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Cyclic Loading and Unloading Test and Energy Consumption Analysis of Sandstone under Dry-wet Cycle

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Abstract:

The problem of geological disasters caused by rock damage and metamorphism under dry wet cycle is very serious. Studying damage and deterioration effect of rock under periodic dry wet cycle is necessary, the "desiccation-saturatation-drying" process in laboratory is used to simulate the repeated fluctuation of reservoir water level, which is used to study the influence of dry-wet cycle on the mechanical properties and energy mechanism of sandstone, and carries out conventional uniaxial and triaxial compression tests and variable amplitude cyclic loading and unloading compression tests on sandstone under different dry wet cycles. The test results show that the maximum total strain energy decreases logarithmically with the increase of *n* in the test of sandstone under different dry wet cycle, and the rock sample has irreparable damage under the repeated and alternating action of "water saturation and water loss"; Under the condition of uniaxial cyclic loading and unloading, the cumulative energy consumption ratio increases in the form of quadratic parabola with *r*. the closer it is to the peak strength, the faster the growth rate is. The energy consumption ratio near the peak strength is about 0.6, which is significantly higher than that of monotonic compression test (0.1 ~ 0.3); At lower confining pressures, the initial dissipated energy and hysteretic energy of the rock sample increase slowly. With the increase in the number of dry wet cycle, the difference between dissipated energy and hysteretic energy increases gradually, the shear strength of rock sample decreases gradually at the post peak stage, the lateral strain develops rapidly, and the confining pressure does negative work, so that total strain energy after peak loading and unloading is lower than the total strain energy at the peak point; The dissipated energy, hysteretic energy and released elastic strain energy develop unsteadily after the peak, and the slope of the curve is much greater than that before the peak.

Keywords: *Dry-wet cycle, Variable amplitude loading and unloading, Unloading modulus, Energy feature, Energy consumption ratio.*

I. INTRODUCTION

Reservoir water action, rainfall and groundwater infiltration are the main factors of reservoir bank landslide. Reservoir bank landslide directly affects the life and property, scenic relics, shipping, railway

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and highway operation in the reservoir area [1-3]. Due to rainfall, rise and fall of reservoir water level and other reasons, the rocks (massive crystalline rock, layered clastic rock and layered carbonate rock) in the drawdown zone of the reservoir area are often in the state of alternating dry and wet cycles, This alternating action of dry and wet cycles (physical, chemical and Mechanical) is more serious than the deterioration of rock (body) caused by long-term immersion. It belongs to "fatigue damage", which develops cumulatively with the number of cycles (i.e. each effect is not significant, and repeated times can increase the nonlinear accumulation of the effect), until it reaches the critical state of slope stability and promotes the occurrence of geological disasters [4-7]. In order to control these engineering disasters, the mechanical properties of intact rock under dry wet cycle must be analyzed and studied first. Du, B. et al. [8-10] Conducted impact compression test on red sandstone and studied the influence of dry wet cycle on the dynamic mechanical properties of rock mass, through the study, it was found that the dynamic compressive strength of red sandstone increases exponentially with the strain rate under the same number of drying and wetting cycles, and the strain rate sensitivity decreases with the increasing number of drying and wetting cycles, they also conducted a comprehensive study on the influence of dry wet cycle and strain rate, the dynamic compressive strength equation of red sandstone is obtained.

According to the law of thermodynamics, energy conversion is the basic characteristic of the physical process of matter, and the destruction of matter is an unstable phenomenon driven by energy. H Du et al. investigated the dynamic mechanical properties of rocks with structural planes under periodic cyclic dynamic disturbances and performed uniaxial compression tests on rock samples. The effects of different disturbance stress amplitudes on the strength, deformation characteristics, energy dissipation characteristics and fracture laws of rock samples are studied, and finally a damage constitutive model is proposed [11, 12]. Shi, Z. et al proposed a composite structure, believing that the embedded structure and the central structure could be deformed independently to adjust the mechanical properties of rock samples. The influence of embedment structure and center structure on poisson's ratio, relative Young's modulus and energy absorption of composite structure under uniaxial compression was studied [13-16]. Zhou, Y. et al measured the full-field strain of granite samples under different loading amplitude by using 2d digital image correlation method. According to these deformation data, the threshold of rock breakage under ultrasonic vibration is obtained. It is also found that the logarithm of the time required to satisfy this value decreases linearly with the increase of the amplitude coefficient. Based on the two-dimensional particle flow program, numerical simulation of rock samples is carried out to reproduce the initiation and propagation process of cracks during the loading process of rock samples and explore the failure mechanism [17].

In this paper, the sandstone in a slope drawdown zone in the Three Gorges Reservoir area of Chongqing is selected as the research object. The indoor conventional uniaxial and triaxial compression tests and variable amplitude cyclic loading and unloading uniaxial and triaxial compression tests are carried out on the sandstone samples in the "dry" and "saturated" states under different dry and wet cycles. The mechanical properties of the sandstone under two water bearing conditions under different dry and wet cycles and the characteristic differences between various stages of deformation and failure process are discussed, from the perspective of energy, the law of energy accumulation and dissipation in the process of

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sandstone deformation and failure and the parameter states of peak strength point are analyzed, revealing the energy dissipation and release mechanism of sandstone damage and failure, providing a direction for determining the macro damage evolution equation of sandstone under Dry-wet circulation.

