

Shear mechanical characteristics of jointed limestone under dynamic CO₂ aqueous solution corrosion and its engineering application

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Abstract: Continuous degradation of the shear properties of joint rock masses caused by aqueous solution erosion is a critical factor affecting slope stability. Therefore, we proposed a dynamic dissolution testing method based on gas-liquid circulation under gas-liquid-solid three-phase coupling conditions. Dynamic dissolution tests and direct shear tests were conducted on joint samples in CO₂ solution environment. The deterioration law of the shear mechanical parameters of the joint samples was characterized. Meanwhile, by combining three-dimensional morphology and microstructure scanning technology, the deterioration mechanism of the joint samples under the dynamic dissolution effect of CO₂ solution was revealed. Results show that the shear-displacement curves of the joint samples can be divided into three stages: initial locking, intermediate failure, and late-stage shear-friction-resistance sliding. As the number of dissolution cycles increased, the shear hardening characteristics and stress levels of the samples decreased. After 30 dynamic dissolution cycles, the internal friction angle and cohesion decreased by 37.78% and 29.73%, respectively. Concurrently, progressive microstructural damage and pore development reduced the joint surface roughness and the compressive strength of joint rock masses, weakened frictional interlocking between joint surfaces, and thereby degraded shear mechanical performance. Finally, a numerical stability model incorporating dissolution-induced degradation of shear parameters was established. Analyses indicate that the decline in the safety factor of jointed slopes is primarily governed by the deterioration of joint shear parameters. Owing to spatial variations in stress states, the potential slip path dynamically migrates from shallow to deeper joints. The methods and findings provide a theoretical basis for long-term stability assessment of joint slopes.

Keywords: rock slope; joint surface; dynamic dissolution; shear mechanical characteristics; deterioration mechanism; time-varying stability

1 Introduction

Rock mass joint surfaces, as typical discontinuous geological interfaces form through prolonged geohistorical evolution, constitute one of the critical factors governing the physico-mechanical properties, deformation-failure mechanisms, and stability control of rock masses^[1]. The presence of joints significantly alters the seepage field within rock mass structures and serves as primary sites for water-rock dissolution reactions. Under natural environmental conditions, the degradation of joint shear mechanical properties induced by solution dissolution and weathering processes represents a predominant trigger for slope instability. Consequently, investigating the dissolution evolution patterns of rock joints and characterizing the shear mechanical property degradation laws of dissolved joint surfaces carry substantial implications for slope hazard mitigation.

At present, numerous researchers have conducted a series of water-rock interaction studies on dissolution-affected rock masses, with particular attention to the

prototypical dry-wet cycling effect. By subjecting specimens sequentially to drying and immersion to simulate dry-wet cycles^[2–21], investigators have observed that increasing the number of cycles produces marked cumulative damage in the samples' microstructure, which in turn causes progressive deterioration of their macroscopic physical and mechanical properties. Meanwhile, to evaluate the influence of the pH of the solution on the erosion effect during the dry-wet cycles process, some scholars have conducted dry-wet cycle experiments in solution environments with different pH values^[22–35]. They studied and analyzed the deterioration law of rock mass under the coupled action of chemical solutions and dry-wet cycles, and based on the laws of chemical kinetics and thermodynamics, quantitatively analyzed the dissolution process of rock minerals and its influence mechanism on mechanical properties. It was found that acidic solutions will accelerate the precipitation of rock sample mineral ions, thereby enhancing the damage effect of the solution on the microstructure of the rock samples, and ultimately leading to a significant deterioration of the macroscopic

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physical and mechanical properties of the rock samples. However, during the aforementioned dry-wet cycling test process, the test solutions during the immersion stage were all directly prepared using chemical solutions and remained in a static state throughout the test. This ignored the fact that the CO_2 solution formed by the gas-liquid circulation is the most important corrosive medium in the real natural environment^[36–37]. Moreover, the water-rock interaction in the real natural environment is usually a dynamic erosion process of the solution on the rock matrix. In this process, the solution is in a flowing state, and the mineral ions that are dissolved and precipitated from the rock mass will be transported along with the water solution, thus not forming an accumulation on the rock surface and hindering the continuous progress of the erosion reaction^[38–39]. Therefore, the nature and state of the water solution set in the current wet-dry cycle test are quite different from those of the actual solution environment, and as a result, the test results obtained may have a significant deviation from the deterioration laws of rock masses under real environmental conditions. Meanwhile, the current research on the dry-wet cycling test mainly focuses on intact rock samples, neglecting the controlling role of joint zones on the stability of the rock mass^[40–41]. Although some scholars have quantitatively analyzed the surface roughness of jointed rock samples using different indicators and studied the variation laws of the shear mechanical properties of joint samples^[42–47]. However, there are still few reports on revealing the time-dependent deterioration laws of the shear mechanical properties of joint samples under dynamic dissolution. Therefore, it is necessary to conduct dynamic dissolution tests under the CO_2 solution environment for joint samples to more effectively analyze the deterioration laws of the mechanical properties of jointed rock samples in the actual natural environment.

In view of this, this study proposes a dynamic dissolution experiment method under CO_2 solution environments based on gas-liquid cycling. Taking the karstic rock slopes of a reservoir area in Yunnan as the background, for its bedrock, the dynamic dissolution test and direct shear test of joint samples in the CO_2 solution environment are carried out. The deterioration laws of the shear mechanical properties (peak shear strength, residual strength, internal friction angle, and cohesion) of the joint samples with the dissolution period are analyzed. Meanwhile, combined with three-dimensional morphology, scanning electron microscopy (SEM) and computed tomography (CT) technology, the dissolution evolution process of the joint surface of the samples and the deterioration mechanism of the shear mechanical properties of the joint samples are deeply analyzed. Finally, a time-varying stability analysis method considering the degradation of shear mechanical parameters in dissolution-jointed rock masses is established to study the temporal variation patterns of

slope safety factors and failure modes, aiming to provide experimental references and theoretical support for predicting the stability and service life of joint slopes.

2 Sample preparation and test procedures

2.1 Sample characteristics

This experiment is based on a construction project of a certain reservoir area in Yunnan province. The experiment rock samples are taken from the slope of this reservoir area by core drilling sampling. The mineral test by X-ray diffraction (XRD) reveals that the main minerals of this rock mass are calcite (50.8%) and dolomite (28.6%), as shown in Fig. 1. The contents of the major element oxides in the rock mass are analyzed by X-ray fluorescence spectroscopy and are shown in the Table 1. It can be seen from the table that the contents of calcium and magnesium are relatively high, with the contents of CaO and MgO reaching 50.36% and 4.85% respectively. The remaining elements are present in trace amounts. Through mineral identification, it can be known that the rock mass in this area is typical limestone.

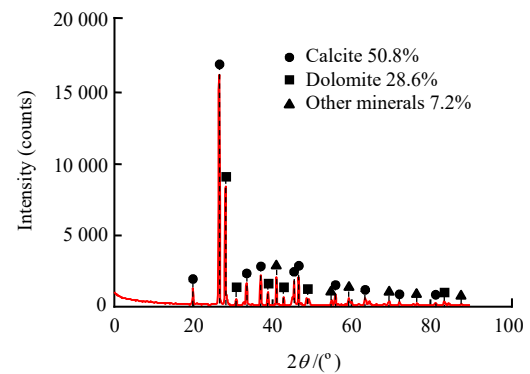


Fig.1 X-ray diffraction analysis of rock samples

Table 1 Mass percentage contents of major element oxides in the rock samples (unit: %)

CaO	MgO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CuO	SrO	SO ₂
50.36	4.85	0.12	0.06	0.08	0.01	0.02	0.01

2.2 Sample preparation

The degradation of the shear mechanical properties of joint rock masses is primarily attributed to the deterioration of joint surface morphology and the reduction of the strength of its matrix^[48]. Therefore, samples targeting the joints and joint matrix strength of rock mass are separately prepared in this study.

Preparation of joint samples: Due to the difficulty in collecting rock samples containing natural joints on-site and the significant variability of the rock, an artificial method is employed to prepare joint samples for this experiment. Considering the size and shape limitations of the testing apparatus, the core samples retrieve from the site are prepared into cubic samples of 50 mm×50 mm×

50 mm. Subsequently, the samples are screened for appearance, quality, and wave velocity, and those with obvious defects in appearance and significant differences in quality and wave velocity are eliminated. Finally, for the selected samples, the Brazilian splitting method is used to split along the joint layer, and the shear direction is marked to achieve the purpose of artificially preparing the joint surface.

To prevent the significant differences in the initial morphology characteristics of the joint surfaces of the samples from affecting the subsequent shear test results, samples with relatively flat joint surfaces and no obvious fractures around are selected. Meanwhile, the SIMSCAN22 adaptive non-contact three-dimensional laser scanner is used to scan the structural surfaces of the samples, and based on the acquired point-cloud data, the samples' roughness characteristic parameters $\theta_{\max}^*/(C+1)$ and the maximum potential area contact ratio A_0 are calculated (Eq. (1))^[49]. Finally, 63 groups of joint rock samples with approximately consistent roughness characteristic parameters are selected from the candidate samples as test samples (3 parallel samples). The detailed process regarding the roughness calculation can be found in previous studies^[49–50].

$$A_{\theta^*} = A_0 \left(\frac{\theta_{\max}^* - \theta^*}{\theta_{\max}^*} \right)^C \quad (1)$$

where A_{θ^*} is the potential contact area ratio corresponding to the apparent inclination angle θ^* in the shear direction; $\theta_{\max}^*$ is the maximum apparent inclination angle; and C is the dimensionless fitting parameter of the distribution of the apparent inclination angle on the joint plane.

