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The equilibrium gravel coverage of the deflated gobi above the Mogao Grottoes of Dunhuang, China

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Abstract Blown sand has caused considerable damage to the Dunhuang Mogao Grottoes of China. Controlling the blown sand requires a clear understanding of the processes that govern its production and movement. Experiments were conducted in a wind tunnel and in the field to define the relationships between sand production and gravel coverage in the gobi above the Mogao Grottoes. The gravel that covers the gobi's surface controls wind erosion, irrespective of its shape and size. The equilibrium coverage by gravel over which no further sand is emitted due to wind erosion increases and the equilibration time that is taken to form the equilibrium gravel coverage decreases with increasing wind velocity. Gravel coverage has reached an equilibrium state in the portion of the gobi directly above the grottoes,

but decreases towards the Mingsha Mountains. Drifting sand from these mountains is the main source of sand damage at the Mogao Grottoes. If no additional sand from the mountains were supplied to the gobi, gravel pavements would reach an equilibrium level of coverage and prevent further production of blowing sand. Sand blown from the gobi represents secondary reactivation of sediments originally produced in the Mingsha Mountains. Therefore, to control the blowing sand above the Mogao Grottoes, emphasis should be placed on controlling erosion from the Mingsha Mountains rather than local erosion of sand in the gobi.

Keywords Mogao Grottoes of China · Aeolian sand transport · Control of blown sand · Gravel coverage

Introduction

The Mogao Grottoes of Dunhuang lie in the western end of the Hexi Corridor of Gansu Province, in northwestern China (Fig. 1). They are officially protected because of their great historical importance. Because of their valuable frescoes, the Mogao Grottoes have been called the “art gallery of the world” and “a museum on a wall”, and were named a UNESCO World Cultural Heritage site in 1987. The Mogao Grottoes, 25 km southeast of Dunhuang City, were cut into the steep cliff of a diluvial fan terrace on the

western bank of the Daquan River. The cliff runs north–south, and the grottoes face east (Fig. 1). From the top to the bottom, the cliff is composed of a late-Pleistocene diluvial gobi conglomerate, mid-Pleistocene diluvial–alluvial Jiuquan conglomerate, and early Pleistocene deposits of glaciofluvial Yumen conglomerate (Wang 1990; Qu et al. 2001). The Jiuquan Formation forms the wall of the grottoes. Above the grottoes lies a region of flat gravel pavement (called “gobi” in Mongolian) that stretches 700 to 1,000 m westwards to the Mingsha Mountains, which comprise megadunes of shifting sand.

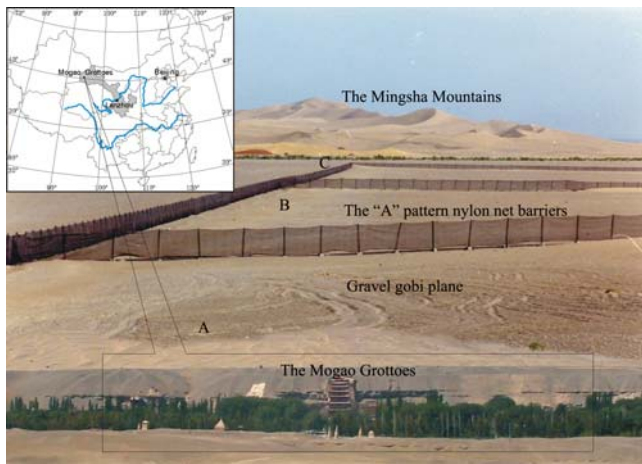


Fig. 1 The Mogao Grottoes, and their location in China

The Mogao Grottoes have been threatened by blowing sand for decades due to their location in an extremely arid inland region with a unique environment (Fan 2003; Qu et al. 2001; Wang et al. 2004a). As early as the 1940s, the influence of blown sand on the grottoes was creating concern (Fig. 2). It was once believed that the grottoes would be buried in sand (Jin 1986; Wang 1990). Since then, long-term efforts have been devoted to preventing the blowing sand. To control the blown sand more efficiently, researchers began seeking to understand the physical mechanisms responsible for the production and movement of the blown sand, and developing new control technologies in the 1980s. Lin et al. (1993) and Qu et al. (2001) reported the first results of studies of the movement and intensity of blowing sand in this area. On the basis of their research, they suggested the use of nylon barriers in the shape of an “A” to create a shelter system (Fig. 1). This shelter system was effective for several years, but it became less and less effective as sand



