American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-14, Issue-3, pp-31-44
www.ajer.org
Research Paper Open Access

A Review of the Mechanical Deterioration Mechanisms of Sedimentary Rocks under Multi-Field Coupling Effects

Xu Zhiwei[1], Cheng Yun[1,2,3], Wang Zhaoyu[1], Song Zhanping[4], Zhou Guannan[2], Sun Yinhao[4]

[1]School of Civil Engineering, Yancheng Institute of Technology, Yancheng 224051, China
[2]China Railway Construction Bridge Engineering Bureau Group Co., Ltd. Tianjin 300300, China；
[3]Shaanxi Key Laboratory of Geotechnical and Underground Space Engineering, Xi'an Shaanxi 710055, China；
[4]China Railway Construction Urban Transportation Development Co. Ltd. China Railway 20th Bureau Group Co. Ltd. Suzhou Jiangsu 215151, China;
Corresponding Author: Cheng Yun, Wang Zhaoyu

ABSTRACT: *The mechanical deterioration of sedimentary rocks poses a significant challenge to the stability of underground engineering structures. This study systematically investigated the degradation mechanisms of four typical sedimentary rock types (sandstone, shale, limestone, and slate) under multi-field coupling effects. The influence of bedding angle, pore characteristics, and loading conditions on crack propagation and failure patterns was analyzed. The results revealed that sedimentary rocks exhibit strong anisotropic behavior, with bedding structures significantly influencing strength degradation and failure modes. The mechanical parameters demonstrate a characteristic U-shaped variation with bedding dip angles, where lower angles promote splitting failure, intermediate angles lead to composite failure, and higher angles favor shear failure. Energy dissipation analysis showed that rock failure is driven by a balance between energy storage and release, with crack propagation intensifying as stress increases. Computed Tomography imaging and acoustic emission monitoring further revealed that microstructural damage accumulates progressively, accelerating degradation in complex environments. The findings highlight the necessity of advanced analytical approaches, including machine learning-based prediction models, Computed Tomography imaging, and multi-field coupling simulations, to enhance degradation assessment and disaster prevention strategies in underground engineering. The present study provides a theoretical foundation for improving the stability assessment of sedimentary rock masses and guiding future research on engineering safety.*

KEYWORDS: *sedimentary rocks, mechanical deterioration, crack propagation, energy dissipation, bedding angle.*

Date of Submission: 08-03-2025 Date of acceptance: 22-03-2025

I. INTRODUCTION

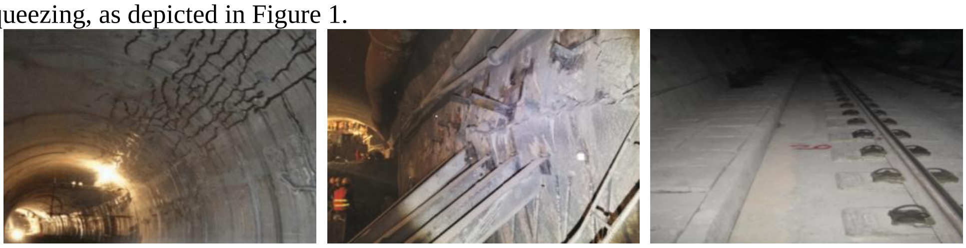
The mechanism of mechanical degradation refers to the gradual weakening of rock mechanical properties under external loads and environmental conditions, which is crucial for predicting long-term stability and disaster prevention in engineering rock masses. As one of the three major rock types in the Earth's lithosphere, sedimentary rocks constitute approximately 75% of the global crustal surface and are widely distributed in geological structures. They play a pivotal role in various underground engineering projects such as tunnels, subways, hydropower development, and mining operations. The mechanical characteristics of sedimentary rocks directly influence engineering design, construction, and long-term stability, making them critical factors in engineering safety[1,2]. Under natural conditions and engineering activities, sedimentary rocks are frequently subjected to multiple stress factors including high stress, elevated temperatures, and groundwater actions, leading to progressive deterioration of their internal structure and mechanical properties. During prolonged stress exposure, rock masses may develop micro-cracks, pore expansion, and even shear slip failures, while water-rock interactions and high temperature environments further accelerate their degradation processes[3–6].

These challenges include multi-field coupling, nonlinearity, cross-scale phenomena, and dynamic conditions under complex engineering requirements[7,8]. Zhang[9] analyzed the permeability characteristics of red-bed rock masses in the Sichuan Basin, conducting macro analyses and regional discussions based on geological features and hydraulic engineering survey data. Zhang et al.[10,11] proposed a composite shallow-deep surrounding rock theoretical model, elucidating the failure mechanism and instability criteria of deep surrounding rock. The variation of rock mechanical parameters during fracturing processes determines fracture formation and distribution, significantly impacting hydrocarbon productivity and wellbore stability[12,13]. Ran[13] established a conversion model for dynamic and static rock mechanical parameters and analyzed the variation patterns of wellbore collapse and fracture pressures under different stress states, developing a wellbore stability evaluation software. These findings have provided theoretical support for the design, construction, and maintenance of various underground engineering projects.

The degradation mechanisms of sedimentary rocks is essential for evaluating the long-term stability of rock masses in engineering projects, forming a crucial foundation for predicting rock failure and ensuring construction safety. This study concentrates on four typical sedimentary rocks (sandstone, shale, limestone, and slate) and systematically examines their mechanical degradation mechanisms through four perspectives: physical characteristics, mechanical degradation traits, micro-mechanical features, and fracture mechanisms.

II. CHARACTERISTICS AND MECHANISM OF TUNNEL CATASTROPHES IN SEDIMENTARY ROCKS

Under the sustained implementation of China's Western Development Strategy, infrastructure construction in the western region has experienced substantial acceleration, particularly in large-scale transportation projects including railways and highways. By the end of 2024, the total operational railway mileage in mainland China had surpassed 159000 kilometers, incorporating 18573 railway tunnels with an aggregate operational length exceeding 23508 kilometers[14]. Notably, the majority of these tunnel projects are situated in sedimentary rock regions characterized by complex geological conditions, which present significant challenges to both construction and long-term operation. Sedimentary rock masses, distinguished by their unique layered structure and pronounced anisotropic mechanical properties, are particularly vulnerable to environmental disturbances such as dynamic loads and water seepage during tunnel construction and operation, often resulting in substantial degradation of mechanical performance. This degradation typically exhibits cumulative characteristics, manifesting as catastrophic phenomena including lining cracks, floor heave, and sidewall squeezing, as depicted in Figure 1.



(a) (b) (c)

Figure 1: Typical disaster types of tunnel surrounding rock (a)Lining cracking. (b)Squeeze inside the side wall. (c)floor heave deformation

The existing railway tunnels have revealed a prevalent phenomenon of floor heave deformation in the base rock, resulting in catastrophic consequences such as floor heave and lining cracks, which significantly compromise the structural stability and operational longevity of tunnels. Sedimentary rock tunnels are particularly susceptible to such disasters due to the high sensitivity of sedimentary rock masses to external disturbance loads in complex environmental conditions. The progressive accumulation of damage along bedding planes under stress eventually leads to the loss of surrounding rock support capacity, triggering catastrophic events. The frequent occurrence of these disasters underscores the critical need for research into the mechanical degradation of sedimentary rock masses. A systematic analysis of the degradation mechanisms and the evolution of mechanical properties in sedimentary rock under varying environmental and stress conditions provides essential scientific foundations for enhancing tunnel engineering safety and extending service life, thereby demonstrating substantial practical significance.

This study systematically investigated the mechanical degradation mechanisms of sedimentary rocks, with a specific focus on sandstone, slate, limestone, and shale. Through comprehensive statistical analysis of CNKI literature spanning the past decade, five pivotal research directions were identified: wave velocity variation characteristics, mechanical property evolution, energy dissipation properties, microscopic mechanical features, and fracture mechanisms. These interrelated dimensions collectively established a robust research framework for understanding the mechanical degradation of sedimentary rocks. The integration of these research directions not only advanced fundamental understanding but also established theoretical support for ensuring safety and sustainability in sedimentary rock tunnel engineering projects.

