

# Estimation of Hydraulic Environment Behind the Mogao Grottoes Based on Geophysical Explorations and Laboratory Experiment

Koizumi Keigo, Oda Kazuhiro, Ito Misae, Piao Chunze, Tanimoto Chikaosa, Iwasaki Yoshinori, Yoshimura Mitsugu, Wang Xudong, Guo Qinglin, and Yang Shanlong

## Abstract

There is moisture movement under the ground as a factor contributing to salt damage at the arid regions. Some parts of wall paintings of the Dunhuang Mogao Grottoes, which is a World Heritage site, have been seriously damaged by the crystallization of salts. This damage is likely to have been caused by short-term factors such as rainwater and flooding, and a long-term factor, namely, groundwater movement. In order to preserve the grottoes, it is important to know the relationship between underground moisture and salts. The purpose of this study is to understand the moisture content and salinity in conglomerate layers behind the Mogao Grottoes by the geophysical explorations and laboratory experiment. The resistivity characteristics of the field sample focused on water saturation with salinity were determined by laboratory tests. By obtaining the distribution of water saturation from the electric resistivity method in the study site, the moisture content in the ground was estimated. To confirm the reliability of the estimation, RI-density log was implemented. These results indicate there is relationship between the hydric environment and salinity concentration in each depth behind the Mogao Grottoes.

## Keywords

Stone heritage • Electrical resistivity • Moisture environment • Salinization

K. Keigo (✉) · O. Kazuhiro · I. Misae  
Osaka University, 2-1 Yamadaoka, Suita, 565-0871 Japan  
e-mail: koizumi@civil.eng.osaka-u.ac.jp

P. Chunze  
Hytec Geotechnical Consultant, 2-11-9 Miyahara, Yodogawa-ku,  
Osaka, 532-0003 Japan

T. Chikaosa  
Earth Watch Corp, 1-10-206 Toyotsu, Suita, 564-0051 Japan

I. Yoshinori  
Geo Research Institute, 4-3-2 Itachibori, Nishi-ku, Osaka,  
550-0012 Japan

Y. Mitsugu  
Soil and Rock Engineering, 2-21-1 Shonaisakaemachi, Toyonaka,  
561-0834 Japan

W. Xudong · G. Qinglin · Y. Shanlong  
Dunhuang Academy, Dunhuang city, China

## 9.1 Introduction

The Dunhuang Mogao grottoes are located 25 km southeast of Dunhuang City. The grottoes were excavated over about 1,000 years, from 366 A.D., and extend about 40 m in height and 2 km in north–south length. Presently, 492 caves, 2,400 painted sculptures and 45,000 m<sup>2</sup> of mural are preserved; additionally, the grottoes were registered as a World Heritage site in 1987.

The Mogao grottoes were cut into the western cross section of a cliff that resulted from the erosion of the old fan deposits by the Daquan River. The grottoes were basically formed by the reasonable consolidated conglomerate layer which can be excavated by human-beings (Kuchitsu and Duan 1992).

The present cliff is divided into five layers: Q<sub>2</sub>A–D and Q<sub>3</sub>. The upper layer (Q<sub>3</sub>) consists of unconsolidated conglomerate and forms the upper portion of the grottoes. The lower layer (Q<sub>2</sub>) is formed by conglomerate consisting of old

fan deposits. Most of the caves are within the Q<sub>2</sub>C and Q<sub>2</sub>D layers, although a few are within the Q<sub>2</sub>B layer.

Recrystallization of soluble salts can be observed owing to the particular desert conditions surrounding the Mogao grottoes, and likely occurs as a result of evaporation of water that became loaded with salt when the surrounding rock reacted with fluids such as rainwater. Such processes cause salt damage in the caves, resulting in the deterioration or collapse of murals as a result of recrystallization of the soluble salts. Salt damage is observed mostly on the ceiling of a cave in the upper layer and is confirmed at the bottom of side wall of a cave in the lower layer. The movement of water (rainwater and floodwater in the upper and lower layers, respectively) may dissolve salt within the ground. Salt damage has occurred in more than 70 caves in the grottoes and is an issue that must be addressed in order to preserve the grottoes.

