CASE HISTORY

Multi-electrode resistivity survey for the moisture distribution characteristics of the cliff of Mogao Grottoes

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Abstract

Designated as a world heritage site by UNESCO in 1987, the Mogao Grottoes is famous for its cultural relics, in particular, the superb murals and painted sculptures. Moisture has been confirmed as the most active factor that could result in mural diseases. Therefore, ascertaining the moisture distribution of the cliff is of great significance for preventing the deterioration of murals and painted sculptures. In this study, a multi-electrode resistivity survey is applied atop the cliff of Mogao Grottoes. By deploying survey lines in two main study areas, the moisture distribution of the cliff is reflected by the resistivity profiles qualitatively. The results show that there is a mutually verifying relationship between the resistivity profiles and the water content of the exploratory well. In general, the resistivity of the cliff body is low in the distribution range of 1–300 Ω·m. It shows that the moisture content of these gullies atop the cliff is even lower. Besides, four potential danger areas are determined on the cliff face. Murals in these caves, which are excavated in these areas, will suffer more serious deterioration due to the moisture migration. The result also ascertains that the resistivity of the cliff could determine the moisture distribution inside the cliff. Moreover, this study can provide a firm scientific basis for protecting the valuable murals and painted sculptures in the caves.

Keywords Multi-electrode resistivity survey · The Mogao Grottoes · Resistivity of the cliff · Moisture distribution

Research aims

Moisture is the main driving force that could lead to severe diseases in murals and sculptures in the Mogao Grottoes. And numerous studies have been carried; however, the large-scale moisture distribution of rock masses behind caves has not been obtained yet. As a non-destructive method, a multi-electrode resistivity survey has been utilized successfully in the investigation of moisture distribution within a smaller area. Since a large number of murals and painted sculptures are preserved in caves on the southern cliff of Mogao Grottoes, it is also necessary to explore the moisture distribution

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characteristics of the whole cliff. The multi-electrode resistivity survey method is chosen in this study because it could not only provide scientific support for solving diseases problems of murals and sculptures in the Mogao Grottoes but also contributes to the investigation of moisture distribution of grottoes in northwest China.

Introduction

First constructed in 366 AD, the Mogao Grottoes represent the greatest achievement of Buddhist art from the fourth to the fourteenth century. A total of 487 caves are presently preserved, housing more than 2000 painted sculptures and about 45,000 m^2 of murals depicting various aspects of medieval politics, economics, culture, arts, religion, ethnic relations, and daily dress in western China. With remarkable historical value, the Mogao Caves were inscribed on the World Heritage List by UNESCO in 1987. Besides, the climate of Mogao Grottoes is characterized by dry and rainless, with a large evaporation capacity throughout the year (Guo 2009). Murals and sculptures in caves are well preserved due to the arid climate. However, about 50% of the wall paintings in Mogao Grottoes still have suffered from deteriorating diseases ever since their creation (Wang 2005). Water is considered the most active factor that harms the relics inside the caves as it damages the murals and painted sculptures (Li et al. 2016). It also shows that many mural diseases, including efflorescence, flaking, and detachment, are related to the migration and accumulation of salts resulting from moisture transformation (Li et al. 2013a, b). Moreover, salts will repeatedly recrystallize due to humidity fluctuations (Li et al. 2015).

Moisture problems have been the focus of the protection of murals and sculptures in Mogao Grottoes. Guo (2009) analyzed the relevance of water environment characteristics and the source of moisture in the caves, it showed that a certain amount of water vapor could be detected at a depth of 150 m of the cliff and there was no free water. By high-density electric resistivity method and X-ray CT scanning, Wang et al. (2010) discussed the permeability of surrounding rocks of caves in order to clarify the regularities of water migration and the deterioration mechanism of wall paintings. Besides, Li et al. (2013a, b) presented research on destructive environmental mechanisms affecting the murals in the Mogao Grottoes, specifically for cave 72, from a meteorological perspective. Yang et al. (2017) investigated the salt migration from underlying cliffs into the wall paintings. It shows that the salt content is very high on the surface of the west wall of caves at a depth of 0.5 m. Even the visitation could certainly induce changes in humidity and temperature in the caves and finally, lead to serious mural disease (Chen et al. 2017). Zhou et al.