III. MULTI-SCALE RESEARCH PROGRESS ON MECHANICAL DEGRADATION MECHANISMS OF TYPICAL SEDIMENTARY ROCKS

3.1 Wave velocity change characteristics

The alteration of wave velocity directly mirrors the evolution of internal rock fractures, rendering wave velocity testing indispensable in rock mechanics and engineering geology[15–17]. This method not only characterizes rock physical properties but also furnishes essential data on mechanical parameters. Concurrently, wave velocity serves as an indicator of rock porosity and density, demonstrating higher velocities in denser rocks and lower velocities in more porous formations. Moreover, wave velocity variations unveil fracture characteristics and rock anisotropy, particularly highlighting velocity discrepancies across bedding planes, emphasizing the complexity of internal rock architecture. Wang et al.[18] investigated elastic wave propagation in Jialing River micritic limestone under triaxial stress conditions. Through uniaxial and triaxial loading experiments, they acquired deformation data and wave velocity changes, subsequently formulating the wave velocity-stress relationship, as illustrated in Eq. (1).

$$\sigma_1 = \sigma_1^{(1)} + \frac{V_{P1} - V_{P1}^{(1)}}{K^{(1)}} \tag{1}$$

Where, $\sigma_1^{(1)}$ represents the uniaxial compressive limit of the rock, $V_{P1}^{(1)}$ is the P-wave velocity corresponding to this compressive limit, and $K^{(1)}$ is a rock property-dependent coefficient.

The results demonstrated that wave velocity exhibited a linear increase with stress during the elastic stage, with high-density, high-elastic-modulus rocks such as limestone showing smaller velocity changes compared to low-density rocks like sandstone. Zhang et al.[19] conducted triaxial loading experiments on homogeneous yellow sandstone, monitoring ultrasonic wave velocity variations and dynamic elastic parameters through comprehensive acoustic emission analysis. Their findings indicated that both P-wave and S-wave velocities followed a quadratic relationship with confining pressure (σ_3), as described by Eqs. (2) and (3). At low confining pressures, rapid crack closure resulted in significant velocity increase, whereas at high pressures, complete pore closure led to velocity stabilization. Notably, S-waves exhibited greater sensitivity to rock damage, manifesting earlier decline than P-waves. Prior to reaching damage stress, P-wave and S-wave velocities maintained a strong linear correlation.

$$V_{\mathrm{p}} = -0.180\sigma_3^2 + 23.331\sigma_3 + 3879 \tag{2}$$

$$V_{\mathrm{s}} = -0.052\sigma_3^2 + 8.202\sigma_3 + 2178 \tag{3}$$

The fracture behavior of sedimentary rocks significantly influences the attenuation mechanisms of internal stress waves, and the acoustic wave evolution characteristics can effectively elucidate the damage mechanics properties of these rocks. Cheng[20] conducted impact tests on high-quality, homogeneous red sandstone from Anyuan, Ganzhou, using an improved static-dynamic combined loading device under various axial pressures. The study measured stress wave waveforms using ultra-dynamic strain gauges and oscilloscopes, systematically investigating the changes in P-wave velocity under loading. The results align with those from reference [19], as shown in Figure 2. The experiments revealed that the P-wave velocity of the sandstone changes significantly with axial pressure. This relationship is closely tied to the elastic modulus and strength, providing valuable insights into the mechanical behavior of sandstone under dynamic loading conditions. Besides, Lan[21] conducted indoor mechanical tests on slate from the Rongjiang Water Conservancy Project, finding that P-wave velocity is highly sensitive to the degree of rock weathering, followed by the presence of open, unfilled cracks. Meanwhile, Li et al.[22] measured the elastic wave velocity characteristics of Longmaxi Formation shale samples from the Xiangxi Shanye-1 Well Project under different stress conditions. They calculated the wave velocity differences in stress environments and discovered that shale elastic wave velocity is positively correlated with density. Additionally, they found that P-wave velocity is significantly higher in the direction parallel to the bedding plane compared to the perpendicular direction.

The anisotropic characteristics of porosity distribution in rock masses substantially influence their mechanical properties and engineering stability, leading to extensive systematic investigations by researchers. Zhang et al.[23] comprehensively reviewed the relationship between rock wave velocity and pressure, emphasizing key findings. The presence of pore fluids reduces effective confining pressure, thereby decreasing the sensitivity of wave velocity to pressure variations. Research indicated that the P-wave to S-wave velocity ratio in sandstone and mudstone increases rapidly below 100 MPa but stabilizes beyond this pressure threshold. Consequently, wave velocity testing technology proves highly valuable for estimating the physical and mechanical properties of sedimentary rocks. Studies have established a strong correlation between acoustic parameters and these properties, offering a scientific basis for the development of subsurface spaces in sedimentary rock formations and enhancing their safety and stability. Through wave velocity measurements, researchers and engineers can derive critical insights into rock behavior, facilitating informed decision-making and effective risk management in geological and engineering projects.

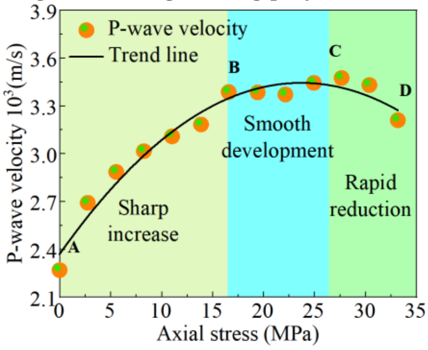


Figure 2: Variation trend of P-wave velocity under loading[20]

3.2 Deterioration mechanism of mechanical properties

The deterioration mechanism of rock mass mechanical properties has emerged as a critical research focus in geotechnical engineering, predominantly influenced by the complex interplay between environmental factors and external loading. In engineering applications, rock masses are frequently subjected to multifaceted influences including chemical corrosion, freeze-thaw cycling, water-rock interactions, and dynamic disturbances. Acidic environments significantly alter the energy absorption and dissipation characteristics of rock masses, leading to marked reductions in mechanical properties under dynamic impact loads. The freeze-thaw process intensifies dynamic damage in red sandstone through the expansion of internal fracture networks, while temperature variations and geological conditions further modulate its macroscopic responses. The mechanisms of water softening, characterized by clay mineral dissolution, pore water pressure changes, and frictional weakening, along with non-uniform deterioration patterns, have been extensively documented in water-rock interaction studies. Through uniaxial compression tests on layered sandstone, Zhao[24] revealed that the rock's compressive strength is lowest when bedding planes are inclined at 30° to the loading direction. Subsequent research by Gao et al.[25] demonstrated pronounced variations in mechanical responses and deformation-failure patterns through uniaxial and triaxial compression tests on sandstone with 0° and 90° bedding angles, noting that confining pressure mitigates anisotropic behavior. By conducting triaxial compression tests on sandstone samples with different bedding angles, Zhang et al.[26] found that the fracture mode and strength of bedded sandstone are related to the bedding angle, showing marked anisotropy. Based on comparative analysis of experimental data, they proposed an optimized Jaeger's plane of weakness(JPW) model, described by Eqs. (5) and (6), which more accurately predicts the anisotropic strength of layered sandstone under different bedding angles and confining pressures.

$$\sigma_1(\beta)=\sigma_1^{0^\circ}+\frac{\sigma_1^{90^\circ}-\sigma_1^{0^\circ}}{90}\beta \tag{5}$$

$$\frac{\sigma_1}{\sigma_c}=\frac{\sigma_3}{\sigma_c}+\left(1+m\frac{\sigma_3}{\sigma_c}\right)^{0.5} \tag{6}$$

where, σ_1 represents the triaxial compressive strength of the rock sample, σ_3 denotes the confining pressure, and β refers to the bedding dip angle. The parameters m and σ_3 are strength parameters determined by fitting the relationship between σ_1 and σ_3. Based on Eqs. (5) and (6), the peak strength of a rock sample corresponding to any bedding dip angle can be calculated.