Fig. 2 Sand accumulation near the Grottoes in 1941

accumulated around the barriers. In addition, the accumulated sand developed into sand dunes lying above the original flat gravel pavement. Attempts were also made to stabilize the shifting sand. Li et al. (1993) and Agnew et al. (1999) attempted to fix the shifting sand and prevent further wind erosion using chemical treatments, but the cost was prohibitive and the treatment could only be practiced in a very limited area. Wang et al. (2004b, c) attempted to eliminate the problem of shifting sand by means of revegetation. They established a shelterbelt system using shrubs supported by drip-irrigation, and achieved promising results. However, there were concerns that infiltration of the irrigation water would cause new damage to the frescoes in the grottoes. Several researchers sought different countermeasures (Zhu 1999; Xue et al. 2000; Qu et al. 2001; Wang et al. 2004a; Zhang et al. 2004).

None of these approaches have eliminated the problems caused by the blowing sand, and the Mogao Grottoes are still endangered. The key reason is that there has been no clear guidance for the sand-control work. Arguments have focused on identifying the source of the sand, as different sources would require different countermeasures. Historically there are two opinions about the source of the sand. Some scholars (e.g., Qu et al. 2001) believed that the sand primarily resulted from the eastward movement of sand from the Mingsha Mountains in the west, and that control work should concentrate on fixing the sands of that region in place or to establish sand-blocking barriers immediately downwind of this area. Others (e.g., Lin et al. 1993) believed that the blown sand is mainly produced by wind erosion in the gobi above the grottoes, and that control efforts should emphasize approaches to eliminating the production of blowing sand from the gobi.

Clearly, it is essential to understand the production of sand and wind erosion in the gobi before determining the main source of the sand. The intensity of wind erosion is determined by factors such as the topography, gravel coverage, moisture content, and vegetation cover of the gobi. The gobi above the Mogao Grottoes is flat, extremely dry, and has little vegetation (Fig. 1). The annual precipitation is 23.3 mm but the annual potential evaporation is 4,348 mm. The gravel cover offers some protection to the underlying sediments by increasing the aerodynamic roughness of the surface boundary layer (Willets and Rice 1988; Gillette and Stockton 1989; McKenna 1998; Liu et al. 1999; Dong et al. 2002). Therefore, the intensity of wind erosion is determined to a large degree by the nature of the gravel coverage. To answer the question of whether the current gravel cover of the gobi above the Mogao Grottoes can effectively prevent erosion of the underlying sediment, wind tunnel and field experiments were conducted. The objectives were to define the equilibrium gravel coverage (i.e., the gravel coverage that would occur without production of

additional blowing sand) and the equilibration time (the time required for equilibrium coverage to develop). The results of these studies should suggest the main source of the blowing sand and thus corresponding control measures.

Experimental conditions and methods

Wind tunnel simulations

The experiment was carried out in the wind tunnel at the Shapotou Desert Experimental Research Station, Key Laboratory of Desert and Desertification, Chinese Academy of Sciences. The blow-type non-circulating wind tunnel has a total length of 37 m, and a 21-m-long working section with a cross-sectional area of 1.2 m × 1.2 m. The depth of the boundary layer can reach 0.4–0.5 m in the working section. Wind speed can be changed continuously from 2 to 30 m s⁻¹.

Five kinds of natural gravels with different particle sizes and shapes were used in this experiment to simulate the naturally occurring gobi pavements. Glass beads of 10 mm in diameter were used for comparison (Table 1). The sand utilized was obtained from the Mingsha Mountains. Figure 3 shows its particle-size distribution.

In each experiment, a layer of one of the gravels (or of the glass beads) was spread on the floor of wind tunnel, and then covered with 50 mm of sand. The experimental bed formed in this manner was 2 m long and 1.2 m wide, and was positioned 18–20 m downwind from the start of the working section of the wind tunnel. Figure 4 shows the layout of the experimentation. Six wind velocities (8, 10, 12, 14, 16, and 18 m s⁻¹) were selected based on the range of wind speeds observed when blowing sand was produced in the study area. This provides experimental data over a gravel Reynolds number range of 3,000–70,000. For each velocity, the wind was allowed to blow until no additional sand was blowing out of the test bed. At this point, the surface was considered to be in equilibrium with the wind. The resulting gravel coverage was assumed as the equilibrium coverage. The calculation procedure for this coverage is described in “[Calculation of gravel coverage](#)” section. How long it took for equilibrium coverage to

