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石窟寺岩体劣化研究进展:机制、试验、数值模拟与防护

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摘要:作为中国历史文化遗产的重要组成部分,石窟寺在保护与传承上面临严峻挑战,这些挑战主要源于岩体的劣化。全面分析石窟岩体劣化的相关研究,涵盖劣化机制、试验研究、数值模拟及保护策略等方面。首先,从岩性、区域构造活动和原生结构等内部因素以及物理、化学和生物劣化机制等外部因素出发,详细阐述劣化机理;随后,介绍室内模拟试验、现场监测试验等研究方法;最后,提出石窟寺保护策略,包括实时监测、纳米材料涂层和生物膜等防护材料的应用,以及温湿度控制。尽管岩体保护工作近年来已有一定进展,但在多因素耦合机制及防护材料长期有效性等方面仍存在不足。因此,有必要加强跨学科融合研究,例如:将实验室模拟、现场监测和数值建模相结合;开发新型技术,如环保防护材料或先进的实时监测系统,以改善石窟遗产的保护工作。

关键词:石窟岩体;劣化机制;试验研究;数值模拟;保护策略

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Deterioration of grotto temple rock masses: A review of mechanisms, experimentations, modeling and conservation measures

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Abstract: Grottoes, as an important part of China's historical and cultural heritage, are confronted with great challenges in cultural preservation and inheritance primarily due to the degradation of the grotto rock masses. This study comprehensively analyzed relevant research on such deterioration, with the review focusing on

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deterioration mechanisms, experimentations, numerical simulations, and protection strategies. On the basis of previous studies, the current paper expounds on the mechanisms by which rock masses deteriorate, from internal factors, namely lithology, regional tectonic activities, and primary structures, to external factors, including physical, chemical, and biological mechanisms. It then introduces the experimental research methods that have been adopted, such as laboratory simulation testing and field monitoring, along with a discussion of progress in numerical simulation. Finally, previously proposed protection strategies are presented, covering real-time monitoring, the application of protective materials such as nanomaterial layers and biofilms, and temperature-humidity control. Although certain progress has been made in the protection of rock masses in recent years, deficiencies remain in terms of analyses regarding how multiple factors exert combined effects and the long-term effectiveness of protective materials. It is therefore necessary to strengthen interdisciplinary integration research, for example, combining laboratory simulations, field monitoring, and numerical modeling, and to develop novel techniques such as environmentally friendly protective materials or advanced real-time monitoring systems to improve the preservation of grotto heritage.

Keywords: grotto rock mass; deterioration mechanism; experimental research; numerical simulation; protection strategy

1 Introduction

Grottoes, as crucial structures embedded in the rich tapestry of China's historical and cultural heritage, hold irreplaceable significance in the continuum of cultural inheritance and the trajectory of artistic evolution^[1]. They serve as solid foundations for the dissemination of culture, playing a pivotal role in safeguarding and promoting the nation's cultural legacy. They also represent the gems of ancient Chinese Buddhist art, epitomizing the quintessence of traditional Chinese sculpture, painting, and architecture, apart from functioning as an essential gateway to exploring the developmental progression of ancient Chinese art^[2]. Grotto buildings themselves are a unique cultural assets that embody the core of ancient Chinese architectural technologies and aesthetic principles, making them critical to the study of Chinese traditional architectural culture^[3]. However, these structures are likewise home to cultural artifacts, such as murals and statues, that are invaluable historical records^[4], thereby documenting diverse dimensions, including religious beliefs, social life, politics, and the economy of a given era^[5-7]. These artifacts are instrumental in deciphering the progress of ancient Chinese civilization.

Currently, the grottoes in China are confronted with the problem of rock mass degradation, which poses a serious threat to cultural preservation and inheritance for these sites. Such deterioration is influ-

enced primarily by natural environmental factors, including weathering, water erosion, and temperature variations, which can cause structural damage in rock and affect the overall stability of grottoes^[8-10]. Human activities, such as tourist trampling and poor management can also accelerate the disintegration of rock masses constituting the aforementioned structures^[11-12].

This problem highlights the essentiality of carrying out research on the mechanisms by which the rock masses that make up grottoes deteriorate and exploring effective measures for protecting these precious cultural heritages. These initiatives entail (1) systematically analyzing the causes and processes of rock mass deterioration to provide a scientific basis for formulating targeted preservation strategies, (2) developing advanced detection technologies to monitor changes in the state of rock masses in real time and inform timely repair measures, and (3) investigating repair materials and technologies suitable for grotto environments to enhance the appropriateness and effectiveness of repairs. Accordingly, the current research comprehensively reviewed the achievements of previous studies on rock mass deterioration, with a focus on experimental and numerical simulation studies as well as analyses of deterioration mechanisms. The aim was to formulate exhaustive strategies for safeguarding the rock masses in grottoes. The technical flowchart guiding this exploration is shown in Fig. 1.

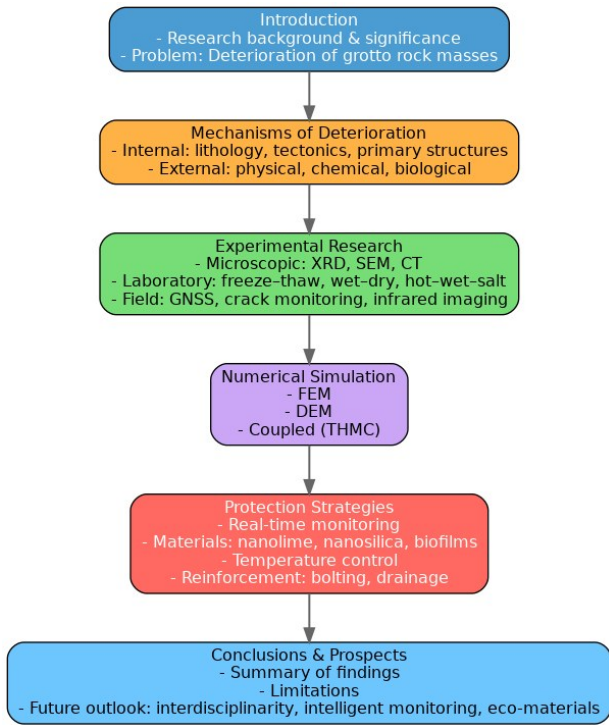


Fig. 1 Technical flowchart of this study

2 Main mechanisms of grotto rock mass deterioration

The exposure of grottoes to external natural

conditions over a prolonged period eases the expansion, interconnection, and convergence of small cracks in the rock masses that compose these structures, resulting in the gradual accumulation of damage^[13-14]. Once this damage reaches a certain threshold, rock mass becomes fractured and unstable, causing precarious situations, such as collapse, toppling, and sliding, thereby putting the long-term preservation of rock monuments such as grottoes at a severe risk. To better protect these architectural forms, an urgent requirement is to explore the mechanisms by which grotto rock masses degrade.

A systematic review of existing research showed multiple causes of the deterioration of rock materials, which encompass both internal and external factors. Internal triggers include lithology and regional tectonic activities, while external causes involve climate, human activities, and the hydrological environment^[15-21]. Fig. 2 presents a VOSviewer diagram of rock mass deterioration in grottoes.

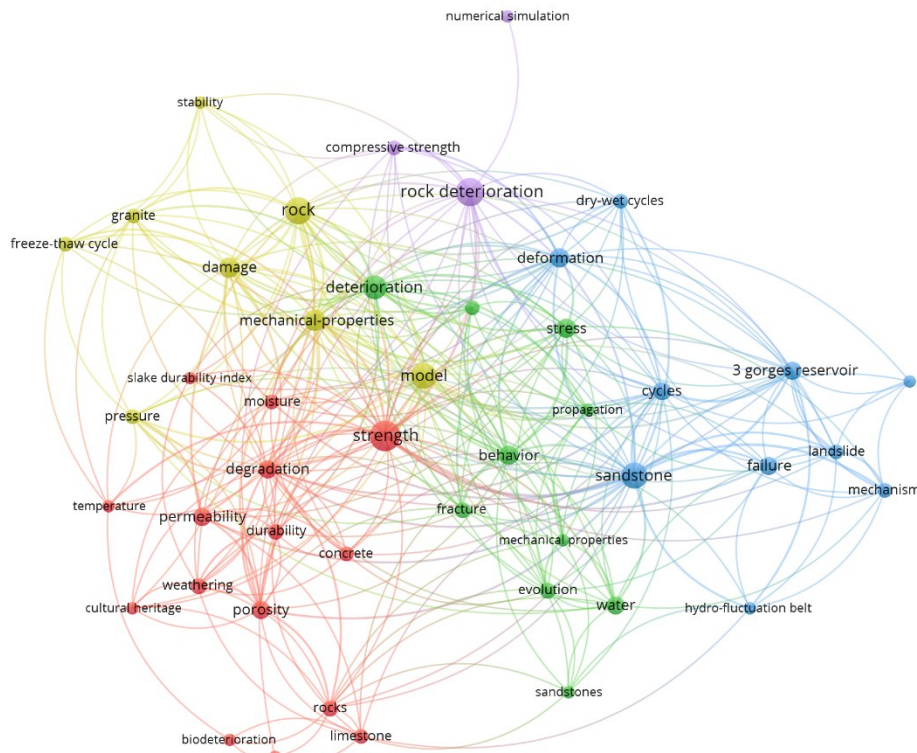


Fig. 2 VOSviewer plots of grotto rock deterioration

As illustrated in the color clustering in the figure, different color regions represent the various directions pursued in exploring the issues of interest. The red cluster revolves around keywords such as “strength” “porosity” and “permeability” indicating that this direction is closely related to the study of changes in physical properties as rock masses deteriorate. The yellow cluster features keywords such as “granite” and “rock” which point to deterioration research on specific rock types. The green regions concentrate on “stress” “model” and “evolution” representing studies on the mechanical mechanisms and simulations of rock mass degradation. The blue areas are associated with the “Three Gorges Reservoir” and “landslide” which concern explorations of rock mass deterioration in specific geographical environments and amid geological disasters. The keywords are connected to each other through lines: The thicker the lines, the higher the frequency of co-occurrence between keywords and the closer their connection. The overall picture reflects that investigations of rock mass degradation are intertwined and mutually influencing endeavors in many respects. The succeeding sections provide a more in-depth explanation of the internal and external deterioration mechanisms explored in previous research.