To investigate the failure mechanisms of hard siltstone, Cheng et al.[27] conducted uniaxial compression tests on specimens with varying bedding dip angles, revealing distinct anisotropic features in their mechanical properties under stress. Specifically, both crack initiation stress and peak stress were markedly influenced by bedding orientation. The study also found that elastic modulus and deformation modulus exhibited similar trends, initially decreasing gradually at lower bedding dip angles before sharply declining and subsequently increasing abruptly as the dip angle increased. Poisson's ratio, on the other hand, displayed an initial gradual increase, followed by a marked acceleration, ultimately reaching a plateau at higher bedding dip angles. In a complementary investigation, Hao et al.[28] examined the mechanical characteristics and crack propagation patterns in sandstone under various bedding dip angles through uniaxial compressive strength tests and Brazilian splitting tests. Their results, consistent with those documented and illustrated in Figure 3, demonstrated that the uniaxial compressive strength of sandstone follows a distinctive "U"-shaped trend, initially decreasing before rising with increasing bedding dip angle, while tensile strength showed a continuous decline. These findings collectively highlight the significant influence of bedding dip angle on the mechanical behavior of sandstone.

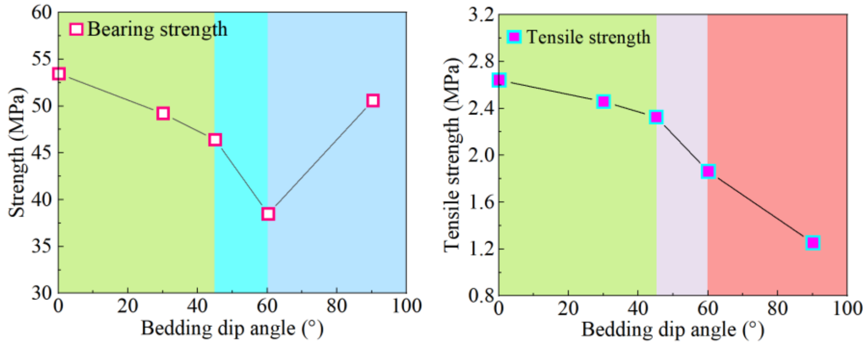


Figure 3: Relationship between strength and bedding dip angle[28]

The investigation by Chen et al.[29] revealed that black shale strength exhibits a distinct "U"-shaped anisotropic pattern with increasing bedding dip angles, with fracture network complexity peaking at a 90° bedding dip angle. Through systematic Brazilian splitting tests, direct shear tests, and three-point bending tests, Heng et al.[30] established that shale's tensile strength and fracture characteristics show significant bedding dip angle dependence, particularly noting that bedding planes demonstrate substantially weaker mechanical properties compared to the rock matrix. Wang et al.[31] demonstrated through Brazilian splitting tests that shale's tensile strength increases proportionally with strain rate, further corroborating the critical role of bedding dip angle in determining shale's mechanical behavior. Expanding the scope of anisotropic studies, Ou et al.[32] conducted comprehensive Split Hopkinson Pressure Bar tests on five sets of slate, identifying pronounced anisotropic characteristics in slate's tensile strength that followed a characteristic "U-shaped" pattern. Mao et al.[33] examined slate specimens from the South-to-North Water Diversion Project's West Route. Their comprehensive analysis, employing uniaxial and triaxial compression testing, yielded significant findings through mathematical modeling based on the single weakness plane theory, as expressed in Eqs. (7) and (8), with supporting graphical data presented in Figures 5. The investigation revealed a strong correlation between theoretical predictions and experimental observations, demonstrating pronounced anisotropic behavior in slate's uniaxial compressive strength.

$$\sigma_{mc} = \frac{13.7}{(1-0.203\cot\beta)\sin(2\beta)} \tag{7}$$

$$\sigma_{1m} = \sigma_3 + \frac{13.7+0.203\sigma_3}{(1-0.203\cot\beta)\sin(2\beta)} \tag{8}$$

where, σ_{mc} represents the uniaxial compressive strength, σ_{1m} represents the triaxial compressive strength, and β represents the bedding dip angle.

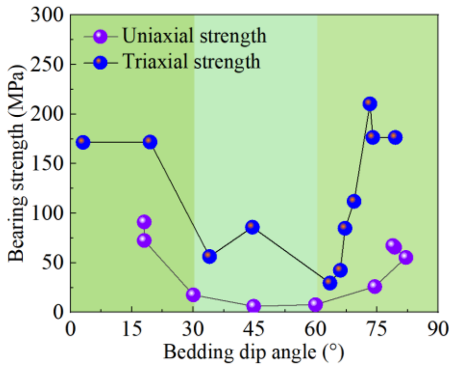


Figure 5: Compressive strength curve of rock sample[33]

The geometric parameters such as bedding dip angle and thickness significantly influence mechanical deterioration mechanisms, as a distinctive tectonic feature in sedimentary rocks. The weak cementation capacity of bedding structural planes renders them vulnerable zones within the rock mass, prone to stress concentration and slip deformation under external loading. The bedding dip angle governs sedimentary rock failure modes and engineering instability by altering the orientation between structural planes and principal stress directions. In sedimentary rocks with low bedding angles, failure is predominantly controlled by interparticle friction and cohesion strength under loads perpendicular to bedding planes. With increasing inclination angles, the slip shear effect along bedding surfaces intensifies, leading to marked reductions in bearing capacity and maximum deterioration. Sedimentary rock mechanical anisotropy directly manifests through bedding structures, exhibiting higher tensile but lower compressive strength parallel to bedding, and the converse perpendicular to bedding - a phenomenon attributed to structural hindrance of stress transfer. Geotechnical engineering practice demonstrates that anisotropy and failure mode transitions induced by bedding dip angle variations are key contributors to underground space surrounding rock instability. Consequently, disaster risk assessment necessitates coupled analysis of structural plane strength parameters and bedding dip angles.

The mechanical deterioration mechanism of layered sedimentary rocks has garnered significant attention from scholars, who have conducted extensive investigations through both engineering practice and theoretical research. Yin et al.[34] established a positive correlation between elastic modulus and strain rate in sedimentary rocks such as limestone, sandstone, and shale, with this phenomenon being particularly pronounced in sandstone due to its pore structure. This correlation was further validated by Hao et al.[28], who performed uniaxial compression and Brazilian splitting tests on sandstone specimens with five distinct bedding plane angles. Their findings revealed a positive relationship between elastic modulus and bedding plane angle, highlighting the substantial impact of bedding structure on rock stiffness, as depicted in Figure 6. When the bedding plane angle was 0°, the weak planes were perpendicular to the loading direction, resulting in diminished specimen stiffness as the load was primarily supported by the matrix, thus yielding a lower elastic modulus. Conversely, as the bedding plane angle increased to 90°, the matrix assumed a greater load-bearing role with weak planes aligned parallel to the loading direction, leading to an elevated elastic modulus. Consequently, the elastic modulus of the specimens exhibited a gradual increase as the bedding plane angle varied from 0° to 90°. Additionally, Wang et al.[35] examined the dynamic and static Young's moduli of organic-rich shale through quasi-triaxial tests, demonstrating that the bedding plane angle significantly influenced Young's modulus. The Young's modulus in the direction parallel to bedding was substantially higher than that perpendicular to bedding, with static mechanical properties undergoing notable changes as stress levels increased. To investigate the deformation anisotropy of layered rock masses, Huang et al.[36] conducted uniaxial compression tests on limestone specimens with varying angles, observing that the elastic modulus initially decreased and subsequently increased with rising bedding plane angles, as illustrated in Figure 8.