Preparation of joint matrix strength samples: The variation law of joint matrix strength is characterized by the change of uniaxial compression strength. Therefore, according to the experimental specification for uniaxial compression of rocks^[51], the rock cores retrieve from the site are prepared into cylindrical samples of $\phi 50 \text{ mm} \times 100 \text{ mm}$, and they are screened in terms of appearance, quality and wave velocity to eliminate the rock samples with large differences, so as to reduce the dispersion of the test results. Finally, 21 rock samples are selected as test samples (3 parallel samples).

2.3 Dynamic dissolution experiment system

To simulate the water-rock interaction environment in the real natural environment, our research group constructed a dynamic dissolution test system^[38] in the CO_2 solution environment through the gas-liquid circulation mode, as shown in Fig 2. This system consists of four parts: CO_2 output system, the gas-liquid circulation reaction chamber, the water-rock interaction reaction chamber and the real-time monitoring system. The operation mechanism of the dynamic dissolution test system is as follows:

(1) CO_2 gas is injected into the gas-liquid circulation reaction chamber via the CO_2 supply system, and a circulation pump facilitates the dissolution of CO_2 gas into deionized water to form a CO_2 solution.

(2) Through the driving effect of the circulating water pump, a dynamic CO_2 solution environment is formed in the water-rock interaction reaction chamber, thereby effectively simulating the aqueous solution environment in the actual rock mass occurrence environment.

(3) The flow rate and pH changes of the solution are detected in real time through the monitoring system.

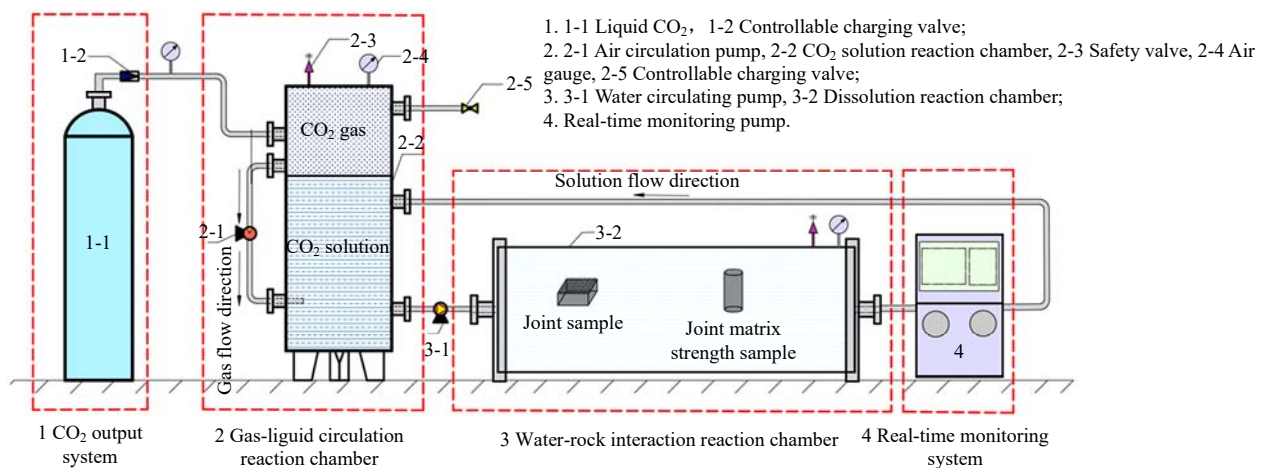


Fig. 2 Dynamic dissolution test system

To ensure that the dynamic dissolution system can accurately simulate the aqueous solution environment in the proposed engineering area, on-site water sample analysis is conducted prior to initiating the indoor dynamic dissolution experiment. This analysis determines the pH range (4.72–5.74) of the local groundwater solution. Based

on this pH range, the volumes of deionized water and CO_2 gas for the dynamic dissolution experiment are subsequently determined. During the experiment, the CO_2 gas pressure is maintained at one standard atmosphere (0.1 MPa), while the volume of deionized water is adjusted to stabilize the solution pH within the range of the local

groundwater pH. The final volume of deionized water is 45 L (gas-liquid volume ratio is 0.39). Fig. 3 shows the temporal variation of the solution pH. As shown, after 2 h of gas-liquid dynamic circulation, the solution pH decreases to 5.12. With continued experimental duration, the pH remained stable within the range of the local groundwater solution. Consequently, the pH of the CO₂ solution formed in the dynamic dissolution system closely approximates that of the aqueous solution in the proposed engineering area, thereby establishing an experimental foundation for investigating the erosive effects of the aqueous solution on rock joints in the target region.

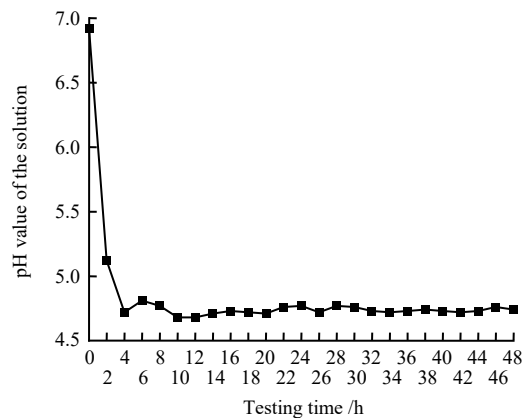


Fig. 3 Time evolution curve of solution pH value

2.4 Test procedures and equipment

To reveal the influence law and mechanism of the dynamic dissolution of solutions on the shear mechanical properties of joint rock masses in the real natural environment, this paper proposes a new dynamic dissolution test method based on the conventional dry-wet cycle tests. This method adopts the “drying-dynamic dissolution” approach to simulate the dynamic dissolution process experienced by the rock mass. In the drying phase, samples are placed in a constant temperature and humidity oven at 105 °C for 24 h. Subsequently, after the samples cooled to room temperature, they are placed in the self-developed and designed dynamic dissolution test system for continuous immersion for 48 h. This process is one dynamic dissolution cycle. In this paper, a total of 7 dynamic dissolution cycles (0, 5, 10, 15, 20, 25, and 30) are set. Moreover, to prevent the inhibition of the water-karst dissolution rate due to the saturation of the solution ion concentration during the experiment, the immersion solution in the dynamic dissolution test is replaced after every 5 dissolution cycles. The joint samples (50 mm×50 mm×50 mm) and joint matrix strength samples (φ50 mm×100 mm) are simultaneously subject to the above-mentioned dynamic dissolution experiment. After the samples reached the preset dissolution cycles, a series of scanning inspections and mechanical tests are conducted on them respectively. The specific experiment process is shown in Fig. 4.

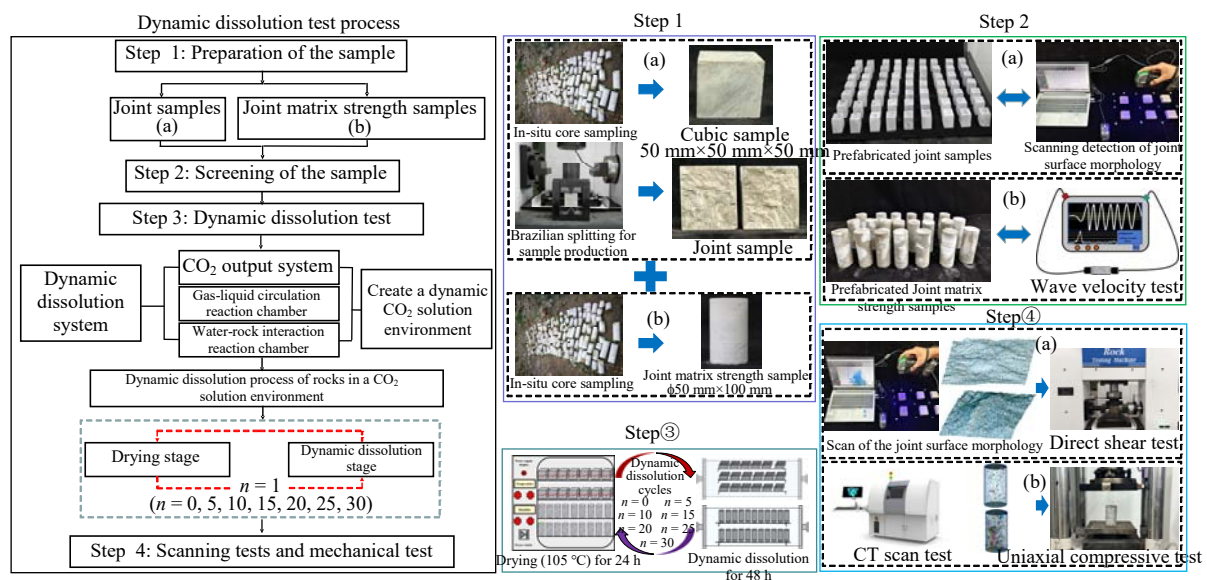


Fig. 4 Dynamic dissolution test process

For the joint samples:

(1) Three-dimensional laser scanning: A handheld SIMSCAN22 adaptive non-contact 3D laser scanner, with a maximum scanning accuracy of up to 0.020 mm, is used to scan the joint surfaces of samples that have reached the preset dissolution cycles, and the scanning data are extracted along the consistent shear direction of

the shear test to calculate the 3D roughness of the joint surfaces of the samples under different dissolution cycles.

