Assessing the deterioration risk of mural paintings in Cave 98 of Mogao Grottoes based on the hygrothermal behavior

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Abstract. Cave 98 is a typical cave in Mogao Grottoes with various and serious degradations. This paper aims to clarify the heat and moisture transfer law of Cave 98 and murals and evaluate whether the current hygrothermal environment is conducive to the long-term preservation of murals. In this paper, a coupled heat and moisture transfer 2D model of Cave 98 was first established, and the accuracy of the model was verified by on-site monitoring data. Then, the spatial distributions of the temperature and moisture in Cave 98 were analyzed, and the quantitative evaluation of the deterioration risk of mural paintings in different locations was further evaluated. The results showed that 14% and 13.8% of the time indoor temperature and relative humidity (RH) exceeded the target range. Salt damage occurred more than 10 days a year, mold contamination occurred just a few days a year, and deterioration occurred at its peak in summer. Dehumidification measures can be taken during periods of high humidity to improve the adaptability of the current preservation environment.

1. Introduction
The Mogao Grottoes is a world-famous cultural heritage with preserved exquisite ancient murals. Currently, there are cracks, detachments, and microbial contamination to varying degrees on the cave murals. The hygrothermal characteristics of the building walls are directly related to the generation and development of salt efflorescence, mold, and other degradations of its murals [1],[2].

The coupled heat and moisture transfer model can simulate the heat and moisture transfer inside porous materials and has now been widely used in heritage conservation. However, most previous studies have been conducted on historical buildings, and the heat and moisture problems of caves have been less studied. Due to the huge differences in the material, geometry, boundary conditions, and historical buildings of caves, a further discussion of the thermal and humid behavior of caves is required. There has been considerable work on the effect of environmental factors on the degradation of Mogao Grottoes [3]-[5]. But there is still a lack of quantitative evaluation of the deterioration of Mogao Grottoes murals based on the hygrothermal environment, indoor air and cliff, resulting in the inability to visualize the spatial and temporal distributions of temperature, humidity, and water content in the cave interior and surrounding cliff.

This paper proposes a 2D coupled heat and moisture transfer model that considers the heat and water transfer processes between the chamber, the cliff, and the outdoor air. The indoor preservation environment of Cave 98 of Mogao Grottoes and the risk of various types of degradations are assessed.

2. Materials and methods
2.1. Outline of Cave 98
Cave 98, excavated during the 5th generation (914-935 AD), is located on the ground floor of the southern section of the Mogao Grottos (Figure 1a). Historically, Cave 98 used to consist of three parts: the front chamber, the corridor, and the main chamber. The remains of the front room of Cave 98 were discovered during archaeological excavations in the 1960s. Currently, Cave 98 retains the corridor and the main chamber (Figure 2). The main types of damages are flaking, efflorescence, cracks, hollowing, and mold, and the damages are most severe on the west wall. To prevent further damage, Cave 98 is not open for visitation all year-round and is only occasionally open as an emergency cave during peak visitor periods [6].

![Cave 98 in Mogao Grottos](image1.png)

(a)

(b)

(c)

Figure 1. Outline of Cave 98 in Mogao Grottos. (a) Cave 98’s location in Mogao Grottos. (b) Exterior view of Cave 98. (c) Interior view of Cave 98.

![The shape of Cave 98](image2.png)

(a)

(b)

Figure 2. The shape of Cave 98 [7]. (a) East-west section. (b) Plan.

2.2. Environmental monitoring
In 2019, the Dunhuang Research Institute continuously monitored the temperature and relative humidity (RH) of the air inside Cave 98 and the outdoor meteorological conditions in the Mogao Grottos throughout the year. The indoor monitoring equipment was a high-precision temperature and humidity sensor (u23-001a, American HOBO, accuracy: ±0.21°C and ±2.50%), and the instrument was placed in the lower part of the central Buddha statue with a 15-minute recording interval. The outdoor weather
station (HMP155A, Finland Vaisala, accuracy: ±0.283°C and ±1.0%) was installed 2 m above the ground in front of Cave 72 and continuously monitored meteorological parameters including air temperature, RH, rainfall, and solar radiation intensity in the Mogao Grottos area in real-time, with a recording interval of 10 minutes.