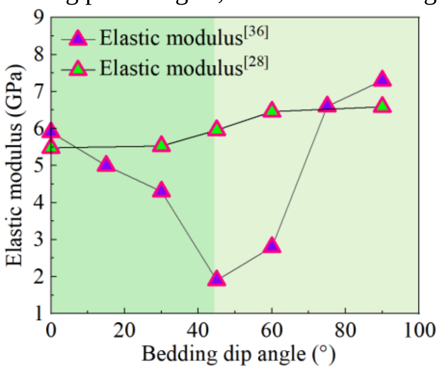


Figure 6: Relationship between elastic modulus and bedding dip angle[28,36]

Table 1: Effect of bedding inclination on mechanical properties of typical sedimentary rocks

Rock type	***Test type***	***Mechanical property***		***Document***
		Deformation property	***Strength property***	
Sandstone	Rock burst test with double unloading	The tendency of rock burst occurrence difficulty is U-shaped	The tensile strength showed a decreasing trend	He et al[37]
Sandstone	Uniaxial and triaxial compression tests	The elastic modulus showed a gradually increasing trend trend of deformation modulus is U-shaped	The trend of compressive strength is U-shaped	Deng et al[38]
Sandstone	Uniaxial compression test	The trend of deformation modulus is U-shaped	The trend of peak stress is U-shaped	Cheng[27]
Sandstone	Uniaxial compression test, Brazilian split test	The fracture toughness showed a decreasing trend	The tensile strength showed a decreasing trend	Hao et al[28]
Slate	Uniaxial compression test	The overall Poisson's ratio showed a gradually increasing trend	The trend of compressive strength is U-shaped	Wang et al[39]
Slate	Dynamic loading test	It gradually controls the damage pattern	The trend of critical failure strength is U-shaped	Ou et al[40]
Slate	Uniaxial and triaxial compression tests	The trend of elastic modulus is U-shaped; Impact failure mode	The trend of compressive strength is U-shaped	Mao et al[33]
Slate	Uniaxial and	The elastic modulus and	The peak strength of	Gao et

	triaxial compression tests	deformation modulus of horizontal bedding are about 50% and 80% larger than that of vertical bedding	horizontal bedding is about 20% larger than that of vertical bedding	al[41]
Shale	Uniaxial compression test	The elastic modulus showed a decreasing trend	The trend of compressive strength is U-shaped	Hou et al[42]
Shale	Uniaxial compression test	The elastic modulus showed a decreasing trend	The trend of compressive strength is U-shaped	Xie et al[43]
Shale	Uniaxial compression test	The trend of elastic modulus is an inverted "U" shape	The trend of initiation stress is U-shaped	Wang et al[44]
Shale	Uniaxial and triaxial compression tests	The elastic modulus and Poisson's ratio show obvious anisotropy characteristics	The uniaxial and triaxial compressive strength is U-shaped	Zhang et al[45]
Shale	Uniaxial cyclic loading and unloading test	The elastic modulus showed a decreasing trend	The trend of compressive strength is U-shaped	Renet al[46]
Limestone	Uniaxial compression test	The trend of elastic modulus is U-shaped	The trend of peak strength and residual strength is U-shaped	Huang et al[36]
Limestone	The Brazilian splitting test	The tensile modulus showed a decreasing trend	The tensile strength showed a decreasing trend	Huang et al[47]

The analytical results indicate that bedding plane angle exerts a substantial influence on the mechanical properties of sedimentary rocks. Table 1 comprehensively summarizes the relationship between bedding plane angle and mechanical characteristics in representative sedimentary rocks. Investigations revealed consistent patterns in mechanical properties and failure modes across various rock types when subjected to different bedding plane angles. The strength and elastic modulus of most rocks demonstrate a characteristic "U-shaped" distribution, showing an initial decrease followed by an increase as bedding plane angle varies, with minimum values typically observed between 30° and 50°. Experimental evidence from uniaxial and triaxial compression tests indicates that sandstones, shales, and slates exhibit distinct "U-shaped" strength variations, accompanied by fluctuating elastic modulus values. Notably, both tensile modulus and Poisson's ratio in shale and limestone decreased proportionally with increasing bedding plane angle, while limestone's tensile strength manifested a continuous downward trend. These findings collectively demonstrate that bedding plane angle substantially affects multiple mechanical parameters (compressive strength, elastic modulus, and Poisson's ratio) and failure modes in sedimentary rocks. This research establishes a theoretical framework for engineering applications involving sedimentary rocks and provides scientific foundation for their sustainable resource utilization.

3.3 Energy dissipation characteristics

Sedimentary rocks, as multiphase composite media, exhibit significant structural heterogeneity due to the complex mineral composition and inherent defects including cracks, pores, bedding planes, and faults. These structural characteristics fundamentally determine the intricate energy dissipation behavior observed in sedimentary rocks, particularly under subsurface engineering conditions. When subjected to external loading, sedimentary rocks experience progressive energy input, accumulation, dissipation, and release processes. Notably, energy dissipation becomes increasingly pronounced during plastic deformation, primarily manifested through mechanisms such as crack propagation, pore closure, and intergranular sliding. These micro- and meso-scale alterations collectively drive the progressive degradation of the rock's mechanical properties. The comprehensive understanding of energy dissipation characteristics in sedimentary rocks is essential for elucidating mechanical degradation mechanisms, establishing reliable constitutive models, and accurately predicting rock stability in engineering applications. Such knowledge provides critical theoretical foundations for risk mitigation and optimization in engineering designs involving sedimentary rock formations.

The strain energy release law during rock cracking is governed by the dynamic equilibrium between elastic strain energy accumulation and sudden release, with the accumulation threshold and release rate serving as predictive indicators for the critical point of rock mass instability, thereby establishing a crucial theoretical foundation for engineering rock mass safety early warning. Through investigation of energy storage and dissipation behaviors in rocks under uniaxial compression, Gong et al.[48] revealed nonlinear variations in energy density before and after peak strength, providing significant insights into the quantification of rock mechanical behavior. Ren et al.[46], in their uniaxial cyclic loading and unloading experiments on Longmaxi Formation shale samples with varying bedding dip angles, demonstrated that the energy dissipation characteristics of acoustic emission and charge signals exhibited consistent overall trends, while specimens with vertical or horizontal bedding angles displayed enhanced energy dissipation relative to other orientations. Wang et al.[49], in their comprehensive study of sandstone's energy evolution characteristics under different confining pressures, developed an energy strength criterion for sandstone, offering novel perspectives for stability assessment under high confining pressures. Their findings indicated that the elastic strain energy of sandstone remained constant prior to peak stress under elevated confining pressures, contributing valuable insights into the understanding of sandstone's instability and failure energy criterion.

Energy consumption analysis establishes a critical physical foundation for assessing essential engineering properties of rock masses, including slope stability and reservoir fracturing mechanisms. Through comprehensive laboratory compression tests, Guo et al.[50] systematically investigated the stress-energy dissipation relationship in karst limestone under external loading conditions, demonstrating that both total strain energy U and releasable strain energy U^e exhibited linear progression with axial strain under natural conditions, as shown in Figure 7. Meanwhile, Wang et al.[51] conducted SHPB system impact tests on damaged sandstone, observing significant increases in reflected and dissipated energy alongside diminished transmitted energy as damage levels escalated, thereby adversely affecting rock mass stability. Through innovative high-speed camera monitoring and Discrete Lattice Spring Model (DLSM) simulations, Wang et al.[52] examined the effects of bedding spacing on sandstone's dynamic fracture behavior and energy evolution, concluding that increased bedding spacing reduced secondary crack formation while accelerating crack propagation velocity and enhancing stress and strain peaks, coupled with shortened energy evolution durations, as depicted in Figure 8. These investigations further demonstrated an inverse relationship between peak elastic strain energy and bedding spacing, whereas absorbed and dissipated energy peaks displayed contrasting patterns. Simulation outcomes indicated diminishing stress, strain, and energy peaks within the rock matrix between beddings as spacing increased.

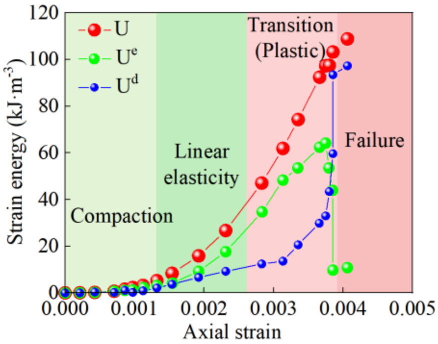


Figure 7: Relation between strain energy and axial strain[50]