To prevent salt damage to the walls of the caves, it is necessary to elucidate the movement of water and soluble salts in the ground around the Mogao grottoes. Moisture behavior in the area can be classed as short term (e.g., rain, flood) or long term (e.g., groundwater). In order to elucidate the mechanisms of the salt damage, this study is intended to estimate moisture conditions, especially salinity, in the ground behind the Mogao grottoes. First, electrical resistivity distribution within the cliff of the grottoes is measured in the field by electrical survey. However, because there are abundant soluble salts in the ground, it is difficult to estimate moisture conditions based on the resistivity distribution without considering soluble salts. Therefore, the characteristics of the electrical resistivity distribution are examined by laboratory experiments focusing on relationship between the degree of water saturation and the salt content by using filed samples. Finally, the moisture conditions of the ground are estimated by converting the resistivity distribution into distribution of water saturation using the results of the laboratory experiments.

## 9.2 Electrical Resistivity Distribution

Electrical resistivity was measured at the top of the cliff of the Mogao grottoes. A borehole was located at a point 150 m west of the Nine-story Pagoda that is the landmark feature of the grottoes. The borehole reached a depth of 120 m. The two-pole method was carried out. Figure 9.1 shows the measurement results, and Fig. 9.2 illustrates a cross-sectional view showing Line100gake and LineV100. It is clear that the electrical resistivity is higher for shallow ground than for deep ground. In particular, a lower resistivity zone of about 45 Ω m exists at 40–80 m depth; additionally, the higher resistivity zone in the vicinity of 100 m depth appears to be a localized phenomenon. A lower resistivity zone can be seen over the

caves in Line100gake. Accurate measurement of resistivity was impossible in the section between LineV100 and Line100gake because the steel wires for the environmental stations were buried in the ground. The results of this measurement indicated that a lower resistivity zone, which may affect the caves, is present at the back of the Mogao grottoes.

## 9.3 Characteristics of Electrical Resistivity of Local Samples

In this study, moisture conditions in the ground behind the Mogao grottoes are estimated from electrical resistivity distribution measured by field survey. In general, electrical resistivity changes under the influence of various elements; therefore, it is important to interpret the resistivity distribution by laboratory tests. In this section, we discuss the relationship between electrical resistivity and water saturation using field samples.

### 9.3.1 Methods

Experiments were conducted in the laboratory to elucidate the relationships between electrical resistivity and water saturation of field samples under changing salt concentration. The samples are conglomerates which were collected near the Mogao grottoes. First, salts contained in the samples were leached by filtering with distilled water. Then, salts were impregnated by injecting aqueous solution that dissolved the certain quantitative saturated salt into the samples leached salts. While gradually drying samples, resistivity and weight measurements of the samples were repeated several times. The experiment was conducted based on four patterns: Case-A calculated the average value of all samples; twice amount of Case-A in Case-B; Case-C gives the

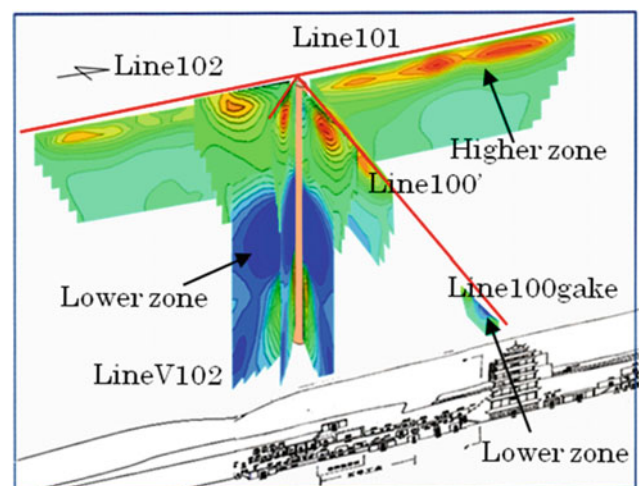
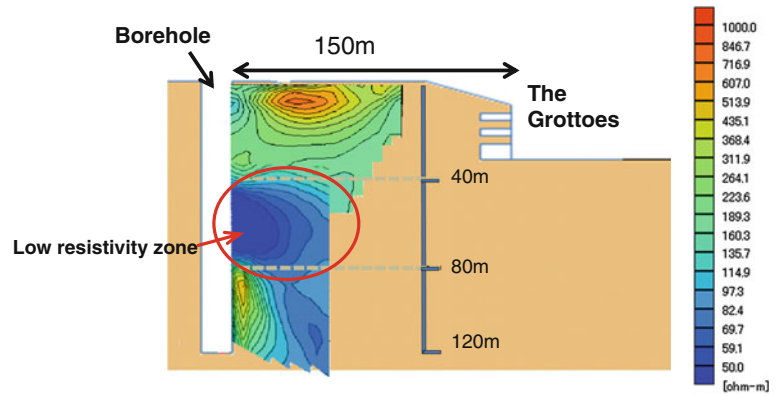


