

REVIEW

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# The history of rescuing reinforcement and the preliminary study of preventive protection system for the cliff of Mogao Grottoes in Dunhuang, China

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## Abstract

Based on the research results and practical engineering experience pertaining to the protection and reinforcement of the cliff of the Mogao Grottoes in Dunhuang, China, this paper presents a method that is mainly based on the analytic hierarchy process (AHP) to evaluate the preservation state and risk of the Mogao cliff, a means that numerical simulation was conducted to quantitatively evaluate the stability and effectiveness of protective measures for the Mogao cliff, a set of reinforcement methods which integrate the key protection techniques based on propping, anchoring, grouting, and anti-weathering and the quality control measures based on assessing their effectiveness for surrounding rocks of the grottoes, and a set of methods for monitoring and warning based on risk theory throughout the entire reinforcement process. The four above-mentioned techniques complement and support with each other, and every stage is based on research. Additionally, the protection and reinforcement concepts implemented at the Mogao cliff are summarized in this paper. Finally, preventive protection and reinforcement techniques for sandy conglomerate grottoes were established based on the research, evaluation, calculation, and monitoring. The techniques presented in this paper can be used as a theoretical foundation and provide technical guidance for the protection and reinforcement of similar cultural heritage sites all over the world.

**Keywords:** Cave temple, Cliff of sandy conglomerate, AHP, Numerical simulation, Heritage conservation

## Introduction

A grotto is a Buddhist art palace integrating wall paintings, painted statues, and architectures, and also is an important part of heritage sites and a historical testimony of the integration of religion and culture. Moreover, grottoes are of great historical, scientific, artistic, social and cultural value. A number of grottoes exist all over the world, such as the Mogao Grottoes, Longmen Grottoes, and Yungang Grottoes in China, Ajanta Caves, Ellora Caves, and Elephanta Caves in India, and Bamiyan

Buddhas in Afghanistan. However, the cliff of grottoes suffers from the influence of fissures [1, 2], collapses [3, 4], falling rocks [5, 6], seepage [7, 8], weathering [9, 10], and vandalism [11]. Hence, researchers and managers carry out a substantial amount of work to protect and strengthen the cliff of such grottoes. For examples, the rockfall of Saptashrungi Gad Temple in India was reinforced by re-sloping, scaling and trimming of loose rock blocks, draping mesh, and anchoring rock bolts [12]. The stabilization of Ajanta Cave above Cave 1 to 5 was undertaken by a concrete retaining wall [13]. The seepage problem of Sokkuram Grotto in South Korea was solved after 3 times of protection and reinforcement which include the pouring of the concrete dome from 1914 to 1916, the waterproofing of the concrete dome in 1917,

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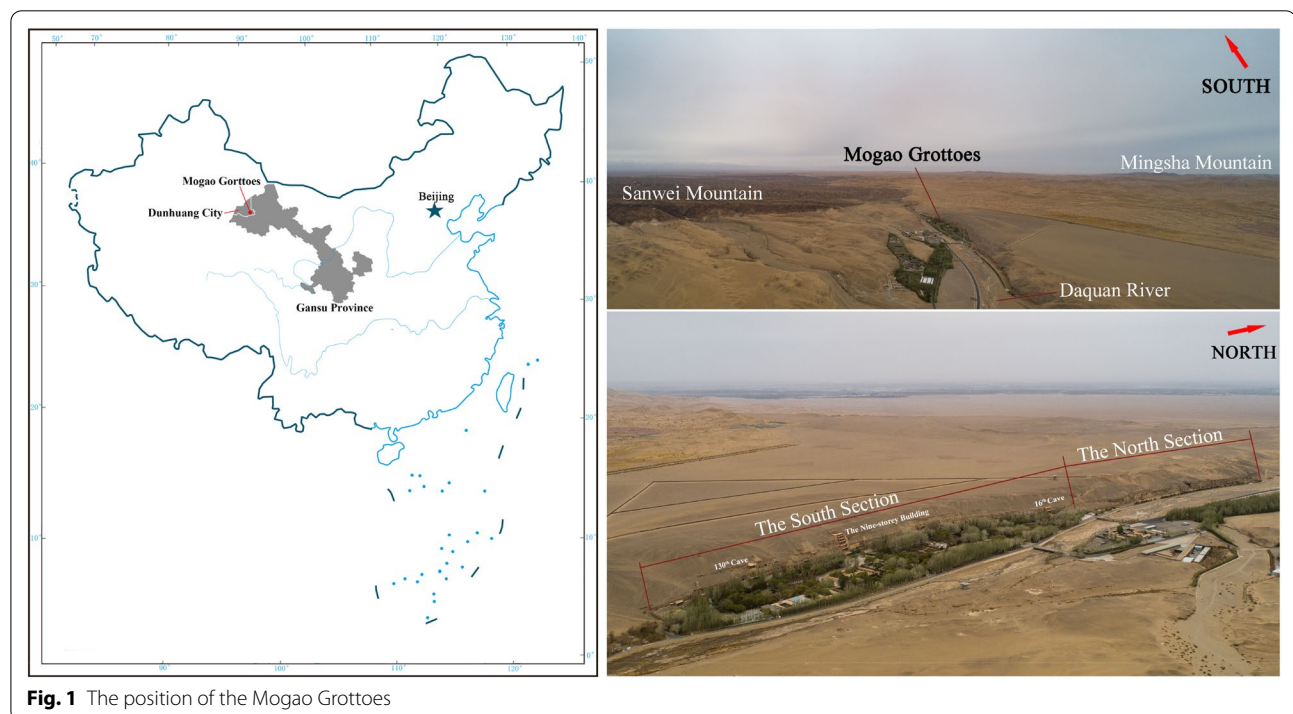
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and the construction of double domes and wooden cave eaves in 1961 [14]. The cliff of Yungang Grottoes in China was reinforced with epoxy resin grouting, anchoring and cave waterproofing [15], the cliff of Maijishan Grottoes was protected by Spraying concrete with steel mesh, and anchoring [16], the cliff of Mogao Grottoes and Yulin Grottoes was protected and reinforced by propping, anchoring, grouting, and anti-weathering [17, 18]. In these practices and experience of reinforcement for the cliff of cave temple, the Mogao Grottoes is one of the most important and famous protection projects.

The Mogao Grottoes are located at the eastern foot of Mingsha Mountain, on the west bank of Daquan River, facing Sanwei Mountain in the east, which is 25 km away from Dunhuang in Gansu province, China. Since the first cave was built in 366 AD, there were 735 caves excavated in the north–south cliff with a height of about 40 m and a length of 1.7 km. There are 45,000 square meters of splendid wall paintings, and over 2000 painted statues in caves of south section, and about 200 caves are used for the monks' daily life, which are located in the north section of the Mogao (Fig. 1).

The Mogao cliff has been deteriorating since its formation under the structural influence and strength of a sandy conglomerate, which is cemented by muddy calcium or weak muddiness. Additionally, the cliff has various typical issues, such as cracks, partial dangling,

and weathering. Since 1956, many domestic and foreign scholars have developed the theoretical foundation and accumulated a substantial amount of practical experience with regard to the conservation of the Mogao cliff. This experience includes the assessment of the conservation state, analysis and calculation of stability, evaluation of the reinforcement effect, and protective monitoring. However, most of these studies have only investigated one aspect of the protection and reinforcement measures for the cliff of the Mogao Grottoes, and systematic investigation has not been carried out with regard to the cliff characteristics, protection and reinforcement techniques, as well as quality control and effectiveness evaluation. Based on research results and data obtained by protection projects, protection and reinforcement techniques for the conservation of the Mogao cliff have been established in recent years. These techniques include a method for evaluating the conservation state and risk of the rock mass, quantitative analysis methods for evaluating the state before and after the reinforcement of the cliff based on the numerical simulation, key protection and reinforcement techniques including the propping of the roof, anchoring, grouting and anti-weathering, and a method based on risk theory for monitoring and warning throughout the entire protection process. These techniques are expected to be used in similar projects for the conservation of grottoes heritage all over the world.



## The protection and reinforcement of Mogao cliff

### The history and effectiveness assessment

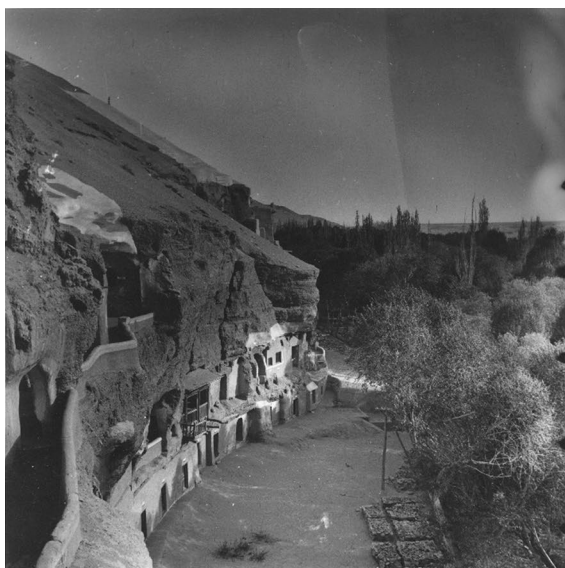
#### for the protection and reinforcement of Mogao cliff

Before 1944, the Mogao Grottoes had been left unmanaged and unprotected for an extensive period of time. Many fissures and collapse incidents have occurred on the Mogao cliff under the influence of earthquakes, rainfall, temperature, sand storms, and humidity (Fig. 2). During its existence, this heritage site has been severely threatened by these issues. The protection and reinforcement of the Mogao Grottoes have been carried out continuously since the establishment of the Dunhuang Institute of Art in 1944. Early on, a wall was constructed and sand cleaning was carried out. Subsequently, the cliff was protected and reinforced, and monitoring and warning systems are installed presently. The protection and reinforcement history of the Mogao cliff has gone through the following major stages since the first cliff body reinforcement in 1956.

