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# Assessment of Deterioration Risk of Maijishan Grotto under the Radiation Difference Based on Heat and Moisture **Transfer Model**

### R B Wu<sup>1</sup>, Y Ma<sup>1</sup>, H R Xie<sup>1</sup>, S Hokoi<sup>2</sup>, Y Q Yue<sup>3</sup> and Y H Li<sup>1</sup>

<sup>1</sup>School of Architecture, Southeast University, Nanjing, 210096, China; <sup>2</sup> School of Architecture Internationalization Demonstration, Southeast University, Nanjing, 210096, China

<sup>3</sup> Art Institute of Maijishan Cave-Temple Complex, Gansu, Tianshui, 741020, China

#### Corresponding E-mail: liyonghui@seu.edu.cn

Abstract. The ambient environment of architectural heritage is an important factor affecting its conservation. Two adjacent rows of Buddha statues in Grottoes No. 3 (semi-open) of Maijishan Grotto in Gansu, China, show apparent differences in the degree of deterioration. This study made a monitoring scheme of grottoes microenvironments such as air temperature, relative humidity, radiation, and surface temperature to explore the cause of the difference. A twodimensional heat and moisture (HAM) transfer model was established and verified to simulate the temperature and humidity on the surface and inside of the Buddha statues. Then, temperature and water content fluctuation and the risks of thermal stress destruction on the surface and near the surface of the Buddha statues were evaluated. The results show that the radiation difference causes thermal stress and water content differences both in heights and in depths. This impact brought by the direct sunlight may contribute to the different deterioration on the two rows of Buddha statues. The eaves shaded the upper row of the Buddha statues much longer than the lower ones. Less severe fluctuation and differences in temperature and water content occur at the middle and upper points. This study evaluates the degradation of Grottoes No. 3 and has guiding significance for its preservation methods.

Keywords. Architectural heritage; Heat and moisture transfer; Radiation; Deterioration; Preservation.

#### 1. Introduction

Under the combined action of environmental factors (solar radiation, temperature, moisture, etc.) and time, most materials will undergo weathering and aging. When this process occurs on the cultural heritage, it will affect the preservation of the heritage, erode its historical, cultural, and aesthetic value, and cause irreversible damage [1, 2].

Grotto temples are a special form of architecture, which is mostly built against the mountains with local materials. They are enormous and immovable, most of which are exposed to the natural environment. Under the influences, such as solar radiation, precipitation, earthquake, etc., weathering and other damages have appeared, threatening the existence of the heritages.

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Long-term exposure to sunlight can cause irreversible damage to cultural heritage. Research shows that thermal stress is one of the key factors leading to the weathering of stones [3]. The thermal stress (repeated thermal fatigue) makes the rock more vulnerable when combining with other weathering mechanisms, such as salt crystallization, freeze-thaw cycling, etc.[4–6].

Periodic changes in the natural environment are thought to be the main drivers of physical weathering. It is pointed out that the performance of natural building materials is largely affected by the change of thermal and humid conditions and is related to pore structure [7]. With water vapor adsorption, the strength of the conglomerate containing the montmorillonite tends to decrease, and it is more prone to deformation [8].

In this study, given the deterioration difference in two rows of Buddha statues, a semi-open grotto (Grotto No.3) of Maijishan Grotto was selected to conduct solar radiation-related research. A new monitoring scheme and a two-dimensional heat and moisture model were set up to analyze and evaluate the risks dominated by solar radiation, this study may have guiding significance for the preservation methods and the design of protective eaves.

# 2. Materials and Methods

#### 2.1. Heritage Profile

Maijishan Grotto (N: 34°35"; E: 106°00") is a World Cultural Heritage announced in 2014 by UNESCO in Gansu Province, China. The area of Maiji Mountain belongs to the Danxia landform (glutenite), the specific composition is about 29% montmorillonite, 42% illite, kaolinite, and 23% chlorite.