II. MATERIALS AND METHODS

2.1 Specimens Fabricating

The medium weathered sandstone in the hydro-fluctuation belt of a slope near the water surface in the three gorges reservoir area is selected to be processed into the rock samples with *D*=50mm in Diameter and *h*=100mm high by the vertical core extraction machine(Fig 1). Rock samples can be divided into two categories, one is "saturated" specimen under dry-wet cycle, the other is "dry" specimen under dry-wet cycle, and each type of specimen is divided into 6 groups, each group of 4 specimens, leaving a group of spare, and the other groups were subjected to dry-wet cyclic tests with *n*=0, 1, 3, 6, 10 times, respectively. In this paper, referring to the indoor mechanical test method [18], the samples are firstly put into the oven and dried for 24 hours at $105^{\circ}c$, and saturated for 24 hours through the intelligent concrete vacuum water satiety machine, this process is a dry - wet cycle, the number of dry and wet cycles is referred to as DAW.

(a) Bottom view (*b*) Elevation

Fig 1: Some samples of sandstone and testing equipment

2.2 Test Procedure

For each group of rock samples after different times of dry-wet cycle tests, two specimens were selected to do the routine uniaxial and triaxial compression tests (the confining pressure is 6MPa), and two samples were selected to perform the variable amplitude cyclic loading and unloading uniaxial and triaxial compression tests respectively, this experiment is hereinafter referred to as CLU.

The instrument is a fully automatic rheological triaxial instrument, the axial displacement is controlled by LVDT（0.02mm/min）in the loading stage, and the axial force is used to control the loading and

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unloading (10bar/min) at the unloading stage. The loading and unloading curve and the peak value under CLU scheme are obtained. Specific steps of the experiment: firstly, the uniaxial compressive strength of sandstone in dry and saturated states under different DAW is obtained by conventional uniaxial compression test, and the uniaxial strength of rock samples is estimated. The first load is about 10% of uniaxial strength, then unloaded to 0. Thereafter, the load is increased by about 10%（may float up or down due to test conditions）of uniaxial strength every time until the rock sample is destroyed.

Fig 2 shows the peak values of uniaxial amplitude variation cycle loading and unloading of sandstone in two states under different wetting and drying cycles. It can be seen from the figure that uniaxial variable amplitude CLU can strengthen rock samples, and with the increase of cyclic times, the strengthening effect is gradually enhanced. The peak strength of variable amplitude CLU test decreases gradually with the increase of n, and decreases rapidly in the initial stage, and then slowly in the later period. The peak strength of the test is higher than compression strength of the conventional uniaxial test. For "saturated" rock samples, the difference between them decreases with the increase of cycle times.

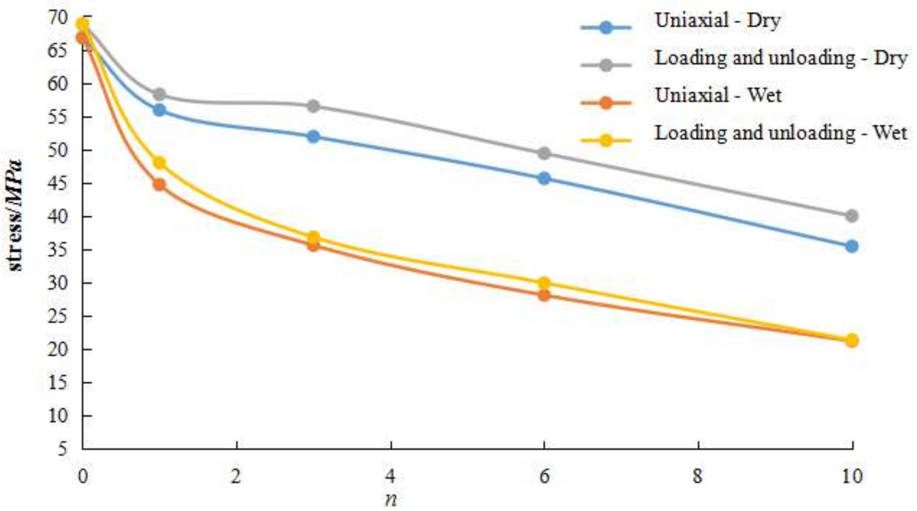

Fig 2: The relationship between the peak intensity and *n* of two types of experiments

III. RESULTS AND ANALYSIS

3.1 Results of Experiment

The stress-strain curves of uniaxial CLU of sandstone under various DAW are shown in Fig 3. The relationship between axial loading stress, axial direction, circumferential directions and volumetric strain of rock samples in uniaxial compression test is given. From the loading and unloading curve of sandstone, it can be seen that the loading curve and unloading curve does not coincide, and the unloading curve is a slightly concave smooth curve, forming a plastic-loop (hysteresis loop area (dissipative energy) refers to the area formed by the loading curve section of each cycle of sandstone in the CLU test and the unloading

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curve segment of the previous cycle) The figure shows that the area of the hysteresis loop increases with the increase of loading and unloading times, and moves towards the direction of strain increase.