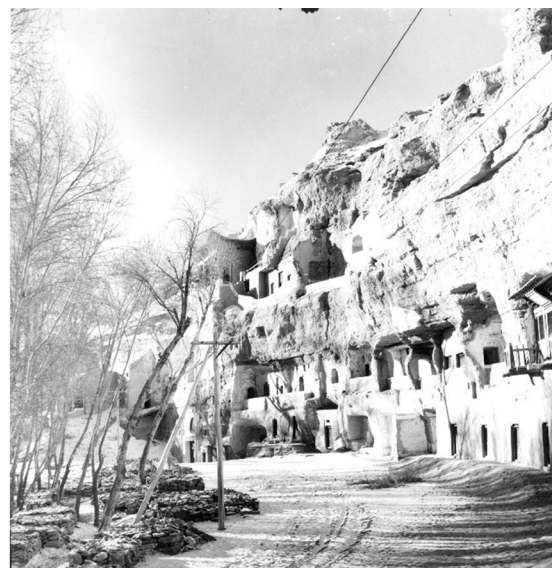
1. In 1956, the experimental reinforcement of the cliff between the 248th Cave and the 261st Cave was mainly implemented by roof-propping using stone masonry pillars and a wooden walkway on the roof-propping [19]. However, there were some problems regarding the shape of the reinforcement and structures owing to the lack of cave reinforcement experience.
2. In 1963–1966 and 1984, the cliff with a length of 800 m and the 400 caves of the Mogao Grottoes were

reinforced in four phases of protection projects for the conservation of the Mogao cliff and caves. The reinforcement measures included withstanding and propping using a beam-column structure for the dangerous rock mass, resisting collapse using a gravity retaining wall, and cleaning by removing the dangerous rock mass at the top of the slope of the Mogao cliff [19]. These measures have been in place since they were implemented, and their good reinforcement effects have provided a solid foundation for the protection and utilization of the Mogao Grottoes.

3. In 1999, the cliff between the 248th Cave and the 261st Cave was reconsolidated by removing the dangerous rock mass and repairing the wooden walkway. Other measures implemented in this section include chemical strengthening by PS-spraying (Potassium Silicate Spraying with modulus 3.8–4.0) the barely weathered rock of both the erect cliff and the sandy conglomerate layer on the slope, and strengthening the cliff fissures by grouting [19, 20]. Thus, more scientific reinforcement measure was applied in this section, and the reinforcing system of this section was improved.
4. In 2000–2003, the flooding threat for the Mogao Grottoes was eliminated by the Daquan River flood control project. Additionally, the cliff in the northern section of the Mogao Grottoes was reinforced by anchoring and PS-spraying. Hence, the historical conditions of the site have been retained [20].



**a** Fissures on cliff (April 16, 1955)



**b** Collapse on cliff (January 25, 1956)

**Fig. 2** Preservation state of Mogao Grottoes before reinforcement



5. In 2010–2011, the dangerous rock masses in the southern section of Mogao, which had not been reinforced by previous protection projects, but reinforced by anchoring, grouting, and PS-spraying. The measures were evaluated by considering the wind erosion and rain erosion. At this stage, with the introduction of wind erosion, rain erosion, and other factors, the effectiveness of the protection and reinforcement measures was evaluated. Thereafter, the protection and reinforcement of the Mogao cliff formed the completely closed loop of research-calculation-reinforcement-evaluation.
6. Since 2013, the dangerous rock mass close to the 196th Cave in the south section, and the B71Cave and the B65 Cave in the north section, were reinforced. These daily protective maintenance tasks have improved the protection and reinforcement system of the Mogao Grottoes.

In summary, the protection and reinforcement of the Mogao cliff can be divided into the experimental reinforcement phase since 1956, the rescuing reinforcement phase from 1963 to 1984, the scientific protection phase from 1999 to 2011, and the daily maintenance phase since 2013. Additionally, with the implementation of the National Science and Technology Support Program ‘Research and Demonstration of Key Technologies for Risk Pre-Control of World Cultural Heritage Sites,’ the protection and reinforcement of the Mogao cliff are currently in the stage of preventive protection at the same time [18, 21].

#### **The technique and concept for the protection and reinforcement of Mogao cliff**

By reviewing the protection and reinforcement history of the Mogao cliff, it is evident that the main means of reinforcement for the Mogao cliff are ‘withstanding,’ ‘propping,’ ‘resisting’ and ‘cleaning’ at the stage of experimental and rescuing protection. The main purpose of these measures is to prevent the cliff from collapsing and causing the destruction and disappearance of the Mogao Grottoes. Considering China’s national conditions and technical capabilities, the reinforcement concepts at this stage, and the current conservation state of the Mogao Grottoes, the reinforcement measures provide good conditions for the long-term preservation and sustainable usage of the Mogao Grottoes.

At the scientific protection phase, with the improvement of relevant national policies, the technical strength of the industry, and the changing and refinement of the personnel structure and cooperation scope of the Dunhuang Academy, the conservation of the Mogao cliff used the system of ‘anchoring, grouting, and anti-weathering’

based on scientific research with regard to PS, calcined ginger nuts, and mature anchoring technology. Additionally, the technology of the protection system is more in line with the requirements dictated by the Principles for the Conservation of Heritage Sites in China and related laws and regulations.

At the daily maintenance and preventive protection phase, more work priorities and processes are focused on inspection, monitoring, warning, and maintenance.

Since 1956, concepts regarding the protection of cultural relics and the related technical requirements in China, and also the protection and reinforcement of the Mogao cliff, have been gradually investigated and integrated into a comprehensive technological system of protection and management. This system includes the concept of retaining the historical conditions, roof/propping/grouting/anti-weathering reinforcement technology, and a management plan for monitoring, warning, and maintenance.

On the other hand, the stability of the middle and lower parts of the Mogao’s cliff was effectively improved after the reinforcement from 1956 to 1984, but the protection and reinforcement in the rescuing protection stage is relatively lacking in research and evaluation. With the deepening of understanding of the properties of Mogao’s cliff and the maturity of anchoring technology in the protection of cultural relics, anchoring technology was used for the reinforcement of the cliff in the upper part from 2010 to 2011, so the stability calculation based on the assessment of diseases and the evaluation of physical properties of Mogao’s cliff has been started in the reinforcement of cliff in this stage. Besides, the monitoring of the cliff was also introduced with the using of the 3D scanner in the cultural heritage field and the establishing of the warning monitoring system for Mogao Grottoes. Hence, evaluation or implementation of the cliff’s preservation status, stability calculation, monitoring, and protection and reinforcement have all appeared in different stages of the cliff protection and reinforcement history, and a framework system for cliff protection and reinforcement has also been initially established. However, the internal correlation and mechanism of each aspect have not been systematically studied, because these works have carried out for over 60 years since 1956. Consequently, the protection and reinforcement system of the Mogao Grottoes will be thoroughly reviewed in this paper based on the protection research, evaluation, monitoring, and reinforcement of the Mogao Grottoes over the past 60 years.

#### **Evaluation of the conservation state of Mogao cliff**

Since the end of the twentieth century, the conservation of cultural heritage sites, and relevant protection techniques and materials, have improved along with rapid

development of China's economic [22–27]. The geological conditions, physical and mechanical properties, disease types and characteristics, and the preservation state of the Mogao cliff have been systematically investigated and evaluated. Additionally, the evaluation and research results have provided an important foundation for the analysis of basic cliff properties, theoretical calculations, effectiveness of reinforcement measures, evaluation of reinforcement effects, and protective monitoring in the process of protection and reinforcement.

