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Rainfall influence and risk analysis on the mural deterioration of Dunhuang Mogao Grottoes, China

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Abstract

The Dunhuang Mogao Grottoes are a significant cultural heritage site in the Silk Road, famous for its wonderful murals and statues. The rainfall causes the changes of humidity in the caves, which can easily activate the salts diseases of murals. In order to prevent the deterioration of the murals, the environmental monitoring tests were conducted to analyze the microclimate changes of the cave in rainfall weather, and proposed the risk prevention measures and suggestions. The results indicate that the temperature of caves has small change, but the humidity shows a clear trend of increase. The humidity and the duration of high humidity increases with the increase of the rainfall grade and frequency. The optimal starting time for environment control in the cave is when a_{atm} and a_{cave} are consistent, and the relative humidity is controlled below 62%. The caves with lower layer, larger degree of openness and small volume are most vulnerable to water vapour diffusion. The environment monitoring should pay more attention to the continuous rainfall weather and the vulnerable caves. The research has great significance for the prevention of ancient mural deterioration.

Keywords Mogao Grottoes, Ancient murals, Rainfall, Microclimate, Risk prevention

Introduction

The ancient mural is the bearer of human thought inheritance, as well as an important component of our cultural heritage [1, 2]. There are 45,000 square meters of ancient murals in the Mogao Grottoes of Dunhuang. Owing to its outstanding value it was listed in the World Heritage List by UNESCO in 1987 [3, 4]. For over 1600 years, the murals in the Mogao Grottoes have been subject to natural environmental changes, resulting in various salt diseases of flaking, blistering, hollowing, and scaling [5–7]. This not only leads to the continuous loss of historical information, but also seriously affects the aesthetics of these ancient murals.

Salt diseases of murals are closely related to the environmental changes in the caves [8–11]. The murals of the Mogao Grottoes are composed of a plaster layer, white powder layer, and pigment layer, and the salt types in the plaster layer are mainly NaCl and Na_2SO_4 [12–14]. When the fluctuation range of temperature and humidity exceeds a critical value, NaCl undergoes dissolution-crystallization changes, and Na_2SO_4 undergoes hydration-dehydration phase changes. These salts generate stresses during crystallization and hydration, leading to structural damage of the mural plaster layers [15–17].

Rainfall is one of the main factors causing humidity increase in the caves [18, 19]. In the region where the Mogao Grottoes are located, the rainfall is concentrated between June and August, with short duration and high intensity. In rainy weather, the humidity of the cave

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increases significantly. Once the humidity of the caves exceeds the critical value, the salt disease will be activated [20, 21]. At present, the measure taken by the management sector of Mogao Grottoes is to close the cave doors and suspend the opening for tourism. In order to prevent the deterioration of the murals, this study analyzes the microclimate changes in the caves under different grades of rainfall through environmental monitoring tests, and puts forward risk prevention measures and suggestions.

Methodology

Research object

The Dunhuang Mogao Grottoes are located at the western end of the Hexi Corridor in northwest China, with the Mingsha Mountain to the southwest, the Sanwei Mountain to the southeast, and the desert to the north. Its geographical coordinates are 40°02′N and 94°48′E (Fig. 1). It is the largest and most significant Buddhist cultural site in China and even in the world, with 735 caves, 45,000 square meters of murals, and over 2000 colored sculptures ranging from 4th to 14th centuries. The area where Mogao Grottoes are situated has a typical warm-temperate arid climate, with an average annual temperature of 11.2 ℃, an average annual humidity of 31%, and an average annual rainfall of only 39 mm [19]. The ancient murals are well preserved mainly due to their remote location, the dry climate and to being in a relatively confined cave environment.

The caves are excavated in steep conglomerate and are staggered in four layers on the cliff [22, 23]. In order to eliminate the influence of spatial location and architectural structures, three representative caves of C16, C332, and C71 were chosen. These three caves are on the same lowest level and are similar in shape. The concentration of water vapour in the atmosphere increases as height decreases during rainfall; the lower the geographical location of the cave, the greater risk of wet air influx into the cave. The selection of representative caves also considers the principle of highest risk. Based on the degree of connectivity between the cave and the atmosphere, C16 represents a semi-enclosed cave, while C332 and C71 represent enclosed caves. Based on their internal space size, C16, C332, and C71 represent large, medium, and small caves, with the volumes of 66 m^3, 321 m^3, and 1574 m^3 respectively.

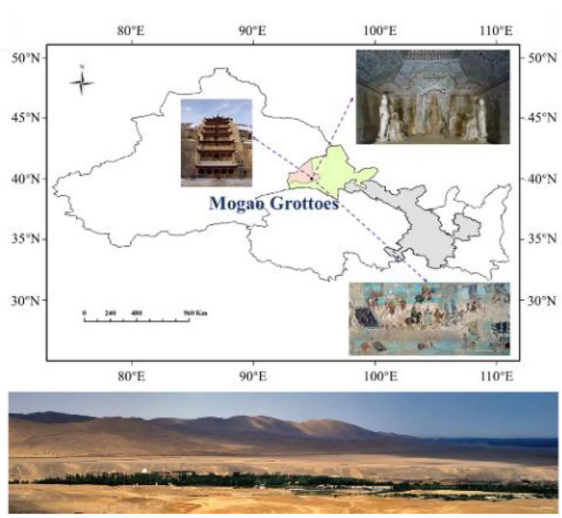

Fig. 1 The geographical location of Mogao Grottoes

Environmental monitoring test design

The environmental monitoring tests include the atmospheric environment and the microclimate in the cave (Fig. 2). The atmospheric environment monitoring point is located at the top platform above the cliff, and the monitoring indexes include rainfall, wind speed/direction, temperature, humidity, air pressure, and solar radiation intensity. The monitoring equipment is a fully automatic meteorological monitoring station produced by Campbell Scientific in the USA, and the rainfall monitoring equipment is a TE525MM. The microclimate monitoring point is located in the main chamber of the cave, and the monitoring index is temperature and humidity. The monitoring equipment is a HOBO U23-001 produced by ONSET, USA, with temperature range

