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Damage and conservation of the high cliff on the Northern area of Dunhuang Mogao Grottoes, China

Abstract The Mogao Grottoes have 750 caves, 45,000 m^2 of wall paintings, 2,415 painted sculptures, five wooden temple fronts from the Tang and Song dynasties, and thousands of columns with carved designs of lotus flowers and ornamental tiles. The Mogao Grottoes are one of the largest and best-preserved Buddhist art treasure houses in the world. The diverse range of wall paintings and sculptures and the profound and varied Buddhist art at the site prompted UNESCO to list the grottoes as a World Heritage Site for its cultural values. The Mogao Grottoes consist of two areas: the Southern Grottoes Area and the Northern Grottoes Area. Almost all the Buddhist art treasures are located in the southern area. The northern area is mainly where the monks and the creators of the arts of Dunhuang resided. In this paper, the causes of damage to the grottoes are analyzed by investigating the geohazards occurring on the side slopes on the high cliff in the northern zone. This paper will analyze the causes of deterioration through the investigation of deterioration in the upper section of the cliff face and goes on to discuss the main causes of deterioration of the cliff body: the development of fissures, wind erosion, rain erosion, and flood scouring. The following measures have been undertaken to deal with the above problems: bolt anchoring, grouting of fissures, use of bracing supports in some areas, and stabilization of caves and cliff face. Through the above measures, the upper section of the upper face in the northern zone has been effectively treated according to the principles of "restoration to historic condition and not altering the historic appearance."

Keywords Dunhuang Mogao Grottoes · Cliff · Damage · Protection · Weathering

Introduction

The Dunhuang Mogao Grottoes (Fig. 1a) are excavated into the cliff face at the eastern foot of the Mingsha Mountain in Dunhuang city in the northwest of China (Fig. 1b). The caves stretch about 1,600 m long from north to south, consisting of five tiers from the top to the bottom. The Grottoes have a history of more than 1,600 years. They were first built in A.D. 336, and later became a huge group of caves with rich contents after construction through the Sixteen Kingdoms (A.D. 304–439), Northern Wei (A.D. 386–534), Western Wei (A.D. 535–557), Northern Zhou (A.D. 557–581), Sui (A.D. 581–618), Tang (A.D. 618–907), Five Dynasties (A.D. 907–979), Song (A.D. 960–1279), Western Xia (A.D. 1038–1227), and the Yuan Dynasties (A.D. 1206–1368). Until now, 750 caves with 45,000 m^2 of wall paintings, 2,415 painted sculptures, five Tang and Song wooden cave temple fronts, and thousands of columns with carved designs of lotus flowers and ornamental tiles have been preserved. These constitute the largest, best-preserved Buddhist art treasure house in China and perhaps even in the world (Dunhuang Academy 2000). Because of the extremely rich wall paintings and sculptures and the profound and diversified Buddhist art, the grottoes were listed as a World Cultural Heritage Site by UNESCO in 1987.

The northern area is an important part of the Mogao Grottoes, while 248 of a total of 750 caves are located on this area. The full length of the cliff face is more than 700 m, and the average height is about 18 m. Although most of the caves in this area have no wall paintings or sculptures, there are some wall paintings that have very high art value, such as caves 461–465 (Fig. 2). These caves in the northern area had been neglected for a long time. However, since the 1980s, Dunhuang Academy has undertaken a series of excavations in the northern area and discovered that these caves were mainly the residences of the creators of the artistic works and monks at Dunhuang; they included caves used by the monks as living quarters, meditation caves, burial caves, and caves for storage. The archaeological excavations, for the first time, revealed the nature and function of the northern area caves, the relationship between the southern and the northern area, and thereby proved that the northern area caves are an important part of the Mogao Grottoes with special historical, artistic, and scientific value (Peng and Wang 2000).

Although some parts of the cliff face in the northern area have no caves, probably due to geological reasons (sand accumulation or weak interlayer in the rock bed), caves are also densely distributed on the other part of the cliff, like honeycombs in a very irregular form up to five or six stories as shown in Fig. 3.

The host rock of the Dunhuang Mogao Grottoes, Quaternary conglomerate, is characterized by weak calcareous cementation and poor resistance to weathering. Therefore, weathering, fissure development, and collapse of the cliff surface can be easily caused due to temperature variation, wind, and rainfall erosion. These kinds of geohazards could cause further damages to the caves (Li 2002, 2003). According to historical records, there were more than 1,000 caves and many wooden temple fronts in front of the Tang Dynasty caves (Li 1981). However, there are no less than 500 well-preserved caves, indicating that many caves have been destroyed. In the 1960s, caves in the south area were stabilized with retaining walls that controlled the further deformation of the dangerous cliff surface to a large extent. However, as an important component of the Mogao Grottoes, the north area still suffers from a different type of deterioration and needs to be conserved. Based on these needs, field investigations were performed to reveal the major form of damage to the north area and to find out suitable countermeasures for effectively controlling and ensuring the safety of caves on the north area.

Geological condition of the cliff rock in the northern area

The Dunhuang Mogao Grottoes are located on the upper edge of Daquan River alluvial fan, a cliff body which has been cut out by the Daquan River. The cliff body joins the Mingsha Mountain to