2.1 Internal causes of rock mass deterioration

2.1.1 Lithology

Shi et al.^[22] identified lithological characteristics as internal causes of various types of damage of grotto rock masses. Different rocks have varying characteristics, so discussing the deterioration of rock masses first requires the clarification of the type of rock involved in degradation. In China, grottoes are made of sandstone (80%), conglomerate, limestone, crystalline rock, mudstone, and marble. Among these, sandstone has low mechanical strength, high porosity, and considerable water permeability, rendering it highly susceptible to weathering and deterioration^[23]. Grottoes made of conglomerate exhibit good rock integrity but are relatively loose, leading to poor lithification and severe weathering^[24]. Limestone and mudstone grottoes have relatively strong resistance against weathering, but the surfaces of the former are easily dissolved in an acidic environment^[25], while the latter are considerably porous and have a substan-

tial capacity for water absorption, making them vulnerable to damage under wet-dry and freeze-thaw cycles^[26]. Grottoes composed of crystalline rock exhibit reasonably high mechanical strength. Note that the resistance of a given type of rock to damage may vary due to differences in diagenetic conditions. Therefore, the influence of these conditions on rock mass deterioration warrant further discussion.

Diagenetic conditions drive cementation, which is essential in the transformation of sediments into sedimentary rocks^[27]. Common types of cement include calcareous (e. g. , calcite), siliceous (e. g. , quartz), ferruginous (e. g. , iron oxides), and clayey (e. g. , kaolinite) cement. For grottoes made primarily of calcareous cement, the acidic substances that accumulate during the dry deposition of dust and harmful gases can dissolve the cement, resulting in the weathering of the rock surface and a decline in strength^[28]. Siliceous cement is an authigenic mineral commonly found in clastic rock reservoirs and is a key determinant of reservoir properties^[29-31]. Ferruginous cement refers to the material formed by iron oxides or hydroxides in sedimentary rocks, especially in sandstone. Finally, clayey cement is formed by clay minerals (kaolinite, illite, chlorite, etc.) and binds loose sediment particles together in sedimentary rocks, thus increasing the hardness of such materials.

Diagenetic conditions are also significantly influenced by microscopic pore structure. Research indicates that considerably porous rocks are typically highly absorptive of water. These materials contain unconnected pore channels, which can prolong water retention, thereby promoting physical and chemical interactions between rocks and water—effects that may diminish rock strength and subsequently weaken weathering resistance^[32-34].

Another diagenetic factor is the mineral composition of rocks, which significantly affects the damage sustained by grottoes. Cullers et al.^[35] conducted a series of experiments on three groups of sandstones collected from the same area. The results showed that the sandstone with a high concentration of alkali feldspar is strongly resistant to weathering, indicating that mineral components considerably influence the durability of rocks. Sandstone, however, has mineral components that are sensitive to chemical re-

actions in an acidic environment. This assertion is supported by the work of Geng et al.^[36], who studied the influence of an acidic environment on the Yungang Grotto sandstone. They found that sulfuric acid and nitric acid react with feldspar and calcium carbonate in sandstone cement, destroying the pores and internal structure of the sandstone. To these insights, Wang et al.^[37] added that the different minerals in rocks have various thermal expansion coefficients, which causes rock masses to undergo heterogeneous weathering under long-term thermal cycles.

2.1.2 Regional tectonic activities

Grottoes in different regions significantly differ because of the distinct tectonic activities to which they are subjected. In regions affected by intense tectonic events, such as northwestern China, the rock masses constituting grottoes may develop deformations that include tilting, bending, and fracturing. The ground vibrations caused by earthquakes can lead to the cracking, collapse, and even the destruction of the overall structure of rock masses. Take the Mogao Grottoes as an example; these structures are most at risk at the onset of an earthquake, sustaining mainly shear failure toward the free surface^[38]. Regional tectonic activities can also affect the path by which groundwater flows, facilitating water-rock interactions and exerting a wide-ranging and serious impact on cultural structures such as grottoes. Investigations have shown that nearly 70% of the grottoes in China are distributed across earthquake-prone areas^[39].

2.1.3 Primary structures

The primary structures in rock masses are formed during rock formation, and the integrity of the masses that they constitute is tremendously affected by weak intercalated layers, bedding planes, and structural planes.

Weak intercalated layers are characterized by low strength and high compressibility, rendering them vulnerable zones in a rock mass (Fig. 3(a)). Under internal and external forces, they tend to cause differential weathering in a rock mass and form rock cavities. Weak intercalated layers also significantly increase the heterogeneity and anisotropy of a rock mass, directly affecting the mechanical behavior and stability of the geological formation and causing its

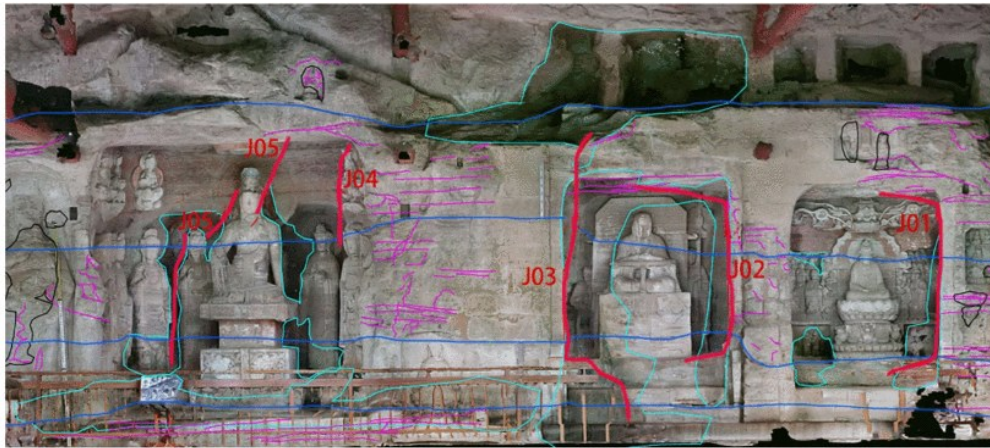
deterioration^[40]. Such layers are commonly complex and highly dispersed systems composed of multiple mineral components with varying contents, of which the main clay minerals are montmorillonite, illite, and kaolinite^[41]. Since minerals have different physical and chemical properties, they exert varying effects on the strength of intercalated layers. Under specific conditions, weak intercalated layers may gradually crack due to weathering. Their light weight also means that there is relatively minimal friction between them and surrounding rocks, making for poor stability. Amid rainwater erosion or wind force, these intercalated layers may be dislodged from the parent rock and scatter to the bottom of a slope. Although this kind of rock collapse is typically small in scale, it is enough to trigger the peeling of a rock mass surface^[42].

Bedding planes are the surfaces between layers in sedimentary rocks, marking the boundaries between layers with different sedimentary components and sedimentary histories (Fig. 3(b)). These planes, which strongly affect the fracture behavior of layered rocks, have a strength normally lower than that of the rock matrix^[43]. Research has shown that the existence of bedding planes enhances rock heterogeneity, resulting in differences in the strengths and elastic moduli of rocks oriented in different directions^[44]. For instances, Meng et al.^[45] conducted three-point bending tests on semicircular bending rock specimens and found that the angle of the bedding plane significantly affects the fracture toughness. With increasing bedding plane angle, the stress intensity factors for mode I (opening mode) and mode II (sliding mode), as well as the effective fracture toughness of the rock specimens, decrease. The existence of weak bedding planes can also help aqueous solutions to more smoothly penetrate a rock mass, accelerating the weathering of carbonate cement in the rock formation^[46].

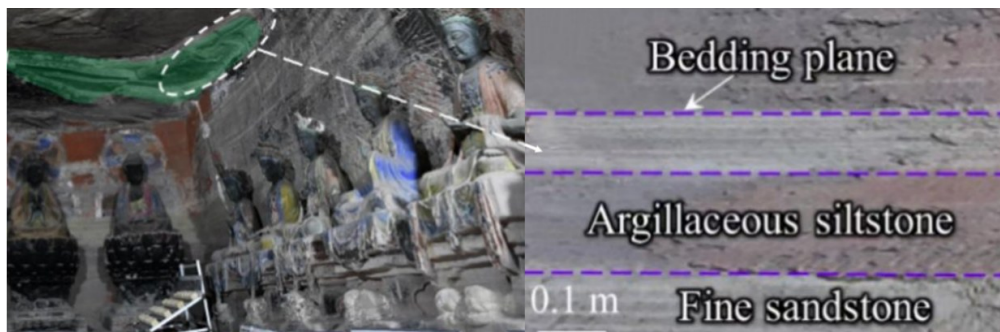
When subjected to external forces, a rock mass typically deforms and fails along its structural planes first (Fig. 3(c)). Structural planes include joints, faults, and interlayer shear zones. Their existence destroys the continuity of a rock mass, thus affecting its stability and integrity and easily inducing rock mass failures, such as collapse, sliding, and falling

blocks^[47-48]. Structural planes also induce stress concentration at these weak points. Especially when rock is under stress, it first develops a crack at the weakest structural plane, which then amplifies stress concentration. In their study on the rock masses in

the Mogao Grottoes cliff, Guo et al.^[49] found that structural planes can serve as channels for rainwater to penetrate into the cliff, which in turn accelerates the weathering of the rock formations.