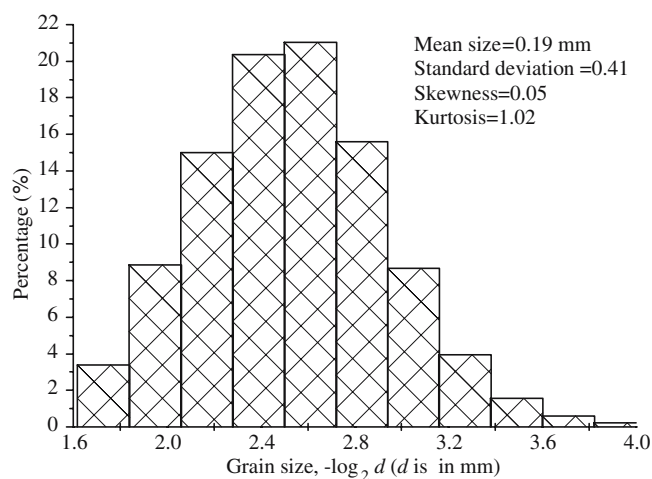


Fig. 3 The grain size histogram for the sand used in the wind tunnel experiment

develop was recorded and the final state was photographed using a digital camera.

Field experiments

In October 2002, a 100 m × 100 m experimental field was established in the northwestern surface of the gobi directly above the Mogao Grottoes (Fig. 5). The surface of this field was flattened and compacted, then a mixture of gravel sizes was spread on this surface and a 50-mm-thick layer of sand was added above the gravel.

One reference point was set up on each side of the field, with one point at the center, to allow comparisons of photographs taken at different times. On day 28 of each month from October 2002 to January 2005, close-up photographs at each reference point were taken using a digital camera, and the images analyzed as described in “[Calculation of gravel coverage](#)” section. Sand samples were collected to permit analysis of the physical

Table 1 The gravels and their mean diameter used in this study

Gravel no.	GR01	GR02	GR03	GR04	GR05	GR06
	10.0	5.2	8.9	9.8	26.8	54.9
Mean diameter (mm)						

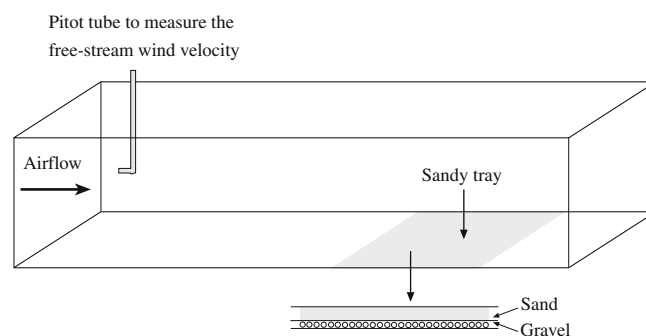


Fig. 4 Layout of the experimentation

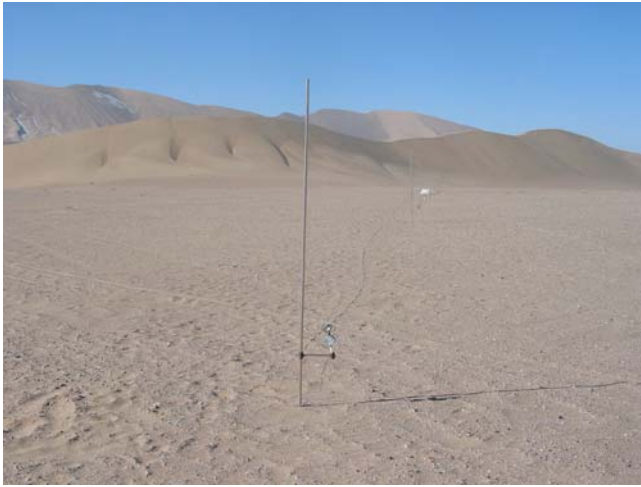


Fig. 5 An overview of the experiment plot

composition of the surface. Wind speeds during the experimental period were recorded by an automatic data-acquisition system.