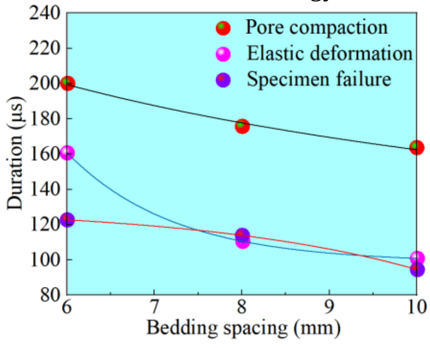


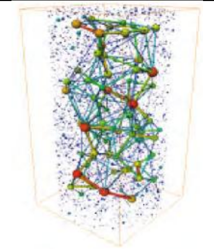
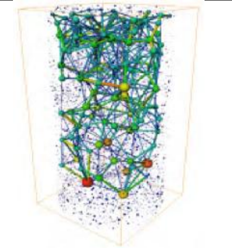
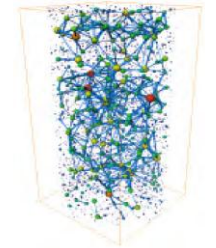
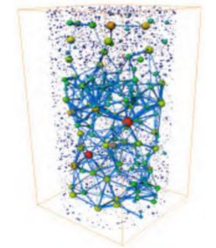
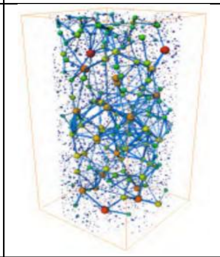
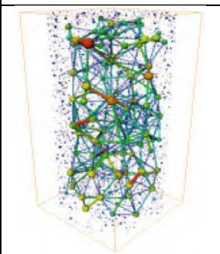
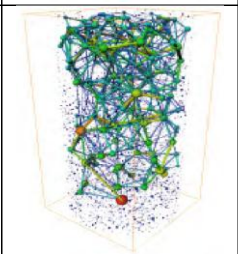
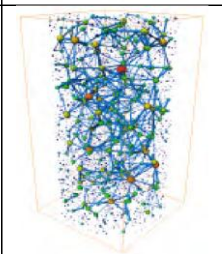
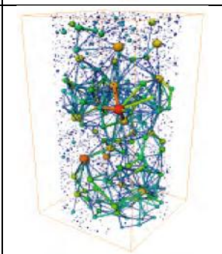
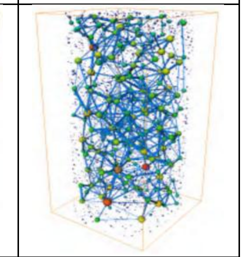
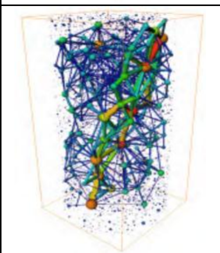
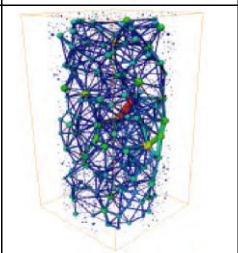
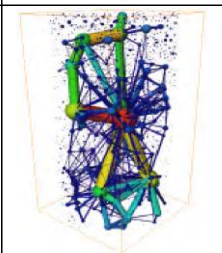
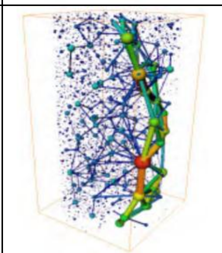
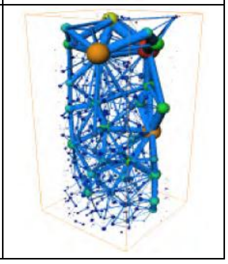
Figure 8: The duration of energy evolution with different bedding spacings[52]

Synthesizing the above research findings, we observe that the total energy, elastic energy and dissipated energy of typical sedimentary rocks all increase with rising stress, revealing the energy response characteristics of sedimentary rocks. The distinction lies in the post-yield phase, where elastic energy begins to decline while dissipated energy significantly escalates. The expansion of fractures, changes in porosity, and friction among particles dissipate a substantial portion of the input energy, undermining the bearing capacity and structural stability of sedimentary rocks. Through systematic investigation of energy dissipation characteristics, we can more accurately unveil the degradation mechanisms of sedimentary rocks under external loads, providing theoretical foundations for establishing constitutive relationships and strength criteria of sedimentary rocks, as well as scientific support for stability prediction and disaster prevention in engineering applications involving sedimentary rocks.

3.4 Microscopic mechanical properties

The mechanical degradation of sedimentary rocks is fundamentally governed by their micro and mesoscopic characteristics, encompassing microscopic fractures, porosity, and bedding structures. Studies have demonstrated that environmental conditions, loading methods, and structural features critically influence the microscopic response mechanisms during mechanical loading, ultimately determining the rock's macroscopic mechanical behavior. These microscopic alterations substantially impact the rock's strength, deformation characteristics, and failure patterns under varying stress conditions. Such comprehensive understanding enables more precise prediction of sedimentary rock behavior in engineering applications, thereby enhancing structural safety and optimizing design approaches for projects involving sedimentary rock formations.

Table 2: Three-dimensional pore structure model of freeze-thaw sandstone in compression failure process[53]

State under load	***Sample 1***	***Sample 2***	***Sample 3***	***Sample 4***	***Sample 5***
Before loading					
Before peak failure					
After failure					

The Computed Tomography (CT) technology emerged as a pivotal instrument for the direct observation and quantification of internal structural alterations. Liu et al.[53] employed CT imaging to evaluate the damage attributes of sandstone subjected to freeze-thaw cycles, as depicted in Table 2. To elucidate the microscopic pore and throat distribution and structural characteristics of tight reservoirs, Bai et al.[54] employed multi-scale CT imaging technology to characterize tight sandstone microstructure, as depicted in Figure 9. Their study pioneered innovative methodologies for investigating pore and throat structures in nano-oil and gas reservoirs, significantly advancing our comprehension of sedimentary rock micromechanical structures, particularly under extreme conditions. Yang et al.[55] conducted direct shear, compression, and permeability tests complemented by SEM observations to assess the impact of moisture content and dry density on the cohesion, internal friction angle, and microscopic porosity of white sandstone. Their results demonstrated that elevated moisture content diminishes the internal friction angle and exacerbates microstructural degradation. Concurrently, Li et al.[56] systematically analyzed sandstone deterioration mechanisms across compaction, elastic, and plastic stages by integrating resistivity and acoustic emission techniques to monitor the damage progression. Their findings revealed that resistivity exhibits heightened sensitivity during crack initiation, whereas acoustic emission intensifies prior to rupture.

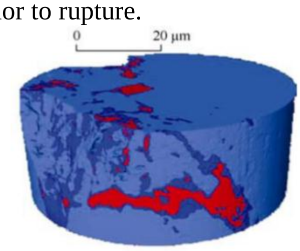


Figure 9: Nano-scale pore-throat distribution of tight sandstone[54]

Moreover, acoustic emission (AE) technology has emerged as a crucial methodological approach for quantifying the evolutionary mechanisms of rock damage. Diao et al.[57] conducted acoustic emission uniaxial compression tests to examine the AE characteristics during the failure process of slate with varying bedding plane angles. Their findings demonstrated that slates with 0° and 45° bedding angles primarily experienced shear failure, whereas those with 90° angles predominantly exhibited tensile failure. Notably, a sudden surge in AE energy was identified as a precursor to deterioration. Following this research direction, Sun et al.[58] investigated the micromechanical characteristics and deterioration mechanisms of slate through uniaxial compression tests. Their analysis revealed that variations in ring-down counts and the proportion of low-frequency, high-amplitude signals could serve as instability precursors, with fluctuations in the multifractal spectrum width $\Delta\alpha$ providing early characterization of the deterioration process, as demonstrated in Figure 10.

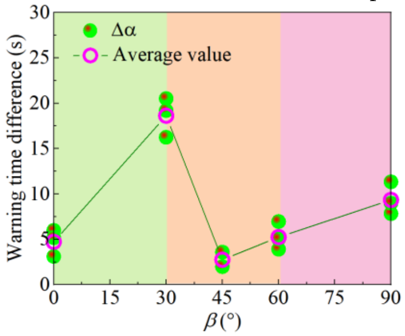


Figure 10: The variation curve of $\Delta\alpha$ early warning time with bedding angle[58]

Structural characteristics of bedding planes and aperture dimensions were also found to significantly influence the degradation mechanisms of sedimentary rocks. Dong et al.[59] developed a numerical model to analyze the impact of bedding angle and aperture size on shale instability characteristics. Zhang et al.[60] systematically examined the micromechanical effects of bedding angle on shale failure mechanisms and crack propagation. Their study established that bedding angle governs the development of failure modes. Parallel research by Wang et al.[61] focused on the AE characteristics of fractured sandstone under varying loading rates, particularly in the context of dynamic disaster early warning. The observed pattern of alternating AE signal surges and quiet periods was identified as a valuable early warning indicator, providing novel theoretical foundations for incorporating micromechanical parameters into dynamic disaster warning systems. Li et al.[62] systematically investigated the deformation and failure mechanisms of red sandstone fractures under both dry and saturated conditions. The research demonstrated that acoustic emission signal acquisition techniques effectively captured the compression failure characteristics of rock fractures. As evidenced by Figure 11, the spatial correlation between acoustic emission localization points and experimentally measured surface failure zones validated the reliability of the acoustic emission monitoring method. This investigation provided quantitative insights into the controlling influence of fundamental mechanical parameters and fracture surface characteristics on the compression deformation and failure processes of rock materials.