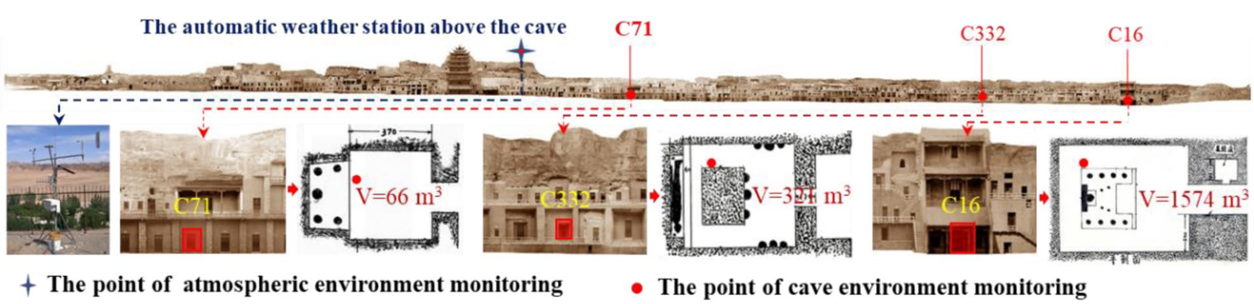

Fig. 2 The layout of environmental monitoring points

−40 ℃ to 70 ℃, accuracy ± 0.2 ℃, and relative humidity range 0−100%, accuracy ± 2.5%.

Analysis method

Rainfall amount and duration represent the characteristics of rainfall. Rainfall ≥ 0.1 mm is defined as effective rainfall, and rainfall with an interval of less than 6 h is defined as a single rainfall event. The grades of rainfall are classed according to the amount of rainfall in different time periods (GB/T 28592-2012). According to the classification standard of 12 h rainfall, the ranges for light rain, moderate rain, heavy rain, and torrential rain are 0.1–4.9 mm, 5–14.9 mm, 15–29.9 mm, and 30–69.9 mm, respectively. According to the classification standard of 24 h rainfall, the ranges for light rain, moderate rain, heavy rain, and torrential rain are 0.1–9.9 mm, 10–24.9 mm, 30–49.9 mm, and 50–99.9 mm, respectively.

The characteristics of microclimate are represented by temperature, absolute humidity, and relative humidity. The temperature reflects the intensity of water vapour thermal movement inside the cave. The absolute humidity reflects the density changes of water vapour inside the cave during the rainy season, while relative humidity is used to determine whether salt has undergone deliquescence. Temperature and relative humidity data are directly measured by monitoring equipment, and absolute humidity data are converted from temperature and relative humidity [24].

The absolute humidity can be calculated as follows:

$$\mathrm{a} = \mathrm{A}\frac{e}{T + 273} \tag{1}$$

where a is absolute humidity, g/m^3; e is the actual water vapour pressure, h Pa; A is a constant with a value of 217; T is temperature, ℃.

e is calculated using relative humidity as follows:

$$\mathrm{RH} \approx \frac{e}{E_s} \times 100\% \tag{2}$$

where RH is the relative humidity, %; E_s is the saturated water vapour pressure of the air, h Pa.

E_s is calculated using Magnus' semi-empirical formula as follows:

$$E_s = E_0 \cdot 10^{\frac{aT}{b+T}} \tag{3}$$

where E_0 is the saturated water vapour pressure at 0 °C, usually 6.11 h Pa; a and b are constants, and the values are 7.45 and 237.3, respectively, under the water surface conditions.

Results

The area where the Mogao Grottoes are located has long sunshine time and strong evaporation. When light rain occurs, most of the water vapour is dissipated by high temperatures, and only a small amount diffuses into the caves. This study mainly focuses on the potential impact of moderate, heavy, and torrential rainfall.

Typical rainfall events

According to the meteorological monitoring results of the past 30 years, moderate rain, heavy rain, and rainstorm happened in 2015, 2011, and 2016, respectively (Table 1). After heavy rain, two light rains and a drizzle occurred with rainfall amounts of 4.8 mm and 1.0 mm, and durations of 240 min and 60 min, respectively. Before the torrential rain, there was light rain with a rainfall amount of 0.3 mm for 40 min. After the torrential rain, two rainfall events occurred with rainfall amounts of 8.6 mm and 3.5 mm, and durations of 80 and 620 min, respectively, which were moderate and light rains.