Calculation of gravel coverage

The digital photographs recorded in the wind tunnel tests and in the field were analyzed using the Arcinfo 8.3 (ESRI, Redlands, Calif.) geographic information system software to calculate the gravel coverage. For the mixed gravels in the field experiment, the coverage of the surface by gravel larger than 2 mm in diameter was noted.

Results and discussion

Equilibrium gravel coverage

The wind tunnel experiments revealed that the process of wind erosion on the gobi surface was selective: erodible sand grains were blown away, but non-erodible gravels were left behind. In this process, the gravel coverage gradually increases as wind erosion progresses, and the intensity of wind erosion simultaneously decreases, eventually reaching zero, as more and more gravel is exposed. Consequently, an equilibrium level of gravel coverage develops.

For all gravels used in this study, the equilibrium level of gravel coverage varied as a function of wind velocity (Fig. 6). The equilibrium coverage generally increased with increasing wind velocity, and the relationship could be expressed by a logarithmic function (Table 2). At low wind velocity (8 m s⁻¹), the equilibrium gravel coverage was between 25 and 35% for all gravel types. At moderate wind velocity (12 m s⁻¹), the

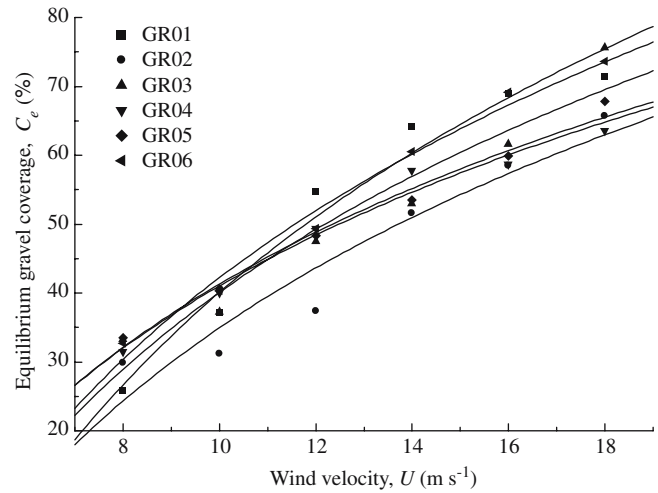


Fig. 6 Variation in equilibrium gravel coverage as a function of wind velocity

equilibrium coverage was between 35 and 55%. At high wind velocity (18 m s⁻¹), the equilibrium coverage was between 60 and 75%. These results suggest that whether a gravel cover can control wind erosion will depend on the average and maximum local wind strengths.

Equilibration time

Equilibration time is the time needed for the equilibrium gravel coverage to develop. The results of the wind tunnel tests indicated that the greater the wind speed, the shorter the equilibration time for all the gravels. Figure 7 shows the relationship between equilibration time and wind velocity. Further analysis indicated that the equilibration time decreased exponentially with increasing wind velocity (Table 3). At low wind velocity (8 m s⁻¹), the equilibration time was most strongly affected by the shape and size of the gravels (i.e., the times ranged from 35 to 60 h). At moderate wind velocity

Table 2 The relationship between equilibrium gravel coverage and wind velocity

Gravel no.	<i>a</i>	<i>b</i>	<i>R</i> ²
GR01	-98.438	60.164	0.9685
GR02	-74.763	47.648	0.9184
GR03	-75.246	50.088	0.9299
GR04	-52.144	40.462	0.9799
GR05	-53.619	41.223	0.9857
GR06	-80.423	53.269	0.9850

* $C_e = a + b \ln(U)$, C_e is the equilibrium gravel coverage, U is the free-stream wind velocity, a and b are regressive coefficients, R^2 is the correlation coefficient at 0.05 significance level