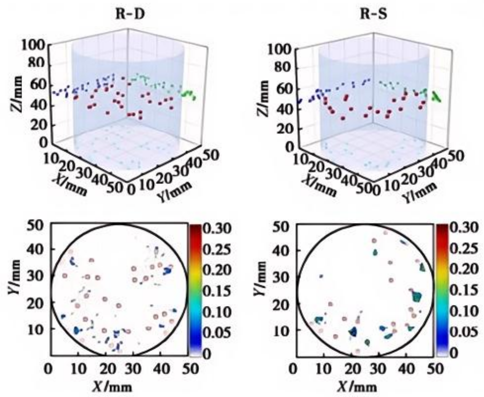


Figure 11: Comparison between AE positioning points and experimentally measured asperity damage areas[62]

The mechanical degradation of sedimentary rocks was primarily governed by microstructural characteristics, environmental conditions, and loading methods. Microscopic cracks and pore features demonstrated substantial anisotropic behavior under mechanical stress, directly regulating crucial mechanical parameters including cohesion and internal friction angle. The decrease in internal friction angle and accelerated microstructural deterioration induced by increased water content, coupled with the progressive evolution of pore structures during freeze-thaw cycles, constituted the fundamental mechanisms of environmental-driven degradation. The substantial impact of bedding structures and aperture characteristics on failure modes, along with the transformation of crack propagation patterns under confining pressure, highlighted the pivotal role of structural features in mechanical degradation processes. Modern analytical techniques, such as acoustic emission monitoring and resistivity measurements, provided reliable empirical evidence for developing comprehensive damage variables and evolution equations.

3.5 Fracture mechanism

The elucidation of fracture mechanisms in sedimentary rocks during mechanical metamorphism is essential for predicting rock mass instability and ensuring engineering safety. Research has demonstrated that the fracturing behavior of sedimentary rocks under external loading exhibits distinctive micro- and meso-scale characteristics, primarily governed by internal fracture systems, pore structures, and loading conditions. Among these factors, the bedding structure, as a prominent structural characteristic of sedimentary rocks, significantly influences fracture mechanisms and mechanical behavior through the interaction of key parameters including bedding inclination, loading direction, and confining pressure.

Numerous experimental studies have demonstrated that the bedding dip angle is a critical factor determining the fracture patterns of sedimentary rocks. Through systematic investigation of Tournemire shale, Niandou et al.[63] revealed the controlling mechanism of bedding structure and loading direction on fracture patterns, concurrently discovering the significant regulatory effect of confining pressure on rock plastic deformation. Hou et al.[64] systematically studied the mechanical response of shale with varying bedding dip angles through uniaxial compression tests, demonstrating that specimens parallel to the bedding orientation exhibit higher strength reserves and energy absorption capacity, whereas those perpendicular to the bedding direction are more prone to brittle fracture, as shown in Figure 13. Based on comprehensive research on layered shale, Gao[65] further classified shale fracture patterns into three typical mechanisms: vertical splitting tensile failure, bedding plane slip failure, and composite shear failure traversing both matrix and bedding planes. These findings fully illustrate the decisive role of bedding dip angle in the mechanical deterioration process of shale.

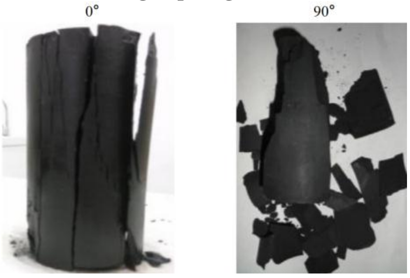
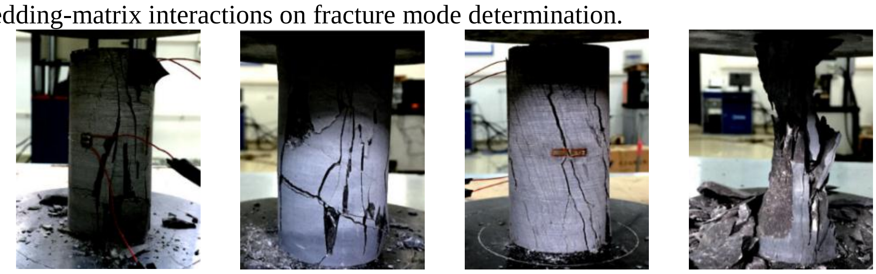


Figure 13: Fracture pattern variation for specimens with bedding orientation[64]

Moreover, Deng et al.[38] performed compression tests on layered sandstone with varying bedding dip angles, categorizing the fracture patterns into three distinct types: tensile splitting fracture, shear slip fracture along bedding planes, and composite shear fracture involving both matrix and bedding planes, thereby emphasizing the complexity of sandstone fracture behaviors. In the case of limestone, Huang et al.[36] observed that fracture patterns transition sequentially through four modes—axial splitting failure, mixed splitting and sliding failure, sliding failure along bedding planes, and splitting failure along bedding planes—as the bedding dip angle increases, as illustrated in Figure 14. Through uniaxial compression tests on layered slate, Sun et al.[58] identified precursor signals of instability under different bedding dip angles, noting a progressive shift in fracture modes from tensile splitting to splitting shear, then to shear sliding, and ultimately back to tensile splitting failure. Similarly, Zhao et al.[66] demonstrated that the fracture patterns of layered slate are primarily governed by shear-sliding failure and mixed tensile-shear failure along bedding planes, underscoring the critical influence of bedding-matrix interactions on fracture mode determination.



(a) (b) (c) (d)

Figure 14: Fracture patterns of slate with different bedding dip angles[36]: (a) axial splitting failure (b) mixed splitting and sliding failure (c) sliding failure along bedding planes (d) splitting failure along bedding planes.

Extensive research has demonstrated that the fracture mechanisms of sedimentary rocks are governed by the complex interaction of multiple factors, primarily including bedding structure, loading conditions, and confining pressure. The bedding dip angle was found to play a pivotal role in determining fracture patterns, with low-angle bedding promoting crack closure and high-angle bedding facilitating crack propagation along weak planes. Regarding loading direction, experimental evidence revealed that rocks exhibited greater compressive strength and energy dissipation capacity under parallel loading compared to perpendicular loading, which typically induced brittle failure. Confining pressure emerged as a critical regulatory factor, substantially enhancing the rocks' plastic deformation capacity through the delay of both crack propagation and closure processes, thus reducing rock mass instability. These interacting factors resulted in distinct fracture modes, including splitting tensile failure, bedding plane slip-shear failure, and composite shear failure, indicating that sedimentary rock fracture represents a complex physical process involving the coupling of inherent structural characteristics and external loading conditions. These findings not only provide essential theoretical insights into the mechanical degradation mechanisms of sedimentary rocks but also establish a scientific basis for assessing the stability of underground engineering structures. Future investigations should prioritize the long-term mechanical behavior of sedimentary rocks, particularly focusing on their response under complex stress paths and water-rock interaction conditions.

IV. CONCLUSION

Research on the mechanical degradation mechanisms of typical sedimentary rocks have achieved substantial advancements globally. These mechanisms demonstrate considerable complexity and diversity across multiple dimensions, including physical characteristics, mechanical parameter variations, energy dissipation patterns, and micro-meso-scale features. Under external loading conditions, physical attributes such as pore structures and bedding dip angles significantly influence mechanical parameters like elastic modulus and compressive strength, exhibiting distinct linear variation trends during degradation. Energy dissipation analyses have established that rock failure fundamentally stems from the interplay between energy dissipation and release. Furthermore, micro-meso-scale investigations and fracture mechanism analyses have elucidated the degradation behaviors and fracture patterns of sedimentary rocks in complex stress environments, offering deeper insights into the intrinsic degradation process. The mechanical degradation of sedimentary rocks is predominantly governed by bedding structures, pore characteristics, and loading conditions, progressively manifesting as crack propagation, pore expansion, and splitting failure phenomena.

