

A Study of Stress-Strain Characteristics of Sandstone under Uniaxial Compression Subjected to Wetting-Drying Cycles

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ABSTRACT: To study the mechanical characteristics of sandstone subjected to wetting-drying cycles, the paper studies the failure characteristic stress of sandstone subjected to wetting-drying cycles based on a uniaxial compression test, i.e. crack initiation stress σ_{ci} , dilatancy stress σ_{cd} , and peak strength σ_f . There is no significant linear correlation between the crack initiation stress and the number of wetting-drying cycles. Based on the law of conservation of energy, the energy characteristics and damage mechanisms of sandstone during failure. The result shows that the total strain energy U , releasable elastic strain energy U^e , and dissipated strain energy U^d absorbed per unit volume of rock are decreasing linearly with the increase in number of wetting-drying cycles. Research finds that shifting from positive volumetric strain to negative volumetric strain (i.e. transforming from compression to dilation) would lead to release of elastic strain energy U^e and drastic rise of dissipated strain energy U^d , and is the turning point from crack propagation to approximate failure. The wetting-drying cycles accelerate the failure of sandstone specimens and reduce the dissipated strain energy U^d required for failure, presenting as a decrease in peak strength and elasticity modulus at the macroscopic level.

KEYWORDS: Sandstone, Uniaxial Compression, Wetting-Drying Cycle, and Strain Energy.

1. INTRODUCTION

Precipitation-induced water level fluctuations drive repeated wetting-drying cycles within the hydro-fluctuation belt of reservoirs, triggering progressive rock degradation that is more severe than that caused by prolonged immersion. This degradation manifests as cumulative damage—a fatigue-like process in which individual cycles induce minor, often reversible microstructural changes; however, their nonlinear accumulation over multiple cycles leads to irreversible deterioration. The damage accumulates in a manner that accelerates with cycle number, eventually reaching the failure threshold of the reservoir bank slope, beyond which slope instability and geological hazards (e.g., landslides, slumping) are triggered.

In recent years, many scholars have studied the degradation mechanism of wetting-drying cycles (Jiang et al., 2022; He et al., 2025; Lou et al., 2025). Hu et al. (2018) have studied the constitutive model and the law of damage evolution of mudstone subjected to wetting-drying cycles. Wan et al. (2016) have studied the stability of clay overburden in refuse landfill containing vegetation root systems. Torres-Suarez et al. (2014) have studied the mechanical behavior of Colombian Andes mudstone in loading and unloading cycles and wetting-drying cycles. Suddepong et al. (2014) have studied the resistance of cement-stabilized reclaimed asphalt pavement against wetting-drying cycles. Akcanca and Aytekin (2012) have discussed the expansive characteristics of the lime stabilized sand-bentonite mixture subjected to wetting-drying cycles. Pathak and Alfaro (2010) have studied the wetting-drying cycle characteristics of geogrid-reinforced clay under load. Sarkar and Bhattacharjee (2014) have proposed a numerical solution to analyze the evolution of moisture distribution in concrete exposed to drying and wetting cycles induced by intermittent precipitation. Sahmaran et al. (2007) have discussed the sulfate corrosion resistance of ordinary cement and mixed cement in dry-wet and cold-hot environments. Ye et al. (2011) have studied soil degradation in the rocky desertification regions subjected to wetting-drying cycles.

This study employs a laboratory-simulated "drying-saturating-drying" cycle to approximate the repeated water level fluctuations in reservoir zones. Uniaxial compression tests are conducted on

sandstone specimens—under both dry and saturated conditions—subjected to multiple wetting-drying cycles, aiming to investigate their stress-strain behavior and energy dissipation characteristics. The findings contribute to a deeper understanding of the degradation mechanism of sandstone under cyclic hygric stress, offering both theoretical insight and practical significance for the long-term stability assessment of reservoir slopes and geological structures.