Grotto No. 3 is a semi-open grotto in the middle of the south façade of Maiji Mountain (Figure 1). It is with a length of 36.5 meters and a height of about 50 to 60 meters from the ground. The Buddha statues are stone-based sculptures upon which are clay and drawings. The outer front eaves have collapsed and been damaged. During the field research, it is observed that there are differences in the shadow area on different layers of Buddha statues in a day, and the preservation condition showed some difference between the upper (better) and lower rows of the Buddha statues. Therefore, it is preliminarily inferred that solar radiation is a key factor affecting the preservation.

#### 2.2. Monitoring Scheme

To clarify the risk and related factors of deterioration, a monitoring scheme was designed (Figures 2 and 3). Two vertical radiation sensors were set in the same direction and height as the heads of the statues (type: HOBO S-LIB-M003, precision:  $\pm 10 \text{ W/m}^2$  or  $\pm 5\%$ ; measurement range:  $0 - 1280 \text{ W/m}^2$ ). Three K-type thermocouples were put at different heights of the two rows of statues (upper, middle, and lower points) to measure the surface temperature (type: TESTO 176 T4; precision:  $\pm 0.3^{\circ}$ C; measurement range: -195 - 1000 °C). The sensors were applied to the bedrock with 1-2cm thick clay. The clay was also used to repair the paintings, which has been desalinated, thus no risk of damaging the statues or the drawings. Both recorders were set with an interval of 10 minutes.

#### 2.3. Simulation Model

A HAM model with temperature and water chemical potential as driving forces put forward by Matsumoto is the theoretical basis of our model [9]. At present, simulation and analysis on architectural heritages from the perspective of hydrothermal transfer based on this theory have been fully applied [10–12]. The model is established compiling with FORTRAN language on the platform of Intel Visual Studio. In the model, a simplified north-south section (facing South-southeast 15 degrees) and abstracted outlines were selected for calculation. A selected area (grotto part) of the whole model was shown in the figures for illustration. There are three kinds of materials (Figure 4): the rock (grey and yellow part), the clay (red part), and the concrete walkway (blue part). Considering the calculation accuracy and efficiency, the mesh is divided (Figure 5). Thus, each node has a corresponding length, width, and material properties. The calculation time step is 30 seconds.

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Ambient air temperature, relative humidity, and solar radiation (Horizontal) records (2020.04.01 - 2021.03.31) near Maiji Mountain were used as the boundary condition. The left boundary (15m deep from the surface of the mountain) is considered steady at 10.9°C, the average temperature of a year. The upper or lower boundary of the model is 15 meters far from the selected area (Figures 4 and 5). They are set to have no heat or water flow. Solar radiation of other directions or forms is calculated based on the horizontal one. The influence of convection by the wind is represented by the comprehensive convective heat transfer coefficient, which was set as  $10 \text{ W/(m}^2 \cdot \text{K})$ . Due to the shielding effect of the rock eave, no rain or wind-driven rain was observed in the field research, thus no precipitation is added on the surface inside the eave.



Figure 1. Grotto No.3.





Figure 2. Buddha statue.





**Figure 4.** The distribution of materials used in the model (Around the Buddha area).



Figure 5. Size of the computational grids in the model (Width\*Height; Unit: meter).

# 3. Measured and Calculation Results

# 3.1. Measured Results

Three months of data (from August 7, 2020, to November 2, 2020) was obtained after the monitoring (Figure 6). Before October 15th, limited direct sunlight reached the surface of the two rows of Buddha statues (less than  $100W/m^2$ ) and the surface temperature of the three points fluctuates with the ambient air temperature. After that, the sunlight began to shine on the lower row of statues, with the maximum at 560.6W/m<sup>2</sup>. It is observed that both the solar radiation and the surface temperature are widely divergent from those in the upper row, with instant temperature differences reaching 12.10 °C. Taking

October 16th and 17th as an example (Figure 7), it can be found that the surface temperature is positively correlated with the amount of solar radiation. The lower point experiences a greater temperature difference between day and night, for example, rising 12 °C in 3 hours.



Figure 6. Monitored data of three months.



Figure 7. Monitored data on 10.16-10.17, 2020.