(2) Scanning electron microscopy (SEM) observation: A Nova Nano SEM450 high-resolution field emission scanning electron microscope is used to examine the microstructure of the joint samples, in order to analyze the evolution characteristics of the microstructure of the

joint samples under different dynamic dissolution cycles.

(3) Shear test: Shear tests are conducted on joint samples that had reached the preset dissolution cycles using a YSW-600Y microcomputer-controlled electrohydraulic servo testing machine. The samples are first secured in the shear box with the joint plane aligned to the shear direction. Normal stress is applied using force control at a loading rate of 0.1 kN/s until the predefined normal stress levels are reached, which are set at 3, 5, and 7 MPa for this study. Subsequently, a tangential load is applied under displacement control at a loading rate of 0.05 mm/min. The test is terminated when the shear displacement reached 5 mm.

For the joint matrix strength samples:

(1) CT scanning: In-situ CT scans are performed on the samples that reached the preset dissolution cycles using the 3D CT Nano Voxel 2000/3000/4000 detection system, and the scanning results are three-dimensional reconstructed using Avizo software to analyze the variation laws of the internal pore distribution, maximum pores and porosity of the samples with the dissolution cycles.

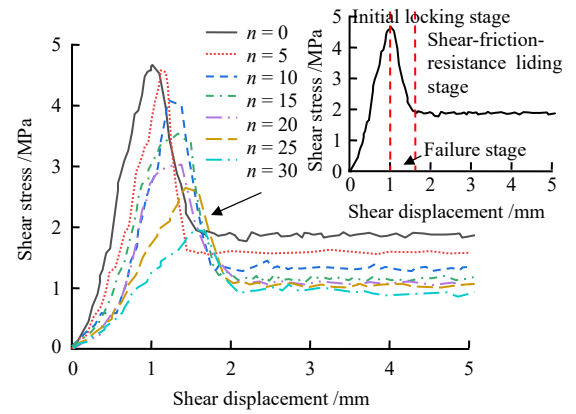
(2) Detection of main ion concentrations: The concentrations of Ca^{2+} , Mg^{2+} and HCO_3^- in the soaking solutions at each experimental stage are detected using inductively coupled plasma atomic emission spectroscopy.

(3) Uniaxial compression test: Uniaxial compression tests are conducted on samples that reached the preset dissolution cycles using a YAW-2000D microcomputer-controlled electrohydraulic servo press, at a loading rate of 0.5 MPa/s, thereby obtaining the peak compressive strength of the samples under different dissolution cycles.

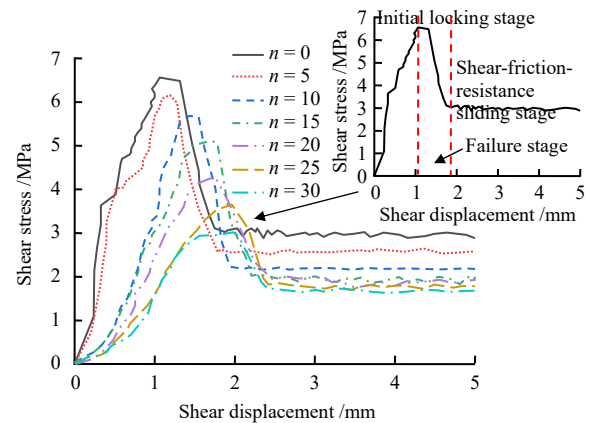
3 Test results and analysis

3.1 Degradation law of joint peak and residual shear strength

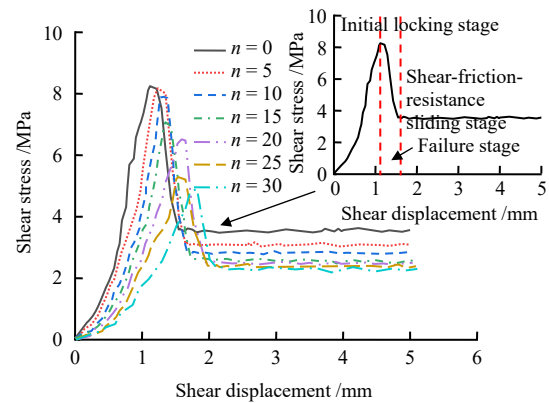
Figure 5 shows the shear-displacement characteristic curves of joint samples under different axial pressures (3, 5, and 7 MPa) and dissolution cycles. According to the shear stress response characteristics, they can be divided into three stages: locking, failure, and shear-friction-resistance sliding. The tangential stiffness of the joint samples is defined as the slope of the tangent line of the shear stress-displacement curve^[52]. As can be seen from the figure, with the increase of the dissolution cycles, the tangential stiffness of the joint samples gradually decreases. This is mainly because the roughness of the joint surface of samples without dissolution are relatively high. Therefore, during the shearing process, a combined locking effect is formed between the grooves of the joint surfaces, resulting in the obstruction of tangential deformation. Furthermore, obvious shear hardening characteristics occur, so its shear stiffness is relatively large. With the continuous increase of the horizontal displacement, the shear-displacement characteristic enters the failure stage. The initial locking structure between



(a) 3 MPa



(b) 5 MPa



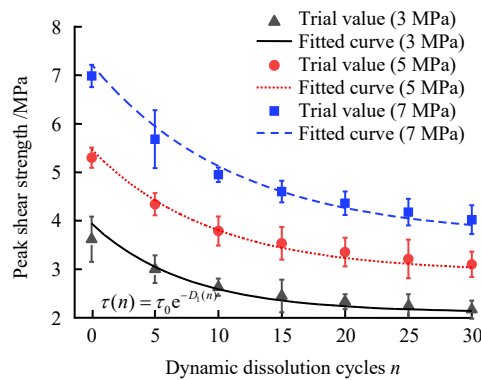
(c) 7 MPa

Fig. 5 Shear stress-shear displacement curves

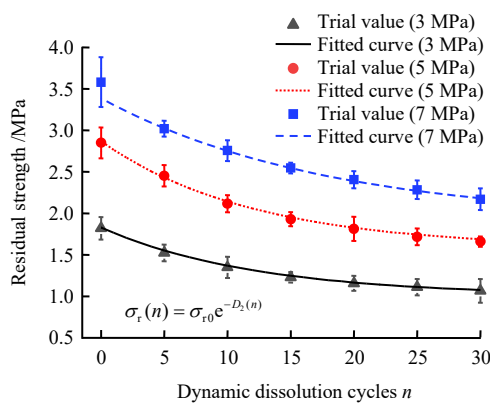
the joint surfaces is gradually damaged, and the joint surfaces undergo relative displacement, which further leads to a significant decrease in the shear strength of the joint surfaces. Finally, it enters the shear-friction-resistance sliding stage. At this stage, the micro-convex bodies generated by sawing on the joint surface form a new locking structure under the action of axial pressure, thereby presenting relatively stable residual deformation characteristics. After the dissolution effect, the roughness of the joint samples surface decreases. Therefore, during the horizontal pushing and shearing process, the locking

effect between the joint surfaces weakens, the initial shear hardening characteristics of the samples are significantly weakened, its shear-displacement curve shifts downward as a whole, the peak shear strength decreases, and the shear displacement reaching the peak shear strength gradually increases.

Based on the data in Fig. 5, the peak shear strength and residual shear strength of the joint samples under different dissolution cycles are statistically analyzed and their regular curves are plotted. The results are shown in the following figure. The average peak shear strengths of the joint samples without dissolution under normal stresses of 3, 5, and 7 MPa are 3.62, 5.30, and 6.98 MPa, respectively. After 30 dynamic dissolution cycles, the average peak strengths of the joint samples decrease to 2.17, 3.10, and 4.02 MPa, representing degradation magnitudes of 40.06%, 41.51%, and 42.41%, respectively, showing an overall exponential decrease. The formula of its deterioration is shown in Eq. (2).