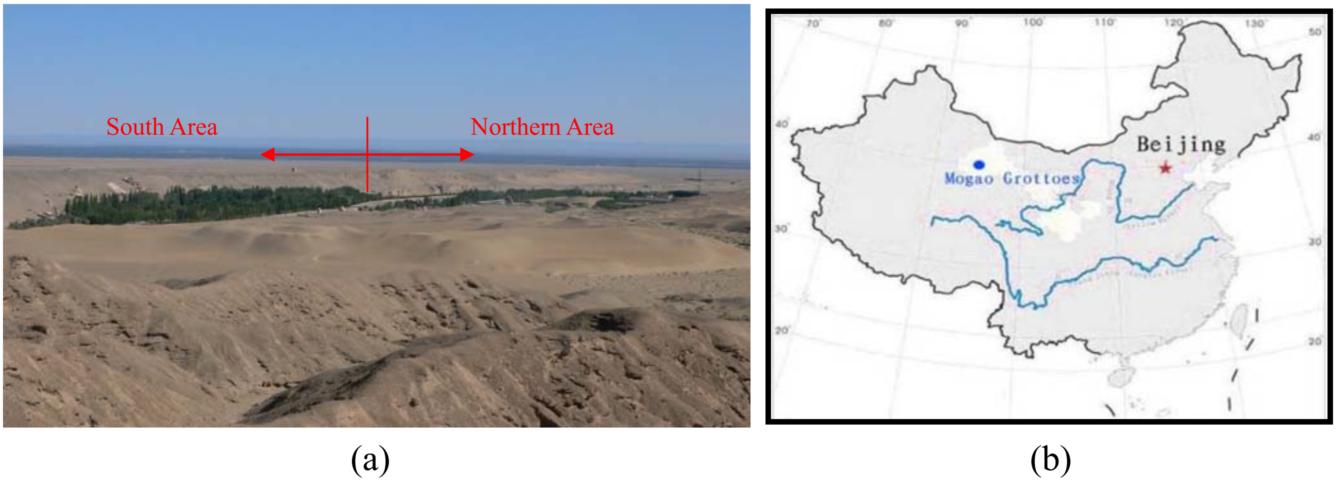

Fig. 1 Dunhuang Mogao Grottoes (**a**) and its location in China (**b**)

the west and the Sanwei Mountain to the east and is composed of Presinian metamorphic rocks. The Gobi Desert is to the north. There are several faults between the Sanwei Mountain and the sedimentary conglomerate; the nearest fault location is about 1 km far from the Mogao Grottoes (Fig. 4).

Geological investigation shows that the strata at Mogao Grottoes site can be divided into three series, i.e., the lower Pleistocene series (Yumen group, Q_1), the mid-Pleistocene series (Jiuquan group, Q_2), and the upper Pleistocene series (Gobi group Q_3). Because the caves of the Mogao Grottoes are distributed in the Jiuquan (Q_2) group, which is mainly composed of conglomerates, so the Q_2 conglomerates are also called “a cave stratum” (Li 1986). The strata can be divided further into four engineering geological rock groups, namely, A, B, C, and D group from the upper part to the lower one as shown in Fig. 5 (Wang et al. 2000).

Group A Thick-bedded conglomerate interlaid by thin-bedded fine conglomerates with a thickness of 6.8 m. The composition of this group is 81% gravel, 16% sand, and 3% silt and clay with a mean grain size of about 15.7 mm in argillaceous and calcareous cementation.

Fig. 2 Exquisite wall paintings in cave 465 of the northern area of the Mogao Grottoes

Group B Thin-bedded sandstone with a thickness of about 2 m. This group consists of 16% gravel, 79% sand (mainly fine sand), and 5% silt and clay with a mean grain size of about 0.166 mm. This rock group appears as a sandstone lens in the cliff surface at higher level.

Group C Thick-bedded fine conglomerate interlaid with thin-bedded conglomerate. This group has a thickness of about 14.5 m, and contains approximately 76% gravel, 22% sand, and 2% silt and clay with an argillaceous and calcareous cementation.

Group D A thick-bedded fine conglomerate interlaid with a medium–coarse conglomerate with a thickness of about 6.0 m. This group contains 50–60% gravel, 35–45% sand, and 5% silt and clay with a mean grain size of 2.0–3.8 mm in calcareous and siliceous cementation.

The particle size distribution and mechanical strength for layers A, B, C, and D are listed in Tables 1 and 2.

Because the genesis of the stratum is alluvial proluvial, the layers of each strata type are not very regular. All the four rock groups can be seen as high as the nine-storied pagoda in the southern area. The southern and northern areas belong to the same series of strata. As a lenticular body, layer B is missing in many places.

Discontinuities responsible for cliff damage

There are a large number of fissures in the cliff in the northern area which greatly influence the stability of the slope rock or caves. Figure 6 shows that most of the fissures on the slope surface, while Table 3 lists their length and width. All the fissures can be divided into three categories based on generation reason, namely, tectonic fissure, unloading fissure, and longitudinal fissure as explained below.

Tectonic fissure

The fault zones which are relatively close to Mogao Grottoes include the Sanwei fault and the Guanyinjing fault; the Sanwei fault is located in front of Sanwei Mountain and is about 1 km from the nearest part of the Mogao Grottoes (Fig. 7). Under the influenced of the overthrust movement of the Sanwei Mountain along the Sanwei fault, a series of tectonic fissures are generated in the cliff rock in the north area.

Fig. 3 Cliff face in the northern area of Dunhuang Mogao Grottoes

The tectonic fissures follow a NE40–60° direction with a dip angle of 60–85° cutting through the cliff rock from the top to the bottom (Fig. 8).

Unloading fissure

The unloading fissures were generated as a consequence of lateral unloading of the cliff rock during the cliff excavation by the river. These fissures, widely distributed in the whole precipice face, stretch almost parallel to the cliff face in the direction of SN/75–85°E, open wide at the top, and open narrow at the bottom. Generated latterly than the tectonic fissures, the unloading fissures stretch parallel to the cliff face and extend only to tectonic fissures as termination boundaries. This group of fissures separates some of the big rock mass from the host rock of the cliff and mostly cut across the caves' two sidewalls, vault, and floors of the caves. The large rock mass may move down along the fissure faces, causing collapse under gravity (Fig. 9).