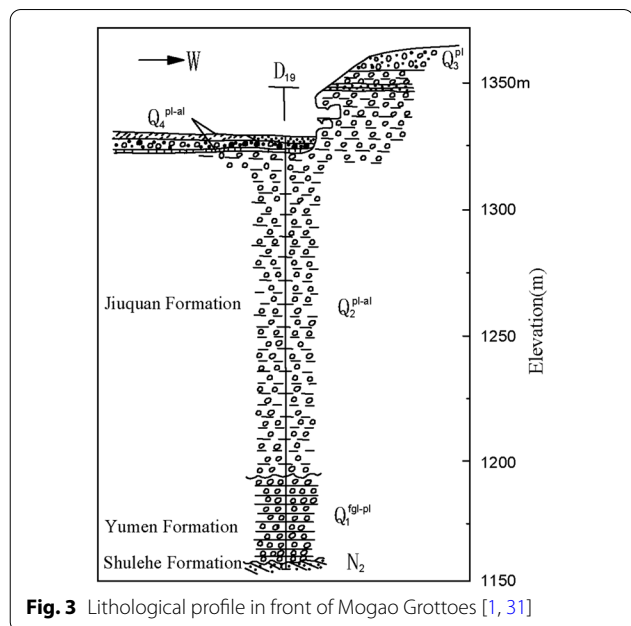
### Evaluation of the cliff's geological conditions

The Mogao Grottoes are excavated in the cliff of the valley located at the east of Mingsha Mountain. There is a similar geomorphic unit for the horizontal top of the cliff, and the Daquan valley lies in front of the cliff. Only a slight difference exists on the slope at the edge of the cliff. Additionally, the influence mechanism of 12 faults around the Mogao area is approximately similar throughout the cliff [28]. Thus, the important considerations in the analysis of the geological conditions for the Mogao cliff include stratigraphic lithology, hydrogeological conditions, and unfavorable geological phenomena.

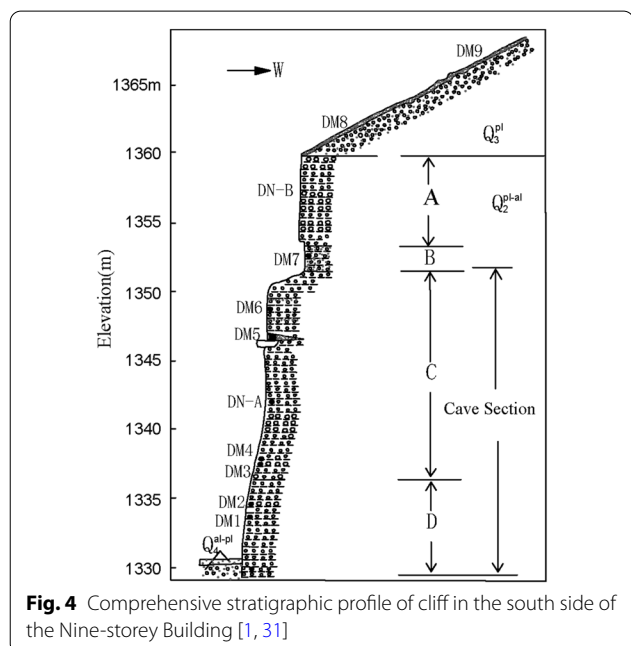
### Investigation of stratigraphic lithology

Previously, based on the quaternary geological studies of the Hexi Corridor, research results for the Dunhuang Basin, survey results for the Mogao cliff, and test results for cliff specimens, various scholars [29, 30] have divided the Mogao cliff and its underlying strata into the Lower Pleistocene Yumen Formation sandy conglomerate layer (Q1), Middle Pleistocene Jiuquan Formation sandy conglomerate layer (Q2), and Upper Pleistocene Gobi Formation conglomerate layer (Q3). For these strata, only the Yumen Formation sandy conglomerate layer is exposed in the vicinity of the seismic platform in the upper Daquan River. The caves are excavated in the Jiuquan Formation, and the Gobi Formation is mainly exposed at the top of the Mogao cliff [1, 31]. The different Mogao strata are shown in Fig. 3.

The caves of the Mogao Grottoes and Yulin Grottoes are excavated in the erect cliffs comprising the Jiuquan sandy conglomerate. Hence, various scholars have referred to the Jiuquan conglomerate as the 'cave stratum' [30]. However, the lithological and mechanical properties of the formation directly affect the stability of the caves and their cliffs. Therefore, the investigation of the lithological properties is key for the conservation of the Mogao cliff. Wang [32] measured and mapped the comprehensive stratigraphic profile and analyzed cliff specimens from the south side of the Nine-storey Building of the Mogao Grottoes. Then, he divided the cliff into four engineering geological rock groups based on the

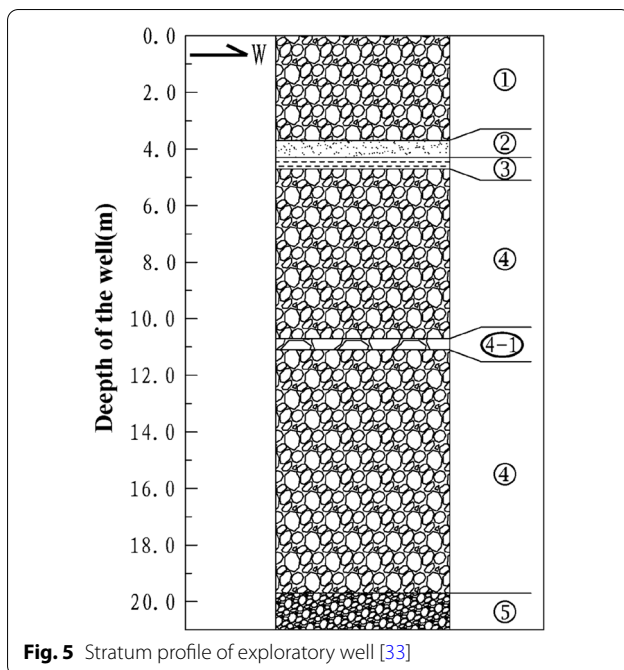


**Fig. 3** Lithological profile in front of Mogao Grottoes [1, 31]



**Fig. 4** Comprehensive stratigraphic profile of cliff in the south side of the Nine-storey Building [1, 31]

lithological characteristics and engineering properties of the strata. Figure 4 shows the profiles categorized as A, B, C, and D from top to bottom. To further understand the internal strata of the Mogao cliff, Yang [33] dug a 21-m-deep exploration well in the rock mass at the west side of the Nine-storey Building. The distance from the Nine-storey Building to the well is 150 m, and Yang extensively catalogued the well (Fig. 5). And the position



of lithological profile, stratigraphic profile, and the well mentioned above is shown in Fig. 6.

However, this was mainly based on point surveys using the profile and well. Therefore, Guo [34] conducted an investigation deeper into the strata of the upper and middle Mogao cliff, and divided the formation of different sections of the Mogao cliff into five types based on a large number of on-site investigations and mapping. These five types are the slope cliff without a sandy stratum, stepped cliff without a sandy stratum, erect cliff without a sandy stratum, stepped cliff with an obvious sandy stratum, and slope cliff with an inconspicuous sandy stratum (Fig. 7).

The above-mentioned studies did not describe the distribution state of the Mogao cliff in a clear and comprehensive manner. However, all of them have played an important role in the protection and reinforcement of the Mogao Grottoes. To determine the distribution characteristics of the Mogao cliff strata in the greater district, we investigated the area behind the Mogao cliff using a ground penetrating radar and surface wave exploration (Fig. 8).

From the research results pertaining to the geological conditions of Mogao, the division of the strata and engineering rock groups of the Mogao cliff is becoming clearer and more comprehensive with the improvement of survey techniques at different stages. Most studies have used these research results as foundation data for the protection of the Mogao cliff. Moreover, although the Mogao strata have simple lithology, their distribution is complex.

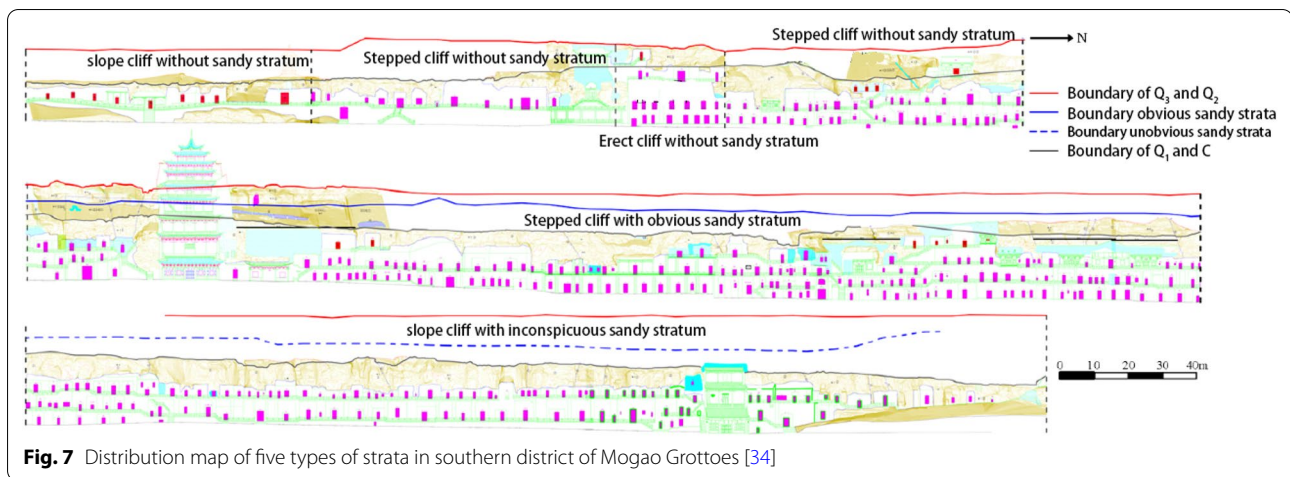
#### **Research on the state of water vapor in Mogao cliff**

The Mogao rock mass is a sandy conglomerate with poor cementation, therefore, its strength decreases after the cement is leached and eroded by water. Moreover, water or water vapor can cause salt dissolution in the rock and migration with moisture transport, and the salt content is enriched in a part of the rock or on the surface of the wall paintings in the caves. Eventually, the rock properties will be changed and the wall paintings will be destroyed by efflorescence, detachment, and other diseases. Therefore, elucidating the distribution and transport law is very important for protecting and reinforcing the Mogao Grottoes.