(a) Peak strengths of the joint samples



(b) Residual strengths of the joint samples

Fig. 6 Degradation patterns of peak strength and residual strength of joint samples

The variation of the residual shear strength with the dynamic dissolution cycles is basically consistent with the deterioration law of the peak strength. The average residual strengths of the joint samples without dissolution action are 1.95, 3.02, and 3.58 MPa, respectively. After

30 dynamic dissolution cycles, the average residual strengths of the joint samples decrease to 1.07, 1.68, and 2.17 MPa, representing degradation magnitudes of 45.13%, 44.37%, and 39.39%, respectively. The overall attenuation is also exponential, and the formula of its deterioration is shown in Eq. (3).

$$\tau(n) = \tau_0 e^{-D_1(n)} \quad (2)$$

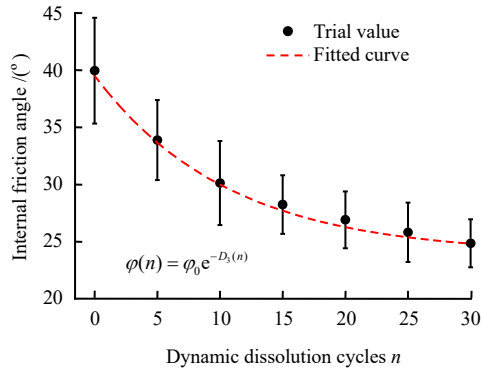
where n is the dynamic dissolution cycle; τ_0 is the peak shear strength of the joint sample without dissolution; $D_1(n)$ is the damage coefficient of the peak shear strength of the joint sample after the n dissolution cycles; and $\tau(n)$ is the peak shear strength of the joint sample after the n dynamic dissolution cycles.

$$\sigma_r(n) = \sigma_{r0} e^{-D_2(n)} \quad (3)$$

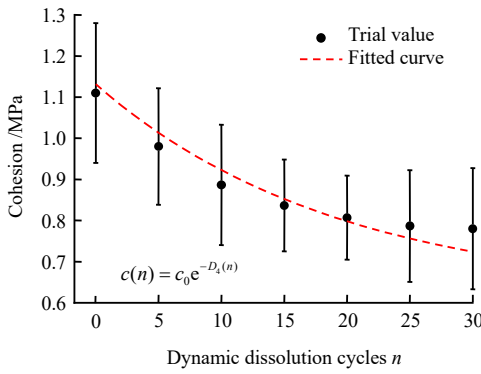
where σ_{r0} is the residual shear strength of the joint sample without dissolution; $D_2(n)$ is the damage coefficient of the residual shear strength of the joint sample after the n dissolution cycles; and $\sigma_r(n)$ is the residual shear strength of the joint sample after the n dynamic dissolution cycles.

3.2 Degradation law of joint shear strength parameters

Based on the Mohr-Coulomb failure criterion and the peak shear strength under different normal stresses, the internal friction angle and cohesion of the joint samples under different dissolution cycles are calculated, as shown in Fig. 7. The average internal friction angle of the joint samples without dynamic dissolution is 39.96° . After 5 dynamic dissolution cycles, it decreases to 33.89° , a reduction of 15.18%. After 30 dynamic dissolution cycles, the average internal friction angle of the samples decreases to 24.86° , the total deterioration rate reaches 37.78%, but the stage deterioration rate decreases to 3.72%. The average cohesion of the joint samples without dynamic dissolution is 1.11 MPa. After 5 dynamic dissolution cycles, it decreases to 0.98 MPa, a reduction of 11.71%. After 30 dynamic dissolution cycles, the average cohesion of the joint samples decreases to 0.78 MPa, the total deterioration rate reaches 29.73%, but the stage deterioration rate decreases to 1.27%. The experimental results show that the dynamic dissolution effect has obvious timeliness in the deterioration of the internal friction angle and cohesion of the joint samples, and the deterioration effect gradually decreases with the passage of the dissolution cycles. The overall variation trend of the shear strength of the joint samples parameters is approximately consistent with the variation trends of the aforementioned peak and residual shear strengths. Therefore, this paper proposes two empirical formulas similar to Eqs. (2) and (3) to capture the deterioration law of the shear strength parameter with the dissolution cycles, as shown in Eqs. (4) and (5).



(a) Internal friction angle of the joint samples

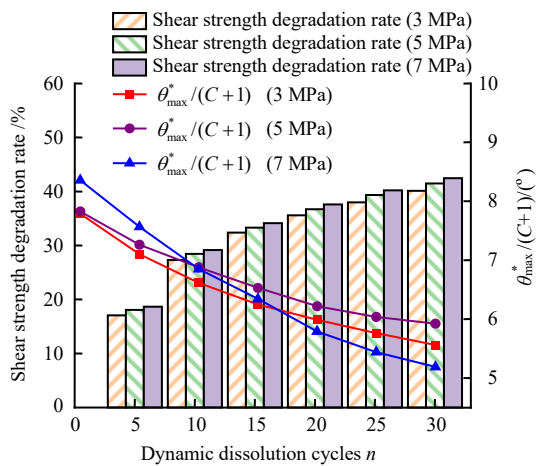


(b) Cohesion of the joint samples

Fig. 7 Evolution patterns of shear strength parameters of joint samples

$$\varphi(n) = \varphi_0 e^{-D_3(n)} \quad (4)$$

where φ_0 is the internal friction angle of the joint sample without dissolution; $D_3(n)$ is the damage coefficient of the internal friction angle of the joint sample after the n dissolution cycles; and $\varphi(n)$ is the internal friction angle of the joint sample after the n dynamic dissolution cycles.

(a) Relationship between $\theta_{\max}^*/(C+1)$ and shear strength degradation rate

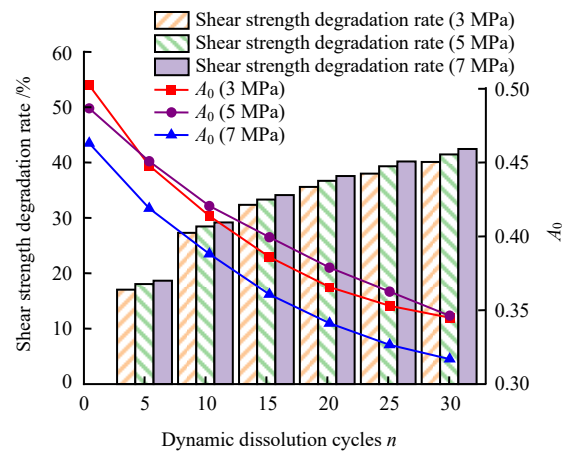
$$c(n) = c_0 e^{-D_4(n)} \quad (5)$$

where c_0 is the cohesion of the joint sample without dissolution; $D_4(n)$ is the damage coefficient of the cohesion of the joint sample after the n dissolution cycles; and $c(n)$ is the cohesion of the joint sample after the n dynamic dissolution cycles.

4 Mechanism of deterioration of joint shear mechanical properties

The variation in the shear mechanical properties of joint rock mass is mainly controlled by the morphological characteristics of the joint surface and the changes in the strength of the joint matrix^[48]. Fig. 8 shows the relationships between the roughness characteristic parameters $\theta_{\max}^*/(C+1)$ and A_0 of the joint surfaces and the degradation rates of shear strength with respect to dissolution cycles. It can be seen from the figure that with the passage of the dissolution cycles, both $\theta_{\max}^*/(C+1)$ and A_0 are negatively correlated with the deterioration of the peak shear strength. After 30 dynamic dissolution cycles, $\theta_{\max}^*/(C+1)$ under different normal stresses decreases by 28.61%, 24.30% and 37.93% respectively, and A_0 decreases by 31.32%, 28.86% and 31.57%, respectively. Concurrently, the degradation amplitude of the shear strength of the joint samples gradually increases. After 30 dynamic dissolution cycles, it reaches 40.09%, 41.47% and 42.43% respectively under different normal stresses.

The aforementioned analysis indicates that the reduction in joint surface roughness leads to degradation of the samples' shear strength, the root cause is the dynamic corrosive action of the CO₂ solution, which damages the microscopic structure of the joint surfaces. Consequently, scanning electron microscopy (SEM) is used to examine joint surfaces after different dissolution cycles. The typical SEM detection images are shown in the Fig. 9,

(b) Relationship between A_0 and shear strength degradation rate**Fig. 8 Relationship between the roughness characteristic parameters of the joint surface and the shear strength degradation rate**

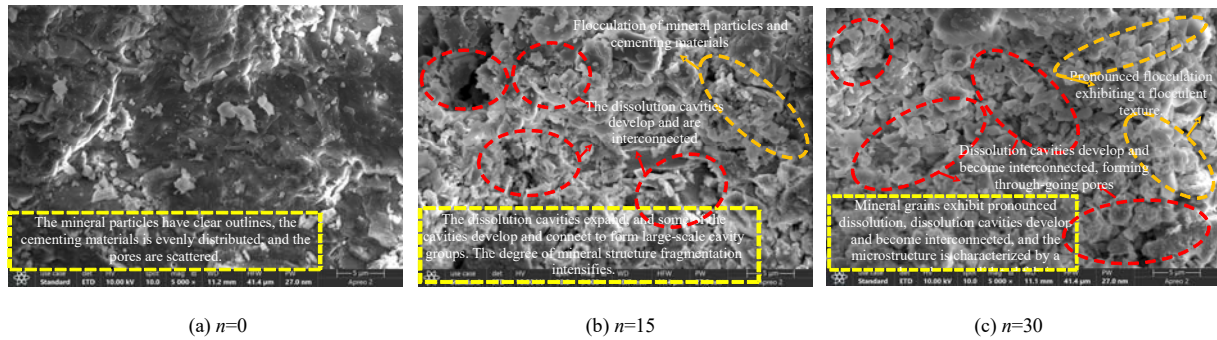


Fig. 9 Microscopic structural characteristics of joint samples

with a magnification of 5 000 times. As can be seen from the figure, under the dynamic dissolution action of the CO_2 solution, the microstructure characteristics of the joint surface of the samples change significantly. Prior to dissolution, the joints exhibit an orderly, compact microstructure with tightly bound mineral grains and cementing material, low porosity characterized mainly by a few undeveloped primary pores sparsely distributed, and no obvious dissolution-induced cracks. After 15 cycles of dynamic dissolution, clear signs of dissolution appear on mineral grains and their cementing matrix: cementation is weakened, intergranular contacts become looser, particle surfaces develop flocculent-like features, and primary pores and fissures progressively develop and interconnect while new pores and cracks form. Overall, the microstructure evolves from a dense state toward a more porous, loosened condition. The degree of flocculent alteration of the rock mineral grains progressed with the dissolution of the cementing material. After 30 cycles of dynamic dissolution, mineral-grain surfaces exhibited pronounced flocculent features over a substantially larger area, pores and fissures between grains coalesced and interconnected to form large-scale pores and pore networks, and the samples' overall microstructure became porous and loosened.