Environmental background values

Owing to the blocking effect of windows and doors, the changes of temperature and humidity in caves lag behind atmospheric during rainfall events [25, 26]. In order to analyze the effect of rainfall on the microclimate of caves, the temperature and humidity for 2 days before rainfall were used as the background values. The environmental monitoring results showed that the background values of atmospheric temperature were larger than in the cave, while the background values of relative humidity and absolute humidity were smaller than in the cave in summer. C332 and C71 have the same closing degree but the different volumes. Comparing and analyzing the

Table 1 Characteristics of different levels of rainfall

Rainfall events	Date	Rainfall amount (mm)	Rainfall duration (min)	Start and end time	Preceding rainfall (occurrences)	Subsequent rainfall (occurrences)
Moderate rain	6/18/2015	10.4	550	1:20am–10:30am	/	/
Heavy rain	6/15/2011-6/16/2011	40.1	1545	21:45pm–23:30pm	/	2
Torrential rain	8/18/2016	32	590	2:30am–22:20pm	1	2

environmental background values of the two caves, it is found that the larger the cave volume, the smaller the daily ranges of temperature, relative humidity, and absolute humidity. However, although the volume of C16 is larger than that of C332, the daily range of temperature, relative humidity, and absolute humidity in the C16 is larger than in C332 (Table 2). Based on the effect of volume on the microclimates of caves, it is inferred that the greater the openness, the wider are the fluctuations in temperature and humidity of caves.

Microclimate changes in caves during rainfall

(1) Temperature

The atmospheric temperature decreased significantly in rainy weather. The minimum values of atmospheric temperature during moderate rain, heavy rain, and torrential rain were 13.68 ℃, 15.08 ℃, and 14.24 ℃, which were 39.12%, 24.03%, and 33.80% lower than the background value. The duration of atmospheric temperature being intermittently lower than the cave was about 2 d, 6 d, and 9 d respectively (Figs. 3, 4 and 5). The higher the level and frequency of rainfall, the longer does the low atmospheric temperature continue.

The change of temperature in the cave is very small in rainy weather. During moderate rainfall, the average temperatures of C71, C332, and C16 were 18.84, 15.79, and 16.16 ℃, with the maximum daily range being 2.86, 1.07, and 2.00℃, respectively (Fig. 3). During heavy rainfall, the average temperatures of C71, C332, and C16 were 19.12, 16.96, and 16.22 ℃, with the maximum daily ranges being 2.98, 2.05, and 2.28 ℃, respectively (Fig. 4). During torrential rainfall, the average temperatures of C71, C332, and C16 were 22.36, 20.99, and 19.89 ℃, with the maximum daily range being 2.12, 1.11, and 2.68 ℃ (Fig. 5). The fluctuation of average temperature of the three caves is 2 ℃ less than that of the background values.

Table 2 The environment background value of Mogao Grottoes

Mogao Grottoes		Temperature (T, ℃)				Relative humidity (RH, %)				Absolute humidity (a, g/m^3)			
		Ave	Max	Min	Daily range	Ave	Max	Min	Daily range	Ave	Max	Min	Daily range
Atmospheric environment	6/16/2015	25.52	28.43	22.47	5.96	22.32	38.45	12.38	26.07	5.21	7.64	3.25	4.39
	6/13/2011	25.91	31.36	19.85	11.51	15.44	25.91	9.93	15.98	3.61	4.87	3.07	1.80
	8/15/2016	29.09	34.71	21.51	13.2	24.41	37.68	13.96	23.72	6.63	8.17	5.18	2.99
C71	6/16/2015	19.11	20.52	18.56	1.96	36.59	47.48	30.15	17.33	5.98	8.34	4.82	3.52
	6/13/2011	19.76	22.12	18.48	3.64	26.67	42.26	23.99	18.27	4.83	8.18	4.11	4.07
	8/15/2016	23.66	25.67	23.05	2.62	38.43	47.18	34.89	12.29	8.15	10.78	7.61	3.17
C332	6/16/2015	15.63	16.36	15.36	1.00	41.29	44.22	39.33	4.89	5.48	6.11	5.14	0.97
	6/13/2011	15.28	16.20	15.00	1.20	29.33	31.32	22.25	9.07	4.49	5.16	2.98	2.17
	8/15/2016	21.21	22.08	20.87	1.21	49.20	51.89	46.76	5.13	9.06	9.76	8.77	0.99
C16	6/16/2015	16.13	17.72	15.4	2.32	43.25	47.66	38.02	9.64	5.74	6.52	4.98	1.54
	6/13/2011	16.00	17.12	15.36	1.76	33.16	37.67	23.89	13.78	4.50	5.46	3.25	2.21
	8/15/2016	20.22	21.77	19.41	2.36	49.64	54.63	46.03	8.60	8.64	10.25	7.93	2.32