The rock sample experienced plastic deformation (occurrence of plasticity and damage zone) before the peak value. Because the rock sample was finally brittle drop during uniaxial compression, the stored elastic strain energy was suddenly released because the stress was reduced when the rock sample was unloaded at the peak point and the macroscopic crack is further extended to brittle failure.

With the increase of the number of drying-wetting cycles, the depression degree of sandstone principal stress-strain curve deepens, that is, the initial compaction section becomes larger, and the initial damage of sandstone gradually becomes larger. With the increase of loading amplitude, the unloading plastic strain increases gradually. Dry-wet circulation "saturation" status under the action of sandstone and uninstall the peak strength is lower than that in "dry" condition, deformation significantly, concave phenomenon is more prominent, as a result of the action of water, making early unloading plastic deformation is "dry" condition of sample, sample had been pressure when unloading fissure and new crack to open, the water into the rock fracture of more convenient, As a result, the mechanical properties of the specimen are further reduced, which is an important reason for the increase of the hysteresis loop area of sandstone water in "saturated" .

Due to the action of water, the unloading plastic deformation in the early stage is larger than that in the "dry" state. During unloading, the original compacted cracks and the new cracks of rock samples are reopened, which makes the water more convenient to enter the rock fractures, causing the mechanical properties of specimens to be further reduced, which is an important reason for the increase of the hysteresis loop area for sandstone water under "saturation" condition. Due to the adjustment of the pressure head and the initial microcrack of rock, the plastic strain appears obviously during the first cyclic unloading of the specimen, but in the subsequent cycles, the compacting is not obvious, under the action of uniaxial CLU, Under the action of uniaxial CLU, brittle failure still appears after the peak. The external envelope of the stress-strain curve of the whole process of uniaxial CLU of sandstone almost coincides with the conventional uniaxial test curve, but it is not completely repeated. Peak strain increased. The slope of the loading curve (rock sample stiffness) increases with the increase of the number of cycles, and each unloading curve is relatively slow and almost parallel.

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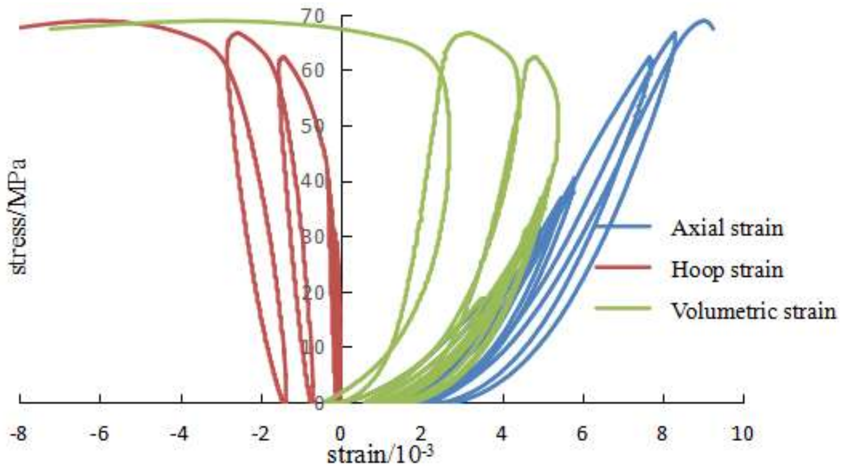

Fig 3: Stress-strain curves of sandstone under uniaxial cyclic loading under different conditions

Reasons for the improvement of uniaxial compressive strength of rock under CLU are as follows: Sample there are obvious at the beginning of the loading pressure dense phase, when unload large plastic deformation, especially as the role of dry-wet circulation makes initial crack gradually increase), for the first time in the process of loading, initial microcracks inside the sample closed, part of the new crack development then, then in unloading phase, new fissure particle contact level structure readjustment and part of the recovery, During the reloading, the new fractures closed again, and the friction strength between fracture planes was improved due to the adjustment of particle structure. After several cycles of loading and unloading, the overall yield strength (failure strength) of rock samples was improved compared with that of conventional uniaxial compression. With the increase of number of cycles and amplitude stress, the rock sample gradually enters the stage of linear elastic stability, and its elastic modulus (slope of loading curve) increases gradually.

3.2 Analysis of Elastic Constants

Suppose the total axial strain is $\varepsilon^{total}(i)$ at each CLU to the maximum axial stress which is $\sigma^{\max}(i)$, and the strain is cumulative plastic strain- $\varepsilon_{1n}^{p}(i)$ when the stress is unloaded to zero. The difference between the two is elastic strain: $\varepsilon^{e}(i) = \varepsilon^{total}(i) - \varepsilon_{\ln}^{p}(i)$, unloading modulus is the secant modulus of hysteresis loop:

$$E_i = \frac{\sigma^{\max}(i)}{\varepsilon^{e}(i)} \tag{1}$$

The ratio of the amplitude of each load to the peak strength in the CLU test is defined as strength ratio:

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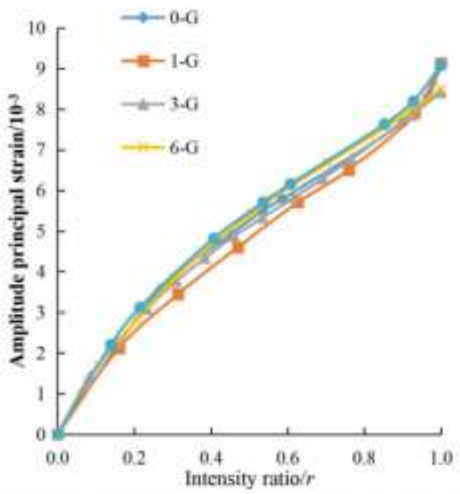
$$r = \frac{\sigma^{\max}(i)}{\sigma_{cn}} \tag{2}$$

Through CLU tests, the plastic, elastic and cumulative plastic strains (irreversible strains) can be separated and the relationship between strain and strength ratio can be obtained, as shown in Fig 4. Sandstone of axial strain amplitude with nonlinear increase with the increase of discharge frequency, early to rise slowly, when its close to breaking strength strain increase slope increases obviously, with the increase of n, its initial micro cracks, unload the irreversible strain gradually rise, multiple loops and unloading under the action of the peak strain increases gradually; Cumulative plastic strain increased with the increase of add unloading times larger, with the increase of n, the initial damage of sandstone, plastic strain showed a trend of increase, the changing rule of the "dry" condition is similar to that of "saturation" state, the plastic strain amplitude is bigger, in the early sample under different dry-wet cycle times of strain, the cumulative plastic strain amplitude difference is "dry" condition is obvious. In the "dry" state, the amplitude axial principal strain and the ratio of pre-peak cumulative plastic strain to loading / unloading amplitude strength of sandstone under different DAWconform to the following relationship:

$$\varepsilon(i) = Mr^2 + Nr \tag{3}$$

In the formula, *M* and *N* are fitting coefficient. The specific value is shown in TABLE I, and the fitting effect is better.



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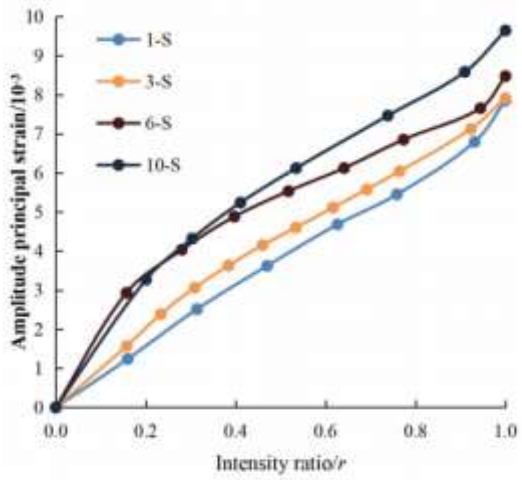
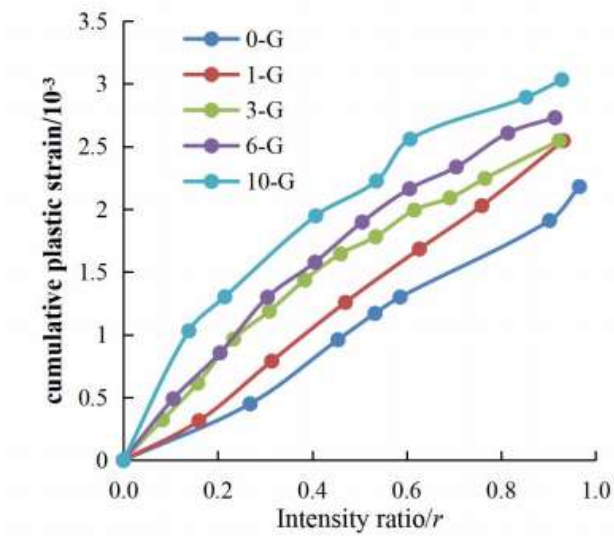


(a) Amplitude principal strain



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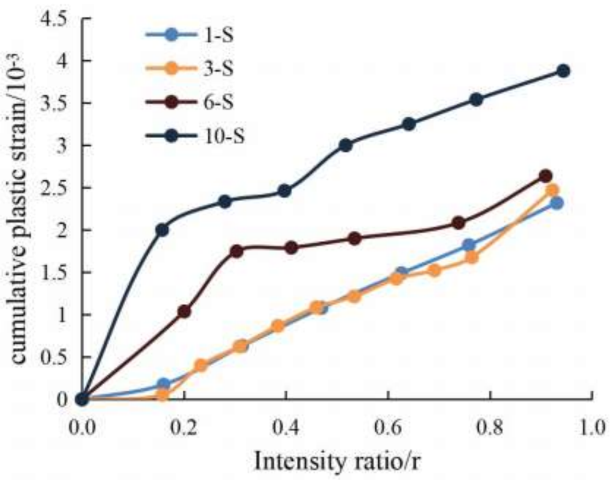

(b) cumulative plastic strain

Fig 4: Principal strain, cumulative plastic strain and strength ratio of sandstone under DAW