The degradation of shear mechanical parameters of joint rock masses is also controlled by changes in joint matrix strength. To analyze the degradation pattern of joint matrix strength under water-rock interaction, uniaxial compression tests are concurrently conducted. Fig. 10 shows the degradation of uniaxial compressive strength of samples at different dynamic dissolution cycles. The degradation pattern is generally consistent with that of the shear mechanical parameters of the joint samples, exhibiting an overall exponential decay. The uniaxial compressive strength of samples without dissolution is 132.31 MPa, which decreases to 58.63 MPa after 30 dynamic dissolution cycles, representing a degradation rate of 55.69%, as shown in Eq. (6).

$$\sigma(n) = \sigma_0 e^{-D_s(n)} \quad (6)$$

where σ_0 is the uniaxial compressive strength of the

sample without dissolution; $D_s(n)$ is the damage coefficient of the uniaxial compressive strength of the sample after the n dissolution cycles; and $\sigma(n)$ is the uniaxial compressive strength of the sample after the n dynamic dissolution cycles.

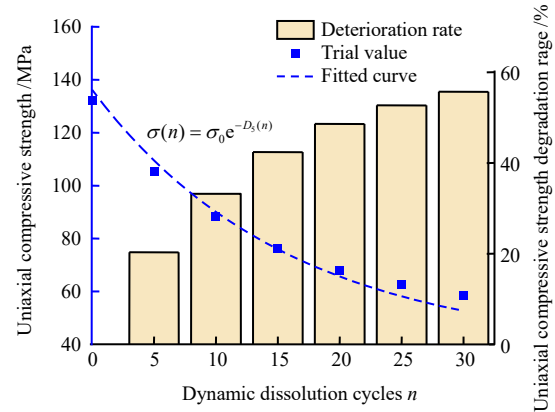


Fig. 10 Evolution pattern of uniaxial compressive strength of the sample

However, the fundamental reason for the attenuation of joint matrix strength is the damage of the microstructure within the rock matrix. Therefore, CT scans and three-dimensional reconstructions are performed on the samples after different dissolution cycles respectively (Fig. 11), and their pore distributions are statistically analyzed simultaneously. Fig. 12 shows the time-history evolution characteristics of the pore size and distribution of the samples. It can be seen from the figure that the pore size of the samples without dissolution are mainly concentrated in the range of 5–25 μm , accounting for 95.83%, and the porosity is only 0.38%. After 30 dynamic dissolution cycles, the proportion of the samples pore diameters ranging from 5 to 25 μm decreases to 64.64%, while the proportions of the remaining larger pore diameters increase, and the porosity increases to 3.62%, an increase of 89.50%.

To better analyze the degradation mechanism of joint matrix strength during dynamic CO_2 solution dissolution, the main mineral ion concentrations in the solution are detected. As shown in Fig. 13, the concentration changes

of Ca^{2+} , Mg^{2+} and HCO_3^- display the same pattern, increasing sharply at first and then tapering off as dissolution cycles proceed. After 5 dynamic dissolution cycles, the dissolved concentrations of Ca^{2+} , Mg^{2+} and HCO_3^- are 145.16, 48.62, and 178.44 mg/L, respectively. After 30 dynamic dissolution cycles, these concentrations have increased by 42.28%, 34.76% and 43.29%, respectively.

To further elucidate the chain reaction mechanism of dissolution–porosity–strength degradation, relationships between major mineral-ion concentrations and porosity,

and between porosity and uniaxial compressive strength, are established, as shown in the Fig. 14. The figure indicates that sample porosity is positively correlated with Ca^{2+} , Mg^{2+} and HCO_3^- concentrations, while porosity is negatively correlated with uniaxial compressive strength. That is, the continuous dynamic dissolution process causes the mineral ions in the sample to precipitate into the solution, which promotes the development and expansion of preexisting pores and ultimately leads to deterioration of the samples' mechanical properties.

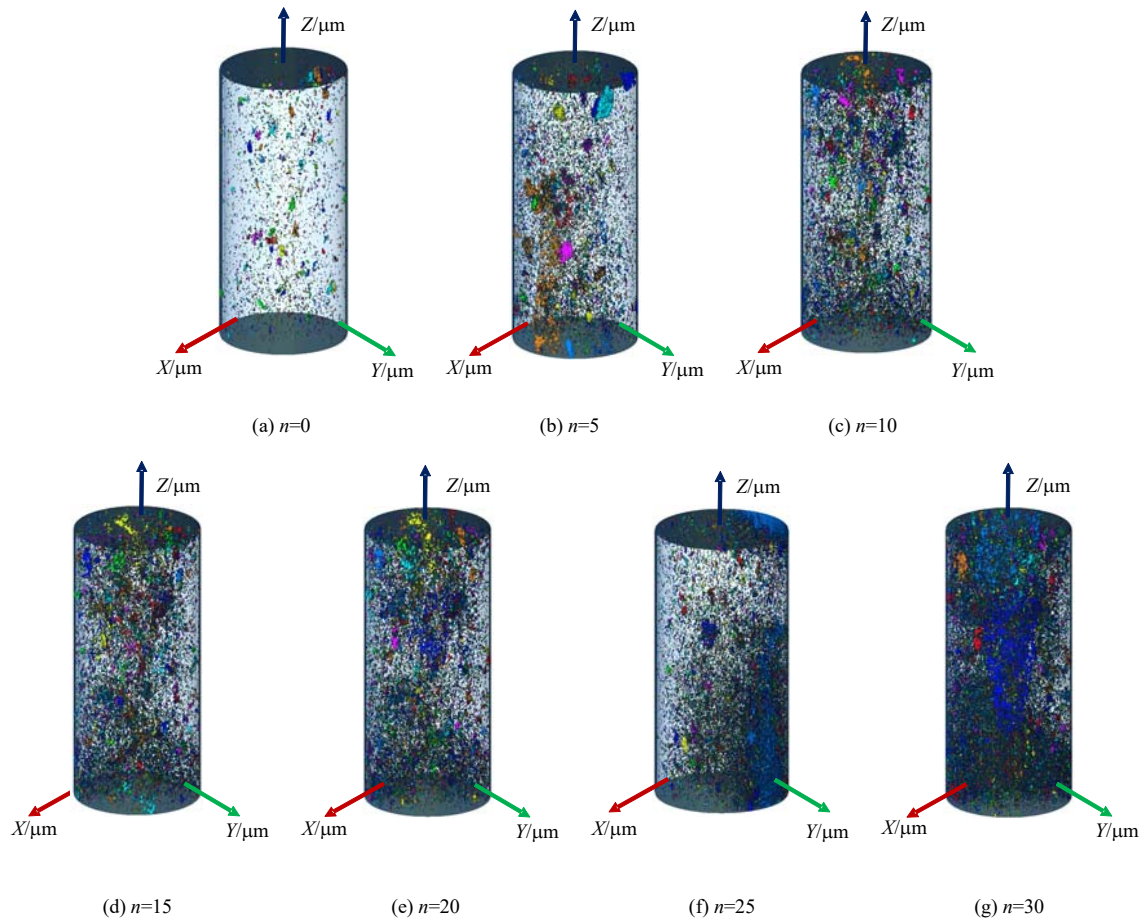


Fig. 11 Three-dimensional reconstruction of CT scans of samples

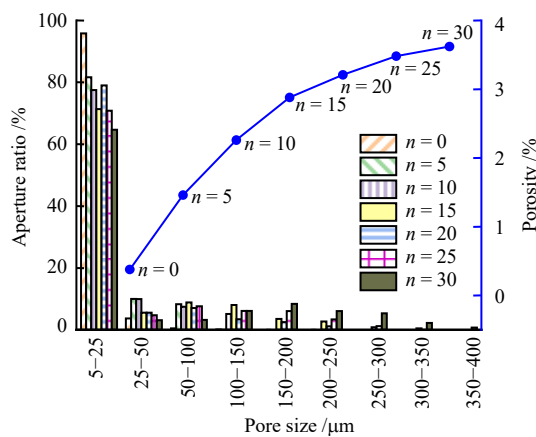


Fig. 12 Temporal evolution characteristics of pore size and distribution in samples