(a) Weak intercalated layers^[50]



(b) bedding planes in a grotto cave^[51]



(c) structural planes (source: Dazu Rock Carvings Research Institute)

Fig. 3 Primary structures that have a relatively great impact on rock mass deterioration

2.2 External factors of rock mass deterioration

2.2.1 Physical deterioration mechanisms

The physical deterioration of the rock masses in grottoes is caused mainly by freeze-thaw cycles, wet-

dry cycles, thermal-humid cycles, and salt crystallization weathering (Fig. 4), but the primary triggers of physical weathering are the first two processes.

A freeze-thaw cycle refers to the process in

which substances repeatedly transform between solid and liquid states due to periodic changes in environmental temperature. The damage that it causes in rocks stems principally from the repeated generation and dissipation of the frost heaving force^[52]. Liu et al.^[53] studied the influence of freeze-thaw cycles on the deterioration of sandstone in the Yungang Grottoes and found that the water content of the rock as well as the frequency of freezing and thawing affect the degree of deterioration caused by freeze-thaw cycles. The larger the initial porosity of the rock, the greater

the saturated water content, resulting in a larger tensile stress generated by the volume expansion during changes in the water-ice phase in the pore walls. Conversely, the more frequent the freeze-thaw cycles, the greater the number of generation-dissipation sequences involving the frost heaving force; cracks in a rock mass also deepen and expand, eventually disintegrating the rock into fragments. Bellanger et al.^[54] discovered that the frost resistance of limestone depends on its ability to withstand the damage caused by the freezing of water in microscopic pores.



(a) A freeze-thaw cycle causes peeling in rock paintings^[55]



(b) A wet-dry cycle leads to the peeling of mural paintings^[56]



(c) Rock pillars exposed to the water-rock cycle^[57]



(d) Salt crystallization weathering^[58]

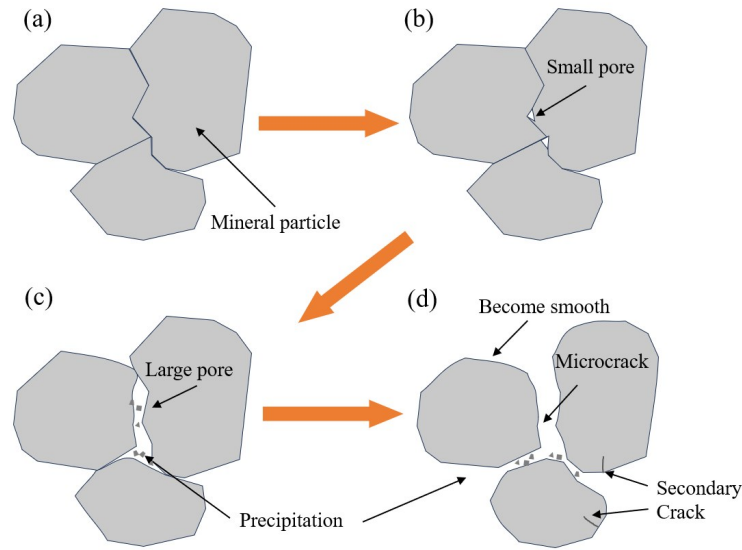
Fig. 4 Causes of rock deterioration

A wet-dry cycle is a natural environmental process recognized as a rock weathering process^[59]. Owing to fluctuations in climatic conditions, rock masses are repeatedly subjected to alternating phases of drying and wetting. When Li et al.^[60] conducted wet-dry cycle tests on sandstone, they found that the strength and deformation properties of the rock decreased with the increasing frequency of wetting and drying. Similarly, Li et al.^[61] discovered that as the number of wet-dry cycles increase, the porosity of sandstone rises, thus diminishing the mechanical strength of the rock. A microstructural analysis conducted by Zhang et al.^[62] illustrated the process by which rock microstructures develop after cyclic drying and wetting (Fig. 5), while the investigation carried out by Guo

et al.^[63] demonstrated that the cycle can cause the cyclic expansion and contraction of hydrophilic clay minerals in rock. During the repeated expansion process, the original structure of rock is damaged, reducing its tensile strength.

Note that the extent of the impact of freeze-thaw and wet-dry cycles on rock masses depends, to a certain extent, on the characteristics of the masses themselves. Considering that most grotto rock masses are sandstone, researchers compared such effects on the deterioration of this material. Khanlari et al.^[64] conducted 30 freeze-thaw cycle tests and 40 wet-dry cycle tests on the same type of sandstone. The saturated uniaxial compressive strength (UCS) and strength degradation rate (SDR) of the sandstone samples are

shown in Table 1 and Fig. 6.



Note: (a) no cycle, (b) 1-10 cycles, (c) 10-30 cycles, (d) >30 cycles (adapted from Zhang et al.^[62]).

Fig. 5 Microstructure development after different wet-dry cycles

Table 1 (a) Freeze-thaw cycle test (adapted from Khanlari et al.^[64])

Rock type	UCS untreated	UCS 5	UCS 10	UCS 15	UCS20	UCS25	UCS30	SDR
Sandstonetype 1	126.80	119.00	101.79	87.20	93.05	84.71	65.18	0.49
Sandstonetype 2	94.69	90.23	60.07	60.42	58.45	52.21	39.97	0.58
Sandstonetype 3	46.31	45.57	47.92	39.65	34.64	35.02	27.55	0.41
Sandstonetype 4	19.94	20.07	19.50	18.63	18.37	14.98	10.66	0.47
Sandstonetype 5	69.82	60.05	46.75	42.27	37.79	31.02	10.52	0.85

Note: The SDR is calculated as follows: $SDR = 1 - \frac{UCS_c}{UCS_u}$.

Table 1 (b) Wet-dry cycle test (adapted from Khanlari et al.^[64])

Rock type	UCS untreated	UCS 10	UCS 20	UCS 30	UCS 40	SDR
Sandstonetype 1	126.8	116.56	96.11	110.71	100.38	0.21
Sandstonetype 2	94.69	77.93	85.93	80.61	75.97	0.20
Sandstonetype 3	46.31	40.91	35.12	43.48	38.39	0.17
Sandstonetype 4	19.94	18.92	18.41	20.35	17.71	0.11
Sandstonetype 5	69.82	57.34	64.58	63.09	56.34	0.19

Take the case of the UCS of Sandstone type 5 after 30 freeze-thaw cycles and 30 wet-dry cycles. The SDR of the material under the freeze-thaw cycles is 0.85, while that under the wet-dry cycles is 0.1, indicating that a freeze-thaw cycle has a greater impact on the UCS of sandstone. Freeze-thaw and wet-dry cycles, similar to the water-rock cycle, involve the interaction between water and rock, but the water-rock cycle is essentially driven by the chemical activity of water. It involves the infiltration of water into rock, the dissolution and precipitation of minerals in the rock, hydration, and possible chemical reactions, which can affect the rock's mechanical

strength.

To explore the degradation of rock's mechanical properties owing to the water-rock cycle, Zhang et al.^[65] conducted a series of experiments on sandstone and granite. Under the aforementioned cycle, the UCSs and elastic moduli of both rocks gradually decrease, while the Poisson's ratio increases. In their examination of the loss of UCS in 35 types of British sandstone in dry and saturated states, Hawkins, et al.^[66] found that every 1% increase in the water content of sandstone from the dry state exerts a significant impact on its strength and deformation ability. Sun et al.^[67] showed that after subcrit-

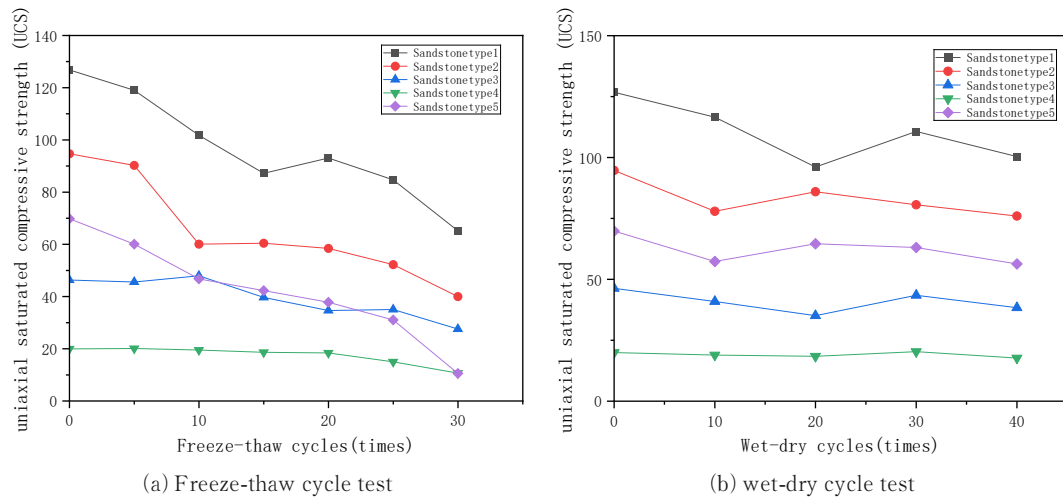


Fig. 6 Curves depicting the influence of the number of freeze-thaw cycles and the number of wet-dry cycles on the UCSs of different Sandstone types (adapted from Khanlari et al.^[64])

ical water-rock interaction, the main pores of granite transition from mesopores to macropores. With rising temperature, some minerals on the surface of granite are dislodged, and traces of dissolution and oxidation become increasingly common, causing a certain degree of damage to a rock mass.

Another important cause of the water-rock cycle is rainfall. During rainfall, a rock mass significantly softens, and expanding tensile cracks appeared on the surface of the formation, as reported by Nian et al.^[68]. These cracks subsequently extend into the joint and fracture systems within the rock mass, creating the main flow channels for rainwater infiltration. Liu^[34] pointed out that when the hydrodynamic pressure generated by water flow in fractures exceeds initiation strength, the original fractures and pores expand and penetrate to form new macroscopic ruptures, further degrading a rock mass.