TABLE I. Fitting coefficient of cumulative plastic strain and strength ratio in dry condition

	state	*M*	*N*	Correlation coefficient/R^2
Amplitude principal strain $\varepsilon^{total}(i)$	0-G	-4.016	12.585	0.9883
	1-G	-2.029	10.665	0.9869
	3-G	-4.7641	12.84	0.9883
	6-G	-5.3287	13.548	0.9943
	10-G	-4.9487	13.572	0.9887
Cumulative plastic strain $\varepsilon_{1n}^{p}(i)$	0-G	0.2315	1.9921	0.9936
	1-G	0.288	2.1179	0.9981
	3-G	-1.7576	4.3247	0.9979
	6-G	-1.8578	4.6835	0.9993
	10-G	-3.2377	6.1877	0.9861

The unloading modulus of sandstone in different stages under CLU is calculated by formula 1. The

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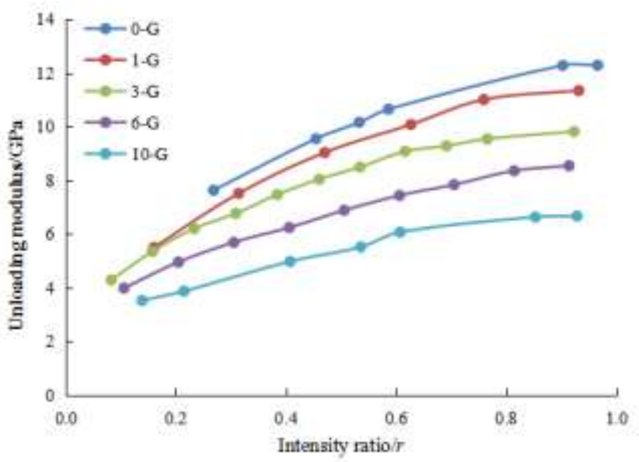
change of unloading modulus reflects the change of stiffness of rock samples after a certain load history. When brittle rocks undergo plastic deformation, their elastic parameters (unloading modulus) will change. The change of unloading modulus is due to the repeated closure and opening of the initial micro-cracks and plastic deformation sprouted and developed irreversible new fissures. Fig 5 shows unloading modulus and strength ratio under different CLU. From the diagram, it can be seen that the unloading modulus increases with the increase of strength ratio before the yield strength, that is, the CLU strengthen the rock samples, The early strengthening effect is more obvious (initial crack closure increases stiffness), the later stage becomes gentle and the peak area has a downward trend, that is, the damage area is produced, after the peak point, the stress- strain curve brittle drop, that is, the softening phenomenon of the rock is caused by the damage. Under the condition of "saturation", the unloading modulus of rock samples fluctuates because of the disturbance of water, and the overall trend is upward. Under "dry" condition, the unloading modulus and strength ratio of each stage of sandstone conform to parabola, in formula 4:

$$E(i) = M'(r)^2 + N'r + W' \tag{4}$$

In the formula, M', N', W' are fitting coefficient. The specific value is shown in TABLE II, and the fitting effect is better.



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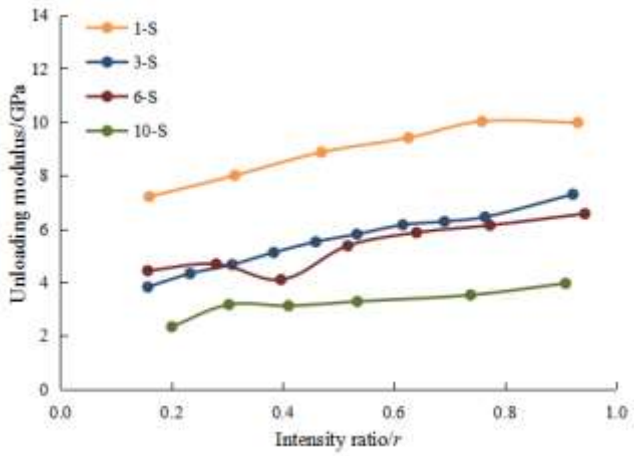

(a) Dry state (b) Saturation state

Fig 5: Relationship between unloading modulus and strength ratio of sandstone in two states.

TABLE II. Fitting coefficient of unloading modulus to strength ratio under dry condition

State	*M*	*N*	*W*	Correlation coefficient/R^2
0-G	-7.0313	15.465	3.9734	0.9991
1-G	-8.0452	16.358	3.1126	0.9981
3-G	-7.1436	13.642	3.2969	0.9979
6-G	-3.8013	9.4699	3.0898	0.9986
10-G	-3.3701	7.7517	2.4335	0.994

Fig 6 shows the relationship between the maximum unloading modulus of sandstone and n in the two states, the maximum unloading modulus of sandstone in the uniaxial loading and unloading test shows a logarithmic decrease of formula (5) with the increase of n. The fitting coefficients are in TABLE III, and the fitting effect is good.