These studies established fundamental theoretical frameworks for constructing mechanical models of sedimentary rocks and predicting engineering stability, while simultaneously providing scientific guidance for stability assessment and disaster prevention in engineering practices. The investigation of mechanical degradation mechanisms in sedimentary rocks necessitates further exploration in the following areas:

(1) The machine learning methodologies demonstrated significant potential in enhancing the prediction accuracy of deformation and instability in sedimentary rock masses. Through training on extensive experimental datasets, machine learning algorithms developed degradation prediction models adaptable to diverse conditions, thereby improving the precision of engineering rock mass risk assessments and offering intelligent support for stability analysis. This approach facilitated the identification of complex patterns and relationships in degradation processes that proved challenging to capture through traditional methods.

(2) The CT imaging technology provided substantial support for investigating the degradation mechanisms of sedimentary rocks. Through high-resolution scanning, CT technology enabled real-time monitoring of internal cracks and pore changes, capturing the evolution of microstructural features without disrupting the testing process. This capability established a scientific basis for precise quantification and dynamic analysis of degradation mechanisms, while also facilitating the visualization and analysis of spatial distribution and connectivity of fractures and pores.

(3) As underground engineering extended into greater depths, the combined effects of temperature, humidity, and other environmental factors on sedimentary rock degradation emerged as a critical research direction. Degradation models based on multi-field coupling more comprehensively represented actual degradation mechanisms, offering more realistic theoretical support for engineering stability assessment and disaster prevention strategies. The understanding of interactions between these fields contributed to the prediction of long-term behavior and the design of effective mitigation measures for deep underground environments.

REFERENCES

[1]. She Shigang, Dong Longjun. Statistics and analysis of academic publications for development of rock mechanics in china[J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(3): 442-464.

[2]. Song Zhanping, Liu Hongke, Zheng Fang, et al. Mechanical behavior and failure response characteristics of hard sandstones considering bedding dip angles[J]. Coalgeology&Exploration, 2023(12): 167-175.

[3]. Li Xinping, Zhao Hang, Luo Yi, et al. Experimental study of propagation and attenuation of elastic wave in deep rock mass with joints[J]. Chinese Journal of Rock Mechanics and Engineering, 2015, 34(11): 2319-2326.

[4]. Meng Zhaoping, Li Mingsheng, Lu Pengqing, et al. Temperature and pressure under deep conditions and their influences on mechanical properties of sandstone[J]. Chinese Journal of Rock Mechanics and Engineering, 2006(6): 1177-1181.

[5]. Jiang Junsheng, Cao Ping. Floor heaving mechanism of soft rock in high-stress deep roadway and its control technology[J]. Journal of Central South University (Science and Technology), 2015, 46(11): 4218-4224.
[6]. Liang Yongqing. Research on mechanical properties of sandstone under high temperature effect[J]. Coal Technology, 2016, 35(3): 76-78.
[7]. Fan Qixiang, Lin Peng, Jiang Shu, et al. Review on the rock mechanics and engineering practice for large hydropower stations along the downstream section of the Jinsha River[J]. Journal of Tsinghua University(Science and Technology), 2020, 60(7): 537-556.
[8]. Wu Aiqing. Developments of rock mechanics in hydraulic engineering and their applications by yangtze river scientific research institute[J]. Journal of Yangtze River Scientific Research Institute, 2021, 38(10): 104-111.
[9]. Zhang Ying. Sichuan basin red rock permeability and the control of water conservancy engineering[D]. China: Chengdu University of Technology, 2010.
[10]. Zhang Dingli, Tai Qimin, Fang Qian. Safety of complex surrounding rock of tunnels and related evaluation method[J]. Chinese Journal of Rock Mechanics and Engineering, 2017, 36(2): 270-296.
[11]. Zhang Dingli, Chen Liping. Compound structural characteristics and load effect of tunnel surrounding rock[J]. Chinese Journal of Rock Mechanics and Engineering, 2016, 35(3): 456-469.
[12]. Xu Haiqiang. Study on rock mechanics parameters and In-Situ stress in Chang 7 member of Fan xue area in Ordos Basin[D]. China: China University of Geosciences Beijing, 2018.
[13]. Ran Limin. The study of formation stress and its application in the zhujing oil field[D]. China: China University of Geosciences, 2015.
[14]. Gong Jiangfeng, Wang Wei, Wang Fang, et al. Statistics of China's railway tunnels by the end of 2023 and introduction of tunnels for key projects opened in 2023[J]. Tunnel construction, 2024, 44(2): 377-392.
[15]. Oda M, Yamabe T, Kamemura K. A crack tensor and its relation to wave velocity anisotropy in jointed rock masses[J]. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 1986, 23(6): 387-397.
[16]. Bucur V, Rasolofosaon P N J. Dynamic elastic anisotropy and nonlinearity in wood and rock[J]. Ultrasonics, 1998, 36(7): 813-824.
[17]. Puzyrev N N, Obolentseva I R, Trigubov A V, et al. On the anisotropy of sedimentary rocks from shear-wave analysis[J]. Geophysical Journal International, 1984, 76(1): 243-252.
[18]. Wang Hongtu, Xian Xuefu. The study on characteristics of elastic wave propagation in rocks under complicated stress states[J]. Journal of Chongqing University(Science and Technology), 1988(5): 104-112.
[19]. Zhang Xulong, Zhang Sheng, Wang Longfei, et al. Identification of pre-peak characteristic stress of sandstone under triaxial loading based on acoustic emission and wave velocity variation[J]. Chinese Journal of Rock Mechanics and Engineering, 2023, 42(11): 2711-2726.
[20]. Cheng Yun. Experimental research on stress wave propagation characteristics of red sandstone under axial static load[D]. China: Jiangxi University of Science and Technology, 2018.
[21]. Lan Guangyu. Mechanical characteristics of slate and its correlation with ultrasonic velocity[J]. Pearl River, 1997(4): 16-19.
[22]. Li Awei, Zhao Weihua, Li Haohan, et al. A study of elastic properties of shales from sangye 1 well in western hunan province[J]. Acta Geoscientica Sinica, 2016, 37(3): 333-339.
[23]. Zhang Jinhan, Wang Qin. Experimental progress on elastic wave properties of sandstones and shales[J]. Progress in Geophysics, 2024, 39(1): 141-161.
[24]. Zhao Wenrui. Strength properties of anisotropic rock of an argillaceous siltstone[J]. Chinese Journal of Geotechnical Engineering, 1984(1): 32-37.
[25]. Gao Chunyu, Xu Jin, and Li Zhonghong, et al. Experimental study of anisotropically mechanical characteristics of sandy slate in Xuefeng mountain tunnel[J]. Rock and Soil Mechanics, 2011, 32(5): 1360-1364.
[26]. Zhang L, Niu F, Liu M, et al. Fracture characteristics and anisotropic strength criterion of bedded sandstone[J]. Frontiers in Earth Science, 2022, 10: 879332.
[27]. Cheng Yun, Song Zhanping, Xu Zhiwei, et al. Failure mechanism and infrared radiation characteristic of hard siltstone induced by stratification effect[J]. Journal of Mountain Science, 2024, 21(3).
[28]. Hao Ruiqing, Zhou Yuguo, Gao Xinyue, et al. Study on the influence of bedding angle on the mechanical properties and fracture failure behavior of sandstone[J]. Mining Research and Development, 2024, 44(2): 103-109.
[29]. Chen Tianyu, Feng Xiating, Zhang Xiwei, et al. Experimental study on mechanical and anisotropic properties of black shale[J]. Chinese Journal of Rock Mechanics and Engineering, 2014, 33(9): 1772-1779.
[30]. Heng S, Li X, Liu X, et al. Experimental study on the mechanical properties of bedding planes in shale[J]. Journal of Natural Gas Science and Engineering, 2020, 76: 103161.
[31]. Wang Y, Li C, Hu Y, et al. Brazilian test for tensile failure of anisotropic shale under different strain rates at quasi-static loading[J]. Energies, 2017, 10(9): 1324.
[32]. Ou X, Zhang X, Feng H, et al. Static and dynamic brazilian tests on layered slate considering the bedding directivity[J]. Advances in Civil Engineering, 2020, 2020(1): 8860558.
[33]. Mao Navy, Yang Chunhe. Study on effects of discontinuities on mechanical characters of slate[J]. Chinese Journal of Rock Mechanics and Engineering, 2005(20).
[34]. Yin T, Chen Y, Li X, et al. Effect of high temperature and strain rate on the elastic modulus of rocks: a review[J]. International Journal of Earth Sciences, 2021, 110(8): 2639-2660.
[35]. Wang Y, Zhao L, Han D hua, et al. Anisotropic dynamic and static mechanical properties of organic-rich shale: The influence of stress[J]. GEOPHYSICS, 2021, 86(2): C51-C63.
[36]. Huang Chun, Zuo Shuangying, Wang Song, et al. Analysis of indoor uniaxial compression test on layered anisotropic rock masses[J]. Journal of Yangtze River Scientific Research Institute, 2016, 33(5): 58-62.
[37]. He Manchao, Li Jieyu, Ren Fuqiang, et al. Experimental investigation on rockburst ejection velocity of unidirectional double-face unloading of sandstone with different bedding angles[J]. Chinese Journal of Rock Mechanics and Engineering, 2021, 40(3): 433-447.
[38]. Deng Huafeng, Wang Wei, Li Jianlin, et al. Experimental study on anisotropic mechanical properties of layered sandstone[J]. Chinese Journal of Rock Mechanics and Engineering, 2018, 37(1): 112-120.
[39]. Wang Congcong, Li Jiangteng, Lin Hang, et al. Anisotropic mechanical characteristics of slate in uniaxial compression[J]. Journal of Central South University(Science and Technology), 2016, 47(11): 3759-3764.
[40]. Ou Xuefeng, Zhang Xuemin, Zhang Cong, et al. Study on bedding effect and damage constitutive model of slate under compressive dynamic loading[J]. Chinese Journal of Rock Mechanics and Engineering, 2019, 38(S2): 3503-3511.