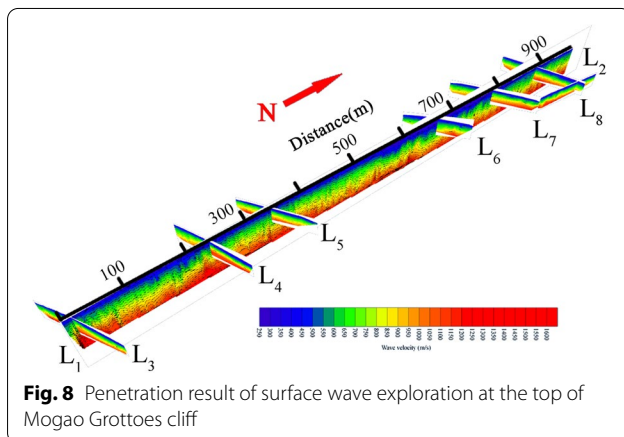
Yang [33] excavated and sampled the exploration well at the top of the Mogao cliff, and analyzed the moisture state of the rock mass within a distance of 20 m from top







**Fig. 7** Distribution map of five types of strata in southern district of Mogao Grottoes [34]



**Fig. 8** Penetration result of surface wave exploration at the top of Mogao Grottoes cliff

of the well. Guo [36] systematically expounded the distribution and source of water and salt in the rock mass by monitoring the temperature and humidity conditions at different depths, and using electrical resistivity tomography (ERT) on the western bare-wall of the 98th Cave of the Mogao Grottoes. Chen [37] discovered the water vapor's transport channel related to the structure of the rock mass using three-dimensional (3D) ERT under different scales on the western bare-wall of the 108th Cave of the Mogao Grottoes. Guo [38] determined the distribution and source of water in the Mogao rock mass using ERT to measure the resistivity for the rock surrounding the grottoes, before and after rainfall, at the tree belt in front of Mogao and at the top of the cliff [38]. The results obtained by these studies have provided an important theoretical foundation for the protection and reinforcement of the Mogao cliff.

### Evaluation of the physical and mechanical properties of the Mogao cliff

To understand the composition, structure, and properties of the Mogao cliff, it is important to investigate its physical and mechanical properties. Such investigations can provide the basic parameters to consider for protection and reinforcement. Hence, Wang [1] and Zhang [39] used X-ray diffraction, the wax sealing method, and the drying method to determine the mineral composition, density, and moisture content of each engineering rock group. Additionally, they used the point load method to test the strength of each group, and investigated the wave velocity of each group using the seismic method and acoustic wave testing. Fu [40], Shi [41], Guo [34], and Pei [42] obtained the physical and mechanical parameters and structure of each rock group using different methods such as laboratory testing and empirical formula calculations. Table 1 lists the physical and mechanical parameters of each engineering rock group and structure of the Mogao Grottoes, based on the results obtained by the studies mentioned for the physical and mechanical properties of the Mogao cliff. Besides, the physical and mechanical properties of Maijishan Grottoes cliff, Beishiku Temple cliff, and Yungang Grottoes cliff are also listed in Table 1. As can be seen from the table, the physical and mechanical properties of different rock groups in Mogao Grottoes are quite different, and it is also different from the properties of Maijishan's sandy conglomerate, Beishiku Temple's and Yungang Grottoes' sandstone.

### Evaluation and survey of cliff diseases

Since the cliff was created after the river cut into the alluvial floodplain and the caves were excavated, the Mogao cliff has been deteriorating and has incurred different types of diseases (such as fissures, collapse, weathering, and gullies) under the influence of natural factors

**Table 1** Physical and mechanical parameters of different cave temple cliff

Sites	Number of the engineering rock group	Density (g/cm <sup>3</sup> )	Compressive strength (MPa)	Tensile strength (MPa)	Cohesion (MPa)	Internal friction angle (°)	Elastic modulus (MPa)	Poisson's ratio
Mogao Grottoes	Q <sub>3</sub>	2.30	–	0.20	0.10	40	100	0.30
	Q <sub>2</sub> -A	2.40	9.50	0.36	0.20	55	200	0.28
	Q <sub>2</sub> -B	2.15	12.6	0.54	0.08	38	87	0.31
	Q <sub>2</sub> -C	2.45	8.60	0.47	0.25	57	300	0.27
	Q <sub>2</sub> -D	2.55	15.8	0.67	0.30	60	500	0.26
	Retaining wall	2.50	–	1.50	0.45	70	1000	0.27
Maijishan Grottoes [43–45]		2.33	10.95	0.94	–	–	–	–
Beishiku Temple [46]		2.02	22.79	–	–	–	–	–
Yungang Grottoes [47, 48]		2.16	30.0	5.39	1	30.45	3494	0.20

(rainfall, snowfall, sun light, wind, and so on) and natural disasters (floods, earthquakes, sandstorms, and so on). The different sections have different stability because the landform has been changed by these diseases. The excavation of the caves did not only cause the redistribution of the internal stress in the cliff but also caused the adverse effect of cave spacing and thin-roof caves, which influences the stability. Future natural disasters, such as earthquakes, floods, and sandstorms, will also adversely affect the stability and development of cliff disease. Therefore, it is of great significance to evaluate the development of diseases and other cliff threats and their effect on the stability and safety of cultural relics.

Many studies have systematically investigated the development of diseases on the Mogao cliff. Wang [20] investigated the weathering of the Mogao cliff and divided the weathering diseases into nine types: cliff-faced conglomerate weathering, sandstone weathering, gentle slope rock weathering, dangerous rock, thin-roof cave, rainfall seepage, existing engineering issues, stratum salt damage, and sand damage. Subsequently, he measured these diseases in detail and marked them on the geological disease distribution map on the scale of 1:200. Shi [49] and Zhang [50] investigated the diseases of the Mogao Grottoes from the perspective of engineering geology and found that these diseases in the northern part of the Mogao Grottoes mainly include cracks, collapses, scarps, dangerous rocks, the collapse of cave roofs, weathering, sandstorm damage, and flood damage. Wang [51] investigated the causes, sources, movement mechanism, and risk of stones falling from the Mogao cliff through field experiments and motion track simulations. Moreover, various studies have investigated the threats faced by Mogao, such as earthquakes [52, 53], floods [54, 55] and sandstorms [32].

Based on these studies, we re-investigated the conservation state of the Mogao cliff with consideration to the influences and effects of threats posed by natural disasters, natural factors in the surrounding environment, and human factors in the process of construction and utilization. We found that the Mogao cliff is exposed to three types of threats from natural disasters: earthquakes, floods, and sandstorms. Additionally, the cliff is influenced by natural factors such as rainfall, snowfall, sun light, and wind, and is also threatened by human factors, including the construction of caves and tourism. Furthermore, we found that four types of diseases, namely, fissures, collapse, weathering, and gullies (Fig. 9), with 15 sub-categories, have developed on the cliff, and that the cliff faces problems such as internal stress redistribution, thin-roof caves, cave spacing, and vibration from tourists. Finally, the cliff has developed three shape types: erect cliff, stepped cliff, and sloped cliff. The classification of these diseases and threats is shown in Fig. 10.

According to properties and characteristics of these diseases and threats, the Mogao cliff deteriorates because of the threats caused by natural disasters and natural factors in past, present and future. The impact of excavation on the cliff has been completed and we can't change the result any more, and the threat caused by tourism is being effectively solved under the opening management measures of Dunhuang Academy. On the other hand, most diseases and issues of Mogao cliff caused by these external factors have been improved through protection and reinforcement, and other small-scale diseases pose a less threat to the Mogao cliff.

