

Research Article

Effect of Cyclic Loading and Unloading on the Deformation and Damage Properties of Sandstone from Beizao, a Coal Mine underneath the Bohai Sea in China

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Mining under the sea is a challenging task in China. Affected by blasting, tunneling, and other engineering disturbance, surrounding rock is often in a state of cyclic loading and unloading stress. In this study, in order to investigate the effect of cyclic loading and unloading and unloading tests of sandstone underneath the Bohai Sea, the GCTS test machine is used to conduct cyclic loading and unloading tests on sandstone. The results show that under cyclic loading and unloading compression, the stress-strain curves of sandstone form a hysteresis loop. The axial residual deformation first decreases, then increases with the increase of cycle number and unloading stress level. Both the circumferential residual strain and volumetric residual strain decrease with the increase of cycle number and cyclic load. The volume deformation first increases, then decreases, and the circumferential strain gradually decreases. In the process of cyclic loading and unloading, the loading elastic modulus gradually increases. Affected by damage, the unloading stress level on the damage parameters of sandstone are analyzed. Before brittle failure of the specimen, the absolute damage parameters of axial, circumferential, and volume show an increasing trend, and the increase rates of circumferential damage parameters and volume damage parameters suddenly increase, which is also the precursor of the sandstone specimen's instability failure.

1. Introduction

In the process of underground coal mining, the surrounding rock of roadway of the working face is mostly affected by various mining-induced stresses. Some accidents, including rock burst and environmental problems, have been caused by underground coal mining [1–5]. In addition, its deformation behavior, strength characteristics, and failure mode are essentially different from those under conventional uniaxial and triaxial loading [6, 7]. Affected by mining and blasting, roadway surrounding rock is often in a state of cyclic loading and unloading stress. For these reasons, exploring the change of rock mechanical parameters under cyclic loading and unloading is of great significance for safe and efficient coal mining and mine disaster prevention.

Cyclic loading and unloading tests are typically used to study the fatigue and damage characteristics of materials. The existing experimental research has confirmed that the mechanical properties of rocks under cyclic loading and unloading differ significantly from those under monotonic loading [8–11]. Zoback and Byerlee [12] conducted cyclic loading and unloading tests on Westerly granite and observed that the dilatancy point of rock was not affected by the number of cycles under the confining pressure of 50 to 200 MPa. Elliott and Brown [13] studied recoverable deformation and unrecoverable deformation of rock under

cyclic loading and unloading and distinguished elastic and plastic components of rock. Singh [14] studied the fatigue characteristics and strain hardening phenomenon of sandstone and found that when the fatigue stress amplitude was reduced, the fatigue life of rock increased, and the higher the number of cycles, the greater the proportion of strain hardening. Yoshinaka et al. [15] carried out cyclic loading and unloading tests on Ohya tuff, Yokohama sandstone and mudstone, and Kobe mudstone and sandstone. They also analyzed the deformation behavior, and dilatancy characteristics of these four soft rocks were analyzed. It was found that the deformation modulus was exponentially related to plastic strain, and the relationship model between internal friction angle and dilatancy angle and plastic strain was given. Li et al. [16] studied the fatigue damage characteristics of frozen rock containing cracks, obtained the fatigue failure law of frozen rock, and pointed out that the fatigue effect of rock containing cracks is stronger than that of intact rock under freezing conditions. Bagde and Petroš [17] carried out uniaxial cyclic loading and unloading tests on sandstone and studied the influence of loading frequency on mechanical parameters. It is considered that Young's modulus, secant modulus, and uniaxial compressive strength increase with the increase of loading frequency. Zhou et al. [18] studied the mechanical properties of red sandstone under cyclic loading and found that the fatigue life of red sandstone decreased first and then increased with the increase of loading frequency and lower limit load ratio. It can be seen that cyclic loading has a significant effect on the damage of rock.