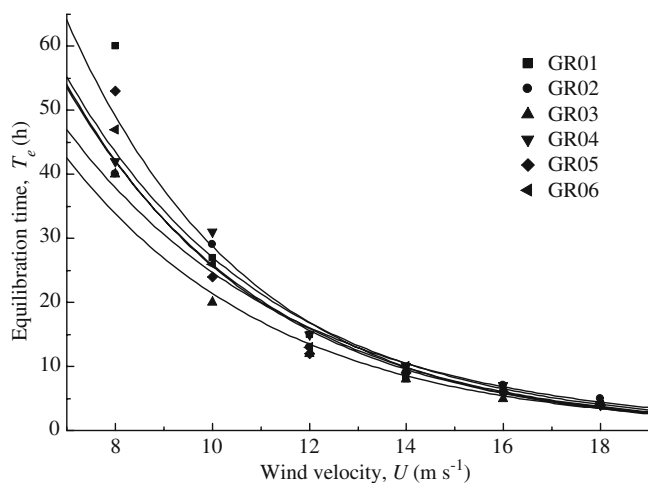


Fig. 7 Variation in equilibration time as a function of wind velocity

(10–14 m s⁻¹), the range of variation in the times decreased strongly. At high wind velocity (> 16 m s⁻¹), there was little difference in equilibration time, and wind erosion stopped within several minutes. Thus, even though strong wind may only last for a short time, it has a strong impact on wind erosion of the gobi surface. These results indicate that when planning to use gravel to prevent wind erosion, local wind conditions must be considered, especially the frequency and duration of the strongest winds.

Field experiment

The land above the Mogao Grottoes is an area where strong winds and blowing sand are frequent and wind direction is highly variable. An automatic meteorological station was established above the Mogao Grottoes to collect data on wind speeds and the duration of winds with a velocity > 5 m s⁻¹ (the threshold wind velocity).

Table 3 The relationship between equilibration time and wind velocity

Gravel no.	<i>a</i>	<i>b</i>	<i>R</i> ²
GR01	415.15	-0.2669	0.9744
GR02	211.33	-0.2147	0.9666
GR03	212.70	-0.2297	0.9783
GR04	291.06	-0.2375	0.9899
GR05	306.94	-0.2481	0.9670
GR06	292.71	-0.2426	0.9857

* $T_e = ae^{bU}$, T_e is the equilibration time, U is the free-stream wind velocity, a and b are regressive coefficients, R^2 is the correlation coefficient at 0.05 significance level

These data were compared with the corresponding variation in gravel coverage. Regression was performed to quantify the relationship between these factors. During the study period, a total of 1,053,080 wind speed records were collected. Of these, 492,512 (46.8%) were greater than 5 m s⁻¹. Of wind speeds greater than 5 m s⁻¹, 97.4% were between 5 and 10 m s⁻¹, and the remaining 2.6% were between 10 and 14 m s⁻¹. Figure 8 shows that under the surface conditions observed, the relationship between gravel coverage and time taken was almost linear, and that there was a strong correlation ($R^2 = 0.96$) between the two variables.

Source of blown-sand above the Mogao Grottoes

Field measurements indicate that on top of the Mogao Grottoes, gravel coverage decreases as it gets close to the Mingsha Mountain. In the frontal gobi area that borders on the grottoes (Fig. 1A), the gravel coverage ranges as high as 66%. Experimental results suggest that this coverage is close to the equilibrium level of coverage, and that as a result, there should be little or no production of blowing sand from this area. It can also be inferred from the research of Xue et al. (2000) and Dong et al. (2002) that there should be no obvious wind erosion in the frontal gobi area above the Mogao Grottoes. Xue et al. (2000) found that in the broad gravel surface above the Mogao Grottoes, gravel coverage should be more than 65% to completely eliminate wind erosion. On the basis of the wind tunnel experiments, Dong et al. (2002) reported that the gobi surface should become aerodynamically stable (and thus, reduce the potential threat of blowing sand and

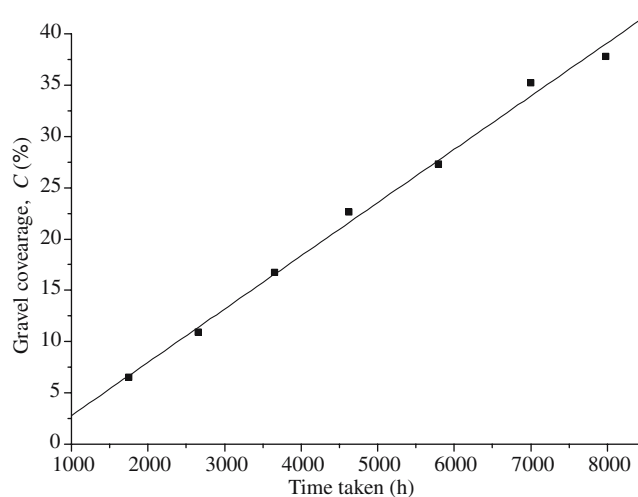


Fig. 8 The variation in gravel coverage as a function of time in the field study

dust storms to nearly zero) when the gravel coverage was more than 50%, irrespective of the gravel size. Farther west (Fig. 1B), between the grottoes and the Mingsha Mountains and near the nylon barriers used to control blowing sand (Fig. 3), the gravel coverage averages about 25.90%. Even farther west, near the foot of the Mingsha Mountains (Fig. 1c), gravel coverage decreases to about 9%. These results suggest that in the two areas farthest from the grottoes, wind erosion and blowing sand will still occur.