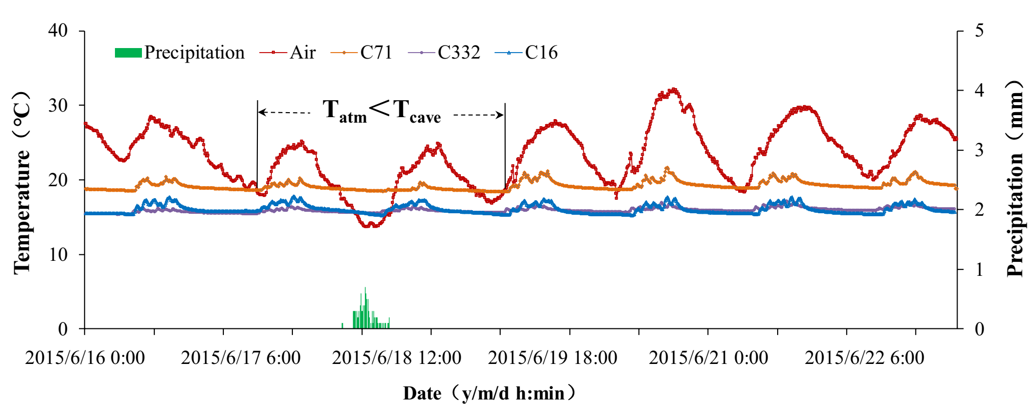

Fig. 3 The Change of temperature during moderate rainfall

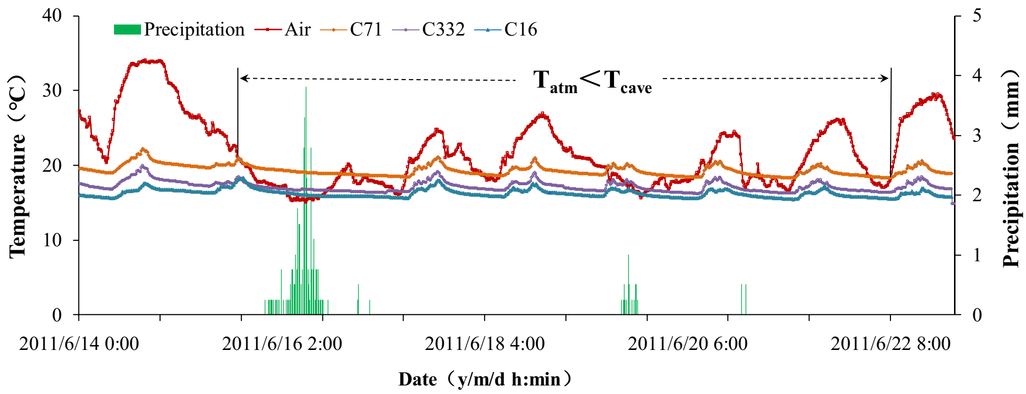

Fig. 4 The Change of temperature during heavy rainfall

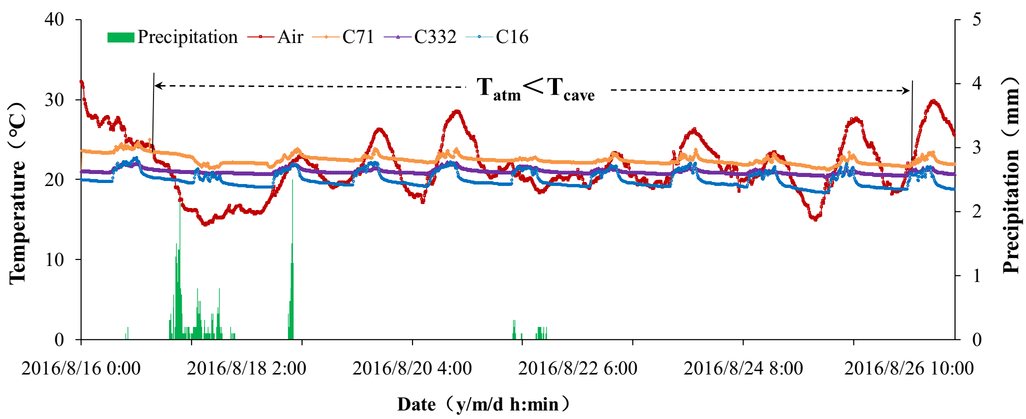

Fig. 5 The Change of temperature during torrential rainfall

The surrounding structure of the caves is a natural rock, with only a narrow entranceway on the east side. Owing to the poor thermal conductivity of the surrounding rock, the temperature inside the caves is relatively stable throughout the year [27]. Rainfall events are mainly concentrated in the summer in the area of the Mogao Grottoes. In sunny summer weather, the temperature of the atmosphere is higher, and the absolute humidity is lower compared to the cave [28, 29]. In rainy weather, the temperature of the atmosphere decreases significantly, even less than the cave temperature for a period of time. As the temperature gradient becomes lower, the heat flux of air convection decreases. Therefore, the variation of temperature in the cave is very small.

(B) Absolute humidity

The absolute humidity of the atmosphere increased noticeably in rainfall weather. During moderate, heavy, and torrential rainfall, the absolute humidity of atmospheric started to increase about 2 days before the rainfall, with the maximum values being 10.99 g/m^3, 15.34 g/m^3, and 18.67 g/m^3, and the duration of its exceeding the absolute humidity of cave was about 61 h, 164 h, and 186 h, respectively.

The absolute humidity of the cave gradually increased as the wet air diffused into the cave. During moderate rainfall, the maximum absolute humidity in C71, C332, and C16 was 11.03 g/m^3, 7.54 g/m^3, and 9.31 g/m^3, an increase of 84.45%, 37.59%, and 62.20% compared with the background values, respectively (Fig. 6). During heavy rainfall, the maximum absolute humidity of C71, C332, and C16 was 13.36 g/m^3, 8.59 g/m^3, and 10.20 g/m^3, having increased by 84.06%, 54.57%, and 80.44% compared with the background values, respectively (Fig. 7). During torrential rain, the maximum absolute humidity of C71, C332, and C16 was 15.31 g/m^3, 13.14 g/m^3, and 15.21 g/m^3, and increased by 59.76%, 28.59%, and 50.35% compared with the background values, respectively (Fig. 8). Owing to the barrier effect of the doors, and windows, the initial time of absolute humidity increase in the cave has a hysteresis quality,