#### The preservation state of Mogao cliff

In recent years, most studies have investigated the geological conditions, physical and mechanical properties,



**a** A fissure of the cliff**b** The disease of collapse**c** Weathering**d** A gully in the cliff**Fig. 9** The four types of diseases in Mogao cliff

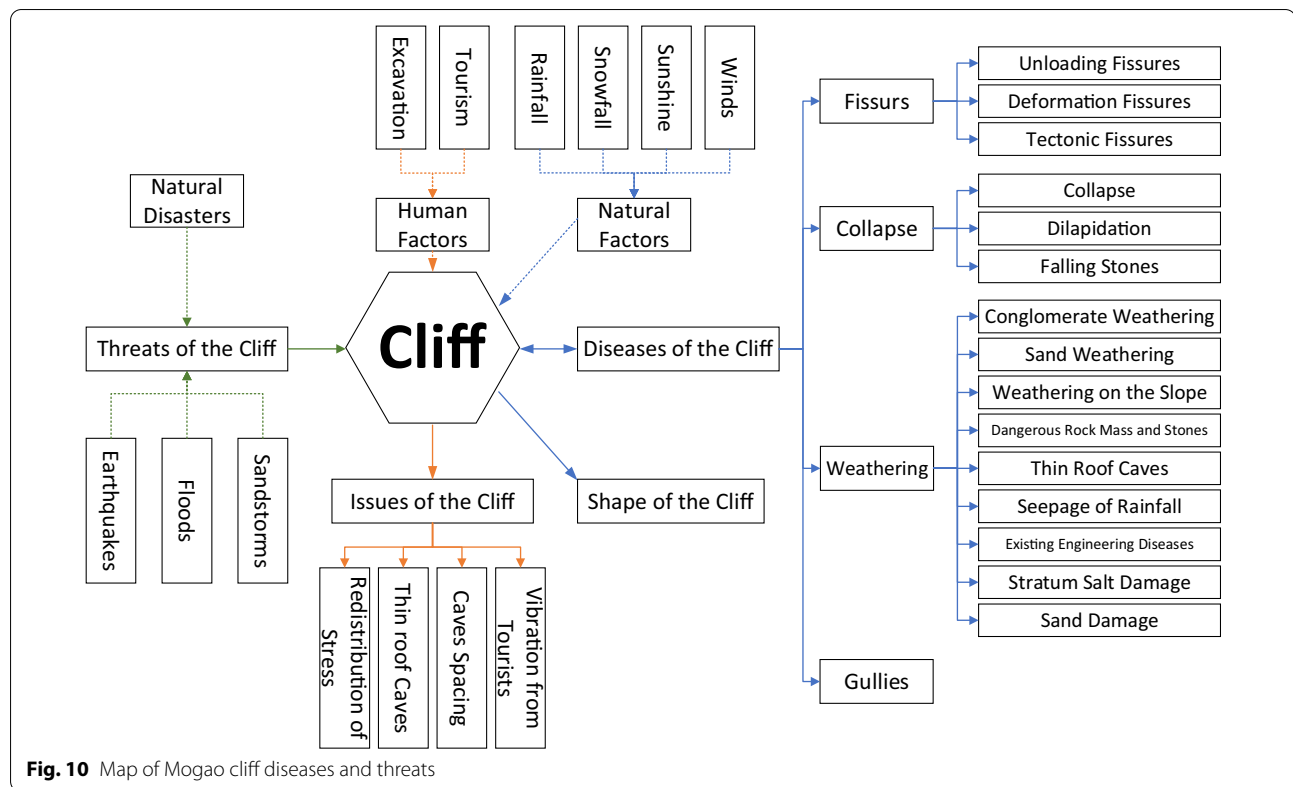
disease types, and threat situation of the cliff based on a local section or local point. Although more comprehensive research results have been obtained, the preservation state with regard to the quality of rock mass and the hazards resulting from diseases are still not clearly understood. Hence, it is necessary to evaluate the preservation state of the Mogao cliff.

Wang [56] analyzed and summarized relevant factors, such as landforms, fissures, caves, gentle slope weathering, and their sub-factors, which may affect the quality of the Mogao cliff rock mass, based on a deep understanding of the engineering geological features of the Mogao Grottoes. Wang completed the grading evaluation of rock mass quality using the analytic hierarchy process (AHP) and an expert system, and determined the weight of each factor (Fig. 11). Additionally, Guo [57] evaluated the hazard of 42 potential dangerous rock masses in the cliff of the southern Mogao section (Fig. 12). The risk assessment factors are as follows: dangerous rock mass, cliff shape, stratum lithology, fissures, and earthquake. The hazard assessment factors are as follows: humans, buildings, infrastructure, and other property. Based on risk theory, Guo pointed out the key areas of concern and explained the main

hazards and potential dangers in each section. The results provide effective guidance for the protection and management of the Mogao Grottoes, and a theoretical foundation for the stability and potential hazard assessment of the caves.

### Analysis and calculation of Mogao cliff stability

In the field of traditional engineering geology, various analytical methods, such as qualitative analysis, semi-quantitative analysis, and quantitative analysis, are used to calculate the stability of the rock and soil mass. In the twenty-first century, with consideration to the actual situation and special characteristics of the Mogao cliff, methods have been established for the analysis and calculation of the stability and consolidation force in long-term practical conservation and reinforcement. These methods combine the preliminary analysis of the in-situ wedge balance and resistance force calculation using the GEOSLOPE software. Moreover, we investigated a set of methods for calculating the reliability of the reinforcement measures and focus points after the reinforcement. These methods provide a theoretical foundation and empirical guidance for the protection and reinforcement of the Mogao cliff.



### Analysis and calculation of reinforcement force

#### Analysis and calculation of wedge balance

In engineering practice, the limit equilibrium method is one of the earliest and most widely used quantitative analysis methods. After assuming the failure mode of the deformation system, we can analyze the stress state of the rock and soil mass under various failure modes according to the mechanical balance principle in the failure mode. Moreover, we can calculate the stability of the rock and soil mass according to the force balance between the anti-sliding force and the downslide force, or according to the moment equilibrium in the dangerous rock and soil mass.

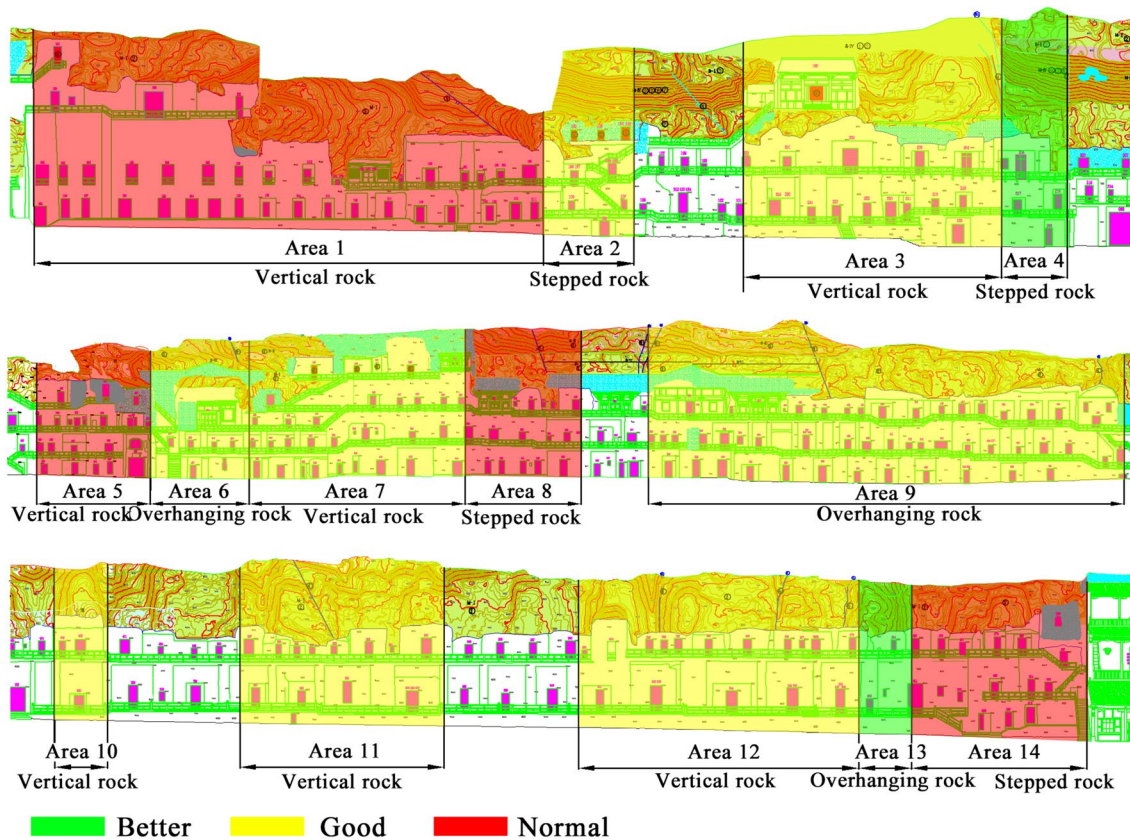
We consider the sliding failure as an example of this case. After investigating the cliff and fissure close to the 100th Cave of the Mogao Grottoes, we simplified the profile of the dangerous rock mass into a wedge according to the theory of the limit equilibrium method.