Longitudinal fissures

Some small-sized fissures exist on the vault partly caused by the slow sinking of overburden rock mass after cave excavation; they are so named because they are distributed along the longitudinal axis of the caves. The longitudinal fissures stretch 2–3 m upward from the roof of

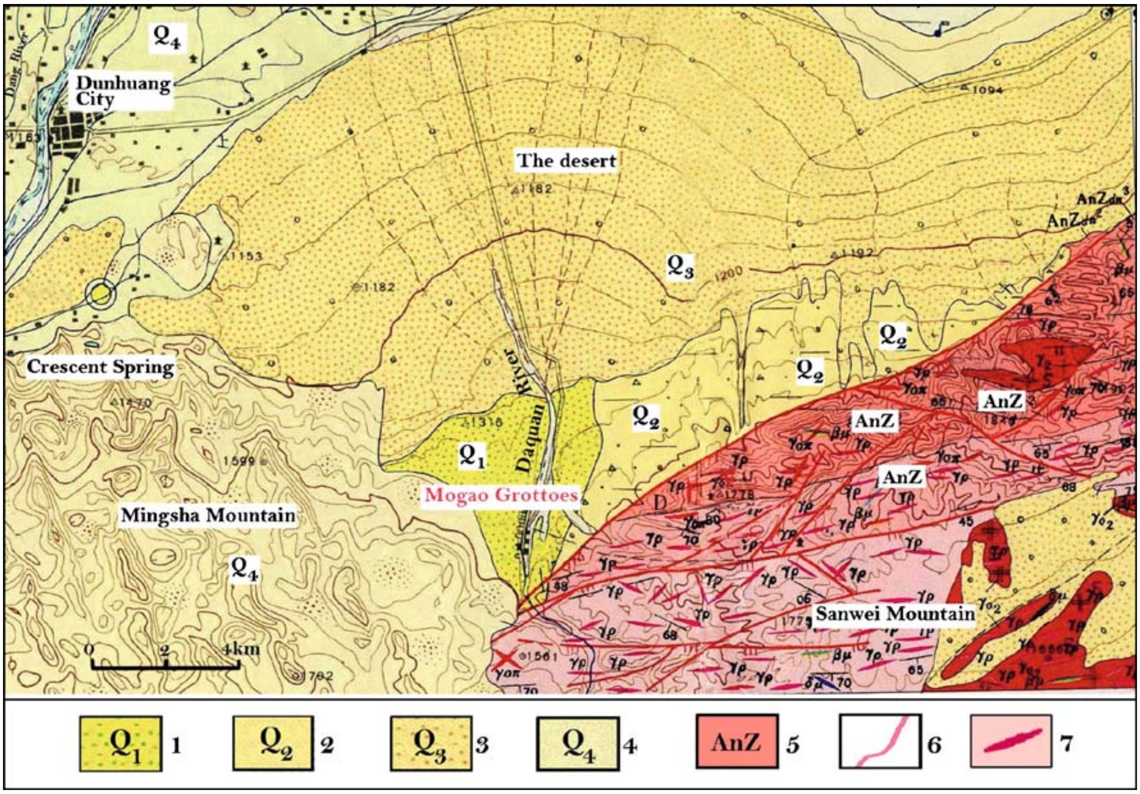

Fig. 4 Geological map of the periphery of the Mogao Grottoes. *1* Lower Pleistocene series, *2* mid-Pleistocene series, *3* upper Pleistocene series, *4* Holocene series, *5* Presinian system, *6* fault, *7* dike

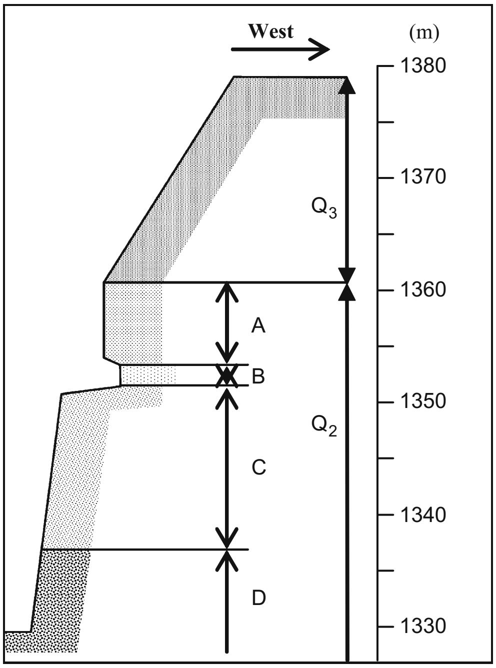

Fig. 5 Stratigraphic section of Dunhuang Mogao Grottoes

Table 1 Particle size distribution of the grottoes strata

Rock group	Rock type	Gravel (%)	Sand (%)	Silt and clay (%)	Mean grain size (mm)
A	Conglomerate	81	16	3	15.7
B	Sandstone	16	79	5	0.16
C	Conglomerate	74–79	19–24	2	5.2–12.2
D	Conglomerate	50–60	5	2.0–3.8	2.0–3.8

Table 2 Statistics of the mechanical properties of the grottoes strata

Rock group	Mean peak compressive strength (MPa)		Mean peak tensile strength (MPa)		Wave velocity (parallel to bedding) V_p (m/s)
	Vertical to bedding	Parallel to bedding	Vertical to bedding	Parallel to bedding	
A	10.6	9.5	0.36	0.36	No data
B	16.3	12.6	0.47	0.62	1,200
C	12.4	8.6	0.33	0.47	1,500–1,930
D	19.4	15.8	0.60	0.47	2,100–2,300