A thermal-humid cycle is the process in which a rock mass undergoes periodic alternations between heat and humidity in an extremely hot and humid environment. In many grottoes in China, rock mass structures that constitute murals and Buddha statues have rich structural layers with different thermal and moisture expansion characteristics. In an environment with substantial differences in humidity and temperature changes, problems such as detachment and cracking in rock masses may occur^[69]. The thermal-humid cycle is a coupled effect of humidity and temperature, so changes in the latter alone bring forth some damage to a rock mass. Smith et al.^[70]

found considerable temperature and stress differences between the surfaces and internal regions of exposed rocks. These differences drive the thermal expansion of various substances in rock masses, thus causing deterioration.

Researchers have conducted various experiments to reveal the mechanism of salt-induced weathering in rock masses. Rothert, et al.^[71] proposed that the degree of salt crystallization weathering depends on the type of salt in a rock mass, the salt concentration in the formation, and the characteristics of pore spaces in such mass. Fang et al.^[72] found that the crystallization expansion of soluble salts under temperature changes and wet-dry cycles promotes the weathering of rock masses. Additionally, Lin et al.^[73] discovered significant differences in the extent of degradation that various salt solutions cause in sandstone samples. Sodium sulfate solution engenders the most pronounced degradation, while sodium carbonate solution exerts the mildest erosion effect.

The findings discussed above indicate the need to implement prevention and control measures on the basis of dominant degradation mechanisms to protect the rock masses constituting grottoes in different climatic zones.

2.2.2 Chemical deterioration mechanisms

The chemical deterioration of grotto rock masses is influenced mainly by chemical reactions, such as weathering via acid rain and salt minerals. Acid rain is produced when sulfur dioxide dissolves in water, which then intensifies damage to both the macro-

scopic and microscopic properties of materials such as sandstone. Notably, the extent of this damage is directly proportional to the solution acidity^[74]. Scanning electron microscopy (SEM) and X-ray diffraction analysis have shown that sulfuric acid can react with rock minerals, especially calcium carbonate and feldspar, among other constituents. This reaction triggers the dissolution of primary minerals and the phase transformation of secondary minerals, thereby causing severe damage to the internal structure of a rock mass^[75].

Research on the damage caused by salt-containing minerals to rock masses has found that the soluble salt content in weathered sandstone samples is

higher than that in core samples, apart from the increase in the concentrations of calcite and clay minerals^[72]. These effects reflect that minerals composed of salt affect the strength of rock masses. Oguchi^[76] mentioned that salts may undergo chemical changes after absorbing water. When anhydrite absorbs water and transforms into gypsum, its volume increases by approximately 7%—a chemical alteration that generates volume changes that affect the stability of rock. Lin et al.^[73] reported that the degree of influence of salt solution types on rock deterioration follows a descending order as follows: sodium sulfate, magnesium sulfate, and sodium carbonate (Fig. 7).

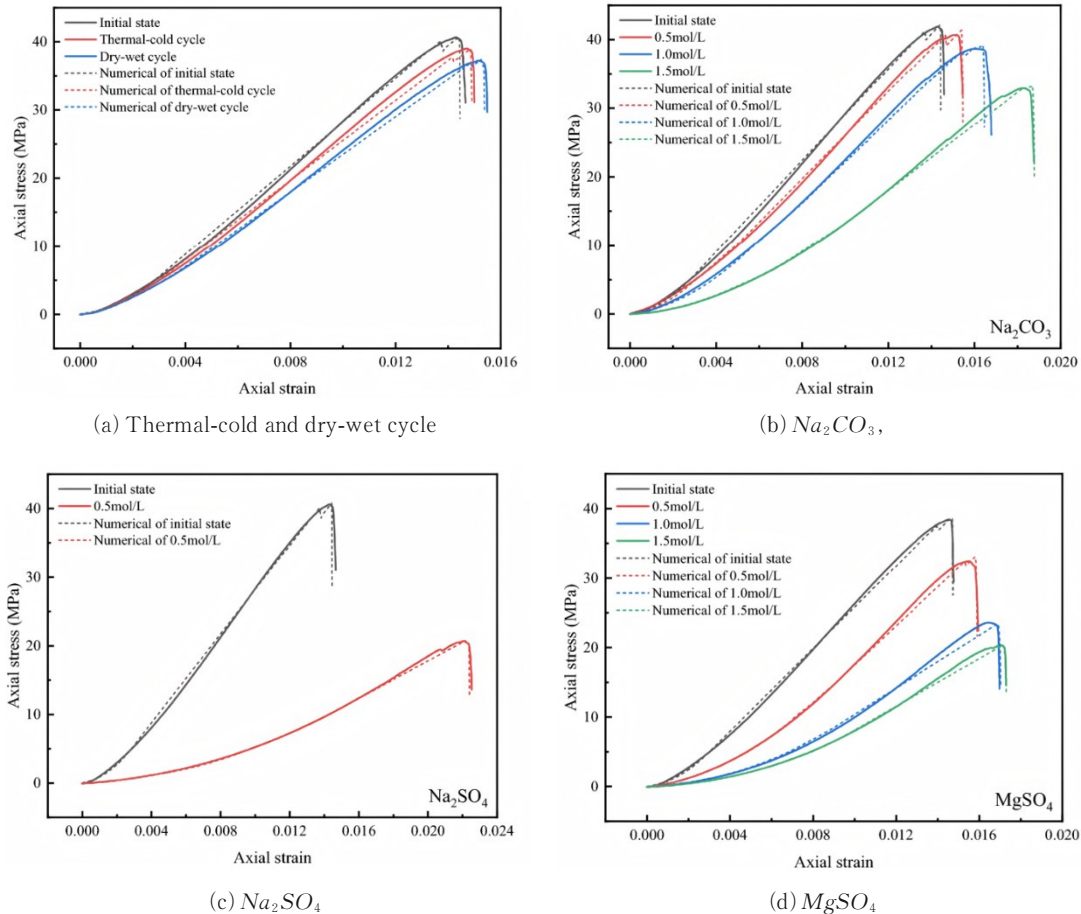


Fig. 7 Stress-strain curve. (adapted from Lin et al.^[73]).

2.2.3 Biological Deterioration Mechanisms

Biological weathering is an important process in the natural decomposition of rocks^[77-78]. It arises from the combined action of plants, animals, and microorganisms, which induces physical and chemical damage to a rock structure. Given the natural environment where rock-mass grottoes are located, biological encroachment is inevitable. This section explores

how these biological factors lead to the deterioration of the aforementioned structures.

In the past, researchers believed that plant roots could widen cracks in rock and damage a rock mass, thus engendering physical weathering in such formations^[79]. However, more recent work, such as the wood anatomical analysis conducted by Malik et al., have negated the notion that rock cracks expand due

to pressure from the growth of plant roots^[80]. This expansion may therefore be related to the chemical properties of plant roots. Research has established that the increased concentration of active substances, such as organic and inorganic acids, can accelerate the chemical weathering of rocks^[81]. Plants absorb organic substances through their roots, increasing the concentration of these acidic substances and thus accelerating rock weathering^[82]. In particular, carbonate rocks, including limestone, are vulnerable to chemical erosion by acidic substances.

In contrast, biological hyphae can penetrate into a rock mass's interior, which is beyond the reach of

plant roots, causing physical damage to the formation^[83]. They not only infiltrate microscopic pores and the mineral particles of rock cultural artifacts but also grow and expand along existing microscopic pores and fissures, culminating in the fragmentation of rock's surface layer and the detachment of mineral particles^[84]. Wang et al. observed a hyphae-rock composite via SEM and found that the hyphae and rock particles are tightly adhered together, facilitating the development of fissures (Fig. 8)^[85]. At the same time, the hyphae produces acidic substances that precipitate severe erosion in limestone and dolomite^[86].

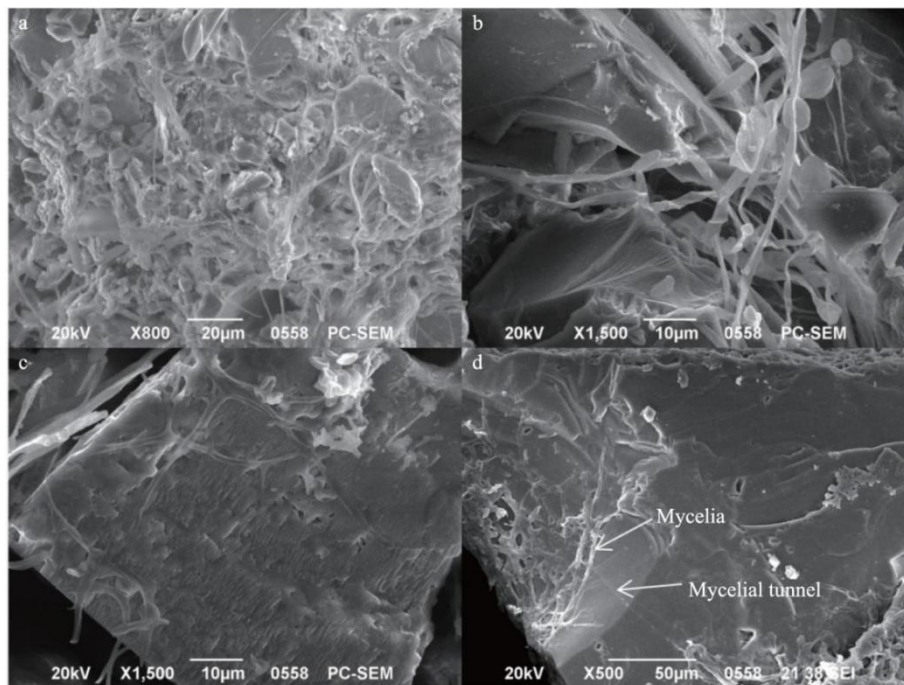


Fig. 8 Inner SEM image of mycelia-rock polymer^[85].