Subsequently, we obtained the typical profile of the Mogao cliff (Fig. 13A). It is assumed that the sliding surface comprises a fissure and its potential failure surface. The self-weight of the dangerous rock mass is denoted as  $G$ , the horizontal seismic force generated by an earthquake is denoted as  $P$ , the hydrostatic pressure after the fissure is filled with water is denoted as  $F$ , and the frictional force generated by the dangerous rock mass on its sliding surface is denoted as  $\phi$ . Hence, we can calculate the safety factor of the dangerous rock mass by balancing the anti-sliding force and downslide force on the failure surface. According to the requirements of the safety factor  $K$  under the state of reinforcement in the field of cultural relics protection in China, we can obtain the reinforcement force  $N$ , which is required to consolidate the dangerous rock mass, by recalculating the balance of the stress system and adding the anchoring force (Fig. 13B).

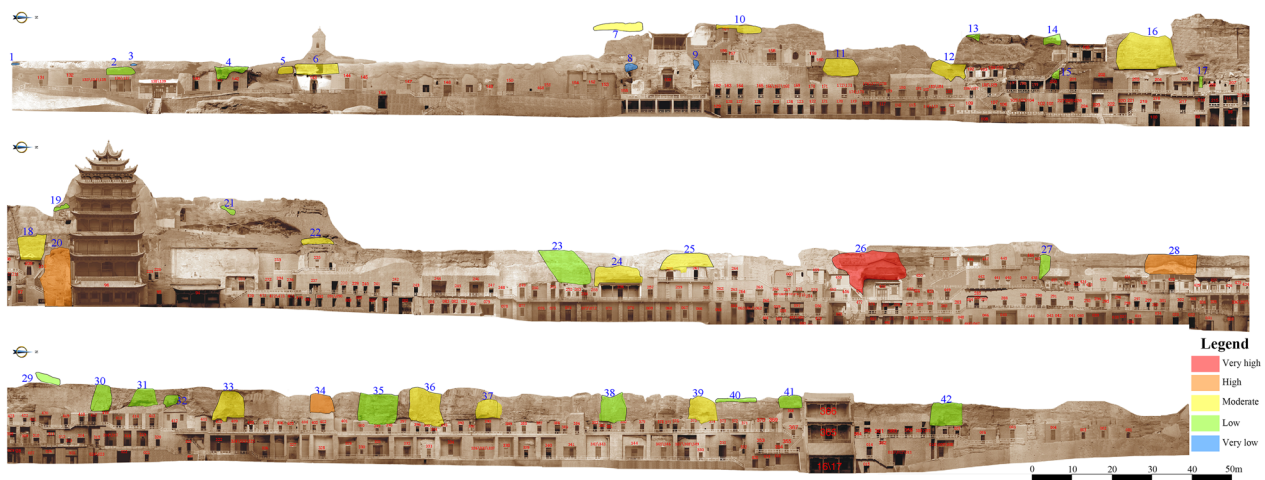
The equation between the safety factor  $K$  and those parameters is as follows:

$$K = \frac{((G + N \cdot \sin\theta) \cdot \cos\alpha - (F + P - N \cdot \cos\theta) \cdot \sin\alpha) \cdot \tan\phi + c \cdot L}{((G + N \cdot \sin\theta) \cdot \sin\alpha + (F + P - N \cdot \cos\theta)) \cdot \cos\alpha}$$





**Fig. 11** Quality assessment for rock mass of Mogao Grottoes [58]

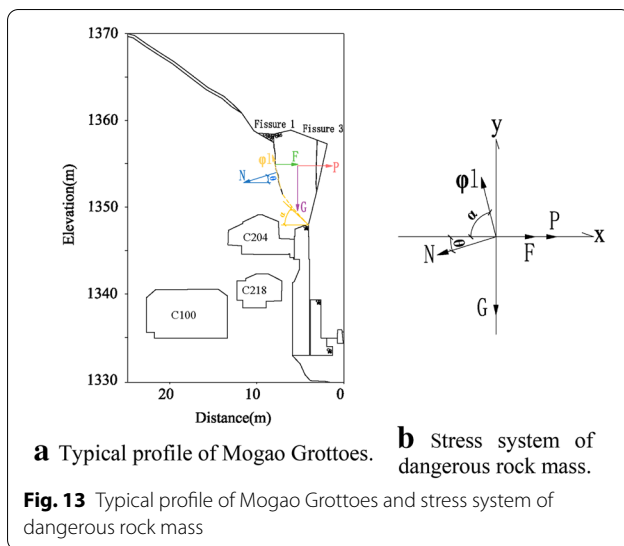


**Fig. 12** Hazard map of potentially dangerous bodies within cliff [57]

In Fig. 13 and the equation,  $K$  is the safety factor;  $N$  is the reinforcement force (kN);  $G$  is the weight of the dangerous rock mass (kN);  $F$  is the hydrostatic pressure when

the fissure is filled with water (kN);  $P$  is the horizontal seismic force generated by an earthquake (kN);  $\alpha$  is the angle of the sliding surface ( $^\circ$ );  $\phi$  is the friction angle ( $^\circ$ );





$c$  is the cohesion (kPa);  $d$  is the fissure depth (m);  $l$  is the length of the sliding surface (m);  $h$  is the fissure height (m);  $\theta$  is the anchoring angle ( $^{\circ}$ ).

#### Stability evaluation based on the in situ situation

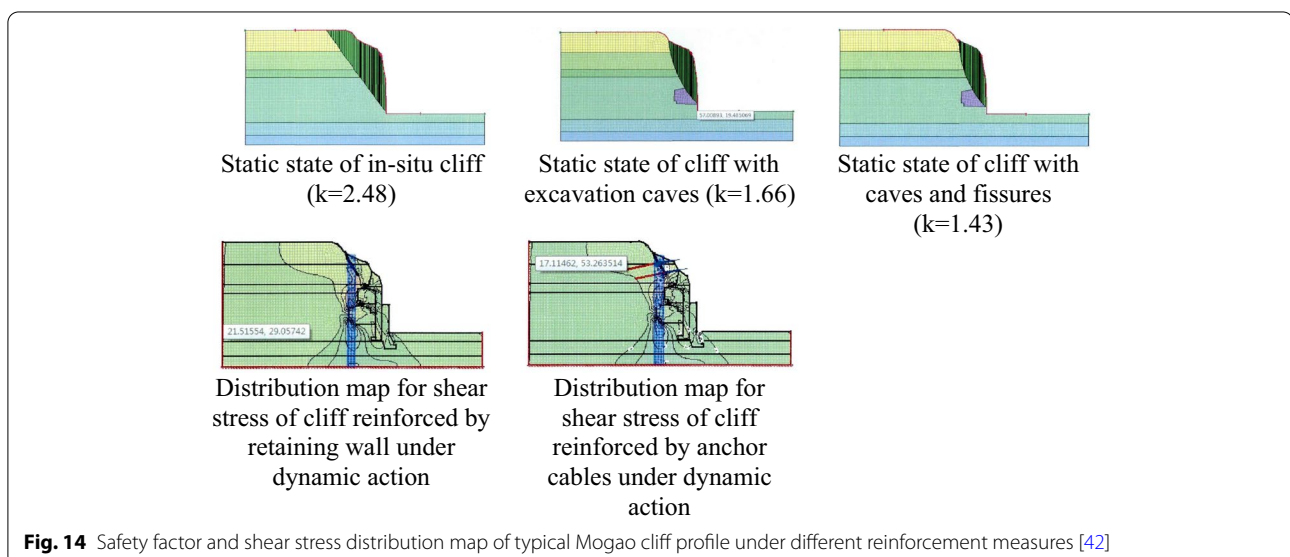
The calculated wedge balance is safer than the actual situation because the rock and soil mass are considered as a rigid body in the simplified calculation. Although this assumption is widely adopted in engineering practice, we cannot ignore that its economic benefits arise from being too conservative. The numerical simulation results are closer to the actual situation because different constitutive models and failure criteria can be selected according

to different types of rock and soil mass. Hence, the numerical simulation has obvious advantages.

Therefore, using the GEOSLOPE software, Pei [42] analyzed the static and dynamic response of five Mogao cliff profiles, including the in situ cliff of unexcavated caves, cliff with excavated caves, cliff with caves and fissures, cliff reinforced with a retaining wall, and cliff reinforced with anchor cables. Pei determined the failure surface, failure models, and evaluation criteria under different calculation situations. Additionally, Pei carried out groundbreaking work to calculate the reinforcement force required for reinforcement measures, and the safety factor after the reinforcement corresponded with the safety factor of the in-situ state in his calculation. Pei believes that the reinforcement measures using the force are the most reasonable measures, and his results have provided the theoretical foundation and a method for evaluating the reinforcement effect for the protection and reinforcement of the Mogao cliff (Fig. 14).

#### Simulation analysis of reinforcement measure reliability

The investigations of Pei using both wedge balance calculation and the GEOSLOPE software have provided reliable support for the protection and reinforcement of the Mogao cliff. However, the Mogao cliff is a rock mass with a particular rock structure that contains complex underground cavern structures. Hence, caution must be exercised when implementing reinforcement measures. It is not only necessary to calculate and verify the reliability of the proposed reinforcement measures before they are applied, but the long-term serviceability of the various measures after the reinforcement should be analyzed and



the key prevention areas of the caves should be investigated after the reinforcement.