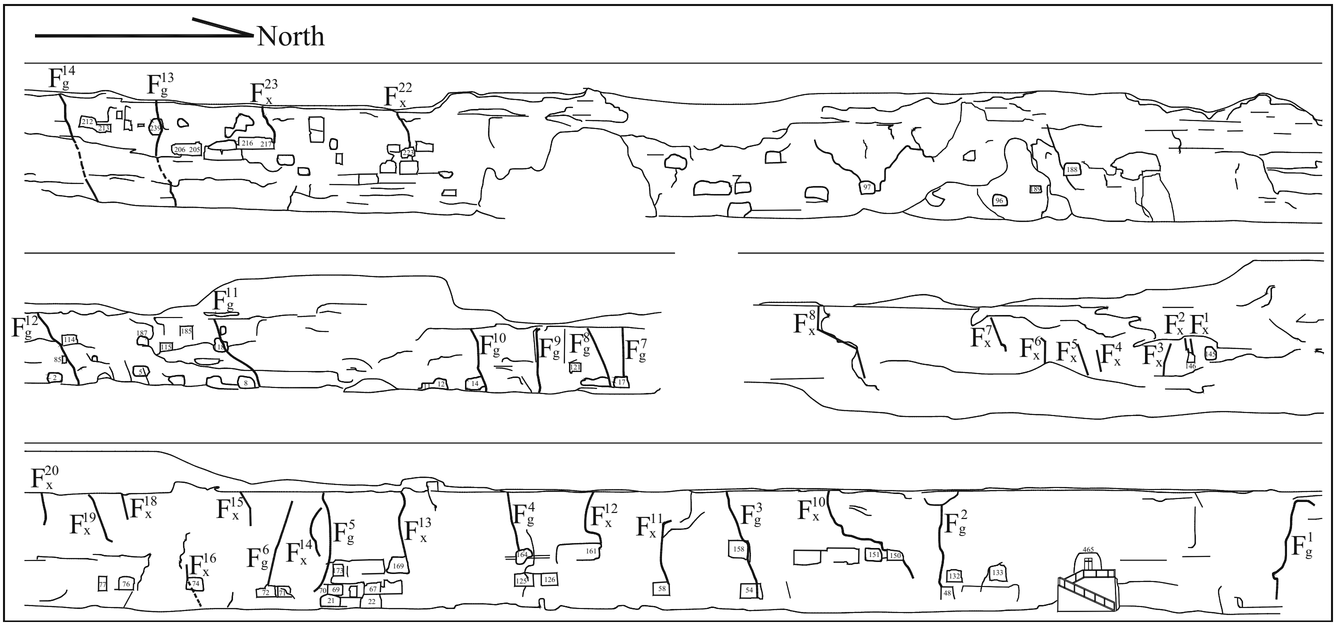

Fig. 6 Representative fissure appeared on the cliff of the northern area

the caves and develop inward from the cliff surface. Due to their relatively small scale, longitudinal fissures can only influence the stability of individual caves in general and have little effect on the overall stability of the cliff body.

Damage of grottoes cliff

The collapse of rock is the greatest threat to cave safety in the north area. Because the caves in this area are concentrated so closely that they are apart from each other in a distance less than 5 m, a rock collapse in cliff

Table 3 Spatial parameters of representative fissure

Fissure name	Length (m)	Width (cm)
F_g^{14}	17	<0.5
F_g^{13}	16	<0.2
F_x^{23}	6	<0.5
F_x^{22}	6	>1
F_{B225}	5	>1
F_{B195}	3	Unknown
F_{B188}	11	Unknown
F_{B94}	2	>20
F_g^{12}	15	<0.5
F_g^{11}	16	1
F_{B14}	4	<0.5
F_g^{9}	12	Closed
F_g^{8}	13	<1
F_{B18}	2.5	1–2
F_x^{19}	8	Unknown
F_{B76}	1.5	2–3
F_{B74}	2	0.2
F_g^{5}	15	2–3
F_g^{4}	8	Closed
F_{B125}	2	1–2
F_x^{11}	9	<1
F_g^{3}	8	Closed
F_x^{10}	18	1–3
F_g^{2}	15	2–3
F_{B133}	4	<1
F_g^{1}	15	Closed
F_x^{2}	1.5	1–2
F_{B146}	2	<2

F_g tectonic fissure, F_x unloading fissure, F_{B133}, e.g., fissure observed in grotto 113

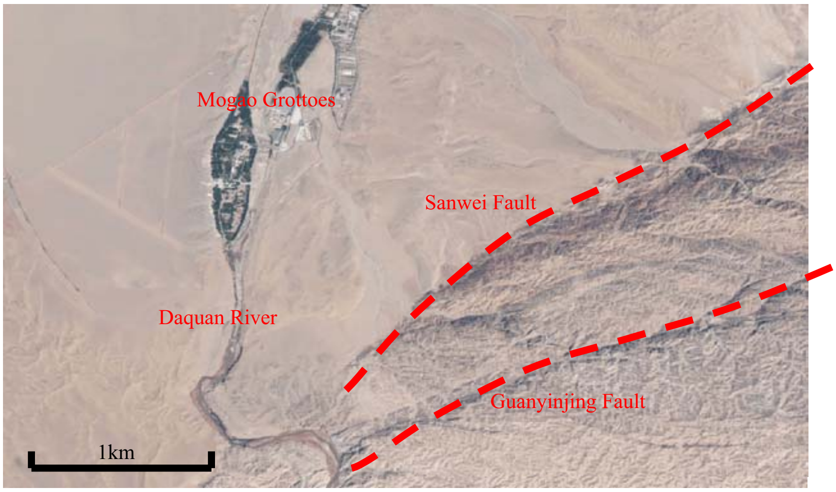

Fig. 7 Geological faults close to the Mogao Grottoes

surface will bring worst damage to several caves. Investigation shows that more than 75% of the total 248 caves in north area are damaged at different levels by rock collapse. For example, 88 caves (accounting for 35%) are partially damaged, 99 caves (35%) lost their east (gateway) walls, and nine caves (3.5%) kept partial traces remained. Detailed analysis reveals that the free surface (e.g., cliff surface and cave opening) and different discontinuities are mainly responsible for the sudden rock collapse as described in the following. On the other hand, natural erosion from weathering, rainfall, air-blown sand, and river flood also contributed to the slow damage of the cliff rock.