2. SPECIMEN PREPARATION AND TEST EQUIPMENT

2.1 Format

The paper should be prepared according to the instructions provided in this section. Use the formatting of this template for the titles, text, tables, figures, and equations of the paper. For the wetting-drying cycle tests, distilled water was used as the immersion medium, with cycle numbers set at $n = 0, 1, 3, 6$, and 10 . After completing the specified number of cycles, each sandstone specimen was subjected to uniaxial compression testing to characterize its mechanical properties. The specimen was first dried in a drying oven for 24 h at 105°C , then immersed in a vacuum saturation bath for 24 h. The process was a wetting-drying cycle. The specimen was placed in an intelligent cement vacuum water saturation machine. The machine was vacuumized for 4 h at -80 kPa . The machine automatically drew water until the specimen was fully immersed. The specimen was left still for 20 h to complete the vacuum saturation process, as shown in Figure 1. A saturated specimen was defined as "dried for 24 h-vacuum saturated for 24 h," after different wetting-drying cycles. A dried specimen was one "dried for 24 h, saturated for 24 h, dried for 24 h" subjected to wetting-drying cycles.

The test instrument was a French TOP INDUSTRIE multi-function rock triaxial rheometer, as shown in Figure 1. The sandstone specimen was processed into a standard specimen, 50 mm in diameter and 100 mm in height, as shown in Figure 2. The sandstone specimen's specific gravity was 2.69 g/cm^3 , and porosity was 2.4%. Displacement control was performed. Axial load was applied continuously at a rate of 0.01 mm/min until failure occurred. The TOP INDUSTRIE test equipment measures axial and lateral strain through

an LVDT (Linear Variable Differential Transducer) and an electronic strain gauge, respectively.

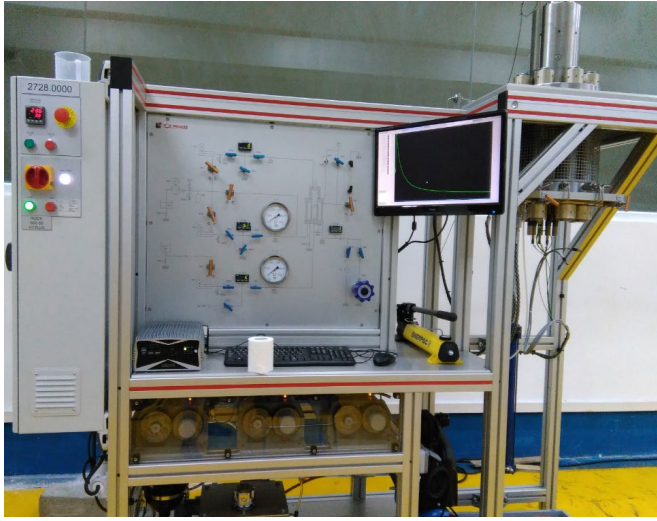


Figure 1 TOP INDUSTRIE test equipment



Figure 2 Sandstone test specimen

3. STRESS-STRAIN CHARACTERISTICS OF SANDSTONE

Figure 3 illustrates the uniaxial compression stress-strain curves of sandstone specimens subjected to different wetting-drying cycle treatments. 0-G represents 0 wetting-drying cycles, in which G signifies that the test specimen is dry. Similarly, 10-S indicates 10 wetting-drying cycles, with S indicating that the test specimen is saturated.

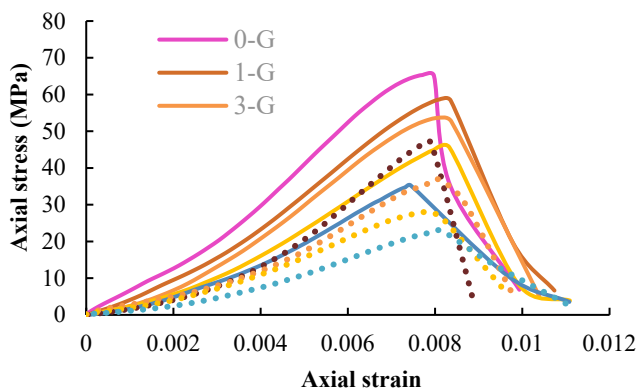


Figure 3 Stress-strain curve of sandstone under uniaxial compression

The axial strain and radial strain could be recorded during the test. The volumetric strain ε_v could be computed on the basis of the following equation:

$$\varepsilon_v = \varepsilon_1 + 2\varepsilon_2 \quad (1)$$

where ε_1 is the axial strain, ε_2 is the radial strain.