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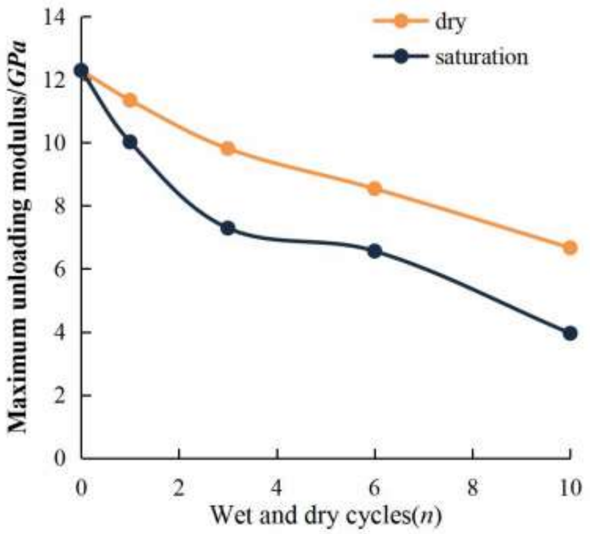

Fig 6: Relationship between maximum unloading modulus and *n* under two conditions

$$E_{\max}(n) = E_{\max}(0)[1 - f\ln(n^g + 1)] \tag{5}$$

TABLE III. Fitting coefficients of maximum unloading modulus and *n* under two conditions

State	Dry		Saturation	
Coefficient	Maximum unloading modulus (single axis)	Maximum unloading modulus (triaxial)	Maximum unloading modulus (single axis)	Maximum unloading modulus (triaxial)
$E_{\max}(0)$	12.29	16.69	12.29	16.69
f	-0.0965	-0.201	-0.272	-0.3895
g	1.9228	0.9074	0.9906	0.6183
R^2	0.9792	0.9692	0.9731	0.9888

IV. ENERGY DISSIPATION ANALYSIS

4.1 Principle of Energy Dissipation

Fig 7 for characteristics of sandstone under uniaxial and uninstall indicator diagram (3 - G, 11 cycles),

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by the first law of thermodynamics[19, 20], the total energy of the input force is U, under the condition of uniaxial cyclic compression, carry the work done for loading area under the curve:

$$U = U_1 + U_2 + U_3 \tag{6}$$

In the formula, U_3 is the released elastic energy which is area in unloading curve. Dissipative energy $U - U_3$ is total external work minus elastic strain energy. The appearance of the hysteresis loop is an experimental phenomenon, and the form of energy is U_2.

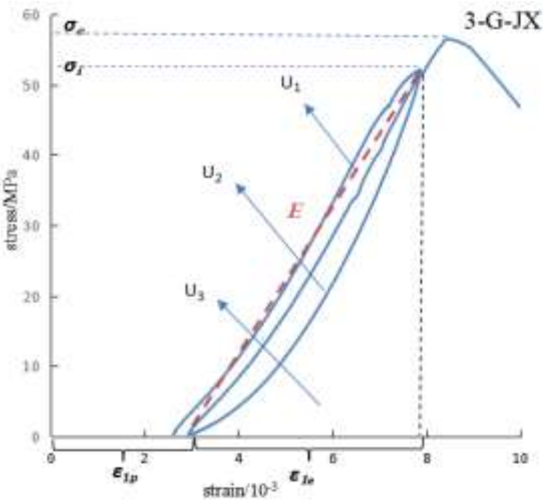

Fig 7: Characteristic indexes of sandstone uniaxial loading and unloading test (3-G, eleventh cycle)

It shows the process of micro-crack closing, developing, through and through to failure, so energy dissipation is the manifestation of rock damage. The magnitude of the energy dissipation ratio ($\frac{U^d}{U}$) reflects the extent of rock failure.

In the tests, the cumulative dissipation energy is used to reflect the energy dissipation degree after different loading and unloading times. The formula of the cumulative dissipation energy is as follows:

$$U^d(i) = \sum_{k=1}^{i} U_k^d \tag{7}$$

In the formula, $U^d(i)$ is the i secondary cycle cumulative dissipative energy.

The cumulative total strain energy after the i cycle is the sum of the cumulative dissipated energy and

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the elastic strain energy at that cycle.

$$U(i)=U_i^e+U^d(i) \tag{8}$$

In the formula, $U(i)$ is i cyclic cumulative total strain energy, U_i^e is the elastic deformation energy under i cycle.

The ratio of $U^d(i)$ to the peak cumulative total strain energy at last stage of loading before the peak is defined as the cumulative energy dissipation ratio:

$$D(i)=\frac{U^d(i)}{U(t)} \tag{9}$$

In the formula, $D(i)$ is the accumulated dissipated energy when loaded to the i cyclic, $U(t)$ is the accumulated total strain energy at the last stage of loading before the peak.

4.2 Energy Dissipation Analysis

By calculating the area, the total work done by the external load, the released elastic strain energy, the dissipation energy, and the hysteresis loop energy under each cycle can be obtained (see Fig 8). The elastic energy, dissipation energy, and hysteresis loop energy increase with the increase of the loading and unloading amplitude-intensity ratio. The total strain energy and elastic strain energy increase rapidly in the initial stage, and the plastic dissipation energy and hysteresis loop energy increase faster in the later stage. Rapidly, the difference between the dissipated energy and the hysteretic loop energy decreases gradually with the increase of the amplitude-intensity ratio. Under the same dry-wet cycle state, the energy characteristic value of rock in the "saturated" state is smaller than that in the "dry" state. Due to the low stress level at the initial stage of loading and unloading, the micro-defects (micro-pores, micro-cracks) inside the rock are in the compaction stage, and the energy dissipated in the first few cycles of CLU is less. , because rock mineral particles produce elastic deformation during the loading process and enter the linear elastic stage, the dissipated energy is basically proportional to the number of CLU; during the unloading process, due to the release of elastic energy, the dissipated energy is relatively large. The dissipative energy of one cycle is not equal to the accumulation of the previous cycles; with the increase of the number of loading and unloading and the stress amplitude, the defects such as micro-cracks in samples with different dry-wetting cycles are further developed, produced and expanded, causing damage to the Accumulation will eventually form macroscopic through cracks, the stored elastic strain energy in sample decreases sharply, and the dissipation energy of the plastic zone formed at the crack tip increases.