2.3. Heat and moisture transport simulation

2.3.1. Fundamental equations. Fundamental equations of numerical simulation used in this study are simultaneous heat and moisture transfer equations by Mastsumoto M [8], as shown in equations (1) and (2). The driving potential of heat and moisture transfer are temperature and water chemical potential, respectively.

Conservation equation of heat transfer:

$$c \rho \frac{\partial T}{\partial t} = \nabla \cdot \left[ \lambda \frac{\partial T}{\partial x} + r \lambda_{ug} \cdot \nabla \mu \right]$$  \hspace{1cm} (1)

Conservation equation of moisture transfer:

$$\rho_w \frac{\partial \mu}{\partial t} = \nabla \cdot \left[ \lambda_{mu}(\nabla \mu - n_x g) + \lambda_T \nabla T \right]$$  \hspace{1cm} (2)

where $c$ is the heat capacity of the material (J/kg·K); $\rho$ is the density of the material (kg/m³); $T$ is the temperature (K); $\mu$ is the water chemical potential of the material (J/kg); $\lambda$ is the heat thermal conductivity of the material (W/m·K); $\lambda_{ug}$ is the water vapor conductivity under the gradient of temperature (kg/m·s·K); $\lambda_{ug}$ is the water vapor conductivity under the gradient of water chemical potential (kg/m·s·J/kg); $r$ is the phase change heat of the vaporization of water (J/kg); $\rho_w$ is the density of the water (kg/m³); $\psi$ is the volume water content of the material (m³/m³); $\lambda_{mu}$ is the water conductivity under the gradient of water chemical potential (kg/m·s·J/kg); $\lambda_{T}$ is the water conductivity under a temperature gradient (kg/m·s·K); $g$ is the gravity acceleration (9.8 (m/s²)); and $n_x$ is the direction of water gradient (vertical direction is 1 and horizontal direction is 0).

Water chemical potential is an indicator of the state of water, determined by temperature and RH:

$$\mu = R_v T \ln(h)$$  \hspace{1cm} (3)

where $R_v$ is the gas constant of water vapor (J/kg·K) and $h$ is RH (-).

2.3.2. Model setting. The two-dimensional numerical calculation model was developed based on the east-west section of Cave 98, and the simulation program in this study was developed using the Fortran programming language. The shape and dimensions of the calculation model are shown in Figure 3. Treating the indoor air as a mass, the heat and moisture in the chamber were considered to come from heat and moisture transfer of the surrounding walls and the air exchange between the interior and exterior, without considering the indoor heat and moisture sources.

The meteorological data monitored by the weather station outside the cave was used as the external climate conditions. At the bottom of the cliff (15 m underground), the temperature is equal to the annual average outdoor temperature and the water chemical potential was constant at 100 J/kg. The lower left boundary and right boundary were assumed as adiabatic and impermeable to moisture.

Since the surrounding ground is the sandy conglomerate layer, the values of heat and moisture properties of Plainfield sand were used [4]. The properties of clay soil and the hygrothermal properties of the mural paintings and the Buddha statue were to the existing studies [9],[10]. The heat transfer coefficients of indoor and outdoor surfaces were 7 (W/m²·K) and 20 (W/m²·K), respectively, and the moisture transfer coefficients of the surfaces were calculated by Lewis' law. Different values of air changes were set according to different months, as shown in Table 1.

The finite difference method was used for the calculation with a time step of 1 s, and the calculation time was 50 years.
Table 1. The monthly values of ventilation rate.