The elastic volumetric strain of rock during uniaxial compression ε_{ve} :

$$\varepsilon_{ve} = \frac{1-2\nu}{E} \sigma_1 \quad (2)$$

where ν is the Poisson's ratio, E is the elasticity modulus, σ_1 is the axial stress.

The total volumetric strain of rock minus its elastic volumetric strain is the volumetric strain of cracks ε_{vc} :

$$\varepsilon_{vc} = \varepsilon_v - \varepsilon_{ve} \quad (3)$$

As can be seen from Figure 4, the damage evolution of sandstone under uniaxial compression and its volumetric strain have the following relationship (Huang et al., 2012):

(1) Compaction stage (OA segment): The stress-strain curve was concave. The original microcracks and voids in the rock were closing under compression. The volumetric strain ε_v and volumetric strain of cracks ε_{vc} exhibited strong gradual compression characteristics.

(2) Elastic deformation stage (AB segment): The stress-strain curve was approximately a straight line, and a continuum following rock compaction. The volumetric strain ε_v was in a linear compressive state. The volumetric strain of cracks ε_{vc} was increasingly slowly and almost remained unchanged.

(3) Stable propagation stage of cracks (BC segment): After loading exceeded point B, the volumetric strain of cracks ε_{vc} was decreasing gradually, and the rock was entering the plastic deformation stage. Microcracks began to form and enlarge as compressive stress increased. The stress state corresponding to point B was crack initiation stress σ_{ci} and its corresponding strain was ε_{ci} .

(4) Accelerated propagation stage of cracks (CD segment): After loading exceeded point C, the volumetric strain ε_v started to decrease gradually, and the rock was entering the dilatancy stage. The stress state corresponding to point C was dilatancy stress σ_{cd} . The corresponding strain was ε_{cd} .

(5) Post-peak stage (DE segment): After loading exceeded the peak strength point D, the concentration effect of the crack-tip stress was significant, and continuous propagation of cracks caused release of stress and energy. The intensive exchange between stress concentration and release caused its strength to be lost. The volumetric strain ε_v and the volumetric strain of cracks ε_{vc} were rapidly and continuously expanding until complete failure of the test specimen. The stress state corresponding to point D was peak stress σ_f and its corresponding strain was ε_f .

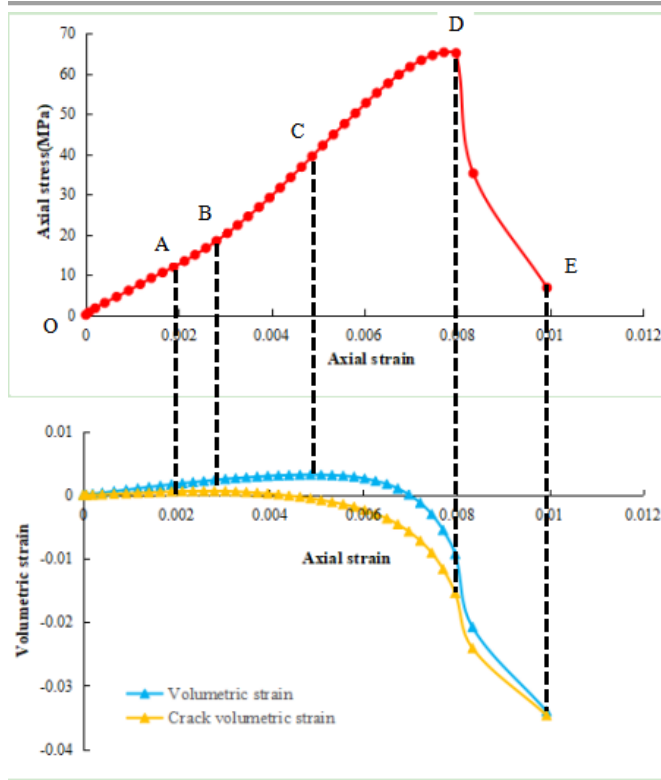


Figure 4 Relationship between axial stress of rock and its volumetric strain and axial strain