Collapse caused by intensive excavation

From a viewpoint of geological engineering, the intensively excavated openings interrupt the balanced state of initial stress in the cliff rock, resulting in a stress concentration in the vertical rock walls between neighboring caves and, therefore, a roof collapse. Damage of many caves in the intensive district will promote the instability of partial slope, as shown in Fig. 10.

Collapse caused by fissure cuts

The cliff body of the Mogao Grottoes is cut into blocks of different sizes by the tectonic fissures perpendicular to the surface and the unloading fissures parallel to the surface of the cliff body. Figure 11 is the statistical results of the representative fissures observed. From Fig. 11, it can be easily found that the unloading fissures, almost parallel to the cliff surface with big lengths, greatly attributed to the large-scaled, dangerous rock blocks on the cliff, which should be mainly stabilized for conservation of the northern area. Meanwhile, the tectonic fissures can also become the channels through which the rainwater could penetrate toward the deep part of the cliff body and then accelerate the weathering of the rock mass. According to the statistics, there are, in fact, 57 caves cut by fissure in the northern area, accounting for 23% of the total caves. This means that the existence of fissures is the first threat to the safety of the caves. Figure 12 shows a small collapse of the cliff body cut by a vertical unloading fissure.

Collapse caused by weak interlayers

As an alluvial formation, there are sandstone lens interbedded in the strata, which are very loose and form weak surfaces under weathering conditions. Therefore, the upper hard rock, hanging on weak bottom, subsides gradually under gravity, generating vertical tensile fissures and the collapse of small rock blocks (Fig. 13).

Fig. 8 Tectonic fissures appeared in a part of the northern area

Fig. 9 Unloading fissures parallel to the cliff face of the northern area

Damage due to weathering

The cliff rock of the Mogao Grottoes is weakly cemented by calcareous and argillaceous materials, with very low strength, large porosity, and poor durability in water (Li 2003). The argillaceous cement contains a relatively large amount of clay minerals, such as montmorillonite and chlorite. It is discovered that the temperature and humidity variance of the environment can easily cause the clay minerals, especially montmorillonite, to swell and shrink under wet–dry cycles. The repeated changes in weather condition, consequently, result in the destruction of the cemented structure and the decline of rock cohesion, further resulting in the partial collapse of the cliff rock or rockfall. Typical rock specimens sampled from the slope surface, representing the weathered rock, and the specimens sampled at a depth of 30 cm, representing the unweathered rock, were tested (Table 4). From Table 4, it can be seen that both the density and the compression strength of the cliff rock had been reduced considerably due to weathering.

Damage due to erosion from rainfall

In the north area of the Mogao Grottoes, there are also big or small gullies widely distributed in the cliff top. This means that rainwater erosion plays a role in cliff damage in the long run. According to meteorological data, the average precipitation of 16 years in the cave area is 40.44 mm, the main rainfalls concentrated greatly during the period from June to August (Fig. 14). In the recent decade, the recorded maximum rainfall is 15.7 mm during 2 h. Obviously, the total precipitation of Mogao Grottoes is very small but the distribution within a year is quite uneven. The sudden storm in summer is another major factor that leads to the destruction of the caves in the north area. It is observed that rainwater even penetrates into some caves at high level through vertical fissures, which is considered to be responsible for the greater damage and, finally, collapse of some caves in history.

Fig. 10 Intensive distribution of caves in the cliff face of the north area

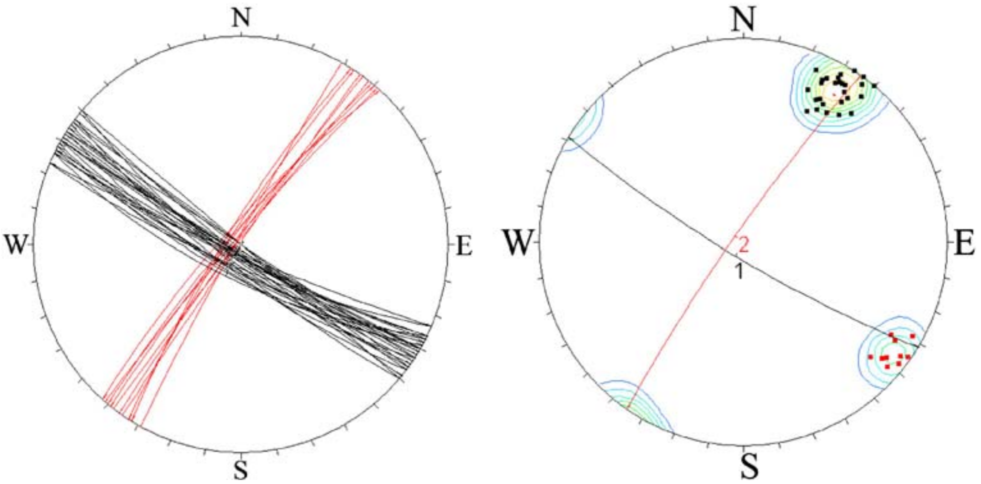

Fig. 11 Stereonet plots (lower Hemisphere and equal area) of representative fissures at the northern area. *Left* data plotted as planes total number of points=37. *Red lines* represent the unloading fissures and *black lines* represent the tectonic fissures. *Right* data plotted as planes total number of points=37. The contour increments every 10%

Damage due to river flood

Even the cliff rock was cut vertically by unloading fissure, the large-scaled rock mass could stand still without triggering factors such as earthquake or foot erosion. Unfortunately, the Daquan River flooded to the cliff foot in the north area in history (Yao and Peng 2007) until the flood dike was built in front of the north area in the early 1980s. Figure 15 shows the free surface eroded by the historical flood at the cliff foot where some caves were destroyed due to rock collapse along the flood erosion surface.