In terms of rock deformation and strength characteristics under cyclic loading and unloading, Fuenkajorn and Phueakphum [19] carried out cyclic loading and unloading tests on rock salt and analyzed the influence of cycle times on the strength and elastic behavior of rock salt. The results showed that the compressive strength of rock salt decreased with the increase of cycle times. In the early cycle, the elastic modulus first decreased, then remained basically unchanged until failure. Liu et al. [20] studied the deformation and failure characteristics of sandstone under cyclic loading and unloading. The test results showed that the axial strain of sandstone under cyclic loading and unloading was larger than that under static loading when dilatancy occurred. The sandstone mainly underwent shear failure. Compared with static loading, the local failure shear band under cyclic loading was wider. Using triaxial cyclic loading and unloading tests, Wang et al. [11] studied the mechanical properties of granite. In the volumetric compression stage, axial residual strain and volumetric residual strain decreased with the increase of cycles, while the deformation modulus gradually increased. However, in the volumetric dilatancy stage, with the increase of cycles, the axial residual strain and volumetric residual strain gradually increased, and the deformation modulus gradually decreased. Qiu et al. [21] studied the damage characteristics of marble based on irreversible deformation and considered that the damage increased with the increase of confining pressure unloading increment. Zhang et al. [22] carried out triaxial cyclic loading and unloading tests on mudstone with different bedding angles and ana-

lyzed the influence of plastic deformation on the inelastic deformation of anisotropic mudstone. They considered that the elastic modulus was negatively correlated with the cumulative plastic strain, while Poisson's ratio was opposite. Yang et al. [23, 24] carried out triaxial cyclic loading and unloading tests on sandstone and marble, respectively. They found that the strength of sandstone under cyclic loading and unloading was higher than that under monotonic loading at low confining pressure, and the strength was basically equal when the confining pressure exceeded 20 MPa. Before the peak, the axial damage was larger than the circumferential damage, while after the peak, the circumferential damage was larger than the axial damage. They also found that with the increase of cycles, the elastic strain of marble first increased, then decreased, and the plastic strain showed a nonlinear growth trend. Meng et al. [25] carried out uniaxial cyclic loading and unloading tests on red sandstone and analyzed the acoustic emission and energy characteristics. It was found that the number of acoustic emissions reached the maximum at each peak of cyclic stress, and the energy density increased with the increase of loading stress. Song et al. [26, 27] studied the deformation field and damage evolution of sandstone under cyclic loading and unloading by the digital image correlation method. The results showed that the damage of rock can be reflected by the maximum tensile strain on the surface of the sample. When the cyclic load reached the critical value, the cumulative damage of rock would evolve into a high local damage area corresponding to the macroscopic failure crack of rock, resulting in rock failure. Wang et al. [28] investigated the characteristics of rock deformation and failure under cyclic loading and unloading and found that compared with the uniaxial compression test, cyclic loading and unloading had a certain strengthening effect on the strength of the rock samples.

In summary, many studies have focused on the deformation, damage, and strength characteristics of rock under cyclic loading and unloading and have achieved good results. However, there have been few studies on mechanical properties of surrounding rock in seabed mining. Based on this, in this study, taking sandstone as the research object, the failure mechanics test of sandstone under cyclic loading and unloading is carried out by the GCTS testing machine, and the deformation damage characteristics of sandstone under cyclic loading and unloading are analyzed. The research conclusions provide theoretical reference for the failure behavior and stability analysis of surrounding rock in seabed mining.

2. Test Overview

2.1. Test Sample. The rock used in the test is sandstone, which is taken from the Beizao Coal Mine in the Longkou Mining Area, Shandong Province. The buried depth is approximately 400 m. The sandstone in the roof of coal 4 is layered light gray and white, with an average thickness of 68.02 m. According to X-ray diffraction test results, the sandstone material is composed of 33.97% quartz, 24.28% albite, 5.290% white mica, 16.98% dolomite, 2.100% calcite,



FIGURE 1: Complete stress-strain curves of sandstone under cyclic loading: (a) UC-C-1; (b) UC-C-2.



FIGURE 2: Failure modes of the sandstone specimens: (a) UC-C-1; (b) UC-C-2.

and 17.38% kaolinite. The porosity of the sandstone material is approximately 9.1%, with a coarse grain size varying from 0.25 to \sim 1 mm.

After drilling, sawing, and grinding, the sandstone was processed into a cylinder sample with a diameter of 50 mm and a height of 100 mm. In the machining process, it was ensured that the two ends of the sample are parallel and smooth without large scratches. The nonparallel degree of the two ends is greater than 0.01 mm, and the diameter deviation of the two ends of the sample meet the requirements of the measurement method. The basic mechanical properties of the sandstone have been investigated in Ref. [29]. The respective uniaxial compressive strength and elastic modulus of the sandstone are approximately 23.35 MPa and 8.32 GPa.