3 Progress in experimental research

In probing the deterioration of grottoes composed of rock masses, researchers have employed multiple experimental methods, including laboratory simulation and on-site monitoring tests.

3.1 Microscopic testing

Detection tests are necessary before laboratory simulation and on-site monitoring experiments are conducted. Several commonly performed detection experiments and the principles underlying their use are presented in Table 2.

3.2 Laboratory simulation tests

Explorations into the deterioration of rock masses in grottoes must not change the significant

cultural and historical value of these sites, thereby necessitating lab simulation tests. A number of common tests used are listed in Table 3.

Studies have illustrated the advantages of lab simulations of rock mass deterioration. A case in point is the work of Lin et al.^[73], who designed complex dry-wet cycle experiments to carry out a cross-scale quantitative analysis of rock deterioration, clarifying the mechanisms by which different salt solutions cause the aging and degradation of sandstone. A flowchart of the core experimental equipment and procedures used in transscale experimental methods is shown in Fig. 9. Yang et al.^[57] developed an intelligent gaseous water adsorption testing system to determine the impact of water-rock interactions on rock

Table 2 Common detection methods, principles, and applications

Experimental technique	Principle	Application examples	References
XRD	XRD uses X-ray substance interaction diffraction. Measuring patterns yields information in materials' microstructures.	Researchers often analyze the mineral content of X-ray diffraction samples both qualitatively and quantitatively.	[57, 87-88]
SEM	It uses a high-energy electron beam to scan a sample surface. By detecting interaction signals, it generates surface microstructure images.	It helps researchers observe microstructural changes, such as crack formation/expansion and mineral grain damage during rock mass deterioration.	[89-90]
IRT	It is a nondirect, nondestructive rock mass testing method.	Han et al. used this technology to obtain the thermal emissivity and crack parameters of rock masses.	[91-92]
MIP	It forces liquid mercury into pores to determine pore distribution and structure.	Zhang et al. used this method to measure the pores of the sandstone in the Nankan Grottoes.	[87]
Hyperspectral imaging	It is a technology for determining object-surface chemical reaction. It simulates human vision, offers spectral information by processing mineral-band reflectance.	Yang et al. used this technology to study reservoir bank weathering, distinguishing degrees by mineral reflectance. On the basis of this technology, Chen et al. quantified rock carving impacts.	[93-96]
CT	It uses X-rays to perform tomographic scanning of rock masses, after which tomographic images are reconstructed using a computer.	Wang et al. used a micro CT scanning system to scan and reconstruct fractured sandstone samples after loading.	[97-98]
EQ	It detects rock surface hardness using a probe.	Mammoliti et al. used this method to assess the weathering of sandstone monuments.	[99]

Table 3 Common laboratory simulation tests

Test	Treatment	References
Freeze-thaw cycle test	One 10-hour freeze-thaw cycle has four stages: cooling, freezing, heating, and thawing—at -20°C and 20°C for freezing and thawing, respectively.	[100-102]
Wet-dry cycle test	In each cycle, samples are fully immersed in water and left for 48 h. Then, they are air-dried naturally in a 26°C windless chamber for over 7 days until mass stabilized.	[103]
Hot-wet-salt cycle test	Using mirabilite (the main salt in Dazu Rock Carvings), researchers observed moisture changes and Na ₂ SO ₄ phase shifts in sandstone, after which the resultant damage was analyzed.	[104]

strength and bearing capacity. This system can simulate water absorption in rocks during rainfall, serving as reference for long-term evaluations of the strength of columnar rock masses. Çelik et al.^[105] performed salt spray and salt crystallization tests to assess the resistance of Döğler tuff against salt damage. Salt spray tests can simulate the impact of salts in the natural environment on building materials and accelerate the testing process, while salt crystallization tests enable the direct assessment of the destructive effects of salt crystallization on building materials, especially the performance differences occurring upon exposure to various salt solutions.

3.3 In situ field testing

For the parts of rock masses with relatively good integrity, in situ field tests are a feasible research method. Since the deformation of rock masses occurs gradually over time, one of the most effective means by which to study such degradation is to direct-

ly obtain instantaneous deformation data on rock masses in situ to analyze the overall change patterns and deformation characteristics of rock masses. Some in situ field detection tests applicable to grottoes are shown in Table 4.

There are also some in situ field tests for rock masses that are not found in grottoes. Although these tests have not been directly applied to grotto rock masses, they may be used for the protection of such formations in the future after methodological improvements and adaptations to the specific environmental and structural conditions of grottoes. For example, when Huang et al.^[112] analyzed the deterioration of typical rock masses in the Wu Gorge of the Three Gorges Reservoir, the most direct way to acquire data was to measure the total area occupied by bedding planes, joints, fractures, pores, and cavities in the observation planes of representative rock masses at different times. After that, relevant formulas

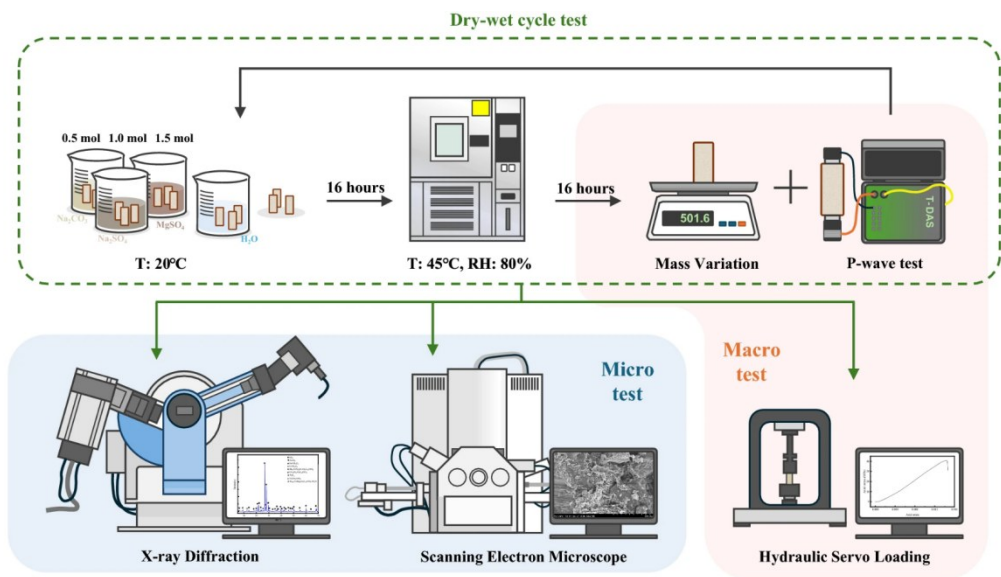


Fig. 9 Flowchart and main equipment used in transscale experimental methods^[73]

Table 4 In situ field detection tests

Method	Monitoring method	Monitoring details	References
Global navigation satellite system (GNSS)	GNSS	Long-term monitoring of geological body deformation and comparison of differences between loess and bedrock	[106-108]
Crackmeter monitoring	Crackmeter	Continuous monitoring of crack deformation	[106, 108]
Noncontact crack monitoring	Noncontact approaches	Nondestructive, high-precision, and real-time collection of crack data	[106]
Grating monitoring	Fixed-point fixtures used to fix and install longitudinal and transverse gratings	Monitoring of deformations of cave roof, fills, and overburden, enabling real-time, full-network monitoring of dome roof rock layers	[107]
Custom-developed laser automatic ranging system	Data collected once every hour before transmission to a remote laboratory warning platform	Monitoring the weathering and denudation rates of the inner surface of a dome roof slab	[107, 108]
Active infrared system	Self-designed and manufactured active thermal stimulation device	Device ensures uniform, stable thermal stimulation of rock surface for quantitative spalling identification	[109]
Electrical resistivity tomography	Four survey lines and 1 monitoring line deployed; surveys/monitoring conducted	Tracking the movement of infiltrated water, monitoring subsurface resistivity variations due to rainfall infiltration, and verifying resistivity responses during artificial infiltration tests	[110]
Small fixed-loop Transient Electromagnetic Method(TEM)	Magnetic field emitted to deduce geological information	Numerical, modeling, and field studies conducted to clarify the seepage capacity and information measured by the small fixed-loop TEM	[111]

could be used to calculate degrees of deterioration.

4 Progress in numerical simulation research

Numerical simulations are crucial contributors to research on the deterioration of rock masses in grotto temples. They can exhaustively identify the internal mechanisms governing rock mass deterioration and provide a scientific basis for the formulation of protection measures. Fig. 10 displays a VOSviewer map of the distinct numerical simulation methods used to explore deterioration in grotto rock masses.

4.1 Finite element method

The finite element method (FEM) transforms complex continuous problems into more tractable discrete problems^[113]. It is particularly effective in dealing with the deterioration issues confronting the rock masses making up grotto temples because it can accurately simulate key factors such as the stress distribution within a rock mass, crack development, and structural response. FEM has been adopted by many researchers to simulate and analyze the mechanical behaviors of rock masses^[114]. An example is Wang et al. ^[115], who developed an improved hybrid FEM.

plinary problems.

