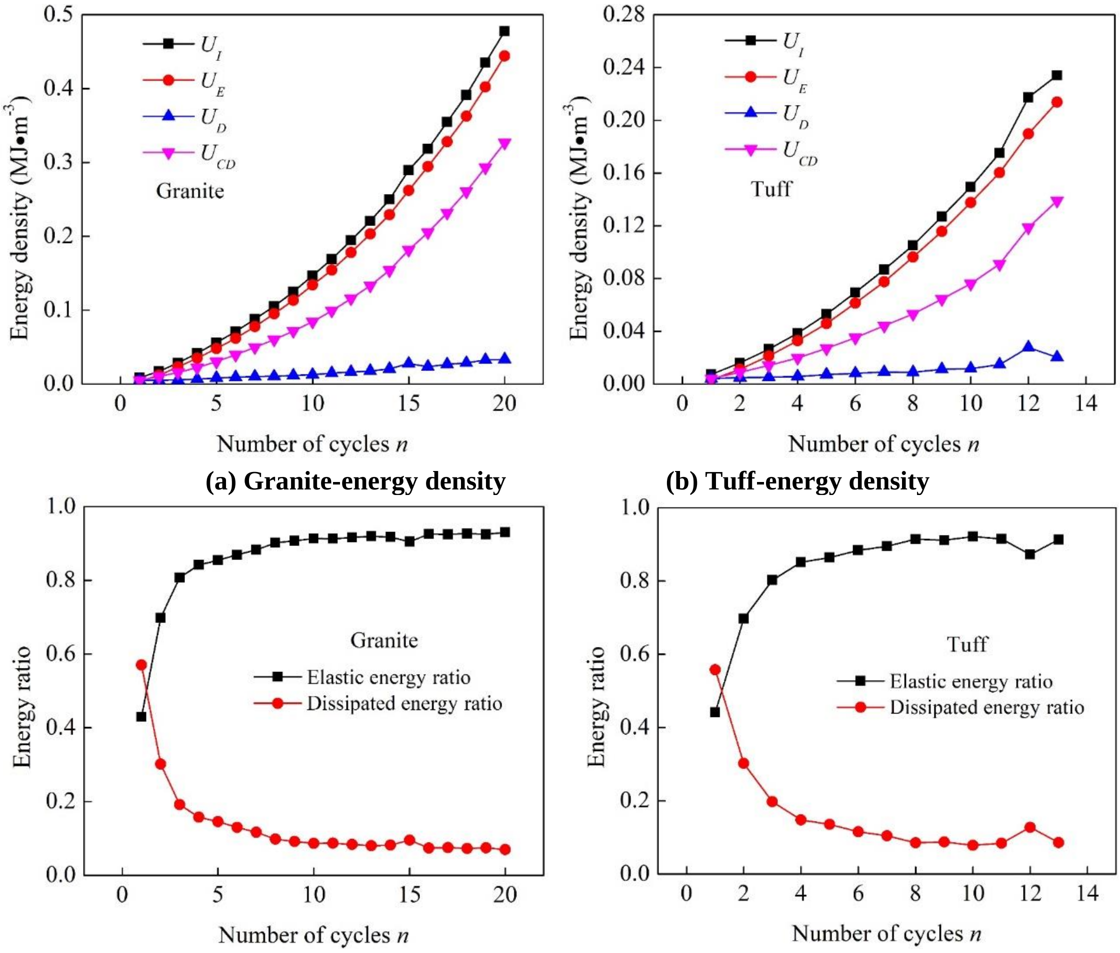


(a) Granite



(b) Tuff

Figure (10): Pre-peak modulus characteristics of granite and tuff under cyclic loading-unloading



(a) Granite-energy density **(b) Tuff-energy density**

(c) Granite-energy ratio **(d) Tuff-energy ratio**

Figure (11): Pre-peak energy characteristics of granite and tuff under cyclic loading-unloading

Pre-peak Energy Characteristics

The process of material deformation and failure is a process of energy input, energy accumulation and energy dissipation. So, there must be a competitive relationship between energy storage and energy dissipation in the damage and failure of materials under cyclic load. The energy-behavior characteristics of granite and tuff under cyclic-compression test are shown in Figure 11. As can be seen from Figure 11, the energy-behavior characteristics of granite and tuff were basically the same under the cyclic-compression test, which are shown as follows: With the synchronous increase of the number of cycles and load level, the input-energy density, elastic-energy density, dissipation-energy density and cumulative dissipation-energy density all showed the evolution characteristics of "arc" growth. The elastic-energy ratio and dissipated-energy ratio showed the evolution characteristics of "increasing first, then stable" and "decreasing first, then stable", respectively.