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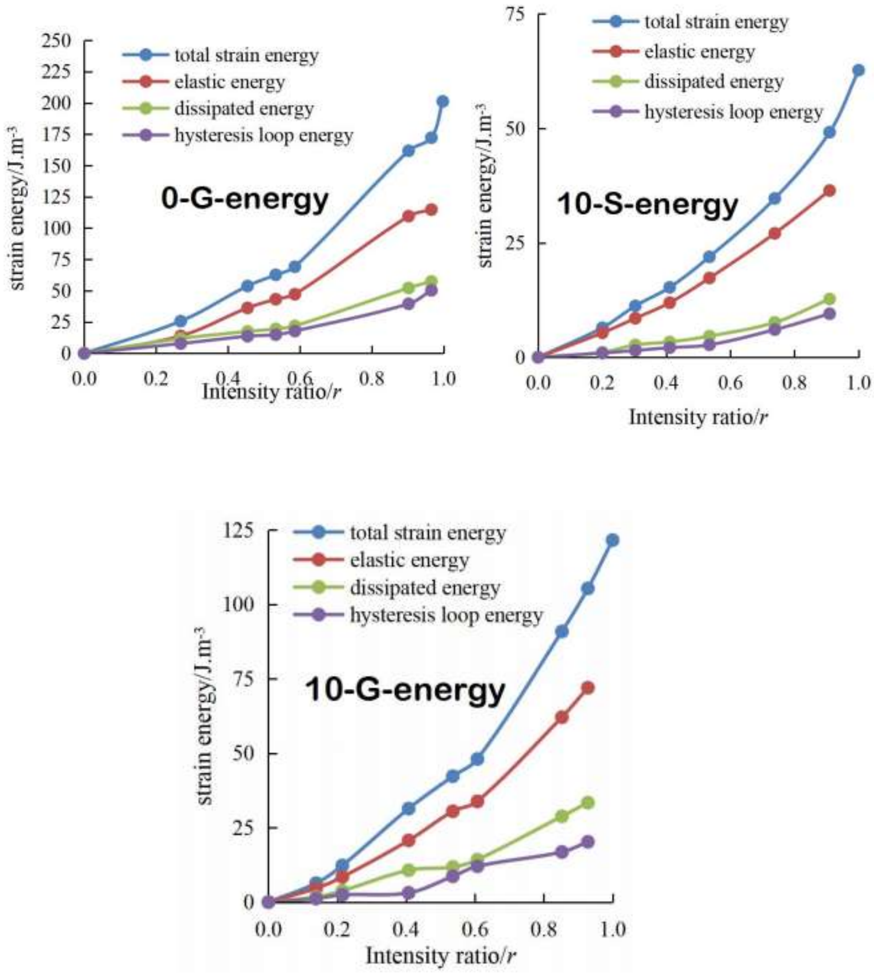

Fig 8: Relationship between strain energy and strength ratio of sandstone under DAW

The cumulative dissipation energy is calculated by substituting (7) the dissipation energy of each loading period in Fig 9. According to the formula (9) to calculate the cumulative energy dissipation ratio in different periods, the specific value shown in Fig. 9 shows that in the peak phase, the cumulative energy dissipation ratio increases with r in the two parabola form, and the closer the peak strength grows faster, The energy dissipation ratio around peak strength is around 0.6, which is significantly larger than that of uniaxial compression test (0.17~0.23), Therefore, the peak cycle test has irreversible damage to rock, and damage variable increases with the increase of cycle number, with the increase of unloading strength ratio, the cumulative energy dissipation ratio of rock sample corresponding to amplitude point is greater than that of uniaxial compressive test.

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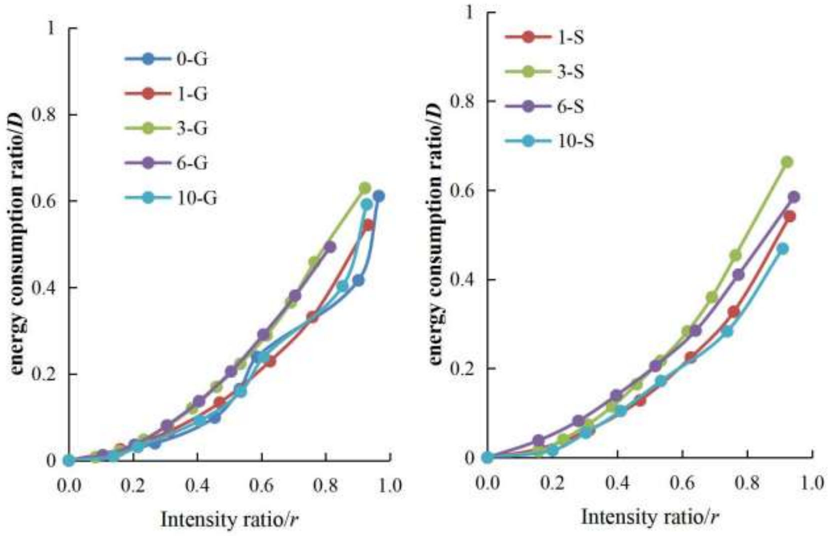