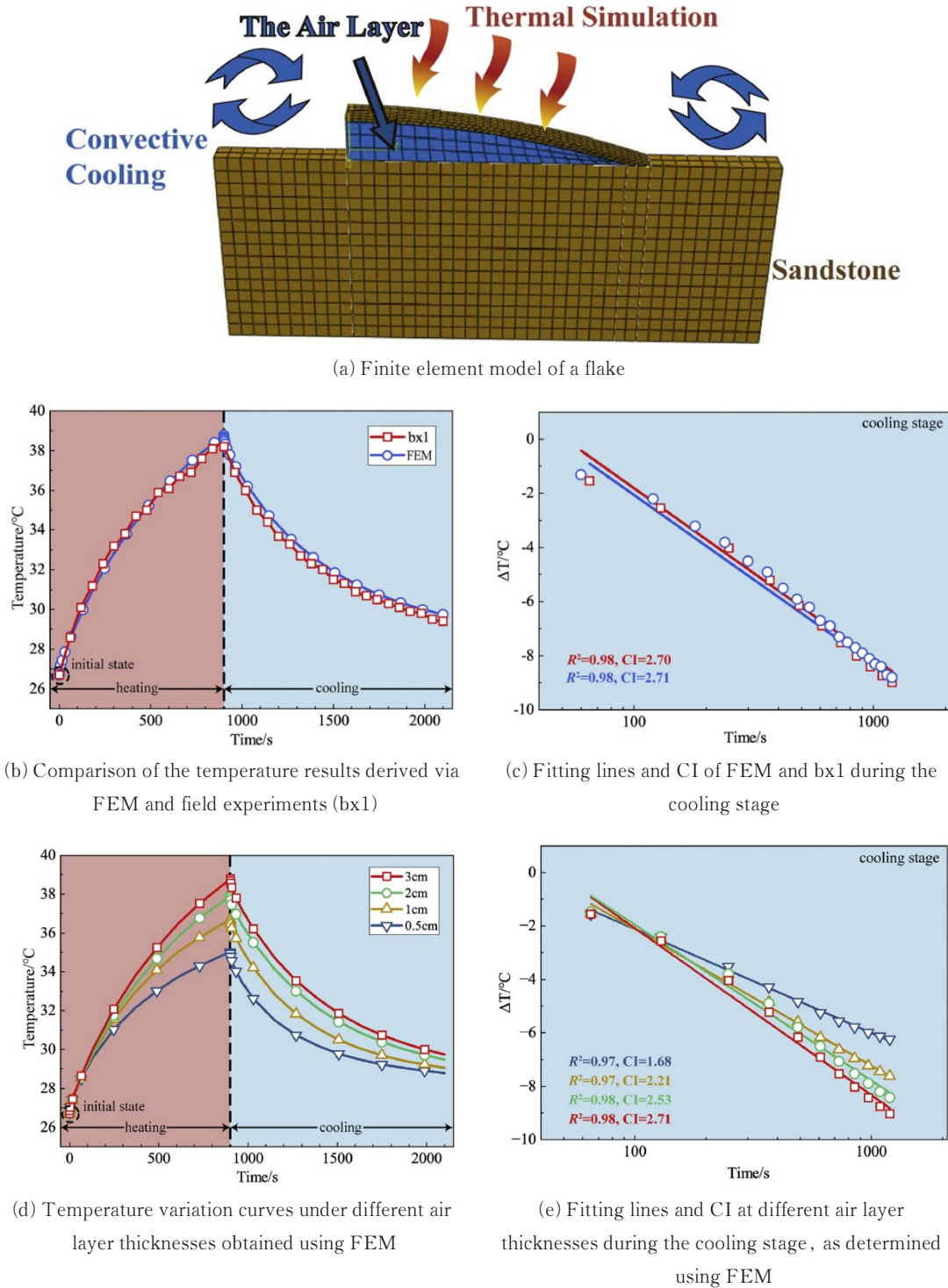


Fig. 12 Design and Validation of a Thermal Finite Element Model for Flaking Damage^[109]

4.2 Discrete element method

The core advantage of the discrete element method (DEM) over FEM in geotechnical engineering lies in its effectiveness in abandoning the continuous medium assumption as well as accurately characterizing discontinuous deformation, failure processes, and the meso-mechanical mechanisms of geotech-

nical materials from a discrete particle perspective. It is particularly suitable for handling problems dominated by large deformations, multifield coupling, and particle interactions^[117]. It is also commonly used in investigations of rock mass deterioration.

Meanwhile, FEM is restricted by continuum mechanics in the exploration of freeze-thaw cycles,

thus preventing it from explaining the physical mechanism governing the damage stemming from the volume expansion of ice in rocks during freeze-thaw cycles. Therefore, DEM is generally adopted when scrutinizing freeze-thaw-induced failure, with researchers specifically using the particle flow code (PFC) in the discrete element modeling of the frost heave affecting rocks. The blue spheres in Fig. 13 represent rock particles, and the green spheres denote ice particles in pores^[118-119]. Considering that the expansion of pore water leading to tensile stress in rocks is the primary driver of rock frost damage, it is reasonable to simulate the rock frost heave on the basis of ice particle expansion. It is critical to use frost heaving as a basis for understanding crack initiation and propagation. Zhang et al.^[120] used the PFC to comprehensively simulate the creep process of rock masses, effectively capturing crack development. When inquiring into the stability of rocks surrounding grottoes, researchers generally use DEM to simulate failure in such rocks given that this method can capture the instantaneous development and propagation

of cracks and intuitively and exhaustively characterize the failure mode in these rocks^[121-122]. For example, Wang et al.^[123] established a numerical model of three-point bending in sandstone with multiple bedding plane structures to probe into the mechanical behavior of rocks making up the Longyou Grottoes. The problem is that this method requires addressing the contact force equilibrium of numerous particles (tens of thousands to millions), but the number of calculations increases exponentially with the number of particles, especially in the simulation of large-scale projects. In these cases, efficiency is relatively low. In addition, Sergio Carrasco et al.^[124] used DEM to replicate the mechanical behavior of particles of different sizes and shape distributions through triaxial shear tests. The researchers analyzed the macroscopic mechanical properties of the particles under different shear strains and thoroughly explored the influence of the interparticle contact network, the force-transfer mechanism, and microscopic anisotropy on macroscopic mechanical behavior.

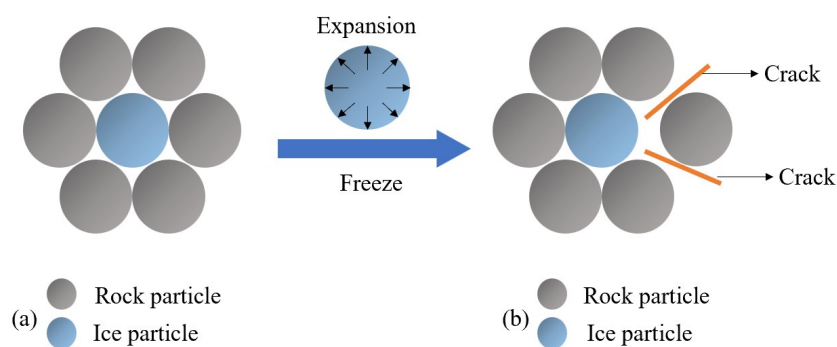


Fig. 13 Schematic of the volume expansion of ice particles (adapted from Yu et al.^[119]).

4.3 Coupled simulation

The deterioration of grotto rock masses occurs under diverse conditions, and research is no longer limited to the scrutiny of a single causative factor, with focus instead directed toward the combined action of multiple determinants, such as humidity-temperature coupling and acid rain-temperature coupling.

The humidity-temperature model, first proposed by Matsumoto, has seen continuous evolution^[125]. This model, compiled on the Intel Visual Studio platform using Fortran language, regards the chemical potential of water and temperature as driving forces. It is a popularly adopted model in exami-

nations of rock mass deterioration, such as that performed by Wu et al.^[126], who inspected the Maijishan Grottoes. The authors established a hydrothermal model to simulate and analyze rock mass deterioration and found that direct sunlight has a significant impact on temperature changes on the statues' surfaces, resulting in high thermal stress. Such a phenomenon, in turn, is positively correlated with the degree of deterioration in rock masses. While temperature fluctuations are a core driver of deterioration, the combined effects of humidity and temperature are critical for a holistic understanding of rock behavior in varying environments. Feng et al.^[127] combined a

model of the relationship between humidity and non-linear elasticity with a model depicting the link between such elasticity and temperature. The authors derived a combined representation of the association among humidity, temperature, and nonlinear elasticity to capture the influence of humidity and temperature on the nonlinear elastic properties of rocks.

Most existing grottoes are made of sandstone. Due to the combined effects of fire and a chemical environment typified by acidic water, sandstone may sustain a prolonged decline in stability. Effectively protecting and repairing historical buildings made of sandstone necessitates investigating the deterioration

patterns and mechanical property mechanisms of sandstone under acid-temperature coupling conditions. Correspondingly, Zhang et al. exposed red sandstone specimens to high temperatures (300°C and 600°C) and immersed them in sulfuric acid solution^[128], after which the authors evaluated the physical and mechanical properties of the specimens through grouped controlled experiments. With rising thermal loading, mass loss in the specimens increase significantly and the number of pores constantly grow, resulting in a continuous decline in the longitudinal wave velocity of rocks (Fig. 14).