2.2. Test Scheme. The test equipment adopts the GCTS RTR-1000 rock triaxial test system of the State Key Laboratory of Coal Resources and Safety Mining of China University of Mining and Technology (Beijing). The GCTS RTR-1000 rock triaxial test system is a closed-loop digital servo control device, which can be used for simple and rapid uniaxial loading test and seepage test of rock samples. The stressstrain curve of rock and a series of mechanical parameters such as elastic modulus, Poisson's ratio, and compressive strength can be measured. The maximum axial load is 1000 kN, the stiffness is 1750 kN/mm, the maximum confining pressure is 140 MPa, and the resolution is 0.01 MPa. The pressurization device is a double piston pressurization system. The axial and circumferential deformations of the rock samples are tested by a 5 mm extensometer.

The axial strain control is used in the process of cyclic loading and unloading, and the loading and unloading rates are 0.02%/min. The interval between each cycle is controlled by strain, which is 0.03%. The loading and unloading scheme is as follows: $0 \rightarrow 0.03\% \rightarrow 0 \rightarrow 0.06\% \rightarrow 0 \rightarrow 0.09\%...$ until failure is reached.

3. Test Results

3.1. Stress-Strain Curves of Sandstone under Cyclic Loading. The stress-strain curves of the sandstone under uniaxial cyclic loading and unloading are shown in Figure 1. It can be seen from the axial stress-axial strain curve that the postpeak curve of sandstone has no obvious strain softening stage, thus forming a typical type II curve. Figure 2 shows the failure modes of sandstone specimens under uniaxial cyclic loading and unloading compression. Compared with



FIGURE 3: Calculation method of deformation parameters of sandstone under cyclic loading: (a) axial strain; (b) radial strain.

the failure modes of the sandstone under conventional uniaxial and triaxial compression in Ref. [30], under the cyclic loading and unloading compression, the cracks of the sandstone specimens increase obviously.

The calculation method of deformation parameters of sandstone is shown in Figure 3. Figure 3(a) shows the ninth cycle of the axial stress-axial strain curve of sandstone UC-C-1, while Figure 3(b) shows the ninth cycle of the axial stress-radial strain curve of sandstone UC-C-1. It can be seen from Figure 4 that each cyclic sandstone forms a hysteresis loop, which is mainly due to the internal microcracks. The distance between the loading starting point and unloading end point is an irreversible strain, namely, residual strain. Among them, ε_1^{ri} and ε_3^{ri} are the axial and circumferential residual strains, respectively. The deformation under the unloading curve is recoverable deformation, namely, elastic strain, where ε_1^{ei} and ε_3^{ei} are the axial and circumferential elastic strains, respectively. The sum of the residual strain and elastic strain is the deformation under the loading curve under this cycle, namely, the total strain, where ε_1^i and ε_{3}^{i} are the axial and circumferential total strains under this cycle, respectively. The elastic modulus is the slope of the straight line of the loading and unloading curve. The elastic moduli of loading and unloading are expressed by E_L^i and E_U^i , respectively.

4. Discussion

4.1. Effect of Cycles on Sandstone Deformation

4.1.1. Relationship among Residual Strain, Elastic Strain, and Number of Cycles. The residual deformation and elastic deformation of sandstone under different cycles are shown in Figure 5. Figure 5(a) shows the relationship between residual strain and cycles, while Figure 5(b) shows the relationship between elastic strain and cycles. The total strain of sandstone under each cycle is the sum of the cyclic elastic



FIGURE 4: Unloading stress level and its difference of sandstone under cyclic loading.

strain and residual strain. The ratios of residual strain, elastic strain, and total strain are shown in Figures 5(c) and 5(d), where R_1^r and R_1^e are the ratios of axial residual strain and axial elastic strain to total strain, respectively. The ratios of circumferential residual strain and circumferential elastic strain to total strain and circumferential elastic strain to total strain can be expressed as R_3^r and R_1^e .

It can be seen from Figure 5(a) that the axial residual strain first decreases and then increases with the increase of cycles. The residual strains of specimens UC-C-1 and UC-C-2, respectively, reach the minimum values at the tenth and seventh cycles, namely, 0.042×10^{-3} and 0.062×10^{-3} . Both the circumferential residual strain and volumetric residual strain decrease with the increase of cycles. With the continuous increase in the number of cycles, the



FIGURE 5: Residual (elastic) strain and their ratios of sandstone under uniaxial cyclic loading-unloading compression: (a) residual strain, (b) elastic strain, (c) proportion of residual strain, and (d) proportion of elastic strain.

microcracks in the sandstone first produce a closure effect, resulting in the axial residual strain gradually decreasing. Then, with the continuous increase in the graded load, the stress concentration occurs at the tip of the microcracks; then, the crack initiation and propagation occur, thus resulting in the gradual increase of the irreversible deformation.