Damage due to wind erosion

Wind erosion causes serious damage to the cliff surface and even the interior wall surface of the open caves at Mogao Grottoes and the destruction of the precipice body. The cliff surface faces the east, so the wind-blown sand coming from the east strongly erodes the cliff surface and the open caves in the period of March to May, the sandstorm season of Northwest China (Huang et al. 2006; Qu et al. 1994, 1996). Influenced by the east wind and the varying rock properties, a large mount of wind-eroded grooves parallel to the rock formation has developed in the cliff face of the north area (Fig. 16).

Conservation/stabilization measures

Different from the general slope conservation project, the cultural sites conservation project not only needs to deal with damage to the cliff body but also the need to observe the principle of "maintaining historic condition when treating a site." Thus anchor technology that has little effect on the historic appearance of the cliff body has been adopted to stabilize the cliff body with supplementary measures that include fissure grouting, stabilization of the caves against weathering and water infiltration, and roof supports added in some locations. Through the application of a series of measures, the state of conservation of the cliff body in the north area of the Mogao Grottoes has been greatly improved.

Bolt anchor

Dangerous cliff blocks were mainly identified by unloading fissures occurrence, followed by a selection of stabilization measure. Taking into consideration the engineering and geological properties of the cliff body in the north area of the Mogao Grottoes, there are two main categories of measures that can be usefully applied in this zone: prestressed anchor cables and mortar-and-grouted bolts have been adopted in the anchoring of dangerous rock masses; prestressed anchor cables can be further divided into a pulling-force-type anchor cable and a pressure-type anchor cable, so as to meet the stabilization needs of different parts of the rock mass (Central Research Institute of Building and Construction 2005).

A pulling-force-type anchor cable is mainly used where there are relatively large volumes of dangerous rock mass; this anchor is a kind of controllable anchor cable. In crucial stabilization areas,

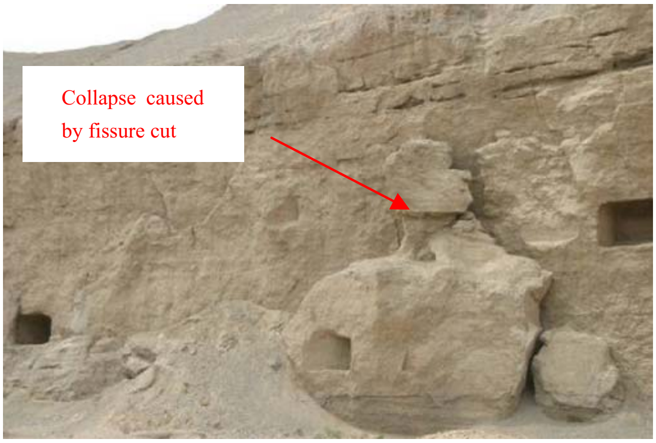

Fig. 12 A rock collapse caused by vertical unloading fissure

Fig. 13 Weak interlayer in the north area

Table 4 Physical characteristics of the weathered and unweathered cliff rock masses

	Bulk density ρ (g/cm^3)	Particle density ρ_s (g/cm^3)	Water absorption ω_a (%)	Porosity, n (%)	Compression strength (MPa)
Weathered rock	1.96	2.56	No data	23.4	2.40
Unweathered rock	2.39	2.56	3.3	6.8	20.30

an inner reaming technique has been adopted so as to improve the anchoring force of the hole in the anchor cable. A pressure-type anchor cable is mainly used in the dangerous rock masses with relatively small volume or the cliff face which has small cracks; it is a kind of local anchor cable. The advantage of this kind of anchor cable is that the force exerted on the mortar in the anchor holes is more manageable and it can stabilize unstable rock mass by anchoring the deep part of the stratum of cliff body, thus reducing the effects to the rock mass in the surface layer by the use of prestressed anchor cables. The mortar-and-grouted bolt is mainly used to stabilize thin, dangerous rock masses with small volume found in some localized areas where there is a high concentration of caves. In addition, an anchor bolt can also balance tensile forces produced by an anchor cable within a rock mass and optimize the loading of rock mass.

Figure 17 shows the stabilization principle for cliff rock by anchor cable. Mechanical analysis shows that the stability of the dangerous cliff block is greatly controlled by a shear failure under lateral earthquake force. According to the Chinese Seismic Intensity Zoning Map, the basic intensity of the Mogao site is VII, but the earthquake fortification intensity selected for the stabilization design is VIII because of the great importance of the stabilization project. The number of anchor cables needed for stabilization of a specific dangerous cliff block is calculated by the following equation:

$$N = \frac{K(W\sin\alpha + Q\cos\alpha) - (W\cos\alpha - Q\sin\alpha)\tan\varphi - cL}{(\sin\alpha\tan\varphi\cos\alpha)F}$$

where K=1.1 is the safety factor, W is the weight of the dangerous block, ϕ=50° is the inner friction angle of the cliff rock, c=0.1 MPa is the cohesion force of the cliff rock, α=45°+ϕ/2 is the angle of the sliding surface, L is the length of the sliding surface, Q=W×0.2 g is the lateral seismic force under earthquake fortification intensity of VIII, N is the number of anchor cables needed for stabilization of a specific dangerous cliff block, and F=40 t is the antipulling force of an anchor cable determined by in situ pulling-out test.

Figure 18 shows the installation of an anchor plate and Fig. 19 shows the distribution of anchor cables outside the cliff surface before cutting off.