Table 1. Comparison of simulation and measured results.							
Point	Value	Average	Difference	Maximum	Difference	Minimum	Difference
Unnor	Measured	15.58°C	0.000	24.10°C	2 9 20 C	8.30C	2 200C
Upper	Simulated	14.70°C	0.00 C	27.92°C	-3.82°C	4.92°C	5.58°C
Middle	Measured	15.76°C	0.06%	23.60°C	4 50°C	8.80°C	2 920C
Mildale	Simulated	14.80°C	0.90 C	28.10°C	-4.30 C	4.97°C	5.85 C
Lowon	Measured	15.98°C	0.870	26.20°C	2.05%	7.90°C	2 65%
Lower	Simulated	15.11°C	0.871	28.25°C	-2.03°C	5.25°C	2.05°C

Table 2. Comparison of simulated and monitored solar radiation at two rows of Buddha statues.

Row	Value	Range(W/m <sup>2</sup> )	Total (hourly, W/m <sup>2</sup> )
Unnor	Measured	0 - 274.40	32,056.50
Upper	Simulated	0 - 239.14	50,790.77
Lowon	Measured	0 - 560.60	49,448.00
Lower	Simulated	0 - 630.85	64,747.87



Figure 8. Verification of the model (simulated and measured temperature at three heights.



**Figure 9.** Annual variation of simulated surface temperature at upper, middle, and lower points.

Table 3. Simulated surface temperature at upper, middle, and lower points.

Point	Min.	Max.	Amplitude	Average	Hour (<0°C)	
Upper	-12.02 °C	21.31 °C	33.33 °C	5.06 °C	958	
Middle	-11.98°C	26.49 °C	38.47 °C	5.51 °C	886	
Lower	−11.92 °C	32.08 °C	44 °C	6.74 °C	817	

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# 3.2. Measured Results

The whole period of weather and monitored data were used for model validation. Thus, the characteristic values (maximum, minimum, average) are compared over the same period. Table 1 shows the results of the comparison between the measured and simulated surface temperature, while Table 2 shows the comparison of the solar radiation. The simulated values of the three points showed the same trend as the measured ones (Figure 8). Due to some simplification in the calculation model (the uneven eave and the effect of the barbed wire), the temperature difference is observable but considered within the acceptable range for evaluation. Therefore, the current model can be used for subsequent analysis and calculation. (Difference Value = Measured Value - Simulated Value)

# 3.3. Simulation Results

3.3.1. Annual variation of simulated surface temperature and solar radiation of the Buddha statues Table 3 show the annual variation of the simulated surface temperature and solar radiation of the Buddha statues at the upper, middle, and lower points. The time of direct sunlight affects the lower part of the statues the most. The difference of the maximum values among the three points indicates that the lower part faces more severe temperature fluctuations, which are 5.53 °C and 10.67 °C higher than the middle and upper ones, respectively. It is also shown in Figure 9 that the high surface temperatures (over 15°C) concentrated in the winter season mainly at middle and lower points. From November 21st to March 1st, the surface temperature of each point began to drop below zero, and the upper point stays below 0°C the longest, and then the middle and lower points. It is deducted that the heat from solar radiation during the day increased the surface temperature of the lower point. As a result, the temperatures drop more slowly to below zero (less duration) during the cold night (Figure 10). In conclusion, the lower point is facing more severe impacts from solar radiation than those of the middle and upper points.

3.3.2. Annual variation of simulated surface temperature and solar radiation of the Buddha statues

#### 1/15 1/15 1/16 1/16 800 30 700 25 600 20 Solar Radiation W/m<sup>2</sup> 500 15 emperature 400 10 300 5 200 0 100 -5 0 -10 21:00 0:00 3:00 6:00 9:00 12:00 15:00 18:00 21:00 0:00 3:00 6:00 9:00 L2:00 L5:00 18:00





1/16

1/16

0.05

1/15

1/15

800



As shown in Figures 10 and 11, January 15th and 16th were taken as an example to explore the variation of temperature and volumetric water content. It is shown in the two days that the surface temperature responds very quickly to the sunlight, as well as the water content. However, this influence shows differences at the three points. The lower point receives the direct sunlight since sunrise and goes on until sunset, while the middle point only has one or two hours after sunrise or before sunset, and almost none for the upper point. This leads to the variation of surface temperature correspondingly. For example, the surface temperature at the lower point was elevated near 24 °C in three hours on the 15th, while at the middle part it was heated to 15 °C in the morning and 20 °C in the

afternoon. As to the volumetric water content, it decreases as the sun shines on the surface, with the greatest evaporation at the lower point. The lower point suffered more severe water content variation.