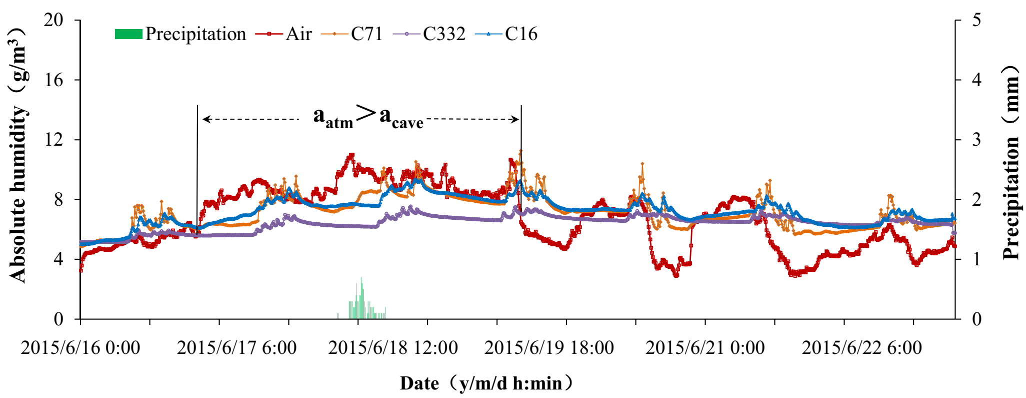

Fig. 6 Change of absolute humidity during moderate rainfall

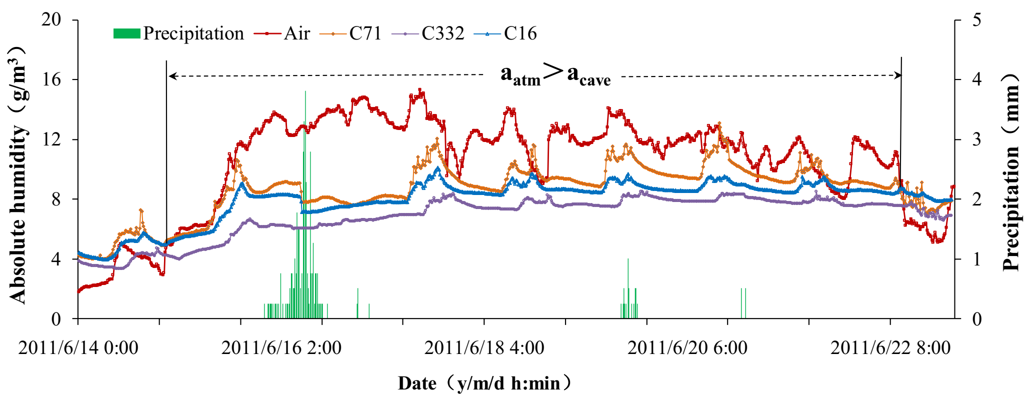

Fig. 7 Change of absolute humidity during heavy rainfall

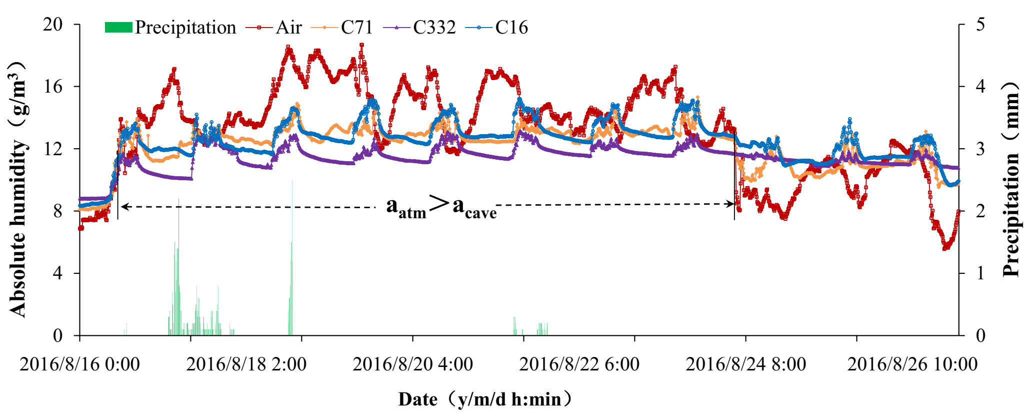

Fig. 8 Change of absolute humidity during a torrential rainfall

and the increase range is smaller than in the atmospheric environment.

The trend of absolute humidity in the cave showed three stages of rising–maintaining–declining. In moderate rainfall, the absolute humidity of the cave began to increase about 1 d before the rainfall and gradually decreased about 2 d after rainfall. In heavy rainfall, the initial time of absolute humidity increase in the cave was basically the same as for moderate rainfall. However, owing to the existence of two late rainfall events, the duration of high humidity increased and the absolute humidity gradually decreased about 3 days after the last late rainfall. The torrential rainfall was short in duration and high in intensity and the rainfall process was accompanied by one early rainfall event and two late rainfall events. Under the effect of the early rainfall and the late rainfall, the absolute humidity of the cave increased to a high humidity state rapidly and decreased about 5 d after the last late rainfall.