Figure 5 presents the variation of stress with the number of wetting-drying cycles. As can be seen from Figure 5, with the increase in the number of wetting-drying cycles, the crack initiation stress σ_{ci} , dilatancy stress σ_{cd} , and peak strength σ_f of the rock test specimen were decreasing gradually. The crack initiation stress σ_{ci} , dilatancy stress σ_{cd} , and peak strength σ_f of the saturated rock test specimen were generally smaller than those of the dry rock test specimen. Figure 6 presents the variation of stress ratio with the number of wetting-drying cycles. As can be seen from Figure 6, σ_{ci}/σ_f , σ_{cd}/σ_f , and σ_{ci}/σ_{cd} ratios were 0.159-0.289, 0.352-0.659, and 0.302-0.564, respectively. No significant relationship was found between these ratios and the number of wetting-drying cycles (n). Table 1 presents the linear fitting result of crack initiation stress, dilatancy stress, peak strength, and the number of wetting-drying cycles. As can be seen from Table 1, the peak strength σ_f , dilatancy stress σ_{cd} , and number of wetting-drying cycles n exhibited a significant linear relationship and were decreasing with the increase in number of wetting-drying cycles. The linear coefficient R^2 was smaller than 0.86.

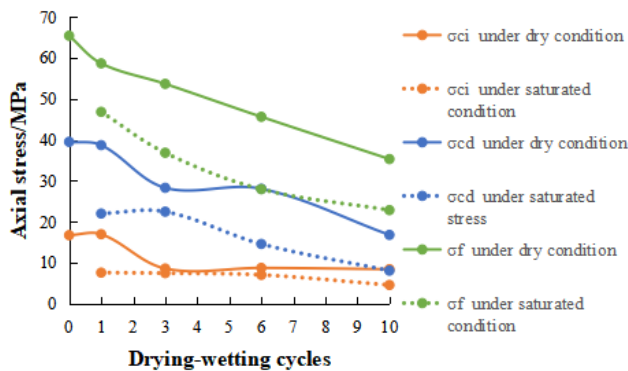


Figure 5 Variation of stress with number of wetting-drying cycles

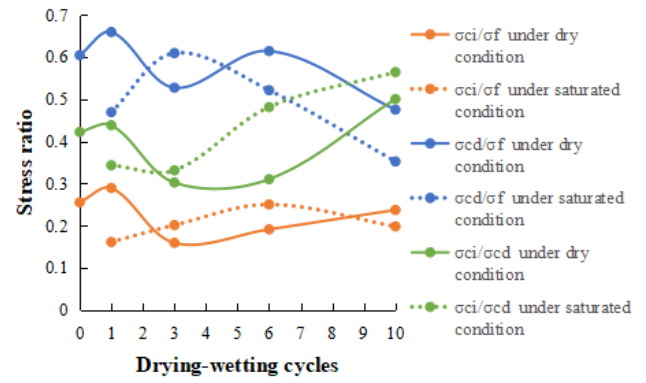


Figure 6 Variation of stress ratio with number of wetting-drying cycles

Table 1 Linear fitting result of crack initiation stress, dilatancy stress, peak strength, and number of wetting-drying cycles

Y	Linear fitting equation	Coefficient of association R^2
peak strength in a dry state σ_f	$Y = -2.853n + 63.117$	0.983
peak strength in a saturation state σ_f	$Y = -2.585n + 46.506$	0.922
dilatancy stress in a dry state σ_{cd}	$Y = -2.207n + 39.06$	0.926
dilatancy stress in a saturation state σ_{cd}	$Y = -1.697n + 25.224$	0.943
crack initiation stress in a dry state σ_{ci}	$Y = -0.885n + 15.381$	0.63
crack initiation stress in a saturation state σ_{ci}	$Y = -0.335n + 8.288$	0.856