Therefore, based on the analysis of the Mogao cliff's characteristics and the structure of reinforcement measures, Shi et al. [41, 53, 59] have used static and dynamic analysis methods to calculate the stability of the surrounding rock and ancillary facilities of the Mogao Grottoes. The above studies have also discussed the seismic stability evaluation method with regard to the surrounding rock of the Mogao Grottoes and its ancillary structures. In another study, the finite element analysis method was used to numerically simulate the displacement field and stress field distribution characteristics of the surrounding rock mass under dynamic loads with different peak acceleration, spectrum, and duration. Additionally, the dynamic response and variation rule of the Mogao cliff and ancillary structures were investigated under earthquake action. These studies have also pointed out key considerations for the future protection and reinforcement of the caves.

After the Mogao cliff was investigated and appropriate reinforcement measures were implemented, Guo [34] analyzed the stress, displacement distribution characteristics, and acceleration variation of the caverns under the action of gravity and seismic loads using the FLAC 3D software. Guo found that the sections of densely excavated caves in the middle of the Mogao cliff are not only prone to tensile stress concentration, but also produce large displacements. Guo also found that the caves at the top of the cliff produced large displacements under seismic loads.

These studies have also provided a reliable theoretical foundation for the protection and management of the Mogao Grottoes. In addition, we have summarized the key considerations included cliff, caves, and ancillary facilities, which should be focused on preservation, management, and research in the future. The details are shown in Table 2.

**Protective monitoring of Mogao cliff**

With the formulating and implementing of Principles for the Conservation of Heritage Sites in China in 2002, the concept of 'preventive measure' has appeared in Chinese industry standard document [60], and the revised China

Principles in 2015 further integrated preventive conservation into the system of cultural heritage conservation [61]. Thus the reinforcement concept has been changed in China. Meanwhile, the protection and reinforcement of Mogao cliff has undergone experimental reinforcement, rescuing reinforcement, and scientific reinforcement since 1956. Especially in the stage of the scientific reinforcement, the reinforcement skills have been effectively improved and a large number of cultural relics have been rescued under the support of international cooperation and a lot of scientific research results. All the cliff of Mogao Grottoes has been effectively protected and reinforced, and the potential dangers of cliff stability have basically been eliminated. In this context, the protective measures for the Mogao Grottoes gradually transformed from 'rescuing protection' to 'preventive protection'. Only by actively preventing and eliminating all types of unfavorable factors that affect the conservation of the Mogao Grottoes, can we extend the life of the Mogao Grottoes to maximize extent and slow down the decline of wall paintings and painted statues. Thus, we can completely conserve the information and outstanding value of the Mogao Grottoes. Therefore, it is necessary to develop and construct a risk monitoring and warning system [21]. Based on the long-term practical experience of conservation, research, and promotion, Dunhuang Academy has constructed a three-in-one protective monitoring and warning system for the daily inspection, regular monitoring, and early warning monitoring of the Mogao cliff.

**Daily inspection of Mogao cliff**

In the study by Sun [62], the inspection methods of the Mogao relics were summarized into four types: annual inspection, daily inspection of caves open to tourists, inspection for emergencies, and inspection of key sections. The inspection of the cliff is part of the Mogao inspection.

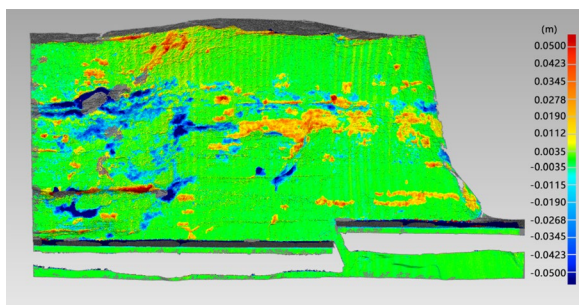
In the annual inspection, a fixed workgroup consisting of approximately 10 staff members investigates every section of the Mogao cliff, compares the results with the data of the previous year to discover changes in the cliff over the last year, and the inspection results are eventually collated and archived. The daily inspections are mainly conducted according to the opening conditions of the Mogao

**Table 2** Table of the key prevention areas in the future

Types	Cliff	Caves	Ancillary facilities
Key considerations	Fissure	① Thin roof caves ② Thin Wall between caves ③ Top and corner of caves ④ Caves near the top of the cliff ⑤ Densely distributed caves	① Facilities which have produced displacements ② Reinforcement measures separated from the cliff



**Fig. 15** Position of 3D scanning



**Fig. 16** Deformation map based on the comparison between 2009 and 2016 results

Grottoes during the busy tourist season. General inspections are carried out once a week in the busy season and once every two weeks off season. Emergency inspections are mainly conducted after natural disasters such as earthquakes, heavy rainfall, floods, and sandstorms, and emergency plans are initiated as needed.

#### Regular monitoring of Mogao cliff

The regular monitoring of the Mogao cliff supplements the inspection of the key section. A 3D scanner and a total station are used for regularly inspect the development of various types of diseases on the Mogao cliff.

Presently, the cliff of the Mogao Grottoes is in a stable state and it is thus possible to effectively monitor the displacement of rock mass under earthquake loads, control the reinforcement process, and evaluate the reinforcement effect. The total station is regularly used in the regular and fixed-point monitoring of typical parts with high cliffs, poor rock mass quality, large number of caves, and high risk. The monitoring period is once every 6 months. Moreover, the weathering progress of the cliff's surface can be ascertained by comparing the results obtained from a regular 3D scan. For example, we scanned the typical weathering cliff between the 203rd Cave and 204th Cave in 2009 and 2016 (Fig. 15). The deformation map of

the 3D models obtained by comparing the two laser scans is shown in Fig. 16. The green part indicates the deformation section within 3.5 mm, which means that there was no deformation on the cliff over the last eight years. Hence, the blue and orange sections may have originated from the consolidation and repairs that took place from 2009 to 2016.

Comprehensive and multi-purpose cliff monitoring provides a strong guarantee for the stability and weathering protection of the Mogao cliff and ensures the safety of cultural relics, personnel, and equipment.

#### Early warning monitoring for Mogao cliff

The monitoring and warning system for the Mogao cliff is an important part of the risk monitoring and early warning system framework for the Mogao Grottoes, and focuses on the stability of the cliff body, water vapor content and its migration in the rock, and weathering of the cliff body. The grotto environment, which comprises the meteorological environment, water environment, earthquakes, vibration, and sandstorms, has been added to the monitoring scope. The monitoring system comprises a front-end data acquisition system and a monitoring and early warning system. In summary, the overall objective of monitoring changes, predicting and pre-controlling risks, and pre-consolidating protection has been achieved at the site of the Mogao Grottoes [21].

#### Discussion

The protection of the grottoes' cliff is a systematic project based on practical experience, and must be fully considered the current preservation situation, systematically evaluate whether or not intervention is needed, deeply analyze if the stability of the cliff should be consolidated according to the in-situ state, calculate and analyze the effectiveness of protection and reinforcement measures in solving practical engineering problems, and finally evaluate the effects before and after reinforcement from a practical viewpoint.

This paper presents a full review of the relevant literature and materials pertaining to the protection of the Mogao cliff. The long-term practical experience with regard to conservation, research, and promotion is reviewed and summarized, and the methods for evaluating the preservation state, calculating and analyzing the stability of the Mogao cliff, constructing protective measures, and carrying out protective monitoring are systematically discussed.

To evaluate the preservation state, we comprehensively evaluated the rock mass quality of the Mogao cliff and assessed the risk of risk-prone sections in the assessment results using the grey mathematical theory and an expert



system. This study is based on the deep understanding of the stratum property characteristics, cliff shape characteristics, migration state of moisture, physical and mechanical properties of the rock mass, physical properties of water, and various types of diseases of the cliff and their characteristics. This study provides the basis for the protection and reinforcement of the cliff and the conservation and management of the Mogao Grottoes.

To calculate and analyze the stability of the Mogao cliff based on the evaluation of rock mass quality and risk assessment for dangerous rock masses, we used the method of analyzing the safety factor compared with the in situ state, and calculated the reinforcement force using wedge balance theory. Subsequently, we simulated and checked the failure surface of the Mogao cliff profile, and investigated the effectiveness of the reinforcement measures under the static and dynamic state. Additionally, we verified the reliability of the reinforcement measures based on the 2D calculation results and simulated the key areas after reinforcement using a 3D numerical simulation software that closely resembles the natural conditions. The investigations reported herein can provide theoretical support for the reinforcement and stability evaluation of a rock mass.

Regarding the construction of protective measures, the history of protective and reinforcement measures for the Mogao cliff was reviewed, and the reinforcement techniques and concepts for the Mogao cliff were summarized and scrutinized. A protection and reinforcement system is proposed based on the principle of retaining historical conditions, the basic management plan of monitoring/early warning/maintenance, and the reinforcement methods for propping/anchoring/grouting/anti-weathering.

With regard to protective monitoring, we summarized and formed a three-in-one protective monitoring system comprising daily inspection, regular inspection, and early warning monitoring, which runs throughout the entire protection and reinforcement process.