The changes of absolute humidity are closely associated with the openness degree and the volume of the cave. The greater the connectivity between the cave and the atmosphere, the more the water vapour diffused into the cave. The C16 has a Qing dynasty hollowed-out wooden window on each side of the door and the largest amount of water vapour diffused into the cave compared with C332 and C71. The absolute humidity of C16 is slightly smaller than C71 on account of the larger volume. C71 and C332 have the same connectivity and water vapour diffusion flux. The absolute humidity of C71 is larger than C332 because of the smaller volume. It is inferred that the absolute humidity shows up as (the open cave) > (the semi-closed cave) > (the closed cave) when the volume is the same and the absolute humidity shows up as (the small cave) > (the medium cave) > (the large cave) when the opening degree is the same.

(C) Relative humidity

The relative humidity of the caves increased noticeably in rainfall weather. During moderate rainfall, the maximum relative humidity of C71, C332, and C16 were 65.59%, 55.02%, and 65.07% and the maximum daily range were 18.60%, 7.48%, and 11.30%, respectively. Compared with the background value, the relative humidity increased by 34.90%, 17.15%, and 34.06% and the daily range increased by 7.33%, 52.96%, and 17.22%, respectively. The relative humidity of C332 did not exceed 62% but the relative humidity of C71 and C16 exceeded 62%, with durations of 6.5 and 26 h, respectively (Fig. 9). During heavy rainfall, the maximum relative humidity of C71, C332, and C16 were 73.54%, 64.61%, and 69.47%, with the maximum values of daily range were 30.83%, 19.68%, and 24.27%, respectively. Compared with the background value, the relative humidity increased by 108.06%, 86.94%, and 81.48% and the daily range increased by 68.75%, 116.98%, and 76.13%, respectively. The relative humidity of C71, C332, and C16 all exceeded 62% and the duration was about 90 h, 80 h, and 120.5 h, respectively (Fig. 10). During torrential rain, the maximum relative humidity of C71, C332, and C16 were 71.81%, 71.50%, and 81.23%, with the maximum daily range being 24.52%, 11.96%, and 19.03%, respectively (Fig. 11). Compared with the background value, the relative humidity increased by 52.20%, 37.79%, and 48.69% and the daily range increased by 99.51%, 133.14%, and 121.28%, respectively. The relative humidity of C71, C332, and C16 all exceeded 62% and the duration was approximately 264 h, 245.6 h, and 271.7 h, respectively.

The changing trend of relative humidity in the cave is basically the same as that of absolute humidity. During rainfall, the changes of temperature are very small and the increase of relative humidity in the cave is mainly caused by the increase of absolute humidity. Relative humidity is affected by both temperature and absolute humidity and it is proportional to the absolute humidity and inversely proportional to the temperature. Although the temperature and the absolute humidity of C16 were both lower than C71, the relative humidity of C16 is greater than C71 under the main influence of temperature. Similarly, the temperature and absolute humidity of C71 are both higher than C332, but the relative humidity of C71 is greater than C332 under the main influence of absolute humidity.