(a) Dry state (b)Saturation state

Fig 9: Relationship between damage variable and strength ratio in uniaxial loading and unloading test

Due to tests, each cycle produces the energy of hysteresis loop, the last loading cycle does not take into account the effect of the hysteresis loop energy, so it is shown from TABLE IV that the maximum total strain energy at the last cyclic peak point of the single shaft cyclic loading test is less than that of the peak input of the uniaxial compression test (except individual specimens). From Fig 10, the maximum total strain energy of sandstone under uniaxial loading and unloading under different DAW is decreased with the increase of *n* and decreases logarithmically in the way of formula (10), the concrete fitting coefficients are shown in TABLE V, and the fitting effect is better by the table.

$$U_{\max}(n) = U_{\max}(0)[1 - f\ln(n^g + 1)] \tag{10}$$

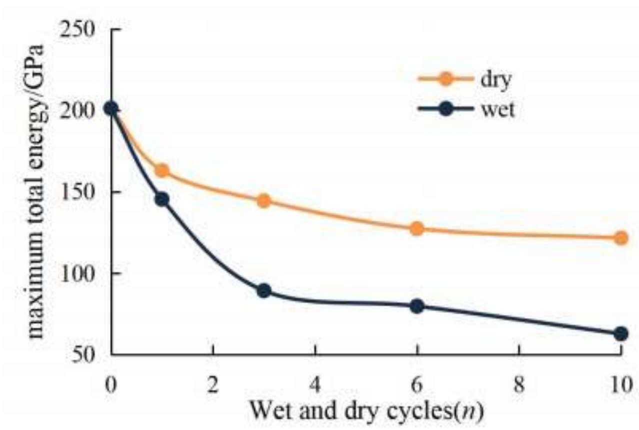

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Fig 10: Relationship between the maximum total strain energy and *n*

TABLE IV. Input strain energy of uniaxial compression tests and CLU test of sandstone under DAW

State	Input strain energy/$kJ.m^{-3}$					Difference
	$U_{max}(n)$	Uniaxial compression U				$\frac{U_{max}(n)-U}{U}\times 100\%$
	peak cycle period	Specimen 1	Specimen 2	Specimen 3	average value	
0-G	201.24	234.59	245.68	290.25	256.84	-21.65
1-G	162.97	164.46	187.67	224.35	192.16	-15.19
3-G	144.38	162.50	176.95	197.57	179.01	-19.35
6-G	127.31	155.19	159.73	158.31	157.75	-19.30
10-G	121.54	132.38	118.55	106.54	119.16	2.01
1-S	145.47	156.88	117.57	138.17	137.54	5.76
3-S	89.20	112.25	124.77	91.09	109.37	-18.44
6-S	79.67	94.97	101.51	96.15	97.54	-18.32
10-S	62.71	76.82	69.62	58.38	68.28	-8.16

TABLE V. Fitting coefficient of Maximum total strain energy of sandstone and *n*

State	Dry		Wet	
Coefficient	uniaxial	triaxial	uniaxial	triaxial
$U_{max}(0)$	201.24	399.75	201.24	399.75
f	-0.2794	-0.2794	-0.4626	-0.5001
g	0.5167	0.8048	0.5633	0.4336
R^2	0.9952	0.9755	0.9688	0.9938

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V. CONCLUSION

In the loading and unloading test, the mechanical parameters of the rock decreased in the process of "water saturation", and the mechanical parameters increased in the process of "water loss", but they could not completely return to the initial state, so the samples produce irrecoverable damage under the repeated action of "saturated water and water loss".

In the pre peak stage of the curve, the cumulative energy consumption ratio increases in the form of quadratic parabola with *r*, the closer to the peak intensity, the faster the growth rate is, The energy dissipation ratio near the peak intensity is about 0.6, which is obviously larger than that of the monotone compression test (0.1~0. 3).Therefore, every cycle before peak loading and unloading tests causes unrecoverable damage to rock. With the accumulation of cycles, the damage variable also increases in nonlinear accumulation. Therefore, with the increase of loading and unloading strength ratio, the cumulative energy consumption ratio of the corresponding amplitude of rock sample is greater than that of the corresponding strength of monotone compression test.

Under different DAW, the maximum total strain energy in triaxial tests of sandstone decreases logarithmically with the increase of *n*, and at low confining pressure, the initial dissipation energy and hysteresis cycle energy of rock samples increase slowly, and with the increase of *n*, The energy difference between dissipation and hysteresis loop increases gradually, the shear strength of rock samples decreases gradually after peak, the lateral strain develops rapidly, and the confining pressure does negative work, so that the total strain energy after peak loading and unloading is lower than the total strain energy at the peak. The dissipation energy, hysteresis loop energy and the release elastic strain energy develop unsteadily after the peak, and the slope of the curve is much larger than that of the pre-peak stage.

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