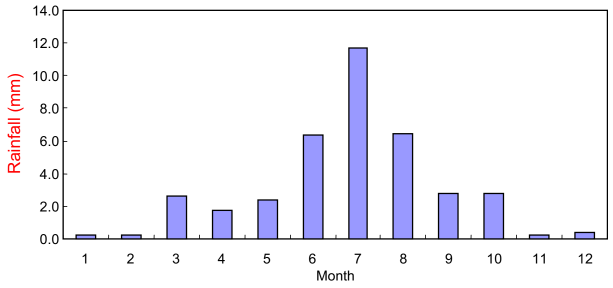

Fig. 14 Histogram of average monthly rainfall of Dunhuang Mogao Grottoes (1989–2004)

Fissure grouting

In the cliff stabilization project, a chemical grouting method has been adopted to stabilize the fissures in the cliff body which can make the open cliff body bond more effectively and also increase the shear strength along fissures. What is more important is that the aggregated mass of the grout can fill the fissures more densely, which can prevent rainwater from permeating into caves along fissures and cause further damage to the site (such as wall paintings) (Jiang and Liu 1989; Ma 1989; Xie 1989; Xiong 1996).

The grottoes along China's Silk Road are mostly cut out of rock mass made of sandstone or glutenite. The mechanical strength of the rock mass is relatively low and the environment where the grottoes are located is relatively dry. A PS-F grout adopted in grouting (PS is the high modulus potassium silicate solution and F is the coal ash) has relatively good fluidity and permeability; the aggregated mass congealed in the fissures can fill fissures of different sizes and the strength of the aggregated mass can be adjusted to a strength that approximates the rock mass. The relationship between PS concentration and strength of the aggregated mass of the grouting material is shown in Figs. 20 and 21. The grout of the aggregated mass is quite consistent, has good freeze–thaw resistance, does not easily disintegrate, and is resistant to acid and alkalis; the aggregated mass basically does not shrink, and both the initial set/final set speed of the grout and the strength of the aggregated mass can be controlled by the adjustment of the modulus and concentration of PS. This grout is suitable for fissures in cliff bodies composed of gravel and can successfully seal off fissures and increase the stability of the cliff body (Wang 2003; Yang et al. 2005).

Weather-proof treatment of rock surface

Because of the nature of the rock formation in the cliff body, there are large numbers of wind erosion grooves that have developed in the cliff face in the north area. Weak silt interlayers in the middle of the cliff body have been partially eroded by wind and erosion has occurred all the way through to the cliff body. This has caused the collapse and backward movement of the upper cliff body. Sudden storms at the Mogao Grottoes area in summer bring water flows over the cliff face and cliff top which converge and form one large water flow on the cliff surface. Sometimes, the surface flow penetrates into the lower caves through fissures causing greater damage.

According to the above circumstances, the weather-proof PS material (Li 2003) has been used to stabilize the cliff's surface. The stabilized area has been divided into three zones: the critical stabilization zone, the priority stabilization zone, and the general stabilization zone according to the location, distribution, quantity, and degree of weathering of the caves in the north area. Different PS concentrations and spraying frequencies have been adopted in accordance with the different weathering degrees of the cliff body. In the final spraying process, a small amount of sedimentary soil with minimum impurity should be added to the PS solution after its milling and sieving to make the surface of the cliff body's appearance look more natural. The color of the cliff face after

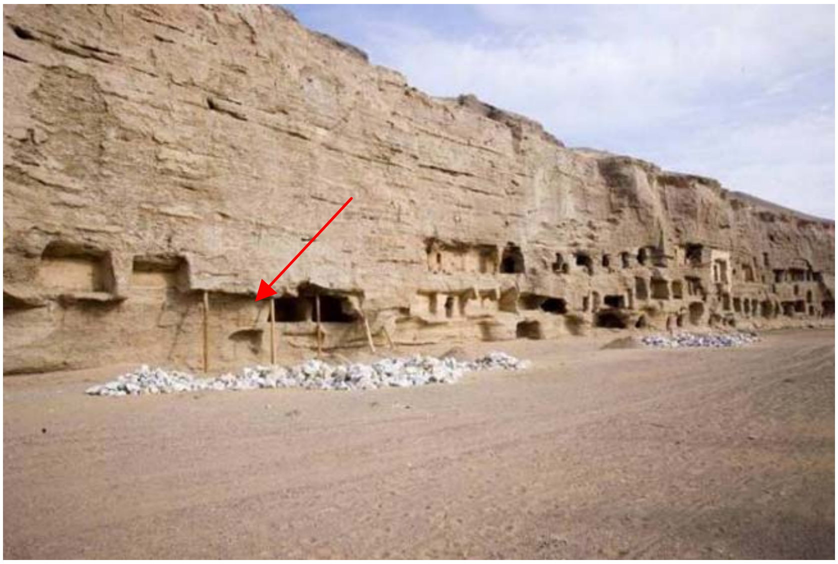

Fig. 15 Collapse caused by historical flood erosion to the bottom of the cliff

construction should be consistent with its original color as far as possible. Figure 22 is the construction site of weather-proof stabilization for the cliff surface by PS spray.

Foot support

The recesses at the bottom of cliff body mainly caused by the flood erosion of the Daquan River in history resulted into some sections of the cliff body to "hang in the air." If an earthquake were to occur, the overhanging rocks will undoubtedly collapse. So, the hanging sections at the cliff bottom are stabilized with columns made by stone blocks (Fig. 23). Onto the column surfaces, PS solution in addition with clay material from weathered cliff rock is sprayed so as to make it as close as possible to its historic appearance.

Summary and conclusions

(1) >Investigation has shown that the main deterioration in the cliff body in the north area of the Mogao Grottoes has been caused by fissure development, collapse of the cliff body, wind erosion, rain erosion, flood erosion, and weathering. The fissures can be divided into tectonic fissure, unloading fissure, and longitudinal fissure, among which the tectonic fissure and unloading fissure are more harmful and should be reinforced effectively. Collapse of the cliff body is mainly caused by fissure cuts, the weak interlayer forming a concave shape, and the partial detachment ("hanging") of the rock body in the lower tiers. Collapse is fatal for caves in the north area.

(2) To conserve the north area in the Mogao Grottoes, anchor technology, PS-F fissure grouting, and PS consolidation of the cliff surface are adopted; the lower sections of the hanging cliff face body have been supported using stone blocks. All these measures correspond with the principle of "treatment of an historic site in a way that retains historical appearanc" (*xiujiu rujiu*).