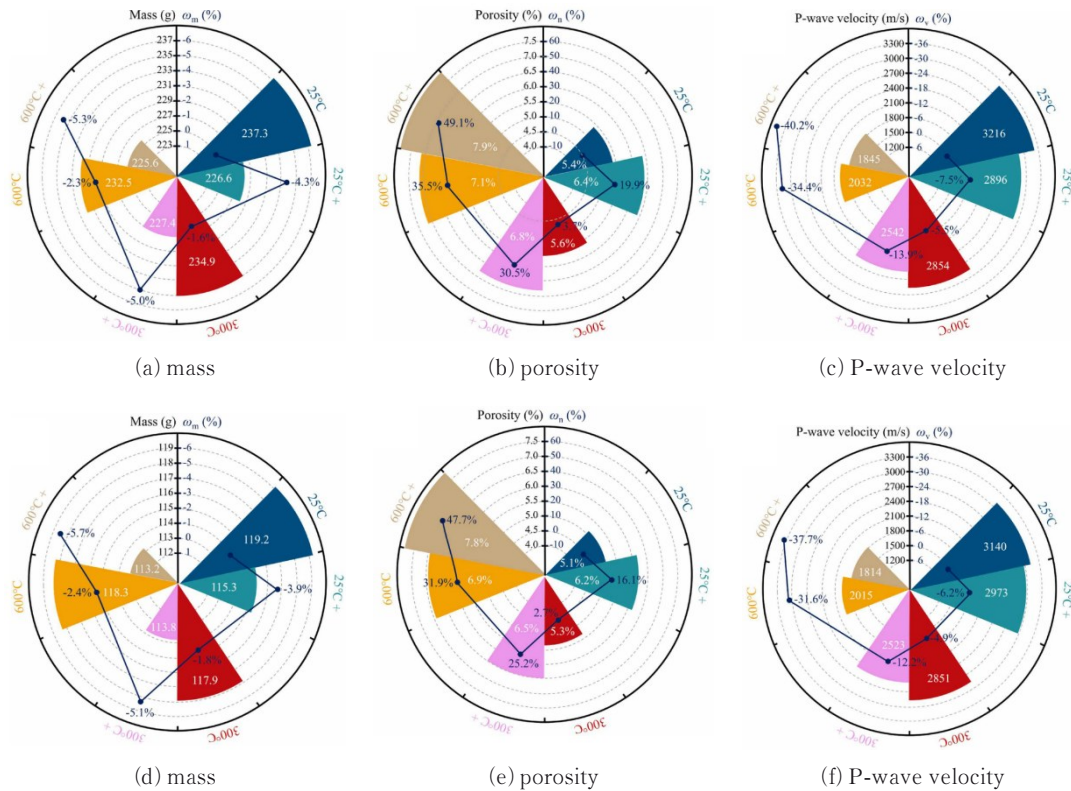
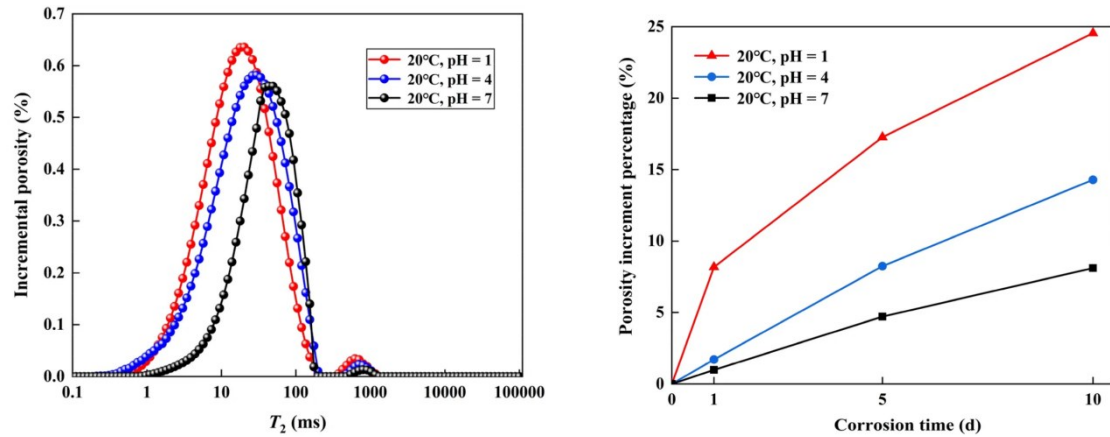


Fig. 14 Variations in mass, porosity and P-wave velocity of cylindrical specimens and variations in mass, porosity and P-wave velocity of disc specimens^[128]

Under medium to low temperatures and different acid-temperature conditions, Zhang et al.^[129] obtained the macroscopic mechanical properties and microstructural changes of sandstone samples during uniaxial compression experiments and nuclear magnetic resonance measurements. The experiments showed that both chemical effects (mineral reactions and partial mineral dissolution) and physical effects (temperature-induced pore expansion and crack propagation) contribute to sandstone damage (Fig. 15).

Among the coupling simulations described

above, that involving acid and temperature better reflects the core characteristics of rock mass deterioration. Acidic media directly weaken the cementing strength of minerals through chemical reactions, and such chemical damage is irreversible. Temperature effects aggravate physical fractures through thermal expansion and contraction, forming a vicious cycle of chemical corrosion-structural loosening-physical fracture between the two. Future research can further focus on multifactor coupling among acid, temperature, freeze-thaw cycles, and other factors to more



(a) T_2 spectra of sandstone samples under different acidic solutions for 10 days at 20°C (b) effect of pH values on the percentage increase in porosity

Fig. 15 Changes in the macroscopic mechanical properties and microscopic structures of sandstone samples^[129]

comprehensively reveal deterioration mechanisms.

5 Protective strategies against deterioration of grotto rock masses

The deterioration of rock masses that make up grottoes poses a threat to the survival of precious cultural heritage. This problem is currently mitigated through the extensive use of real-time monitoring. Examples are sensors, which are employed to accurately capture data such as changes in temperature, humidity, and fissures in rock masses, enabling timely early warnings. New types of restoration materials also continually emerge. These materials not only strengthen the rock mass structure but also present the advantage of breathability, preventing the accumulation of water vapor in the interior of rock formations. These multiple measures can be adopted simultaneously to confer a “protective umbrella” to grottoes composed of rock masses.

5.1 Real-time monitoring for protection

A real-time monitoring system can promptly capture minor changes in the physical and chemical properties of grotto rock masses through various sensors installed on the surface and within such formations. These sensors include temperature and humidity sensors, strain gauges, and displacement sensors. As mentioned in Table 4, monitoring technologies that enable the analysis of monitoring data clearly show how the weathering rate of a rock mass changes under different seasons and climatic conditions. Such dynamic data contribute to a profound grasp of inter-

actions among various deterioration mechanisms, such as chemical and physical weathering^[130-131].

After the implementation of protection measures, such as applying protective surface materials and reinforcing grouting, real-time monitoring can be performed to evaluate the actual effectiveness of these interventions. Following the use of a new type of anti-weathering chemical material, for example, monitoring changes in the relevant parameters of rock masses, such as porosity and strength, allows the determination of whether the material has effectively slowed down the rate of chemical weathering^[132]. If monitoring data indicate a failure in protection, the safeguarding plan can be adjusted in a timely manner, clearing the way for additional measures that include replacing protective material or improving the construction process, thereby improving the quality and efficiency of protection^[133].

5.2 Protective Materials

5.2.1 Nanomaterial Protective Layers

Among traditional stone protectants, organic materials such as silicone polymers, acrylic resins, and epoxy resins are limited in terms of compatibility and durability. Inorganic materials represented by lime water and silicates need improvement with respect to penetration depth and color change^[134-138]. At the same time, there is an increasing focus on the research and development of biomimetic materials.

Nanolime offers unique advantages as a protective material for murals and rock paintings. Its tiny particles can penetrate into the pores and fissures of

rocks. Physically, it fills pores and prevents water ingress, and chemically, it reacts with minerals, thereby forming new phases. Additionally, the reaction of nanolime with calcium carbonate can optimize the structure as well as enhance the stability, strength, and durability of rocks in multiple ways—benefits that reflect broad application prospects. Nanolime was synthesized by Han et al.^[139] using the anion exchange method (Fig. 16) to preserve the Dunhuang murals. The authors experimentally confirmed that nanolime can increase the surface cohesion and hardness of rock samples. However, the chemical inter-

action between nanolime suspension and the pigments used in mural painting can cause color changes, and improper application may lead to serious problems for murals. According to research, an alkaline and highly humid environment possibly induces chemical and color alterations in pigments containing Cu and Pb^[140-141]. Since rock paintings are directly carved, there is no need to consider the chemical changes between nanolime and pigments. Currently, there are few cases of the use of nanolime to treat rock paintings, thus leaving much room for development.

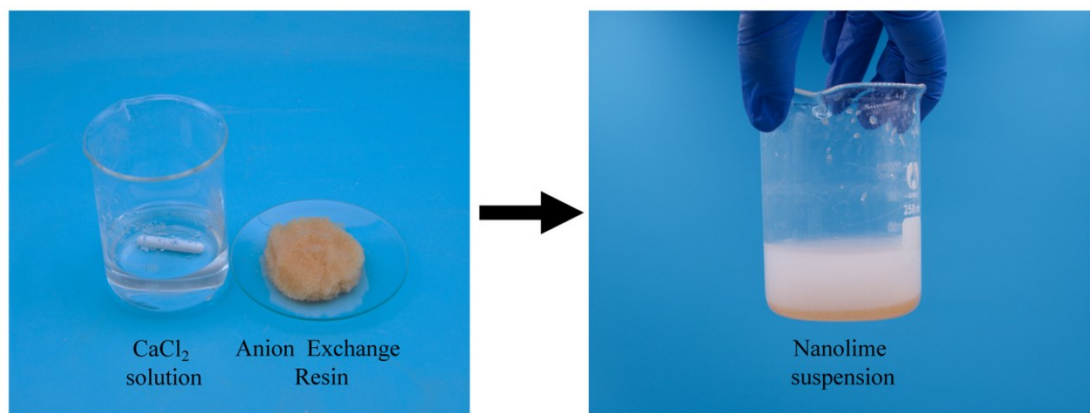


Fig. 16 Nanolime synthesis by anion exchange method^[139]

Nanosilica offers versatile reinforcement mechanisms in rock consolidation, with its effectiveness significantly dependent on application scenarios and material ratios. For the grouting reinforcement of fractured rock masses, micro-nanosilica grout incorporating 3% nanosilica sol optimizes the microstructure at the grout-rock interface, reducing interfacial width from 2 to 3 μm to below 1.5 μm . This microstructural improvement increases the friction coefficient and cohesion, thereby reducing effective stress and ultimately enhancing the peak strength of sandstone by 16.49%^[142]. Nanosilica also effectively improves the tensile strength of rocks (as evidenced, for instance, by the rise in strength of shale samples from 2.23 to 2.59 MPa)^[143].