It can be seen from Figure 5(b) that with the increase of cycles, the axial elastic strain showed a linear growth trend before the peak. The circumferential elastic strain decreases with the increase of the number of cycles, and the decreasing rate increases gradually. In the first six cycles, the volumetric elastic strain of sandstone increases linearly with the number of cycles. Then, with the number of cycles, the increase rate

of volumetric elastic strain gradually decelerates. The bulk elastic strain of UC-C-1 and UC-C-2 samples reaches the maximum value after the tenth and ninth cycles, namely, 1.185×10^{-3} and 1.165×10^{-3} , respectively. Then, with the increase of cycles, the volume elastic deformation gradually decreases.

Figure 5(c) illustrates the relationship among the R_1^r , R_3^r , and cycle times of specimens UC-C-1 and UC-C-2. It can be seen that, with the increase of cycle times, the R_3^r decreases gradually. For example, specimen UC-C-1 sample reaches the minimum in the tenth cycle and then increases gradually with each cycle. The relationship between R_3^r and cycle times first decreases, then increases. Among them, specimens UC- C-1 and UC-C-2 reach the minimum at the fourth and fifth cycles, respectively, and then gradually increase. Figure 5(d) shows the relationship among R_1^e , R_3^e , and the number of cycles. It can be seen that R_1^e increases gradually with the increase of cycles. On the contrary, R_3^e first increases, then decreases.

During the cyclic loading and unloading process, due to the gradual closure of the primary crack, the axial residual strain gradually decreases, and the ratio of residual strain to total strain gradually decreases. Then, with the increase of the cyclic load, the stress concentration occurs at the tip of the original crack, and the crack initiation occurs, resulting in the increase of the axial residual strain.

4.1.2. Relationship between Loading and Unloading Elastic Modulus and Cycles. The relationship between the loading and unloading elastic modulus of sandstone and the number of cycles under cyclic loading and unloading is shown in Figure 6. It can be seen from the figure that, with the increase of cycles, the loading elastic modulus increases gradually. Specimen UC-C-1 reaches the maximum value of 8.965 GPa at the tenth cycle, while specimen UC-C-2 reaches the maximum value of 10.48 GPa at the eleventh cycle, then begins to decrease.

The loading elastic modulus gradually increases. This is mainly because, in the process of cyclic loading, the microcracks inside the rock gradually close, and the rock matrix bears large deformation, resulting in the elastic modulus gradually increasing. In the early stage of loading, the unloading elastic modulus of specimen UC-C-1 gradually decreases, but overall, the relationship between the unloading elastic modulus and the number of cycles is not obvious, and its value changes little.

4.2. Effect of Unloading Stress Level on Deformation. The unloading stress level refers to the starting point when each cyclic stress begins unloading. The unloading stress difference refers to the difference between the unloading stress level of this cycle and that of the previous cycle, which is expressed as follows:

$$\Delta \sigma_u^i = \sigma_u^{i+1} - \sigma_u^i. \tag{1}$$

In the formula, σ_u^{i+1} is the unloading stress level of the i + 1-th cycle, σ_u^i is the unloading stress level of the *i*-th cycle, $\Delta \sigma_u^i$ is unloading stress difference, and *i* is the number of cycles. The magnitude of unloading stress difference can reflect the damage degree of rock samples during cyclic loading and unloading. The unloading stress difference gradually decreases, indicating that the rock continues to undergo damage. The smaller the unloading stress difference, the greater the damage will be.

The unloading stress level and unloading stress difference of sandstone in each cycle are shown in Figure 4. It can be seen from the figure that, with the increase of the number of cycles, the unloading stress level increases gradually. The UC-C-1 and UC-C-2 samples reach the maximum value in the 12th cycle, which are 19.23 MPa and 19.78 MPa, respectively. Then, the failure occurs in the 13th cycle, and



FIGURE 6: Loading and unloading moduli of sandstone under cyclic loading.

the peak values are 18.31 MPa and 19.36 MPa. The unloading stress difference of specimens UC-C-1 and UC-C-2 initially increases with the increase of cycles and reaches the maximum value at the ninth and tenth cycles, respectively, i.e., 2.303 MPa and 2.635 MPa. After that, with the continuous action of the cyclic load, the unloading stress difference gradually decreases, reaching a negative value in the 13th cycle.