Based on these investigations, we propose reliable and comprehensive protection and reinforcement techniques for the Mogao cliff, and a management system for the Mogao Grottoes. The proposed techniques and system can be used in conservation projects of heritage sites similar to the Mogao Grottoes.

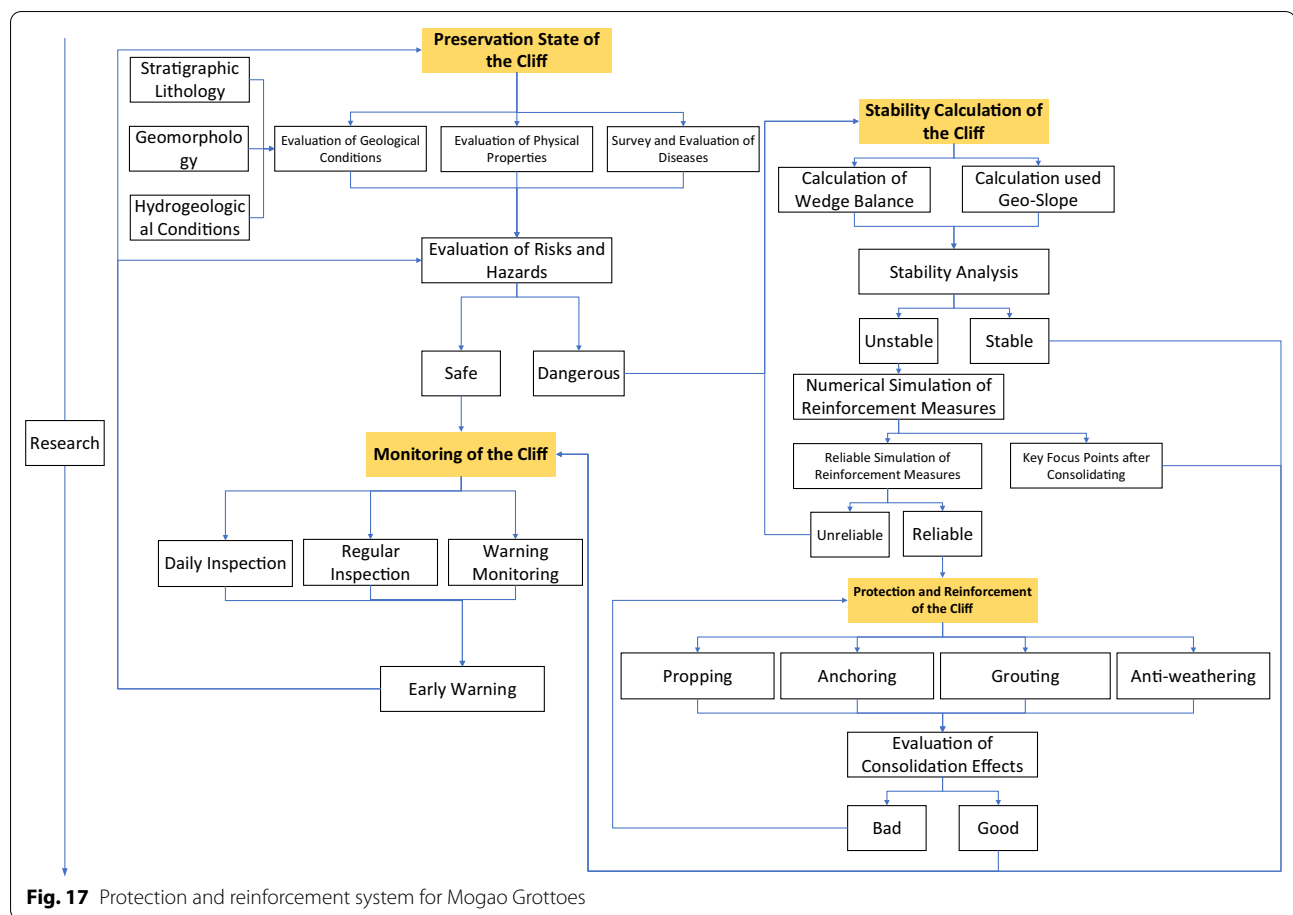
However, based on the conclusions drawn from practical experience, there are still various shortcomings in the current system for evaluating the conservation state, calculating the stability, constructing protective measures, and carrying out protective monitoring. For example, in the physical and mechanical testing of rock mass properties, it is impossible to collect a perfect specimen to investigate the cliff parameters owing to the

characteristics of the Mogao sandy conglomerate. The stability calculation results are often too conservative because the constitutive model of the cliff has not been established, and this can result in the inefficient use of manpower, material resources, and financial resources. In the evaluation of the protection and reinforcement effect, although Dunhuang Academy has developed a series of detection devices for use in combination with practical experience, the problem of insufficient testing apparatus still exists. With regard to protective monitoring, some protection and reinforcement projects have failed to realize monitoring throughout the entire protection and reinforcement process owing to the inadequate development of science and technology and limited financial resources at the earlier stage of protection and reinforcement for the Mogao cliff.

To more effectively protect and manage similar grottoes, we propose a protection and reinforcement system for the Mogao Grottoes based on research and the practical conservation experience obtained at this site (Fig. 17).

A protection project for a grotto often begins with the assessment of the preservation state of its cliff. If the result is dangerous, the next process is stability calculation of the cliff, else it is monitoring and early warning the cliff. During the monitoring process. If there is no danger on the cliff, then the manager will regularly evaluate the preservation state of the cliff. When the early warning mechanism is triggered, a new round of risk and hazard assessment will be carried out. If the result is safe, the monitoring will be continued. Instead, the next process is stability calculation of the cliff. When the calculation result is stable, the dangerous area is continuously monitored and evaluated; else the dangerous area of the cliff will be protected and reinforced. However, the reinforcement project cannot be directly implemented before the reinforcement. Firstly, it is needed to analyze the reinforcement measures through the numerical simulation calculation because it is evaluated on computer instead of cliff. It can not only evaluate the reliability of the reinforcement measures, but also tell the managers the areas that need attention after the reinforcement. Only the calculation and evaluation of the reinforcement measures are reliable can the real reinforcement be started. After the reinforcement project, it is necessary to systematically evaluate the reinforcement effect of the reinforcement measures. If there is any problem with the reinforcement effect, the reinforcement measures must be improved until passing the evaluation. After all the reinforcement, the reinforcement measures and the reinforced cliff shall be included in the monitoring system.

In the whole process, the most important task is the research and investigation. Each work for a grotto must



be based on the deeply study before the implementation of reinforcement measures. It is not possible to directly quote the research results and parameters of other sites. For example, in the monitoring of cliff, the setting of early warning values must be determined after a large number of studies on the cliff of the grotto, rather than directly quote the warning value of the Mogao Grottoes or other caves.

In these steps, the assessment of the preservation state of the cliff mainly includes the risk and hazard assessment for the geological conditions, the physical and mechanical properties of the rock body, and the disease in the cliff. The monitoring mainly includes daily inspections, regular inspections, and early warning monitoring. The stability calculation mainly includes calculation of wedge balance and numerical simulation calculation. The reinforcement measures mainly include propping, anchoring, grouting, and ant-weathering.

## Conclusion

This paper summarizes and teases out a method for evaluating the preservation state of the Mogao cliff, a method for calculating and assessing the stability factor before

and after consolidating the cliff, and the protection and reinforcement techniques, conservation history, and protective monitoring of the Mogao cliff. The protection and reinforcement system of the Mogao cliff is extensively discussed. The proposed conservation and management system can be used for similar grottoes. The main conclusions drawn from this study are as follows:

1. Based on the discussion in this paper and according to practical experience accumulated over the 65 years of preserving the Mogao Grottoes, it is concluded that the cliff protection and reinforcement measures are reliable and effective, and can be used for similar grottoes. The protection and reinforcement system is based on extensive research, on monitoring throughout the entire protection process, on the principles of evaluating the preservation state and stability of the cliff, and on the reinforcement measures of propping, anchoring, grouting, and anti-weathering.
2. The study work should be carried out in every phase of protection and reinforcement. It can provide quantitative parameters for the reinforcement of the Mogao cliff and indicate dangerous sections of the cliff

by evaluating the cliff's conservation state. It can provide the foundation for calculating the reinforcement force, analyzing the reliability, and discovering the key point after reinforcing by calculating the stability of the cliff. The principle governing the protection and reinforcement of the cliff is to completely retain the historical conditions. The basic management plan consists of monitoring, warning, and maintenance, and the consolidation effect should be evaluated after reinforcement. Protective monitoring comprises daily inspection, regular inspection, and warning monitoring, and should be used throughout the entire reinforcement process. Thus, changes can be monitored, the risks can be predicted and pre-controlled, and the protection can be reinforced in advance.

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### Authors' contributions

XW and YW conceived and wrote this article. QG collected the data on historical reinforcement. QP completed numerical simulation by GEOSLOPE software. GZ analyzed the result of 3D scanning. YW also contributed to data analysis and processing. All authors read and approved the final manuscript.

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### Availability of data and materials

Most of the data on which the conclusions of the manuscript can be found in the references or CNKI.

### Declarations

### Competing interests

The authors declare that they have no competing interests.

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