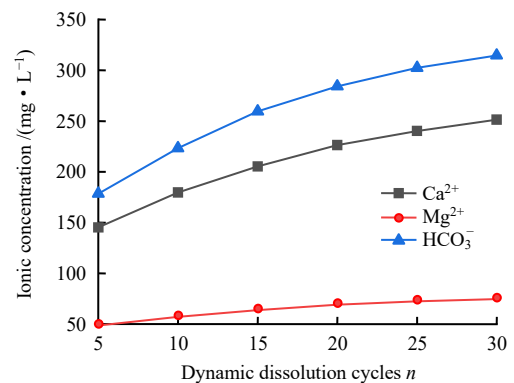
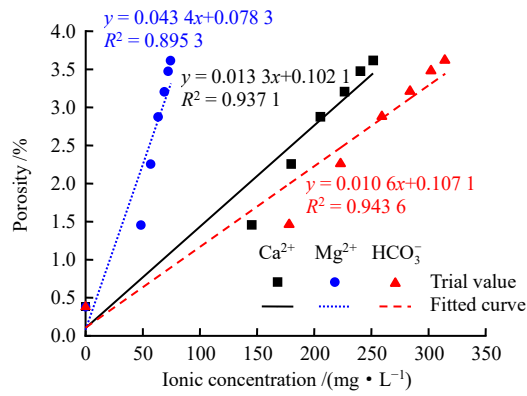
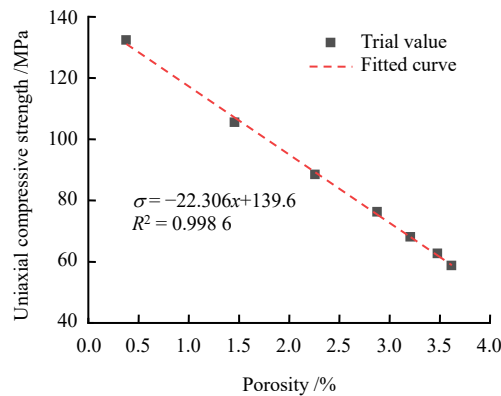


Fig. 13 Evolution curves of main ion concentrations



(a) Relationship between ionic concentration and porosity



(b) Relationship between porosity and uniaxial compressive strength

Fig. 14 Chain reaction degradation mechanism of samples

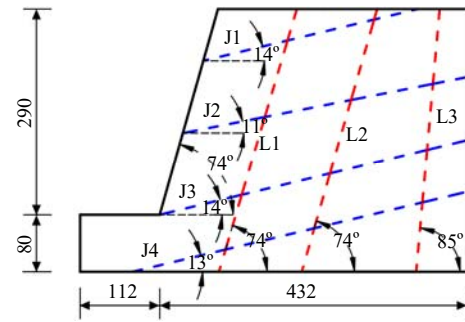
In summary, under periodic dynamic dissolution, mineral grains in the rock repeatedly undergo dissolution, fragmentation and migration, continuously providing new reactive space for the attacking solution. Pores and fissures between mineral grains progressively develop, expand and become interconnected, transforming the joint-surface microstructure from a dense state to a porous, loose state. During this process the joint surface roughness diminishes and gradually becomes smooth, so that the initially matching upper and lower joint faces evolve into a non-mating condition, reducing their frictional interlocking. Concurrently, internal pore development leads to a reduction in the joint matrix strength. Overall, dynamic dissolution by the solution causes progressive damage to the sample's meso-structure and development of porosity, thereby progressively degrading the shear mechanical performance of the joint samples.

5 Time-varying stability analysis of joint slope

The above experimental studies indicate that continuous dynamic dissolution leads to the degradation of shear mechanical properties in limestone joint samples. However, the slope instability is predominantly manifested as shear failure deformation along joint zones^[53–56]. Therefore, it is necessary to investigate and analyze the impact of degradation in the mechanical properties of joint rock

masses on slope stability.

This study focuses on a joint slope in a reservoir area in Yunnan, with its simplified cross-section shown in Fig. 15. The slope has a height of 290 m, a crest width of 350 m, and a slope angle of 74°. The slope contains seven through-going joint sets: J1 with a dip angle of 14°, J2 at 11°, J3 at 14°, J4 at 13°, L1 at 74°, L2 at 74°, and L3 at 85°. These seven joint sets divide the slope mass into 19 distinct areas.

**Fig. 15 Schematic of jointed slope section (unit: m)**

To effectively analyze the impact of the time-varying degradation of shear mechanical parameters in joint zones on slope stability, this paper proposes a time-varying stability analysis method considering the deterioration of shear mechanical parameters of the joint surface with the dissolution cycles for joint slopes. This method integrates finite element discretization, the plastic limit analysis upper bound theory, and mathematical programming theory, and modifies the Mohr-Coulomb yield criterion using Eqs. (4) and (5) (see Eq. (7)), where the internal friction angle and the cohesive in the revised Mohr-Coulomb criterion are functions of the dissolution cycles.

$$F(\sigma, \tau) = (\sigma_x - \sigma_y)^2 + (2\tau_{xy})^2 +$$

$$\{2[c(n)]\cos[\varphi(n)] - (\sigma_x + \sigma_y)\sin[\varphi(n)]\}^2 \leq 0 \quad (7)$$

where $F(\sigma, \tau)$ is the unit yield function; σ_x and σ_y are the stresses in the x and y directions, respectively; τ_{xy} is the shear stress.

Based on this yield criterion, an upper bound mathematical programming model for the time-varying stability analysis of joint slopes is established. By combining the statistical results from dynamic dissolution experiments (Table 2), the safety factor and corresponding failure modes of the joint slope are calculated. The detailed calculation procedure is as follows:

(1) Based on the geometric model and physical and mechanical parameters of the slope, the finite element discrete technology is adopted, and 4 000 triangular finite elements are used to numerically discretize the rock mass and joint zones.

(2) Taking the safety factor of the joint slope as the objective function, a motorized allowable velocity field

Table 2 Statistical results of shear tests

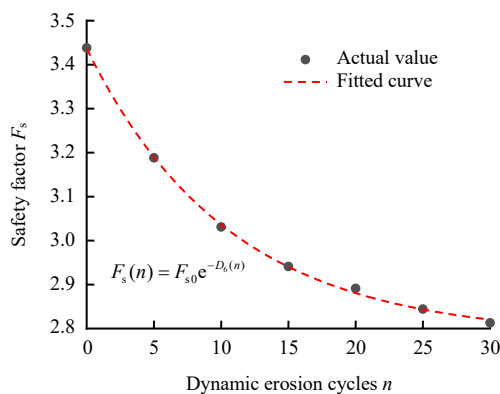
Sample category	Dissolution cycles n	Cohesion c /MPa	Internal friction angle φ /(°)
Joint sample	0	1.11	39.96
	5	0.98	33.89
	10	0.89	30.13
	15	0.84	28.25
	20	0.81	26.92
	25	0.79	25.82
	30	0.78	24.86
Complete sample	—	8.00	40.00

that satisfies the equilibrium condition, yield condition, boundary condition and plastic flow constraint condition is established, thereby formulating the upper limit method mathematical programming model of the time-varying stability of the joint slope is constructed.

(3) Solve the mathematical programming model to obtain the safety factor of the joint slope under different dissolution cycles.

Due to space limitations, the detailed calculation procedures are not described here and can be found in the relevant literature^[57–59]. Moreover, since joints predominantly control rock mass permeability and thus serve as the primary sites for water-rock dissolution reactions, they play a governing role in damage and degradation caused by water-rock interaction. Therefore, in the present numerical calculations, it is assumed that the mechanical parameters of the rock mass outside the joint zones remain unchanged.

Figure 16 shows the evolution curves of the safety factor of the joint slope under different dissolution cycles. It can be seen from the figure that with the passage of the dissolution cycles, the safety factor of the joint slope decays exponentially (see Eq. (8)). The safety factor of the joint slope without dissolution is 3.44. After 30 dynamic dissolution cycles, its safety factor decreases to 2.81, with an attenuation of 18.31%. It indicates that the evolution of the safety factor of the joint slope is controlled by the change of shear mechanical properties in the joint zone.

**Fig. 16** Degradation curve of safety factor of jointed slope

$$F_s(n) = F_{s0}e^{-D_6(n)} \quad (8)$$

where F_{s0} is the safety factor of the jointed slope without dissolution; $D_6(n)$ is the attenuation coefficient of the slope safety factor after the n dissolution cycles; and $F_s(n)$ is the safety factor of the slope after the n dynamic dissolution cycles.

The variation of the slope safety factor is also controlled by its corresponding failure mode. According to the upper limit method theory, when the element undergoes plastic flow, it will generate a relative velocity relative to the fixed element on the boundary. Then, when the element velocity is equal to 0, it indicates that this element has not undergone plastic flow (safety), and when the element velocity is greater than 0, it indicates that this element has undergone plastic flow (failure)^[58,60]. Therefore, in this paper, the failure modes of joint slopes under different dissolution cycles are obtained by statistically analyzing the unit velocities. The failure function $I(t)$ of the defined unit is as follows:

$$I(t) = \begin{cases} \text{safety} & \text{if } u^c(t) = 0 \\ \text{failure} & \text{if } u^c(t) > 0 \end{cases} \quad (9)$$

where t is a different unit, $t = (1, \dots, N)$; $u^c(t)$ is the centroid velocity of element t for a finite element of triangular elements $u^c(t) = (u_1^c(t) + u_2^c(t) + u_3^c(t))/3$.