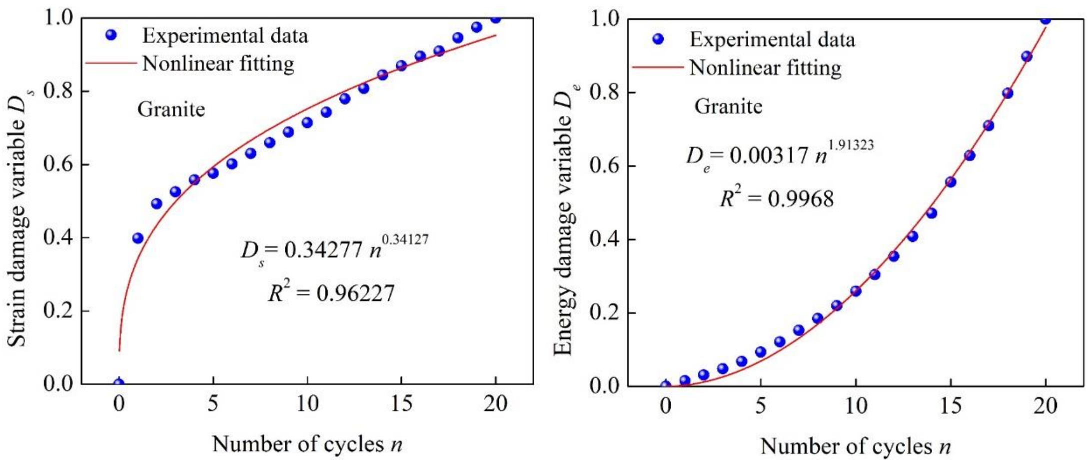
In essence, the energy-evolution characteristics of rock samples under cyclic loading mainly depend on the competitive relationship between different energy mechanisms. Rock samples produce an energy-dissipation mechanism because of plastic-compaction energy dissipation and plastic-damage energy dissipation and rock samples produce an energy-storage mechanism because of elastic-deformation energy accumulation. Because the elastic-plastic deformation of rock samples runs through the whole cyclic loading-unloading process, when the energy-storage mechanism is greater than the energy-dissipation mechanism, the rock samples show better structural stability and the energy state is in dynamic equilibrium. However, when the energy-storage mechanism is less than the energy-dissipation mechanism (not caused by the compaction effect), the dynamic-equilibrium state of the energy of the rock sample will be broken, because the internal accumulated energy is greater than the energy-storage limit and the structural instability of the rock sample will occur.

It can be seen that the elastic-energy ratio of rock samples in the 1st cycle was significantly lower than the dissipated-energy ratio (the energy-storage mechanism was smaller than the energy-dissipation mechanism) and the elastic-energy ratio of rock samples in the 2nd to 20th cycles was significantly larger than the dissipated-energy ratio (the energy-storage mechanism was larger than that of energy dissipation). This result showed that after the initial plastic-compaction deformation, the rock samples basically enter the stage of linear elastic deformation, which promotes the transformation of input energy to elastic properties. However, due to the continuous existence of the cumulative effect of plastic-dissipation energy, the cumulative-dissipation energy of the rock samples increases continuously, which will promote the development of rock sample damage.

DISCUSSION

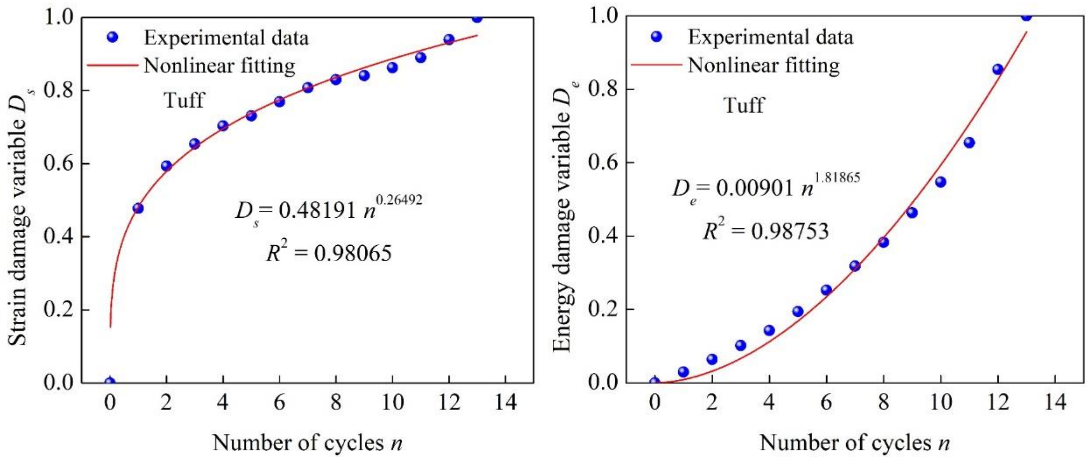
Evolution Characteristics of Cyclic Damages