4. STRAIN ENERGY CHARACTERISTICS AND DAMAGE MECHANISM

4.1 Strain energy characteristics

Figure 7 presents the relationship between the dissipated strain energy U^d and the releasable elastic strain energy U^e in the stress-strain curve under uniaxial compression. According to the research by Xie et al. (2005), in the uniaxial compression test, strain energy absorbed per unit volume of rock U , releasable elastic strain energy U^e , and dissipated strain energy U^d can be written as:

$$U = \int_0^{\epsilon_1} \sigma_1 d\epsilon_1 \quad (4)$$

$$U^e = \frac{1}{2E_u} \sigma_1^2 \quad (5)$$

$$U^d = U - U^e \quad (6)$$

where E_u is the unloading elasticity modulus. For ease of computation, the initial elasticity modulus E_0 is generally substituted for E_u .

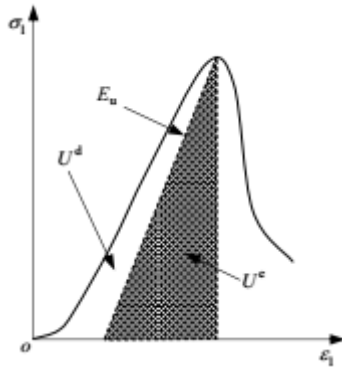


Figure 7 Relationship between the dissipated strain energy and the releasable elastic strain energy in the stress-strain curve under uniaxial compression

Table 2 presents the strain energy of sandstone at the peak point under different numbers of wetting-drying cycles. Figure 8 presents the variation in strain energy at the peak point with the number of wetting-drying cycles. As can be seen from Table 2 and Figure 8, strain energy absorbed per unit volume U , releasable elastic strain energy U^e , and dissipated strain energy U^d were decreasing linearly and gradually with the increase in the number of wetting-drying cycles, n . The strain energy of the sandstone specimen in a dry state was larger than that in a saturation state under the same number of wetting-drying cycles. The variation in strain energy was primarily stored as elastic strain energy.

Table 2 Strain energy of sandstone at the peak point (J/cm^3)

Specimen number	Strain energy at the peak point		
	U	U^e	U^d
0-G	0.2457	0.1981	0.0476
1-G	0.2243	0.1709	0.0534
3-G	0.1976	0.1744	0.0232
6-G	0.1583	0.1382	0.0201
10-G	0.1120	0.1081	0.0039
1-S	0.1382	0.1188	0.0194
3-S	0.1248	0.1043	0.0205
6-S	0.0950	0.0841	0.0109
10-S	0.0776	0.0724	0.0052

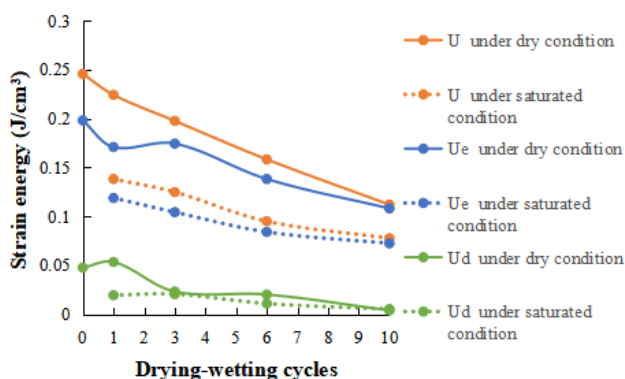


Figure 8 Variation of strain energy at the peak point with the number of wetting-drying cycles