Figure 7 illustrates the relationship between the unloading stress level and deformation parameters of sandstone under cyclic loading and unloading. It can be seen from Figure 7(a) that, with the increase of the unloading stress level, the axial residual strain gradually decreases. Then, when the unloading stress levels of UC-C-1 and UC-C-2, respectively, reach 16.25 MPa and 18.58 MPa, the axial residual strain begins to increase. The circumferential residual strain and volume residual strain decrease with the increase of the unloading stress level, and the decrease rate increases gradually. With increase of the cyclic number, the stress unloading level increases and the damage of the sandstone will be more server. And it produces more internal cracks in the sandstone. These cracks are residual deformation. Therefore, with the increase of the cyclic number, circumferential and volume deformations increase.

The influence of the unloading stress level on the axial elastic strain is shown in Figure 7(b). It can be seen that the axial elastic strain is positively correlated with the unloading stress level. With the increase of the unloading stress level, the circumferential elastic strain gradually decreases, and the reduction rate gradually increases.

4.3. Damage Evolution Law of Sandstone under Cyclic Loading and Unloading. Damage refers to the deterioration process of materials or structures caused by mesostructural defects, which is manifested as the weakening of cohesion of materials and even the destruction of volume elements



FIGURE 7: Relationship between unloading stress level and deformation: (a) residual strain; (b) elastic strain.

under external loads. It is an irreversible process of energy dissipation. Eberhardt et al. [31] proposed the following method for calculating damage parameters suitable for the cyclic loading and unloading process:

$$\begin{split} \omega_{\text{ax}} &= \frac{\varepsilon_1^{\text{ri}}}{\sum_{i=1}^n \varepsilon_1^{\text{ri}}},\\ \omega_{\text{lat}} &= \frac{\varepsilon_3^{\text{ri}}}{\sum_{i=1}^n \varepsilon_3^{\text{ri}}},\\ \omega_{\text{vol}} &= \frac{\varepsilon_{\text{v}}^{\text{ri}}}{\sum_{i=1}^n \varepsilon_{\text{v}}^{\text{ri}}}, \end{split} \tag{2}$$

where ω_{ax} , ω_{lat} , and ω_{vol} are the axial, circumferential, and volumetric strain damage parameters, respectively, which are the absolute damage parameters under each cycle, and *n* is the number of loading and unloading cycles.

The relationship between the damage parameters of sandstone and unloading stress level under cyclic loading and unloading is shown in Figure 8. In the figure, T_{ax} , T_{lat} , and $T_{\rm vol}$ are the axial, circumferential, and volume cumulative damage parameters, respectively. Their values are the sum of all the absolute damage parameters under a certain cycle. For example, the cumulative damage parameters of the sixth cycle are the sum of the absolute damage parameters of these six cycles. Taking UC-C-1 as an example, it can be seen from Figures 8(a) and 8(c) that, with the increase of the unloading stress level, the axial absolute damage parameter ω_{ax} of sandstone first decreases gradually, reaches the minimum value after about 16 MPa, then increases. The circumferential absolute damage parameter ω_{lat} of sandstone first gradually decreases, reaches the minimum value after 4 MPa, then gradually increases, and the increase rate is

accelerated, indicating that the sandstone will soon fail. The volume absolute damage parameter $\omega_{\rm vol}$ of sandstone first decreases, then increases with the increase of the unloading stress level. When the unloading stress level is about 12 MPa, it reaches the minimum, then increases, and the increase rate gradually accelerates. The absolute damage parameters of sandstone specimen UC-C-2 are similar to those of specimen UC-C-1. Based on the same phenomenon of sandstone specimens UC-C-1 and UC-C-2, it can be considered that during the cyclic loading and unloading, the absolute damage parameters (including axial, circumferential, and volume) of sandstone first decrease and gradually increase with the increase of unloading stress level, and the increase rate gradually increases. The main reason for this is that the rock itself undergoes initial damage, including a large number of primary cracks or pores and other defects. In the early stage of loading, the load bears a compaction effect on the microcrack inside the rock. The cracks gradually close, and the initial damage decreases; thus, the absolute damage parameter of the rock first decreases. Then, with the gradual increase of the graded load, the stress concentration occurs at the tip of the microcracks inside the rock, after which the crack initiation and propagation occur. The damage to the rock increases; thus, the absolute damage parameter of the rock begins to increase before the failure.