Figure 17 shows the failure modes of the joint slope under different dissolution cycles. As can be seen from the figure, without dissolution, the joint slope slides along the area near the slope surface. After 15 dynamic dissolution cycles, the failure mode of the joint slope changes, and the area further away from the slope surface begins to slide. Moreover, with the continuous advancement of the dissolution cycles, the failure mode of the joint slope has not continued to change.

To further analyze the evolution process of the failure mode of joint slopes, the distribution results of the displacement field and shear dissipation of the joint slopes are statistically analyzed, as shown in the Figs. 18 and 19. As can be seen from Fig. 18, the maximum displacement of the joint slope is concentrated at the toe of the slope. With the passage of the dissolution cycle, the displacement contour lines of the joint slope gradually extend along the joint surface towards the interior of the slope body, and the displacement range continues to expand. At the same time, the distribution results of shear dissipation of the joint slope (Fig. 19) indicate, the change of shear dissipation energy of the joint slope is significantly correlated with the evolution of the displacement field. In the initial state, the shear dissipation energy of the joint slope is concentrated at the edge position of the maximum displacement area at the toe of the slope. With the increase of the dynamic dissolution cycle, the displacement contour lines of the joint slope extend towards the interior of the slope body, and the shear

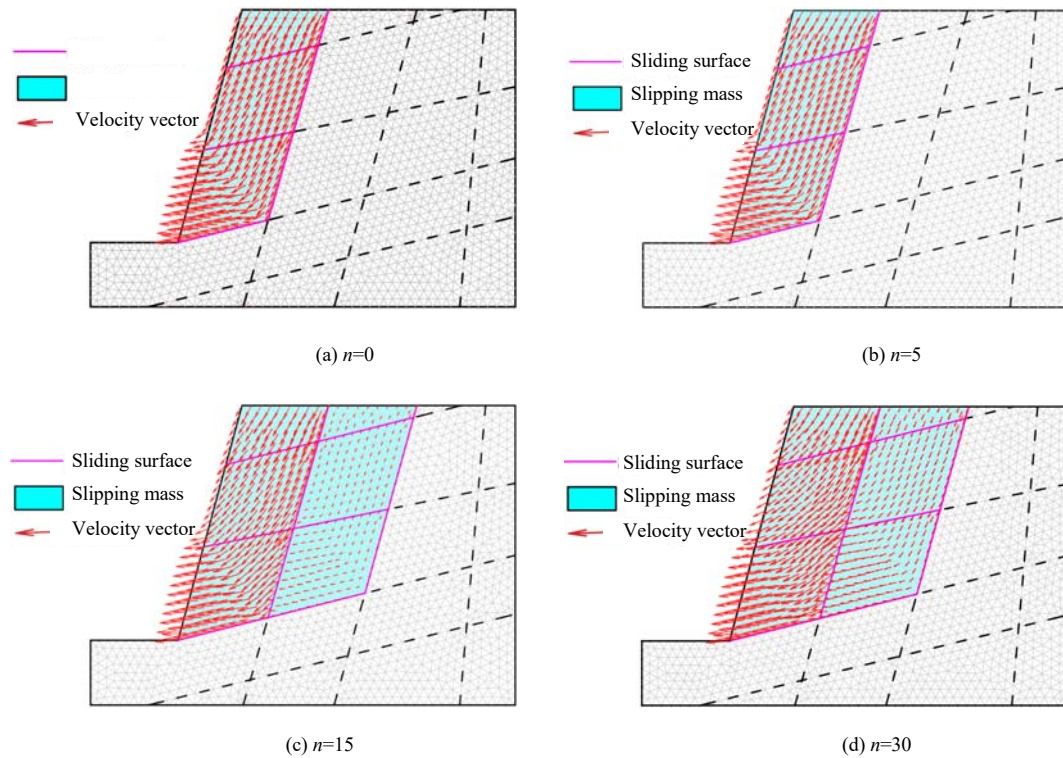


Fig. 17 Failure modes of joint slopes

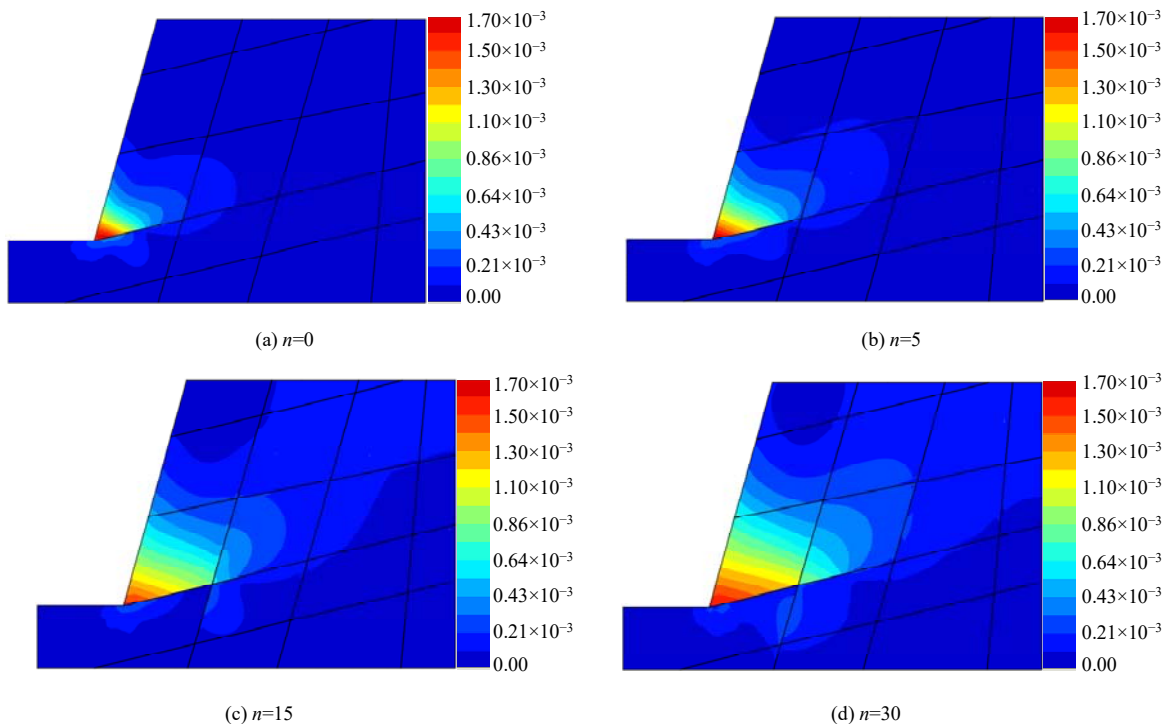


Fig. 18 Variation characteristics of displacement field of joint slopes (unit: m)

dissipation energy along the displacement contour lines expands synchronously towards the interior. From the initial local point-like concentration at the toe to gradually develop into a continuous distribution along the displacement gradient contour lines, and finally forming a development trajectory of shear dissipation energy that is highly consistent with the distribution of

displacement contour lines. Therefore, the deterioration of joint mechanical parameters leads to the continuous accumulation of displacement of the joint slope, and the stress concentration effect at the edge of the displacement contour lines directly drives the expansion of shear dissipation energy. The collaborative action of the two promotes the evolution of the failure mode of the joint slope.