For marble grottoes, a cohesive layer of hydroxyapatite can form on the surface of marble, thus improving the corrosion resistance, freeze-thaw resistance, and consolidation performance of the material. Gu et al.^[144] aimed to enhance the performance of hydroxyapatite in marble conservation and accordingly synthesized nano aluminum phosphate using the

sol-gel method. Nano aluminum phosphate promotes the formation of a cohesive layer of hydroxyapatite on the surface of marble, and all phosphate treatments have been experimentally confirmed to exert no significant change on the hydrophobicity and color of samples. The absence of such alteration effectively reinforces acid resistance, freeze-thaw resistance, and the consolidation of gemstones.

5.2.2 Biofilms

From a chemical and mechanical perspective, the activity of microorganisms on rock surfaces can be dangerous. Research has shown, however, that controlling the presence of microorganisms can contribute to the protection of rock masses—a process known as bioconservation. Bioconservation is typically related to microorganism activity that is intended to reduce the deterioration of rocks and acts as a protective patina on the surface of rock formations^[145-146].

On the rock walls of some grottoes, for instance, it is common to see rock surfaces covered with plants, whose uncontrollable growth can dam-

age the rocks. However, moderate growth under monitoring can help safeguard rock materials. An example is ivy, which can create a microclimate and moderate thermal cycles on rock masses and protect stones from the impact of rainwater and direct sunlight^[147]. Another example is lichens, which form biofilm that protects rock masses from water damage and limits the exchange of material between a rock surface and the external environment. As with any other plant, unchecked growth may damage stones. The protective effects of plants is influenced by multiple factors, and continuous monitoring is required to balance bioconservation and biodegradation^[148].

5.3 Temperature Control

During the protective process for grottoes, attention should be paid to temperature regulation, as this mitigates the physical weathering of rock masses, reduces the risk of crack formation, and inhibits the chemical weathering reactions accelerated by high temperatures. Such regulation also gives rise to a stable environment for the cultural relics housed in grottoes, indirectly stabilizing rock masses and prolonging the lifespan of artifacts^[149]. Temperature regulation should thus be addressed from multiple perspectives.

In terms of cold prevention and warmth preservation, sealants and sealing strips can be used to seal the cracks and holes in a temple to reduce the loss of hot air and the entry of cold air. Simultaneously, insulating boards and cotton can be used to line doors and windows, and curtains or door curtains can be arranged to block cold air and reduce heat loss. Equipment such as air conditioners and floor heating technologies can also be installed to ensure a suitable temperature. When it comes to cooling and sun protection, provisions such as sun umbrellas and awnings can be set up above a grotto temple to block direct

sunlight and reduce temperature. Furthermore, mounting a ventilation system guarantees air circulation and generates natural wind to help with heat dissipation. If necessary, water or sprays can be used to adjust temperature, and cooling and sun protection measures should be implemented during hot periods to reduce the impact of temperature differences. Amid a substantial disparity between day and night temperatures, direct sunlight should be avoided, and ventilation for heat dissipation should be maintained. During low-temperature periods, warmth-preservation measures should be taken. With a considerable temperature difference at night, cold air should be strictly prevented from entering. Dehumidifiers and desiccants can be used to prevent heat loss, or artificial heating can be implemented to maintain environmental stability^[150]. Apart from temperature control, the humidity and light control is of same importance for protection of grottoes. For brevity, these two parts would not be elaborated herein.

5.4 Support for rock mass stability

5.4.1 Rock bolting

Bolting, the most commonly used rock support, is characterized by an important development history and plays a crucial role in the prevention of instability in rock masses that constitute grottoes. To protect the Dunhuang Mogao Grottoes, Wang et al. implemented bolt support via mechanically drilled pressure-type cable anchoring^[151]. This method secured dangerous rocks between Caves 201 and 204 onto the deep, stable rock mass, which not only preserved the original appearance of the formation but also enhanced its stability (Fig. 17). Peng et al. used small-diameter fully grouted bolts to reinforce rock masses in grottoes^[152].

5.4.2 Drainage methods

The grottoes shown in Fig. 18 are located in a

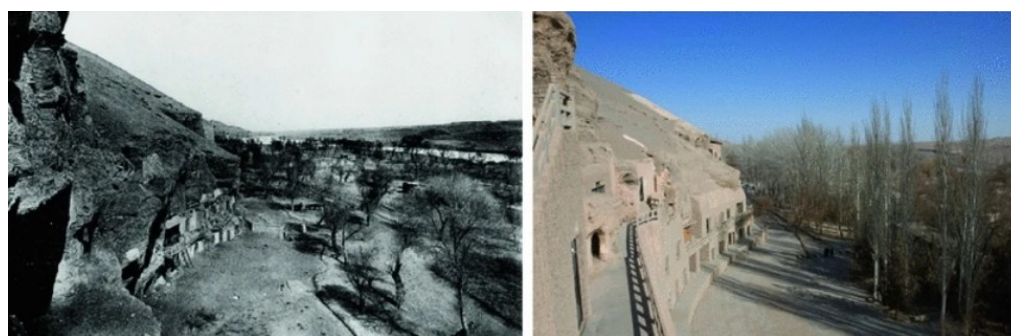


Fig. 17 The Mogao Grottoes Cliff in 1907 (before consolidation) and in 2008 (after consolidation)^[151]

rainy area, and the drainage system effectively prevents water damage-induced instability in the grotto rock masses. Drainage measures for grottoes include surface and underground drainage. The former guides rainwater away from grotto rock masses through constructed intercepting ditches and drainage ditches, among other measures^[153-154]. The latter uses configurations such as drainage holes and drainage galleries to decrease groundwater and reduce the impact of pore water pressure on the stability of rock masses. However, these drainage measures are not applicable to all grottoes. Let us consider the prevention and treatment of seepage at Leshan Giant Buddha^[155], where conventional groundwater treatment measures have had poor effects. Treating water

sources is difficult because temple buildings and cultural facilities such as visitor walkways on the cliff top limit the available space for excavation and pipe installation, and may be damaged by large-scale engineering interventions. Moreover, curtain grouting and drainage drilling cannot achieve the expected results due to the low permeability of the sandstone strata. At present, it is relatively feasible to carry out zonal and phased treatment according to the degree of seepage hazards, focusing on the upper sections of the statue (corresponding to the chest, abdomen, and especially the head). Digging blind drainage holes along the permeable stratum to block seepage paths is worth exploring, but its feasibility, necessity, and safety need to be scientifically demonstrated.^[156]



Note: (a) The Lushena Grand Buddha at Fengxian Temple of the Longmen Grottoes, (b) the Reclining Buddha at Baoding Mountain of the Dazu Grottoes, (c) and (d) the drainage facilities of the Reclining Buddha on Baoding Mountain.

Fig. 18 Grottoes with drainage measures taken

6 Conclusion and Prospects

Current research on the deterioration of rock masses in grotto temples has achieved certain results with regard to aspects such as types of deterioration, influential factors, deterioration mechanisms, research methods, and protection measures. Multiple deterioration patterns as well as their patterns have

been identified. Influencing mechanisms, such as geological structures, water, weathering, temperature, biology, and human activities, have been identified, and the roles of physical, chemical, and biological processes in deterioration have been comprehensively explored. A variety of research methods have been developed, and corresponding protection

measures have been proposed.

Despite these achievements, however, deficiencies remain. For instance, although laboratory simulations (such as freeze – thaw cycles and salt weathering) have revealed important microdegradation mechanisms (e. g. , SEM and CT studies showing pore-scale damage), they struggle to replicate multifield coupled environments and remain limited by sample scale. Similarly, while field monitoring techniques such as GNSS deformation tracking and infrared thermal imaging have provided valuable case-specific results, their wider application is hindered by high long-term costs and challenges of multisource data integration. In numerical simulation, FEM has offered precise analyses of temperature – stress coupling in sandstone grottoes, but it cannot capture discontinuous processes such as frost heave particle-scale failure. DEM studies have provided novel insights into salt crystallization-induced fracturing, but they are constrained by computational demands and parameter calibration risks. Popular research objects are nanomaterials (e. g. , nanolime used to fill the pores of rock and improve its mechanical properties), bioprotective films (e. g. , calcite precipitation induced by slime bacteria), and biomimetic coatings (e. g. , hydroxyapatite, which enhances the acid resistance of marble), but balance between compatibility and long-term effectiveness has yet to be achieved.

Future research should strengthen interdisciplinary integration. The advantages of such integration include lowering costs by combining laboratory precision with field realism, improving data reliability by merging multisource monitoring technologies, and enhancing predictive capacity through hybrid FEM – DEM approaches. These integrated efforts would also directly address existing gaps, such as the incompatibility between laboratory simulations and field conditions, the high cost of long-term monitoring, and the trade-off between material compatibility and durability.

From a policy perspective, the findings of current research and the directions outlined above carry important implications for cultural heritage management in China. Specifically, conservation guidelines could be informed by scientific insights into deterioration mechanisms, helping to prioritize grottoes most

at risk. Standards for protective material development could be guided by evidence on nanomaterials, bioprotective films, and biomimetic coatings, thereby improving their long-term compatibility and effectiveness. Moreover, the identification of monitoring challenges highlights the need for government-funded programs to support the deployment of advanced monitoring systems for key grotto sites, ensuring both real-time and long-term tracking of deterioration. These recommendations can also provide the basis for rational allocation of resources to conservation projects, while systematic evaluation systems will assist policymakers in selecting strategies that balance efficiency, safety, and sustainability.

Such systematic frameworks not only pave the way for a thorough coverage of all aspects relevant to the deterioration of grotto rock masses but also effectively combine experimental and numerical simulation research with practical applications.

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