To characterize the changes in temperature and water content, the difference between the adjacent nodes (spacing 1 cm) with the same material properties (both clay) was compared at the three heights. In another word, the two most superficial nodes were used in the comparison. From the left (inside) to the right (outside), the nodes are clay2, and clay1 successively. As to the temperature, the differences in the same material are relevant to its thermal stress. As to volumetric water content, the difference of the first and the second nodes was compared to show the diurnal changes of water content.

Point	Material	Temperature	Daily variation	Biggest instant difference
Unner	Clay1	-3.68 – 10.35°C	14.04 °C	2 00°C
Opper	Clay2	$-1.85 - 7.36^{\circ}C$	9.21 °C	5.00 C
Middle	Clay1	-3.58 – 19.29°C	22.87 °C	7 28%
Mildale	Clay2	-1.64 – 12.51°C	14.15 °C	7.28 C
Lowen	Clay1	-3.45 - 23.60°C	27.05 °C	7 70%
Lower	Clay2	-1.38 - 17.38°C	18.76 °C	7.70°C

	<b>.</b>		
Table 4. The simulated	temperature of the clay	. (Difference = Clay)	(outer)- Clay2 (inner).

NodeVolumetric water content (m³ / m³)	Volumetric water content (m <sup>3</sup> / m <sup>3</sup> )				
Point Clay2 Clay1					
<b>Upper</b> 0.0471-0.0488 0.0456-0.0496					
<b>Middle</b> 0.0467-0.0486 0.0439-0.0495					
Lower 0.0463-0.0484 0.0433-0.0494					

Table 4 shows the variation of simulated temperature of the clay in the two days. It is shown that the instant temperature difference of different depths at the lower point reaches 7.70°C, while the daily variation of clay1 or clay2 can reach 27.05°C or 18.76 °C, respectively. As shown in Figure 12, the instant temperature difference at the middle and upper points showed the same trend and has less duration time than the lower one when the difference is over 2 or 4 °C. Table 5 shows the diurnal variation of the water content of the two nodes. In the horizontal direction, the deeper the node, the higher the volume moisture content. While in the vertical direction, the higher the position, the higher the volume the difference is structure as Figure 12, that is, larger differences between clay1 or clay2 with longer duration exist at the lower point under direct sunlight.



Figure 12. Temperature differences (within clay) on Jan. 15th and 16th.



**Figure 13.** Water content differences (within clay) on Jan. 15th and 16th.

#### 4. Discussion

As the surface of statues consists of clay (about 2cm) and paintings (about 0.1cm), the bonding between them may be weakened under thermal stress over time. And then deterioration takes place,

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such as the cracking, flaking, and exfoliation of the surface layer, even the shedding of the base layer (carrier of the mural). Based on our result of the temperature difference caused by sunlight, the thermal stress on the surface of the clay will be discussed.

It is known that materials normally expand as the temperature rises, and larger deformation will cause larger thermal stress. The thermal stress of the surface (clay) can be calculated based on a known equation[3]. And the thermal stresses will be used to evaluate the risks to the statues. Both the parameters and the calculation results are shown in Table 6.

$$\sigma_T = \frac{E \cdot \alpha \cdot \Delta T}{1 - \nu} \tag{1}$$

In equation (1),  $\sigma_T$ : thermal stress; *E*: elastic modulus, [Pa]; *a*: linear thermal expansion coefficient,  ${}^{\circ}K^{-1}$ ;  $\Delta T$ : the temperature difference of the clay in a day,  ${}^{\circ}K$ ; *v*: the Poisson's ratio. **Table 6.** Thermal stress of the clay.