<table>
<thead>
<tr>
<th>Month</th>
<th>Ventilation rate [/h]</th>
<th>Month</th>
<th>Ventilation rate [/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.49</td>
<td>Jul</td>
<td>0.2</td>
</tr>
<tr>
<td>Feb</td>
<td>0.34</td>
<td>Aug</td>
<td>0.16</td>
</tr>
<tr>
<td>Mar</td>
<td>0.17</td>
<td>Sep</td>
<td>0.15</td>
</tr>
<tr>
<td>Apr</td>
<td>0.17</td>
<td>Oct</td>
<td>0.25</td>
</tr>
<tr>
<td>May</td>
<td>0.17</td>
<td>Nov</td>
<td>0.4</td>
</tr>
<tr>
<td>Jun</td>
<td>0.2</td>
<td>Dec</td>
<td>0.48</td>
</tr>
</tbody>
</table>

2.4. Model validation

Normalized Mean Bias Error (NMBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), and $R^2$ are used to determine the compliance between simulated data and metered data [11]. Models are declared to be calibrated if they produce NMBEs within $\pm 10\%$, CV(RMSE)s within $\pm 30\%$, and $R^2$s greater than 0.75.

The differences between actual measured and predicted data of indoor temperature and RH are shown in Figure 4. The values of NMBE, CV(RMSE), and $R^2$ are shown in Table 2. The values of NMBE, CV(RMSE), and $R^2$ show the uncertainty of the numerical model is at an acceptable level, so the model proves valid.

![Figure 4. Comparison between measured results and calculated results. (a) Indoor temperature. (b) Indoor RH.](image)
3. Results and discussions

3.1. Monitoring and evaluation results of conservation environment

The values for short-term fluctuations and the time beyond limits are calculated according to the method in the standard EN 15757 (Figure 5). As shown in Table 3, there are 14.0% of the days when the indoor temperature exceeds the limit range, with more of the time in winter. The maximum short-term fluctuation of temperature is 4.6 °C, exceeding ±2.5 °C recommended by EN 15757. There are 13.8% of the days when the indoor RH exceeds the limit range, and more days exceeding the target range from June to August. The maximum short-term fluctuation of RH throughout the year is 44.8%, exceeding the limit of ±15% [12].

![Figure 5](image)

**Table 3.** Evaluation results of indoor temperature and RH.

<table>
<thead>
<tr>
<th></th>
<th>Measured values</th>
<th>Simulated values</th>
<th>NMBE</th>
<th>CV (RMSE)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Max. 17.3 ℃</td>
<td>17.8 ℃</td>
<td>1.02%</td>
<td>4.24%</td>
<td>0.993</td>
</tr>
<tr>
<td></td>
<td>Min. 2.9 ℃</td>
<td>3.3 ℃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Avg. 11.4 ℃</td>
<td>11.6 ℃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RH</td>
<td>Max. 71.0%</td>
<td>71.6%</td>
<td>-0.95%</td>
<td>8.98%</td>
<td>0.962</td>
</tr>
<tr>
<td></td>
<td>Mini. 13.9%</td>
<td>15.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ave. 32.6%</td>
<td>32.3%</td>
<td></td>
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</tbody>
</table>

3.2. Spatial distribution of the temperature and moisture of Cave 98

In summer, the internal temperature of the cliff was lower than the surface temperature of the cliff (Figure 6a). While in winter, on the contrary, the internal temperature of the cliff was higher than the surface temperature (Figure 6b). When the depth of the cliff reached a certain level, the temperature of the cliff was stable at about 12 ℃ in both winter and summer. The thermal inertia of the rock slowed down the fluctuation of the temperature inside the cave throughout the year with the external temperature change.

As for RH, in summer (Figure 7a), the closer to the interior of the cliff, the RH showed an increasing trend. It reached 98% at 2m to 4m from the vertical surface. Subsequently, when the depth increased, the RH of the cliff was about 96%. The influence of the cave on the RH of the cliff was about 4 m. The RH on the surface of the Buddha statue in the center of the cave was higher than the RH inside the statue. In winter (Figure 7b), the RH distribution is similar to that in summer. This distribution is consistent with the results of previous studies [5].