Fig. 9.1 Results of measurements

Fig. 9.2 Cross-sectional view



maximum value of all samples; and Case-D provides the upper limit, i.e., the maximum amount of salt that was detected in aqueous solution in pore water.

### 9.3.2 Results and Discussion

The measurement results are shown in Fig. 9.3; the black-framed inset of Fig. 9.3 is shown in Fig. 9.4. Electrical resistivity increased gradually with increasing degree of saturation, increasing rapidly when the degree of saturation became less than 10%. The resistivity changes were small in the range of high water saturation; however, with increases in salt impregnation, the lower resistivity is indicated. For resistivity of 45 Ω m (i.e., the lowest resistivity obtained in field measurements), Case-B exhibited saturation of 100%, Case-C a saturation of 85%, and Case-D a saturation of 55%. The lowest resistivity zone, in the ground behind the Mogao grottoes, exhibited resistivity of 45 Ω m; therefore, the possibility that the degree of saturation is at least 55% (i.e., conversion ratio of NaCl is  $16.7 \times 10^{-3}$ ) was confirmed.

### 9.4 Moisture Conditions Behind the Grottoes

This section estimates moisture conditions in the area behind the Mogao grottoes based on the results of Sect. 9.3. The resistivity distribution in the field survey was converted into two types of water saturation distributions using the results of laboratory experiments.

Figure 9.5 illustrates the distribution of water saturation. Figure 9.5a shows the distribution of water saturation reflecting the ground environment of Case-B, while Fig. 9.5b shows the distribution of water saturation reflecting the ground environment of Case-D; it is clear that the degree of water saturation is higher in Case-B than in Case-D. These figures cover the same range of resistivity distribution, and the difference in the amount of soluble salts is reflected in the distribution of water saturation. Moreover, for 50–100 m depth, the degree of saturation is 100% for Case-B and 55% for Case-D. Near the top of the caves, the degree of saturation is 60.1% for Case-B and 46.6% for Case-D.