It can be seen from Figures 8(b) and 8(d) that with the increase of the unloading stress level, the cumulative damage parameters of specimens UC-C-1 and UC-C-2 have similar laws. Taking specimen UC-C-1 as an example, the axial cumulative damage parameter $T_{\rm ax}$ of sandstone increases with the increase of the unloading stress level, but the increase rate first increases, then decreases. The relationship between the circumferential cumulative damage parameter $T_{\rm lat}$ of sandstone and the unloading stress level exhibits



FIGURE 8: Damage parameters of sandstone with different unloading stress levels: (a) absolute damage parameter of UC-C-1; (b) accumulated damage parameters of UC-C-2; (d) accumulated damage parameters of UC-C-2.

obvious nonlinearity; i.e., with the increase of the unloading stress level, $T_{\rm lat}$ increases nonlinearly. With the increase of the unloading stress level, the variation of cumulative damage parameter $T_{\rm vol}$ of sandstone can be divided into three stages. The first is the slow growth stage, the cycle number of which is 1~5, and $T_{\rm vol}$ gradually increases, but the increase rate gradually decelerates. The second stage is stationary, and $T_{\rm vol}$ basically remains unchanged with the increase of the number of cycles, which are 0.32 (UC-C-1) and 0.17 (UC-C-2); the third stage is the accelerated damage stage, in which, with the increase of the unloading stress level, the increase rate of $T_{\rm vol}$ gradually increases and almost increases vertically.

The relationship between the absolute damage parameters and cumulative damage parameters of sandstone under cyclic loading and unloading and the number of cycles is shown in Figure 9. It can be seen from the figure that the damage parameters of UC-C-1 and UC-C-2 are basically consistent with the evolution trend of cycles. The axial absolute damage parameter ω_{ax} of sandstone first shows a decreasing trend with the increase of cycles, but the decrease is not obvious; then, it begins to increase. The circumferential absolute damage parameter ω_{lat} of sandstone increases with the increase of cycles, thus indicating that the circumferential residual deformation increases with the loading and unloading cycles. With the increase of cycles, the



FIGURE 9: Damage parameters of sandstone with different cyclic numbers: (a) UC-C-1; (b) UC-C-2.

variation law of the absolute volume damage parameter $\omega_{\rm vol}$ of sandstone can be divided into two stages. The first is the gradual decrease stage, at which time the $\omega_{\rm vol}$ gradually decreases with the increase of the cycle number. Among them, specimen UC-C-1 reaches the minimum in the eighth cycle, while specimen UC-C-2 reaches the minimum in the seventh cycle; the respective values are 0.0019 and 0.0015. Then, $\omega_{\rm vol}$ gradually increases with the increase of cycles, and the respective maximum absolute volume damage parameters of UC-C-1 and UC-C-2 are 0.381 and 0.507.

Comprehensively viewing Figures 8 and 9, it can be seen that the absolute and cumulative damage parameters of the axial, circumferential, and volume show increasing trends before brittle failure occurs. In addition, the increase rate of circumferential damage parameters and volume damage parameters suddenly increases, which is also the precursor of instability failure of the sandstone specimens. In the underground coal mine, the instability failure of surrounding rock may induce roof fall, rock burst, coal bump, or other accidents. Therefore, we must figure out the cyclic loading properties of the sandstone to give some references for supporting the roadway.

5. Conclusions

(1) Under cyclic loading and unloading, the cyclic stress-strain curve forms a hysteresis loop due to the influence of microcracks in sandstone. In the early stage, due to the closure of microcracks in sandstone, the axial residual deformation decreases with the increase of the number of cycles and unloading stress level. Then, with the increase of the grading load, the stress concentration at the tip of the primary crack occurs, and the crack initiation occurs, resulting in the axial residual deformation gradually increasing. The circumferential residual strain and volume residual strain bear a decreasing trend with the increase of the cycle number and unloading stress level; i.e., with the increase of the

cycle number and unloading stress level, the circumferential residual deformation and volume residual deformation gradually increase. The axial elastic deformation increases with the increase of the cyclic number and cyclic load. The volume deformation first increases, then decreases, and the circumferential strain gradually decreases

(2) During the cyclic loading process, the microcracks inside the rock gradually close, and the rock matrix undergoes large deformation. Therefore, during the cyclic loading and unloading process, the loading elastic modulus gradually increases. Affected by damage, the unloading stress difference of sandstone initially increases with the increase of cycles. The effects of the cycle number and unloading stress level on the damage parameters of sandstone are analyzed. Prior to the brittle failure of the specimen, the absolute damage parameters of axial, circumferential, and volume exhibit an increasing trend, and the increase rates of circumferential damage parameters and volume damage parameters suddenly increase, which is also the precursor of instability failure of the sandstone specimen

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

No potential conflict of interest is reported by the authors.

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