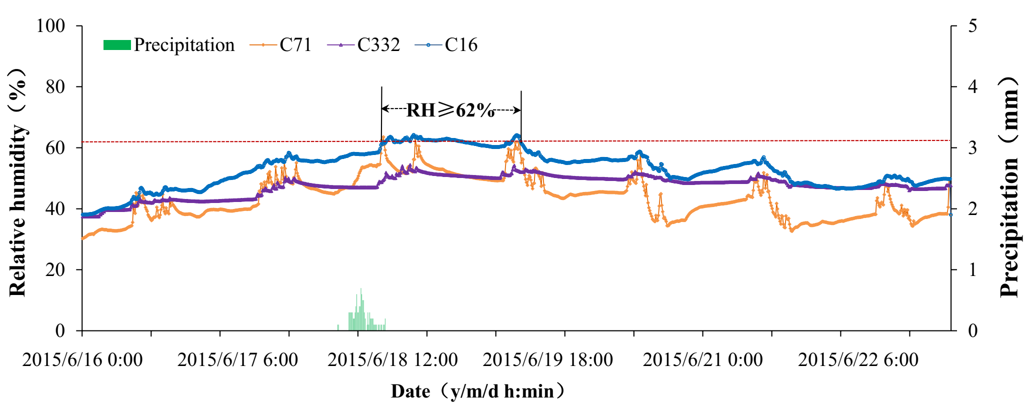

Fig. 9 Change of relative humidity during moderate rainfall

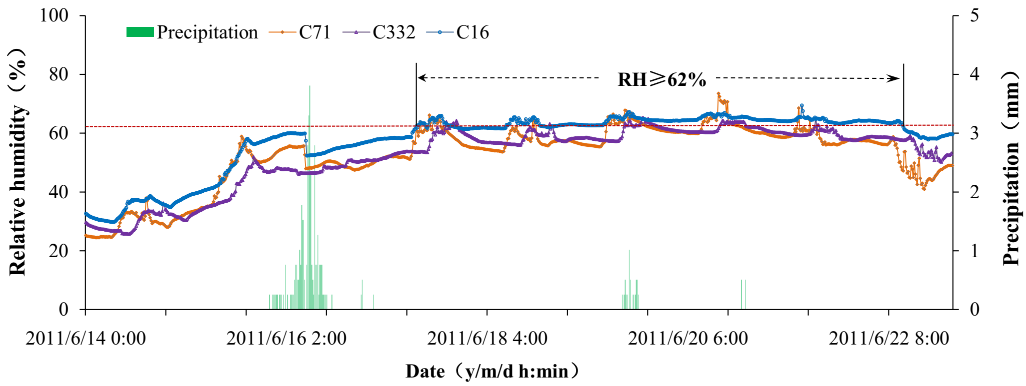

Fig. 10 Change of relative humidity during heavy rainfall

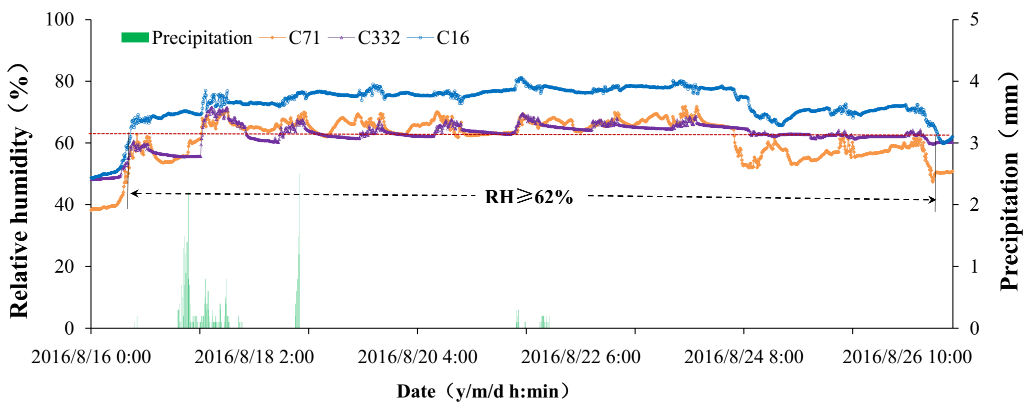

Fig. 11 Change of relative humidity during a torrential rainfall

Risk prevention measures and suggestions

The impact of rainfall on the microclimate of the cave is reflected in two aspects of high humidity and humidity fluctuations [30, 31]. The deterioration of murals is a slow and cumulative process, and the salt diseases are easily activated by environmental changes [32–34]. In order to prevent further deterioration of murals, it is recommended to carry out risk prevention from three aspects of rainfall monitoring, cave environmental control, and tourism management.

Rainfall monitoring

The rainfall in the area of Mogao Grottoes is concentrated and often has continuously rainy weather. According to the results of environmental monitoring, the relative humidity of the caves and the duration of high humidity increase with the level and frequency of rainfall. The early rainfall increased the relative humidity of the atmosphere, resulting in the humidity of the cave increasing rapidly for a short period of time when the rainfall happened. The later rainfall increased the relative humidity of the atmosphere, resulting in the humidity of the caves decreasing slowly when rainfall ended. It can be seen that the greater the frequency of rainfall, the longer the duration of high humidity of the caves. In order to prevent the humidity exceeding the threshold value, continuous rainy days should prompt greater attention being paid to monitoring the rainfall.

The effective early warning index is important to rainfall monitoring. The characteristic parameters of rainfall include rainfall amount, rainfall duration, and rainfall intensity. The relative humidity of C71 and C16 exceeded the threshold value during moderate rainfall. Taking the two caves as an example, the relationship between the duration of high humidity and the rainfall parameters were analyzed. It can be seen that the duration of relative humidity exceeding the threshold value has a nonlinear relationship with rainfall amount and the rainfall duration, but a significant linear relationship with rainfall intensity, with a correlation coefficient of 0.99 (Fig. 12). Therefore, it is suggested to use rainfall intensity as a risk warning index.

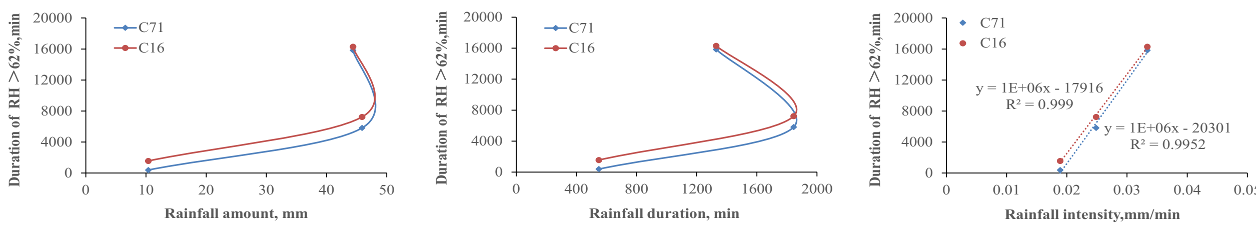

Fig. 12 Relationship between the duration of high humidity and rainfall parameters in the cave