4.2 Analysis of the damage mechanism of sandstone subjected to wetting-drying cycles

According to the law of thermodynamics, the release of strain energy stored in the rock accounted for sudden rock damage (Liang et al., 2012). Figure 9 presents the conversion process of the axial stress-strain energy of the 0-G sandstone specimen. As shown in the figure, before the stress reached peak strength, the total strain energy absorbed by the rock was primarily stored as elastic strain energy. The dissipated strain energy increased sharply when it approached the peak point. Once the stress reached the peak strength, the dissipated strain energy in the rock increased drastically at an angle of approximately 90° , and the cracks were propagating continuously until complete failure. Figure 10-12 presents the conversion process of volumetric strain-strain energy of 0-G, 6-G, and 6-S sandstone. As can be seen from the figure, the dissipated strain energy at Point F (volumetric strain was 0 point), U^d , was divided into two stages. When the volumetric strain was larger than 0 (on the left of Point F), the dissipated strain energy U^d increased somewhat and basically remained unchanged. When the volumetric strain was smaller than 0 (on the right of Point F), the dissipated strain energy U^d started to increase sharply.

At the initial stage of loading, the rock was in a compaction state. With increasing axial stress, lateral expansion dominated. The rock changed from the compaction state to the dilatancy state. The dissipated strain energy U^d started to increase sharply. Point F (volumetric strain was 0 point) corresponded to the turning point at which the dissipated strain energy U^d increased drastically. As can be seen from Figure 10-12, the distance between Point F and Point D in the 0-G test specimen was larger than that in the 6-G and 6-S test specimens, indicating that the wetting-drying cycles accelerate damage to sandstone and decrease the dissipated strain energy U^d required for damage to occur. The peak strength and the elasticity modulus decreased at the macroscopic level.

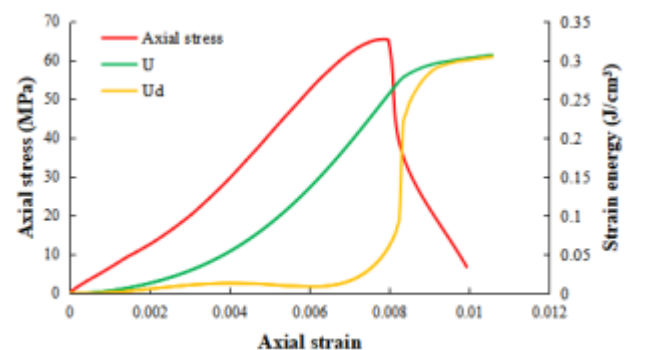


Figure 9 Conversion process of axial stress-strain of 0-G sandstone test specimen

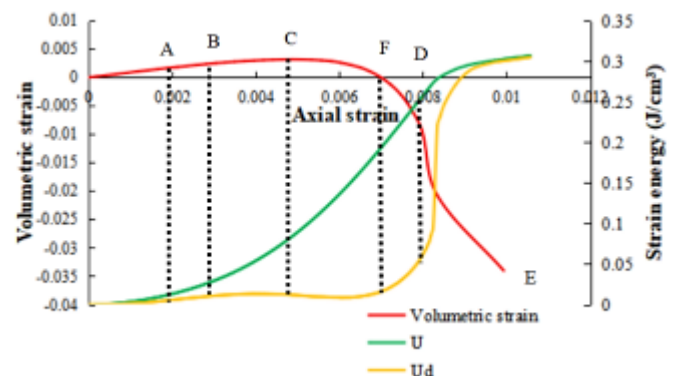


Figure 10 Conversion process of volumetric strain-strain energy of the 0-G sandstone test specimen

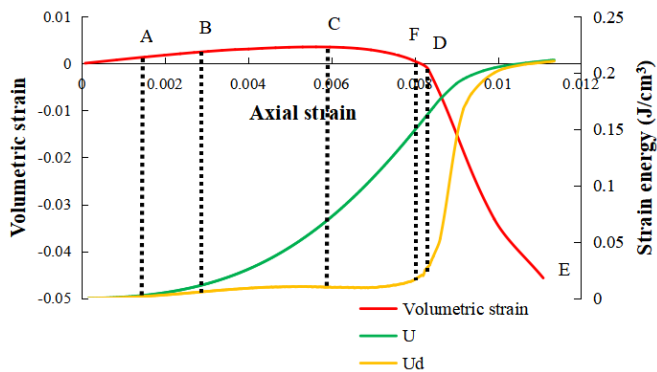


Figure 11 Conversion process of volumetric strain-strain energy of the 6-G sandstone test specimen