[41]. Gao Chunyu, Xu Jin, Li Zhonghong, et al. Experimental study of anisotropically mechanical characteristics of sandy slate in Xuefeng mountain tunnel[J]. Rock and Soil Mechanics, 2011, 32(5): 1360-1364.
[42]. Hou Zhenkun, Yang Chunhe, and Guo Yintong, et al. Experimental study on anisotropic properties of Longmaxi formation shale under uniaxial compression[J]. Rock and Soil Mechanics, 2015, 36(9): 2541-2550.
[43]. Xie Jingyu, Lu Hongzhi, Chen Lei, et al. Micro scopic heterogeneity and mechanical anisotropy of the laminated shale in Longmaxi Formation[J]. Bulletin of Geological Science and Technology, 2021, 40(3): 67-77.
[44]. Wang Hongjian, Liu Da'an, Huang Zhiquan, et al. Mechanical properties and brittleness evaluation of layered shale rock[J]. Journal of Engineering Geology, 2017, 25(6): 1414-1423.
[45]. Zhang Bohu, Ma Haobin, Tian Xiaopeng, et al. Deep layered shale mechanical parameters anisotropy study[J]. Chinese Journal of Underground Space and Engineering, 2020, 16(S2): 634-638.
[46]. Ren L, Zhu B, Li J, et al. Charge signals characterizing the influence of bedding angles on shale damage under cyclic loading and unloading[J]. International Journal of Rock Mechanics and Mining Sciences, 2025, 186: 106001.
[47]. Huang Yinting, Zuo Shuangying, Zhong Shuai, et al. Analysis on anisotropic tensile parameters and fracture characteristics of limestone with different dip angles[J]. Yangtze River, 2022, 53(7): 174-180.
[48]. Gong F, Yan J, Luo S, et al. Investigation on the Linear Energy Storage and Dissipation Laws of Rock Materials Under Uniaxial Compression[J]. Rock Mechanics and Rock Engineering, 2019, 52(11): 4237-4255.
[49]. Wang Y, Cui F. Energy evolution mechanism in process of Sandstone failure and energy strength criterion[J]. Journal of Applied Geophysics, 2018, 154: 21-28.
[50]. Guo Jiaqi, Liu Xiliang, Qiao Chunsheng. Experimental Study Of Mechanical Properties And Energy Mechanism Of Karst Limestone Under Natural And Saturated States[J]. Chinese Journal of Rock Mechanics and Engineering, 2014, 33(2): 296-308.
[51]. Wang F, Wang H, Xu Y, et al. Analysis of Energy Dissipation Characteristics of Damaged Sandstone under Impact Load[J]. Shock and Vibration, 2021, 2021(1): 4200452.
[52]. Wang Yanbing, Song Jiahui, Fu Dai irui, et al. Energy evolution and damage characteristics of sandstone with different bedding spacing based on NSCB impact test[J]. Journal of Mining & Safety Engineering, 2024, 41(5): 920-933.
[53]. Liu Hui, Yang Gengshe, Shen Yanjun, et al. CT visual quantitative characterization of meso-damage evolution of sandstone under freeze-thaw-loading synergistic effect[J]. Chinese Journal of Rock Mechanics and Engineering, 2023, 42(5): 1136-1149.
[54]. Bai Bin, Zhu Rukai, Wu Songtao, et al. Multi-scale method of Nano(Micro)-CT study on microscopic pore structure of tight sandstone of Yanchang Formation, Ordos Basin[J]. Petroleum Exploration and Development, 2013, 40(3): 329-333.
[55]. Yang Zhenjie, Zhang Lingkai. Experimental study on mechanical characteristics and microscopic mechanism of white sandstone in northern Xinjiang[J]. Advances in Science and Technology of Water Resources, 2024, 44(5): 94-102.
[56]. Li Shucai, Xu Xinji, Liu Zhengyu, et al. Electrical resistivity and acoustic emission response characteristics and damage evolution of sandstone during whole process of uniaxial compression[J]. Chinese Journal of Rock Mechanics and Engineering, 2014, 33(1): 14-23.
[57]. Diao Xinhong, Fu Yu, Hong Peng, et al. Acoustic emission characteristics in the failure process of slate with different bedding structures[J]. Journal of Kunming University of Science and Technology(Natural Science), 2020, 45(5): 116-123.
[58]. Sun Bo, Ren Fuqiang, Liu Dongqiao. Research on the failure precursors of layered slate based on multifractal characteristics of acoustic emission[J]. Rock and Soil Mechanics, 2022, 43(3): 749-760.
[59]. Dong Zhuo, Lin Natural. Numerical study on the effects of bedding inclinationangle and hole diameter on uniaxial failure characteristics of shale[J]. Journal of Engineering Geology, 2024, 32(4): 1249-1261.
[60]. Zhang Zhen, Cui Shuai, Liu Huize, et al. Expansion characteristics of the hard shale crack based on AE[J]. Special Oil & Gas Reservoirs, 2024: 1-11.
[61]. Wang Xiaoran, Wang Enyuan, Liu Xiaofei, et al. Macro-crack propagation process and corresponding AE behaviors of fractured sandstone under different loading rates[J]. Chinese Journal of Rock Mechanics and Engineering, 2018, 37(6): 1446-1458.
[62]. Li Bo, Ye Pengjin, Huang Lin, et al. Deformation and acoustic emission characteristics of dry and saturated rock fractures[J]. Chinese Journal of Geotechnical Engineering, 2021, 43(12): 2249-2257.
[63]. Niandou H, Shao J F, Henry J P, et al. Laboratory investigation of the mechanical behaviour of Tournemire shale[J]. International Journal of Rock Mechanics and Mining Sciences, 1997, 34(1): 3-16.
[64]. Hou P, Gao F, Yang Y, et al. Effect of the layer orientation on mechanics and energy evolution characteristics of shales under uniaxial loading[J]. International Journal of Mining Science and Technology, 2016, 26(5): 857-862.
[65]. Gao Min. Study On Mechanical Failure Characteristics And Constitutive Model Of Layered Rocks," Dalian University of Technology[D]. China: Dalian University of Technology , 2022.
[66]. Zhao Ningning, Li Erqiang, Feng Jili. Experimental and numerical investigation on uniaxial compression test of layered slate[J]. Journal of Central South University(Science and Technology), 2022, 53(10): 3978-3988.