Material	E	α	V	Point	Instant difference	Thermal stress	
Clay	0.0887×10 <sup>4</sup> 1.2×10 <sup>-6</sup> MPa m/m • K	$1.2 \times 10^{-6}$		Upper	3.00°C	4.91 kPa	
		$1.2 \times 10^{-1}$	$1.2 \times 10$	0.35	Middle	7.28°C	11.92 kPa
		-	Lower	7.70 °C	12.61 kPa		

It can be seen that the thermal stress on the surface of the statues can reach 12.61 kPa at the lower points within a day in a depth of 1cm, 2.57 times as much as the upper point in a day. It is related to the time that sunlight shines on the surface. The lower point faces more severe thermal fatigue than that the other ones. In another word, the temperature differences of the surface and inner part (1cm deep) triggered by the direct sunlight may cause physical damage to the lower row of the Buddha statues. It has been studied that the tensile strength of some clay is about 10 - 60 kPa, which means that the lower and middle parts of the statues have faced the impact caused by thermal stress already. When the impacts of rapid temperature changes and thermal stress intertwine with other influences, such as salt weathering and freeze-thaw damage, it may result in more deterioration of the lower row of Buddha statues. The upper point has much smaller thermal stress, which means that the shading effect of the cornice protects the Buddha statues to some extent. This may help us understand the risk that similar outdoor cultural heritage may face, and the possible preservation method should be aimed at reducing the impact of direct light.

Since the statues are made of composite materials, the forces between the materials should be considered in the future. The stress caused by the coefficient of moisture expansion shall be considered as well.

# 5. Conclusion

In this paper, the influence of solar radiation on the preservation of the Buddha statues was explored and the conclusions were formulated as follows:

- 1. Direct sunlight has a long-term effect on both the surface temperature and near-surface inner temperature. The response of temperature to direct sunlight is rapid, causing huge temperature differences (up to about 8 °C per hour). The triggered thermal stress at the lower point (12.61 kPa) is 2.57 times as much as the upper one, increasing the risk of degradation.
- 2. The water content changes corresponding to the influence of direct sunlight as well. The difference in water content of the same material in the horizontal direction (lower point) is near 0.002 m<sup>3</sup>/m<sup>3</sup> at most during the period of sunlight. However, the buddha statues always stay dry (saturation degree at 8.69 13.96% all year), thus no significant effect.
- 3. Direct sunlight on the surface of cultural heritage should be avoided for better conservation. Possible preservation methods should be taken especially to the heritages that are made of composite materials with different responses to the temperature.

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### References

- [1] Quindos L. S., Bonet A., Diaz-Caneja N., Fernandez P. L., Gutierrez I., Solana J. R., Soto J. and Villar E. 1987 *Atmos. Environ.* **21** 551–60
- [2] Varas-Muriel M. J., Pérez-Monserrat E. M., Vázquez-Calvo C. and Fort R. 2015 *Constr. Build. Mater.* **95** 611–22
- [3] Al-Omari A., Brunetaud X., Beck K. and Al-Mukhtar M. 2019 J. Cult. Herit. 37 9–16
- [4] Eppes M. C., Magi B., Hallet B., Delmelle E., Mackenzie-Helnwein P., Warren K. and Swami S. 2016 *Bull. Geol. Soc. Am.* 128 1315–38
- [5] Smith B. J., Srinivasan S., Gomez-Heras M., Basheer P. A. M. and Viles H. A. 2008 1–13
- [6] Smith B. J., Srinivasan S., Gomez-Heras M., Basheer P. A. M. and Viles H. A. 2011 Geomorphology 130 76–82
- Benavente D., Cañaveras J. C., Cuezva S., Laiz L. and Sanchez-Moral S. 2009 *Environ. Geol.* 56 1495–504
- [8] Zhang N., He M., and Liu P. 2012 Eng. Geol. 141–142 1–8
- [9] Matsumoto M. 1978 Doctoral Thesis (Japan: Kyoto University)
- [10] Li Y., Xia C., Wu R., Ma Y., Mu B., Wang T., Petropoulos E., and Hokoi S. 2021 Build. Environ. 187
- [11] Ma Y., Li Y., Hokoi S. and Zhang X. 2020 E3S Web of Conferences vol 172 (EDP Sciences)
- [12] Li Y., Ogura D., Hokoi S., and Ishizaki T. 2012 J. Build. Phys. 36 117-39