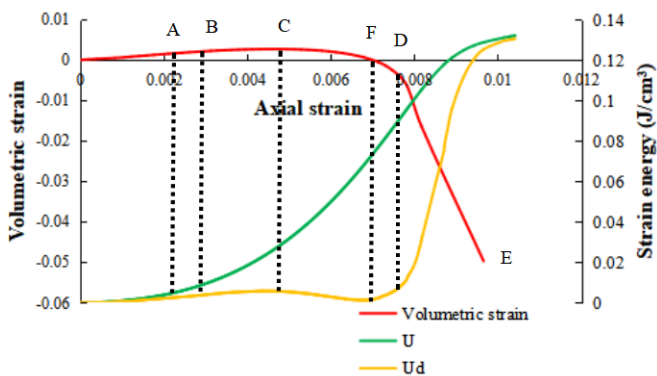


Figure 12 Conversion process of volumetric strain-strain energy of the 6-S sandstone test specimen

5. CONCLUSIONS

Based on a stress-strain test on sandstone subjected to wetting-drying cycles, the paper studies its stress-strain parameters and energy dissipation characteristics and draws the following conclusions:

(1) Peak strength σ_f and dilatancy stress σ_{cd} and number of wetting-drying cycles n exhibit a significant linear relationship and decrease with the increase in number of wetting-drying cycles. The linear coefficient of determination R^2 is larger than 0.92. The linear relationship between the crack initiation stress σ_{ci} the number of wetting-drying cycles n is insignificant. The linear coefficient of determination R^2 is smaller than 0.86. The σ_{ci}/σ_f , σ_{cd}/σ_f , and σ_{ci}/σ_{cd} ratios are 0.159-0.289, 0.352-0.659, and 0.302-0.564. The ratios and the number of wetting-drying cycles, n , show no significant regularity.

(2) Strain energy absorbed per unit volume U , releasable elastic strain energy, and dissipated strain energy U^d are decreasing linearly and gradually with the increase in the number of wetting-drying cycles, n . The strain energy of the sandstone specimen in a dry state was larger than that in a saturation state under the same number of wetting-drying cycles. The variation in strain energy was primarily stored as elastic strain energy.

(3) The release of strain energy stored in the rock is the internal cause of sudden failure in rock. Before the stress reaches peak strength, the total strain energy absorbed by the rock is primarily stored as elastic strain energy. The dissipated strain energy of rock will increase drastically only when the stress approaches the peak value. Once the stress reaches peak strength, the dissipated strain energy in the rock increases drastically at an angle of approximately 90° , and the cracks propagate continuously until complete failure. The dissipated strain energy at Point F (volumetric strain was 0 point), U^d , is divided into two stages. When the volumetric strain is greater than 0, the dissipated strain energy U^d increases slightly and then remains nearly constant. When the volumetric strain is smaller than 0, the dissipated strain energy U^d starts to increase sharply.

(4) Shifting from positive volumetric strain to negative volumetric strain (i.e., transforming from compression to dilation) would lead to the release of elastic strain energy U_e and a drastic rise

in dissipated strain energy U^d , and is the turning point from crack propagation to approximate failure. The wetting-drying cycles accelerate the failure of sandstone specimens and reduce the dissipated strain energy U^d required for failure, presenting as a decrease in peak strength and elasticity modulus at the macroscopic level.

Studying the wetting-drying cycle of rocks is crucial to the stability of reservoir slopes. The core lies in predicting and preventing bank slope instability and geological disasters caused by periodic fluctuations in water level, ensuring the safe operation of reservoirs.

It should be noted that some conclusions drawn in this paper require further verification through additional sandstone experiments.

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