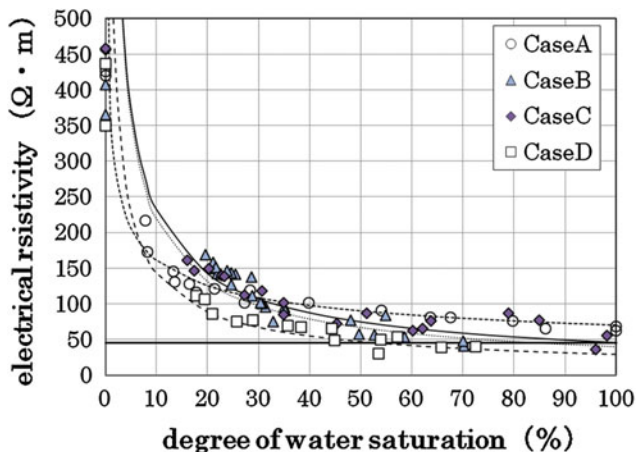


Fig. 9.3 Measurement results

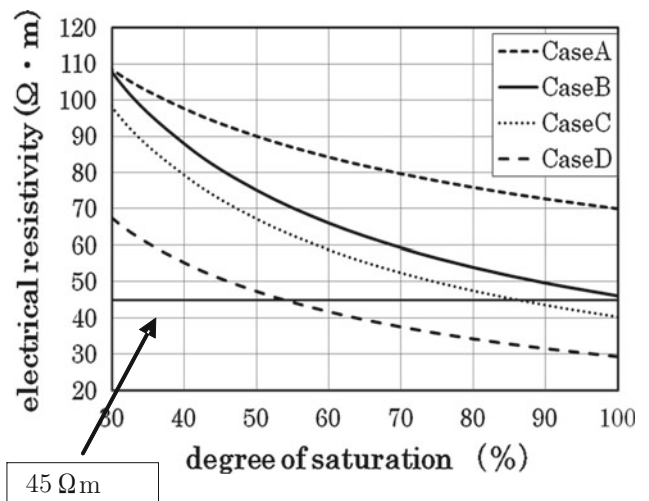
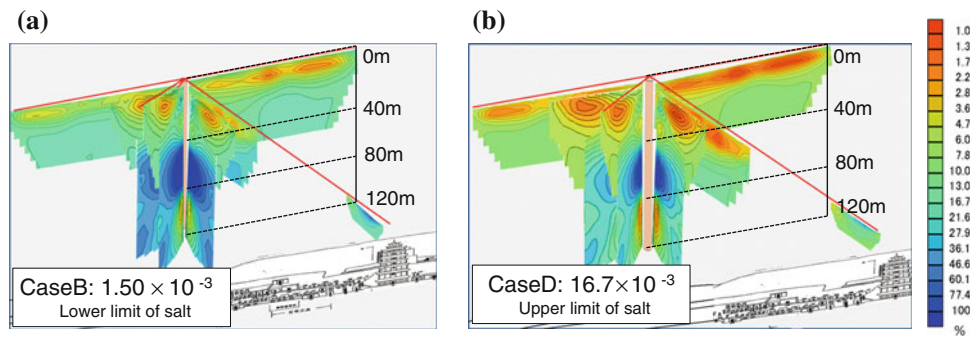


Fig. 9.4 Inset lower resistivity zone

**Fig. 9.5** Distribution of water saturation. **a** *Case-B* lower limit of salt. **b** *Case-D* upper limit of salt



## 9.5 Estimation of Moisture Environment of the Ground Behind the Grottoes by RI-Density Log

RI-density log is carried out to evaluate the results obtained by the electrical resistivity in the borehole and the results of the lab experiments. Figure 6 shows the result of saturation. The evaluation was not intended in the casing part from G.L.0 to 30 m. The degree of saturation which is the depth from 40 to 80 m corresponds with the low resistivity zone obtained by the electrical resistivity method. The peaks of saturation in the section indicate from 55 to 60 %. The result corresponds with the result when salinity becomes maximum.

## 9.6 Conclusions

The resistivity distribution behind the Mogao grottoes was measured by the field surveys, and lower resistivity zones were confirmed at 40–80 m depth and on the top of the caves. In subsequent laboratory experiments, the resistivity characteristics of the field samples with respect to changing water and salt concentrations were identified, and the resistivity distribution derived from the field survey was converted into a distribution of water saturation using the results of laboratory experiments. The results indicated that deep ground is subject to relatively high water saturation

compared to shallow ground. The degree of saturation was more than 55 % when electrical resistivity was  $45 \Omega \text{ m}$ , which was the lowest resistivity measured in the field; therefore, the low resistivity in the surrounding ground is likely to indicate at least 55 % water saturation. The results obtained by the electrical resistivity method correspond with the result of RI density log. In conclusion, water saturation is relatively high at 40–80 m depth, indicating that moisture behind the Mogao grottoes would be exerting an influence on the caves. Our next research should be clarified how to control the moisture movement to the caves through the on-site monitoring.

## References

- Adachi K (2001) Study of water distribution by resistivity measurement Dunhuang Mogao Grottoes. In: 56th annual meeting of J.S.C.E, pp 642–643
- Kitano Y (1994) The chemical composition of land waters in the Dunhuang area and of evaporites in various desert areas of China. *Sci Conserv* 33:1–26
- Kuchitsu N, Duan X (1992) Geological environment of the Dunhuang Mogao-Grottoes, Gansu Province China. *Sci Conserv* 31:79–80
- Miyazaki T, Nishimura T (2011) *Soil physical experimentation*, vol 103. University of Tokyo Press, Tokyo, pp 95–96
- Tanimoto Y (2007) The state of water and salts in the Dunhuang Mogao Grottoes. In: 36th Symposium on Rock Mechanics, pp 141–146