(3) There is a large difference in the mechanical properties between the weathered and unweathered rock masses. PS consolidation of the weathered cliff surface can improve durability against further weathering.

(4) After a series of comprehensive treatment measures, damage to the rock mass in the north area of Dunhuang Mogao Grottoes has been effectively controlled and the stabilization project has been effective.

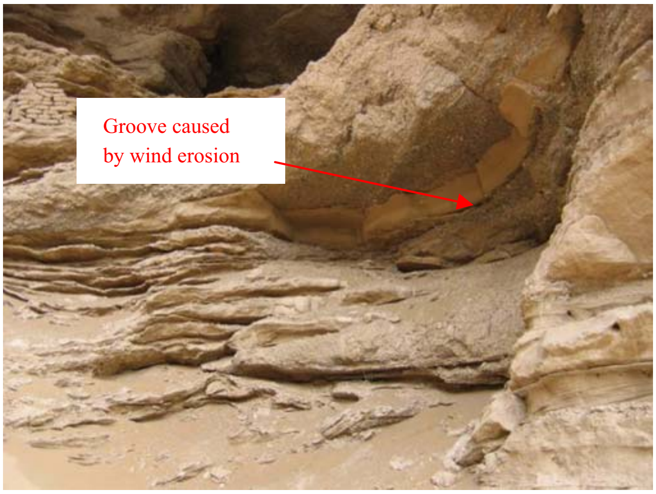

Fig. 16 Wind erosion damage to the cliff rock

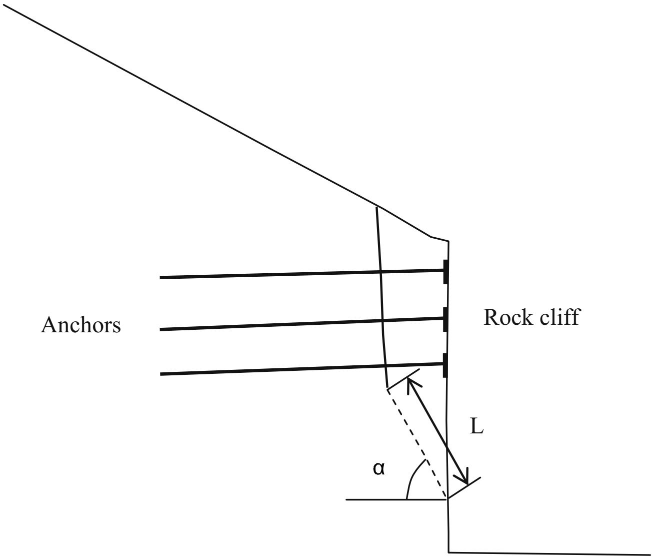

Fig. 17 Mechanical calculation of the stability of dangerous cliff block

Fig. 18 Installation of an anchor plate

Fig. 19 Distribution of anchor cables outside the cliff surface before cutting off

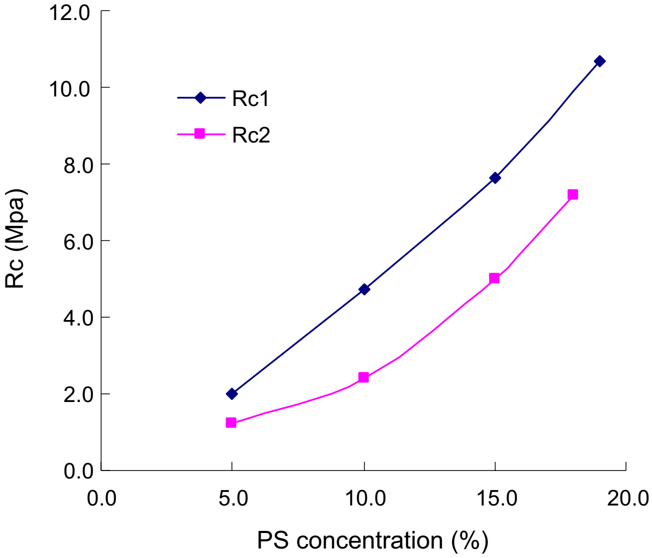

Fig. 20 Relationship between PS-F compressive strength and PS concentration. *Rc1* compressive strength of PS-F which is made of 3.25 modulus PS and coal ash, *Rc2* compressive strength of PS-F which is made of 3.84 modulus PS and coal ash

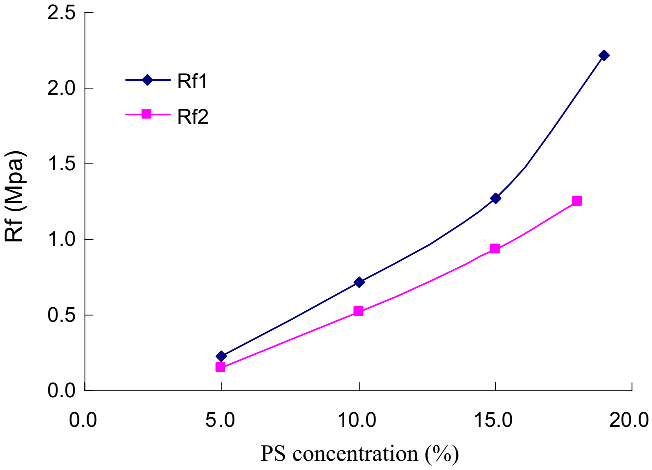

Fig. 21 Relationship between PS-F flexural strength and PS concentration. *Rf1* flexural strength of PS-F which is made of 3.25 modulus PS and coal ash, *Rf2* flexural strength of PS-F which is made of 3.84 modulus PS and coal ash

Fig. 22 Construction site of the weather-proof consolidation by PS spray

Fig. 23 Column support of the hanging sections at cliff bottom

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