The definition of damage variables: the strain-damage variable D_s is the ratio of cumulative cyclic residual strain to the final cumulative residual strain, while the energy-damage variable D_e is the ratio of cumulative cyclic-dissipation energy to the total cyclic-dissipation energy. The damage-evolution characteristics of granite and tuff under cyclic-compression test are shown in Figures 12 and 13. It can be seen from Figures 12 and 13 that the strain-damage variables and energy-damage variables of granite and tuff conformed to the power-function distribution with the increase of the number of cycles ($R^2 > 0.96$). It can be found that the strain-damage variable increased in a convex shape with the number of cycles and the energy-damage variable increased in a concave shape with the number of cycles. This showed that different dependent variables can reflect the different evolution processes and characteristics of cyclic damage of rock samples to a certain extent, but this will not have any effect on the final damage results. In practical application, the corresponding damage variables can be used to analyze the evolution characteristics of cyclic damage behavior of rock samples properly according to the actual demand. For strain damage, the reason for the rapid growth of strain damage in the early stage is that the initial plastic compaction deformation leads to the rapid growth of strain, but with the increase of the number of cycles, the strain damage increases slowly and gradually tends to linear and stable growth. For energy damage, the reason for the slow growth of energy damage in the early stage is that the energy damage-driving effect is not obvious due to the low initial load level, but with the increase of the number of cycles, energy damage increases obviously and gradually tends to linear and stable growth.



(a) Strain damage **(b) Energy damage**

Figure (12): Damage-evolution characteristics of granite under cyclic loading-unloading



(a) Strain damage **(b) Energy damage**

Figure (13): Damage-evolution characteristics of tuff under cyclic loading-unloading

Selection of Rock-sample Size and Limitations of Experimental Scheme

In the field coring, a bit with an inner diameter of 50 mm was used to get a core with a diameter of 50 mm, but due to the complex field test conditions and obvious vibration, the core with a diameter of 50 mm was easy to break in the process of drilling. To solve this problem, the coring scheme was adjusted by consulting the relevant standards and specifications. Referring to the requirements of the standard specifications (GB/T 23561-2009 and GB/T 50266-2013), the diameter of rock samples under uniaxial compression should be 48~56 mm and the height should be 20~2.5 times of the diameter. The rock samples within this allowable range belong to the standard rock samples of the uniaxial-compression test. Therefore, the uniaxial-compression rock sample size (Φ 55 mm × h 110 mm) within this standard range was adopted in the test.

In this study, considering the actual engineering situation of cyclic vehicle load and cyclic blasting load on the surrounding rock of the diversion tunnel, the cyclic loading-unloading test of typical hard rock of the diversion tunnel was carried out, but the test scheme still has some limitations. The strain rate of this cyclic-load test is low; so, the high strain rate effect under cyclic blasting load can not be realized. Therefore, in the later research process, the split Hopkinson pressure bar (SHPB) and explosion impact tests should be carried out combined with field tests to further study the damage mechanism and energy evolution of typical hard rock in diversion tunnels under cyclic impact loading. Thus, it can provide a better reference for the safe construction operation and maintenance of the diversion tunnel.

CONCLUSIONS

In this work, combined with the internal drilling and blasting excavation of the actual engineering rock mass and the external vehicle cyclic load environment of the diversion tunnel, the cyclic loading-unloading tests were carried out on the typical hard rock (granite and tuff) of the diversion tunnel. The typical pre-peak cycle mechanical properties and energy-evolution characteristics of granite and tuff were analyzed. The following conclusions were drawn:

- The pre-peak stress-strain curves of granite and tuff showed the evolution characteristics from "sparse" to "dense" and then to "sparse", reflecting the initial plastic-compaction effect and the late cumulative-damage effect.
- The obvious elastic deformation of rock samples occurred in the whole process of cyclic loading-unloading deformation, which highlighted the elastic-brittleness of rock samples and the plastic deformation of rock samples gradually transformed to elastic deformation with the increase of the number of cycles.
- The main reason that the unloading deformation modulus was slightly less than the loading deformation modulus was the existence of plastic deformation during each cycle, which led to the generation of unclosure degree.
- The elastic-energy ratio of rock samples after the initial compaction stage was significantly greater than the dissipated-energy ratio, which promoted the transformation of input energy to elastic energy. However, due to the continuous existence of the

cumulative effect of plastic-dissipation energy, the cumulative-dissipation energy of rock samples increases continuously, which will promote the development of damage of rock samples.

In this study, considering the actual engineering situation of cyclic vehicle load and cyclic blasting load on the surrounding rock of the diversion tunnel, the experimental study on a cyclic load of typical rock in a diversion tunnel is of great significance in obtaining the relevant parameters of rock mass in a diversion tunnel. In the later research process, the SHPB and explosion-impact tests should be carried out combined with field tests to further study the damage mechanism and energy evolution of the typical hard-rock of the diversion tunnel under cyclic impact loading. This can provide a better reference for the safe construction operation and maintenance of the diversion tunnel.

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