The distribution of water content in the cliff was approximately the same in winter and summer (Figure 8). The overall water content of the cliff is low, ranging from 1% to 3%. The water content of the murals and Buddha statues in the caves is about 5%, higher than that of the cliff, which results
from the difference of material properties between Plainfield sand and clay soil. The water content of the surface of the Buddha statue is about 5%, slightly higher than the internal water content of 4.5%.

Figure 6. Distribution of temperature of Cave 98 and the cliff. (a) summer (Jul. 1, 3pm). (b) winter (Dec. 25, 4am).

Figure 7. Distribution of RH of Cave 98 and the cliff. (a) summer (Jul. 1, 3pm). (b) winter (Dec. 25, 4am).

Figure 8. Distribution of water content of Cave 98 and the cliff. (a) summer (Jul. 1, 3pm). (b) winter (Dec. 25, 4am).

3.3. Evaluation of the deterioration risk of mural paintings
Three feature points (Figure 9) are selected to quantitatively evaluate the deterioration risk of wall paintings in different locations by using temperature and RH as indicators of salt damage and mold growth.

Previous studies have found that NaSO₄ is the main soluble salt in the Mogao Grottos cliff [13]. NaSO₄ changes its form based on temperature and RH conditions [14]. The hourly temperature and RH of the mural surface were compared with the deliquescence temperature and RH of NaSO₄. For more than 10 days throughout the year, the temperature and RH fluctuated frequently up and down the critical value. The risk of salt weathering is highest in the west wall (Point C), followed by the roof (Point B), and the risk in the corridor (Point A) is the smallest. Moreover, the salt damage time occurred around July, and certain dehumidification measures need to be taken in summer (Figure 10a).

Sedlbauer gives a broad range of spore germination lines and mold growth ranges as variables of temperature and RH based on experimental studies [15]. Figure 10b shows the mold risk at the three mural-surface feature points. The mural spends most of its time outside the mold growth zone, but the temperature and RH at three points near July 23 in summer are within the germination scope. It shows that in the current environment, the risk of mold is low throughout the year, but there is a certain risk of mold in summer.

4. Conclusion
This paper evaluates the suitability of the existing temperature and moisture environment of the Mogao Grottoes Cave 98 murals in the cold region of northwest China. Using the coupled heat and moisture 2D transfer model, the relationship between the outdoor environment and the fluctuation of temperature, humidity, moisture content, and evaporation of the mural was established. The risk of mural surface deterioration was quantitatively assessed. The main conclusions are as follows:

The indoor temperature and RH exceeded the target range recommended by EN 15757 standard by 14% and 13.8% of the year, respectively, which was manifested as low air temperature in winter and high RH in summer.
The temperature deep in the cliff of Mogao Grottos is about 12°C, and the RH is about 96%. The depth of the influence of the cave on the RH of the cliff is about 4m. The distribution of water content of the cliff in winter and summer was roughly the same. The overall moisture content of the cliff is low, ranging from 1% to 3%.

The risk of deterioration of murals in different locations was quantitatively evaluated, and it was found that there were more than 10 days of salt damage, while the risk of fresco growth of mold is low, and mid-July was the high incidence of salt weathering and mold. The murals on the west wall are most susceptible to salt efflorescence and mold contamination.

Acknowledgement
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References
[1] Wei S, Ma Q and Schreiner M 2012 *Journal of Archaeological Science* Scientific investigation of the paint and adhesive materials used in the Western Han dynasty polychromy terracotta army, Qingzhou, China 39 1628–33
[13] Zongren Y 2008 *Dunhuang Research* Test for blister and soluble salt in powdering and the layer of plaster for the wall-painting in Cave 351 at Mogao Grottoes 6 39–45