These results appear to suggest that the gobi area above the Mogao Grottoes is the main source of blowing sand. However, other factors suggest that this interpretation is incorrect. There are three main groups of wind directions in this area: S, SSW, and SSE; W, NWW, and SSW; and E, ENE, and ESE. Of these wind directions, the westerly winds (31%) and the southerly winds (30%) are the strongest, and the easterly winds (16%) are relatively weak. Therefore, the major winds responsible for wind-blown sand are westerly and southerly winds from the Mingsha Mountains. The decreasing gravel coverage from the grottoes towards the Mingsha Mountains thus reflects the influence of sand deposits from the Mingsha Mountains. Sand that drifts into the gobi from the Mingsha Mountains is deposited on the gravel surface because the aerodynamic roughness increases near that surface. Closer to the source of the sand, more drifting sand is deposited. When a strong wind arises, the sand that has been deposited on the gravel surface near the mountains will be reactivated. If there were no additional sand supply, the gravel surface would have eventually reached its equilibrium coverage and no additional sand would be produced. At a greater distance from the mountains (e.g., in the frontal area; Fig. 1A), the deposition of additional sand will not balance the amount of erosion, thereby resulting in the development of an equilibrium coverage by gravel. At present, the main source of local sand is from the Mingsha Mountains, and based on the results of present study and the other observations in this section, sand produced from the gobi surface can only be considered to be secondary production (reactivation of sand that originated in the mountains). If there were no accumulation of blowing sand from the Mingsha Mountains, this secondary local production of blowing sand would stop. Therefore, the origin of the damage to the Mogao Grottoes caused by blowing sand lies in the Mingsha Mountains to the west of the gobi surface above the grottoes. To eliminate the problem caused by blowing sand, the source of sand from the Mingsha Mountain must be cut off. If this cannot be achieved, more sand carried by the wind will accumulate in the gobi, thereby making the formerly stable surface increasingly unstable.

Conclusions

The research described in this paper provides several important conclusions:

The gravel cover of the gobi surface controls wind erosion irrespective of the shape and size of the gravel. However, to fully protect the underlying fine sediments from erosion, equilibrium coverage must be reached. Wind tunnel tests indicate that the required equilibrium coverage increases with increasing wind velocity and follows a logarithmic relationship. Equilibration time decreases with increasing wind velocity and follows an exponential relationship. That is, the greater the local wind velocity, the greater the gravel coverage required to keep the gobi surface stable. The greater the wind velocity, the shorter the equilibration time. To effectively prevent wind erosion in the gobi area above the Mogao Grottoes, the gravel coverage must be greater than 50%.

The wind tunnel results and field observations suggest that the gobi surface in the frontal area adjacent to the Mogao Grottoes is stable and highly resistant to wind erosion. However, wind erosion is increasingly obvious nearer to the Mingsha Mountains. In these areas (Fig. 1B, C), the surface becomes increasingly unstable because of the continuous accumulation of blowing sand from the Mingsha Mountains under the influence of the westerly and southerly winds. If there were no further supply of sand from the Mingsha Mountains and wind erosion occurred continuously over a long period, the whole surface of the gobi above the grottoes should equilibrate and reach a steady level of gravel coverage with no additional wind erosion. At present, the main production of blowing sand originates from secondary production of blowing sand that was blown from the Mingsha Mountains into the gobi, where it then accumulated. Therefore, to fundamentally resolve the problem of blowing sand, the supply of sand from the Mingsha Mountains must be cut off. If this source of sand cannot be eliminated, blowing sand will continue to accumulate on the surface of the gobi protected by the gravel, and will change this formerly stable surface into an unstable surface. To completely protect the Mogao Grottoes from the blowing sand, it will be necessary to adopt a combination of approaches that stabilize sands in the Mingsha Mountains: fixing sand in place, preventing additional erosion of sand, channeling the blowing sand away from the sensitive areas, and developing a defensive system of sand barriers.

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