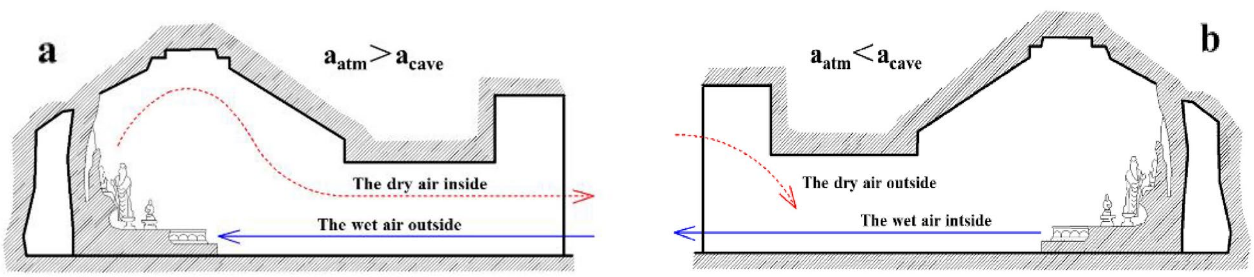

Fig. 13 Diagram of Fick diffusion of water vapour

Cave environmental control

Absolute humidity and relative humidity are both important in the environment control of caves. The cave is connected to the atmosphere through the doors and windows. Under the action of the temperature difference and concentration differences, the air inside and outside the cave exchange heat and mass constantly. During rainfall, the temperature gradient between the atmospheric environment and the cave decreases and the water vapour concentration gradient increases. According to the law of Fick's law of diffusion, water vapour diffuses into the cave from outside when $a_{atm} > a_{cave}$ and the absolute humidity of the cave increases (Fig. 13a). By contrast, the water vapour flows out of the cave when $a_{atm} < a_{cave}$, and the absolute humidity of the cave decreases (Fig. 13b). During rainfall, the fluctuation of temperature in the cave is small and the relative humidity increases with the increase of absolute humidity. The salt diseases of murals are easily activated by the changes of relative humidity [8, 11]. The best starting time to implement environmental control was when $a_{atm} = a_{cave}$. The control boundary condition is RH < 62%, based on the simulation test of mural deterioration [35].

Environment control of caves needs to pay more attention to the vulnerable caves. The Mogao Grottoes have a large number of caves with different sizes, shapes, and degrees of openness. In order to investigate the influence of rainfall on the murals, the monitoring of disease tracking was carried out in C71, C332, and C16. The monitoring results showed that the diseases of murals did not change significantly during seasonal rainfall in C71 and C332, but the salts appeared in the plaster layer and led to the disease of falling off in C16 (Fig. 14) and the plaster layer in the tunnel fell off (Fig. 14b). It can be seen that the greater the degree of openness, the greater possibility there is of salt damage under the same conditions of rainfall. Combined with the variation of humidity in different types of caves, it is found that the vulnerable caves have three typical characteristics of low geographical position, large openness and small volume. In rainy weather, if it is not possible to implement environmental control for all caves at the same time, the vulnerable caves can be selected as the benchmark to predict the microclimate change of other caves and take preventive measures in time.

Fig. 14 The monitoring of mural disease during seasonal rainfall (C16)

Tourism management

Dunhuang Mogao Grottoes is a famous cultural destination on a worldwide basis, and the number of tourists is increasing steadily [36, 37]. At present, the main mode of visiting is that the tourists go directly into the caves to see the murals. In rainfall weather, the caves have to be closed for a long time and so the tourists should not be allowed to visit normally. Therefore, the tourism management regulations should be enacted as soon as possible during rainy weather. The regulations will include the conditions of rainfall, the control cave, and the control time of tourism. Of these, the rainfall condition can be determined by the weather forecast, the control caves can be determined according to their volume and the opening degree, and the control time of tourism can be determined based on the microclimate monitoring results of a given cave.

Conclusion

(1) As the level of rainfall increases, the changes of temperature in the cave are very small, but the humidity increases significantly. The humidity and the duration of high humidity in the caves increase with the increase of rainfall level and frequency. The changing trends of relative humidity and absolute humidity in caves are basically the same and show three stages of rising, maintaining, and falling. The diffusion of water vapour is mainly driven by the water vapour concentration gradient between the atmosphere and the cave. The best starting time for environment control of cave is when $a_{atm} = a_{cave}$ and the control condition is $RH < 62\%$.

(2) Under the condition of the same rainfall, the duration of the relative humidity exceeding the critical threshold have characteristics of semi-closed caves being greater than closed caves and small caves being greater than large caves. The caves at lower layers, with larger openness degree and smaller volume are most vulnerable to water vapour intrusion, which means that more attention should be paid to the risk control of mural deterioration.

(3) The monitoring of rainfall should focus on continuous rainy weather and rainfall intensity is the best early warning index. The early and the later rainfall all increased the relative humidity of the atmosphere, resulting in the humidity of the cave increasing rapidly in a short period of time when rainfall happened and then the humidity of the caves decreased slowly when rainfall ended. The harm caused by continuous rainfall is much greater than for a single rainfall event. The duration of relative humidity at over 62% has obvious correlation with the rainfall intensity.

(4) The regulations for tourism management in rainy weather is an important measure in risk prevention. The rainfall conditions, the restricted caves and the control time can be determined by the weather forecast, the vulnerability assessment of the caves and the microclimate monitoring of the cave, respectively. The regulation is beneficial to prevent the deterioration of murals, as well as to avoid the tourists waiting for a long time.

Abbreviations

V	Volume, m^3
T	Temperature, ℃
a	Absolute humidity, g/m^3
RH	Relative humidity, %
a_{atm}	Absolute humidity of atmospheric, g/m^3
a_{cave}	Absolute humidity of caves, g/m^3
Ave	Average
Max	Maximum
Min	Minimum

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Author contributions
HL was a major contributor in writing the manuscript. QZ supervised the whole process and gave constructive advice. ZZ and QG devised the study plan. WL and WG conducted the experiment and collected the data. All of the authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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