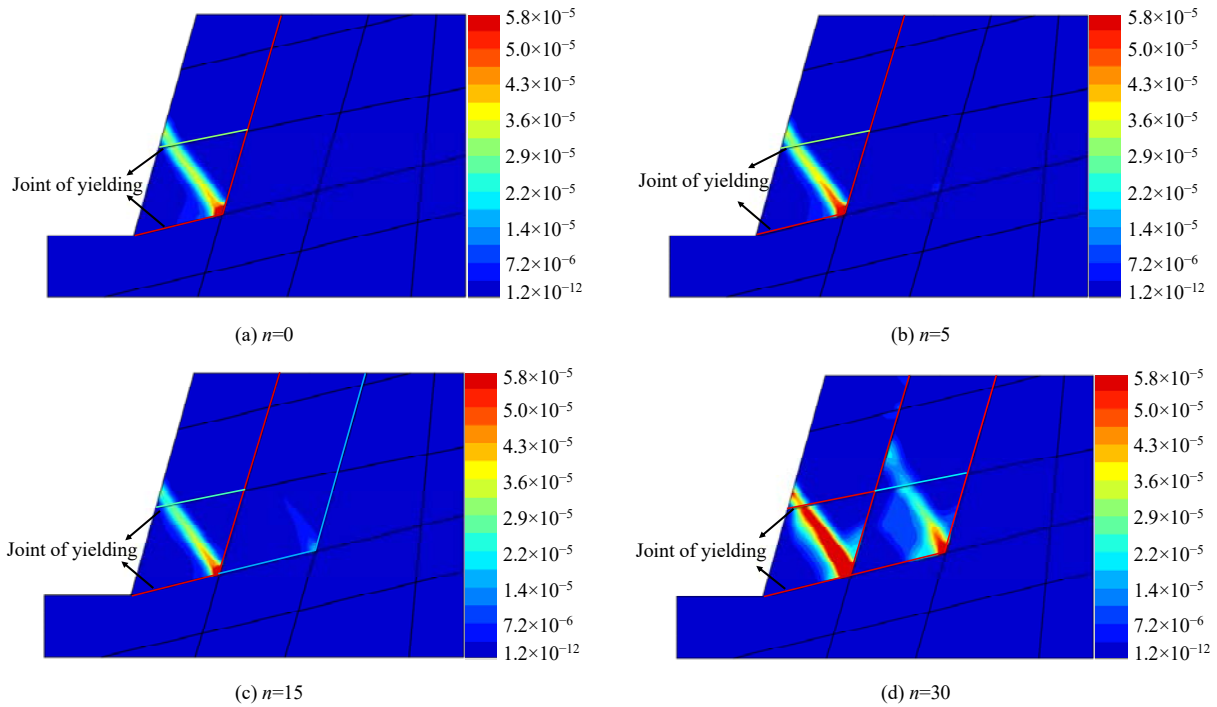


Fig. 19 Variation characteristics of plastic zone in jointed slopes

The failure sliding path of joint slopes is also controlled by the stress state of the joint space position, resulting in significant differences in the corresponding mechanisms of shear strength parameter attenuation in different joint zones. The shallow joints near the slope surface, due to the relatively low load of the overlying rock, have a lower normal stress level. Under the erosion effect of CO₂ solution, the reduction of the shear mechanical parameters of these joints directly leads to the decrease of the anti-sliding resistance of such joints, and subsequently transforms into an unstable boundary. In contrast, the shear mechanical parameters of the joints located deep within the slope have undergone the same attenuation process, but due to being in a high confining pressure environment, they exhibit different mechanical behaviors. The higher normal stress counteracts the weakening effect of the joint's own strength parameters, resulting in a relatively slower rate of decline in the anti-sliding resistance. Therefore, during the instability process of the joint slope, the potential sliding surface is not a specific joint area, but follows the principle of minimum energy consumption and undergoes dynamic migration. As the continuous deterioration of the shear mechanical parameters of the joints continues, the critical sliding path gradually shifts from the shallow joints with completely deteriorated anti-sliding resistance to the deep joints.

To analyze the failure mechanism of the joint slope, the relationship among the slope's safety factor, the shear mechanical parameters of the joints, and the failure mode is established. As shown in Fig. 20, during the 0–5 cycles stage, the stage degradation of the slope's safety factor is the greatest, reaching 7.27%, and gradually decreases to 1.09% with increasing dissolution cycles.

The stage degradation pattern of the joint shear mechanical parameters is consistent with this: during the 0–5 cycles stage, the stage degradation magnitudes of internal friction angle and cohesion reach their maxima at 15.18% and 11.71%, respectively, then progressively decrease to 3.72% and 1.27%. However, the failure mode of the joint slope remains unchanged during the 0–5 cycle stage. That is, in the stage where the safety factor experiences the greatest reduction, the degradation of the joint shear mechanical parameters is also maximal, but the failure mode of the slope does not change. Therefore, in the stability analysis of the joint slope, its stability is mainly controlled by the evolution of the shear mechanical parameters of the joints. The attenuation of the shear mechanical parameters directly weakens the peak shear strength of the joint area, thereby reducing the total anti-sliding resistance of the potential sliding surface of the jointed slope, and ultimately causing the limit

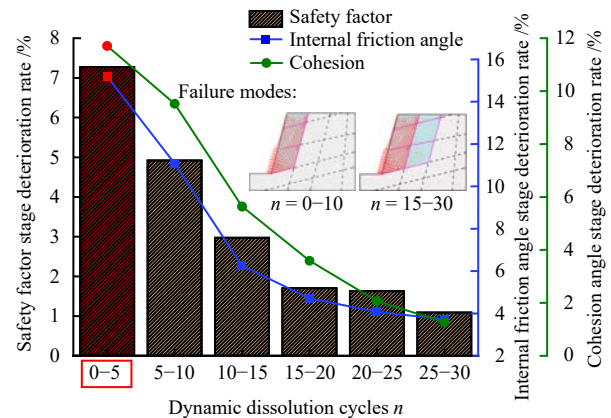


Fig. 20 Analysis of failure mechanism of joint slope

equilibrium state of the joint slope to be broken, and ultimately resulting in the safety factor of the joint slope dropping below the critical value, triggering progressive failure and even overall instability.

6 Limitations and prospects

In summary, this study conducts dynamic dissolution experiments on limestone joint samples in CO₂ solution environments, analyzing the degradation process and mechanisms of the samples' shear mechanical parameters. Meanwhile, a time-varying stability analysis method considering the deterioration of shear mechanical parameters in the joint zone with the erosion cycle is proposed for joint slope. The time-varying evolution process of the safety factor of joint slope and the corresponding failure mode characteristics are analyzed. This study is conducive to simulating the deterioration process of joint rock masses in the real solution environment more realistically and effectively. Moreover, the proposed numerical calculation method can provide effective references and theoretical support for the time-varying stability and life prediction of joint slopes. However, there are still certain limitations and problems that need to be further addressed.

This study does not consider the variability of shear mechanical parameters in the rock matrix and rock joints, as well as the spatial randomness of the geometric parameters and distribution of the joints. The mechanical parameters of both the rock matrix and rock joints not only change over time but also exhibit significant randomness. However, this study treats the rock matrix and joints as homogeneous media, neglecting the variability of their shear mechanical parameters. Regarding the joint zones within the slope, only through-going joints located at fixed positions are considered, without accounting for the influence of non-through-going joints inside the slope body on slope stability. Moreover, non-through-going joints exhibit considerable geometric parameter variability and spatial randomness, which undoubtedly affects the accuracy of research findings on joint slope stability. This study only conducted two-dimensional numerical calculation analysis for joint slopes, which undoubtedly ignores the lateral connectivity of the joint network and also does not consider the influence of spatial seepage effects. Therefore, a reliable analysis method that takes into account the variability of the mechanical parameters of the rock mass matrix and rock fractures, as well as the variability of the geometric parameters and spatial randomness of the fractures, should be further established. Three-dimensional numerical analysis considering the coupling effect of the three-dimensional joint network and spatial seepage should be carried out to more accurately and effectively reveal the time-varying stability characteristics of joint slopes.

7 Conclusion

Based on a gas-liquid cycling approach, this study proposes a dynamic water-rock interaction experimental method. Taking joint limestone from a reservoir area in Yunnan as the research subject, dynamic dissolution experiments under CO₂ solution environments are conducted to analyze the degradation patterns of the shear mechanical parameters of joint samples. Additionally, the microstructure, apparent morphology of the joint surfaces and the degradation of joint matrix strength are assessed to elucidate the degradation mechanisms of the shear mechanical properties. Finally, based on the evolution characteristics of the samples shear mechanical parameters, a time-varying stability analysis method considering the degradation of shear mechanical parameters in joint zones is proposed for joint slope. The main conclusions are as follows:

(1) The shear-displacement characteristic curve of the joint samples shows three-stage features: initial locking, intermediate failure, and late shear-friction-resistance sliding. Moreover, with the progression of the dissolution cycle, the shear hardening feature of the samples decreases, and its shear mechanical parameters deteriorate exponentially.

(2) The microstructure of the joint surface of the samples and the evolution of the pore characteristics inside the joint matrix have obvious sequential damage characteristics. Due to the cumulative damage effect of the CO₂ solution, mineral particles dissolve and fall off, causing the pores and fractures between the crystal particles to continuously develop and form a connected network. After 30 dynamic dissolution actions, the porosity increased by 89.50%. The microstructure of the joint surface gradually changed from a neat and dense state to a porous and loose state. Macroscopically, it is manifested as the roughness of the joint surface and the strength of the joint matrix decreasing, ultimately leading to the gradual deterioration of the shear mechanical properties of the joint rock mass.

(3) Based on the finite element discretization technology, the plastic limit analysis upper bound theory, the mathematical programming theory and the yield criterion revised by the time function of internal friction angle and cohesion, a time-varying stability analysis method for joint slope is proposed. Moreover, the failure modes of joint slopes under different dissolution cycles are statistically analyzed according to the changes in the element velocity field. The numerical calculation results show that with the increase of the dissolution cycles, the safety factor of the joint slope shows an exponential deterioration trend, decreasing from 3.44 to 2.81, with a reduction of 18.31%. Moreover, the deterioration of the safety factor of the joint slope is mainly controlled by the deterioration of the shear mechanical parameters in the joint area, and its correlation with the failure mode is relatively low.

(4) The attenuation of the shear mechanical parameters

of joints directly reduces the total anti-sliding resistance of the potential sliding surface of the joint slope, causing the limit equilibrium state of the joint slope to be disrupted. This subsequently leads to a decrease in its safety factor, and ultimately triggers the progressive failure and even overall instability of the joint slope. Moreover, due to the differences in stress states of the joint spatial positions and the principle of minimum energy consumption, as the joint shear mechanical parameters continue to deteriorate, the sliding path of the joint slope gradually migrates from the shallow joints to the deep joints in a dynamic manner.

Data Availability Statement

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

Author Declarations Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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