(2018) discussed the moisture and heat sources of cave 108 by installing sensors, the result shows that most moisture is coming from the upper east side inside the cave. By sealing the cave and condensing the vapor, the main sources of moisture which is transported from the surrounding rocks of the cave are determined (Li et al. 2016).

Abundant studies have been applied in the distribution regularities and sources of moisture. However, most of them are focused on the horizontal direction of the cliff and single cave. But few are conducted on large scale. A multi-electrode resistivity survey was first applied for the sake of investigating the rainfall infiltration of the Mogao Grottoes. It shows that the moisture caused by rainfall can move to the top of the grottoes through loose stratum and cracks of the cliff slowly (Guo et al. 2008). Eventually, it also confirmed that multi-electrode resistivity method is feasible for the moisture survey of the surrounding rocks of Mogao Grottoes. It is a fact that the multi-electrode resistivity survey is quite susceptible to the variations of water content inside lithological units. The method has already been applied in many fields successfully: mineral and prospecting (Singh et al. 2004; Krishnamurthy et al. 2009; Beresnev et al. 2002), groundwater exploration (Owen et al. 2005; Ewusi et al. 2009), hazard assessment (Al-Zoubi et al. 2007), pollution survey of groundwater and soil (Jiang et al. 2013), and relevant environmental impact assessment (Sundararajan et al. 2012). Besides, the multi-electrode resistivity survey method is also applied in non-destructive archaeological works (Urbini et al. 2007; Dogan and Papamarinopoulos 2003; Loperte et al. 2011; Fang et al. 2013; Dai and Xie 2015). The multi-electrode resistivity technique is now well established with respect to theory and practice, especially for groundwater exploration.

To study the moisture distribution characteristics of the cliff on a large scale, a pre-experiment is conducted in a target area around the exploration well, which has detailed geological data and moisture content information. After the resistivity features of the strata of the exploration well are obtained, a comparatively comprehensive and systematic investigation of the moisture distribution in relation to the whole cliff of the Southern Grottoes Area is applied. The main purpose is to explore potential danger areas that are caused by moisture distribution so as to improve the preventive conservation of murals and sculptures in Mogao Grottoes.

Geological and hydrogeological conditions of study area

Study area

Carved into the cliffs above the Dachuan River, the Mogao Caves are located on the southern margin of the Dunhuang basin (Gansu, China) (Fig. 1), between the Sanwei and Mingsha mountains. With a height of about

30–40 m, the cliff of Mogao Grottoes stretches for about 1.68 km from north to south. Therefore, Mogao Grottoes are also divided into two predominant areas: the Southern Grottoes Area and the Northern Grottoes Area. The study in this paper is mainly carried out atop the cliff of the Southern Grottoes Area.

Geological conditions

A good appreciation of geology is fundamental in hydraulic environment assessment since the geology determines the water conditions (Ewusi et al. 2009). Based on the geological investigation, the cliff strata of Mogao Grottoes could be divided into 4 three series (Fig. 2): the lower Pleistocene series (Yumen group, Q_1); the mid-Pleistocene series (Jiuquan group, Q_2); the upper Pleistocene series (Gobi group Q_3); the Quaternary sediments (Q_4). Moreover, the existing caves in the Southern Grottoes Area are excavated in the Jiuquan (Q_2) group,

so Q_2, which mainly consists of conglomerates, is also called "cave strata" (Li 1986). Ulteriorly, on the basis of the geological profile and rock sampling analysis, Q_2 can be divided into four engineering geological rock groups, namely, Q_2-A, Q_2-B, Q_2-C, and Q_2-D groups from top to bottom (Wang et al. 2000). Besides, an exploration well was excavated in the west of the 96 caves. The strata of the exploration well can be divided into 6 layers (Fig. 2): ① Layer: loose gravel layer. The particles are sub-angular and sub-circular with good particle gradation. A large amount of sand is contained in this layer. ② Layer: fine sand layer containing silty clay mass and visible gravel. A discontinuous and lenticular distribution could be found. It is associated with the lower silty clay layer. ③ Layer: silty clay layer accompanied with gravel particles in the form of lenticular occasionally. The liquid limit of the layer is 37.5%, the plastic limit is 25.0% and the plasticity index is 12.5. ④ Layer: gravel layer which is not bonded. The layer is well-graded with fine particles; the particles are sub-circular, and the particles
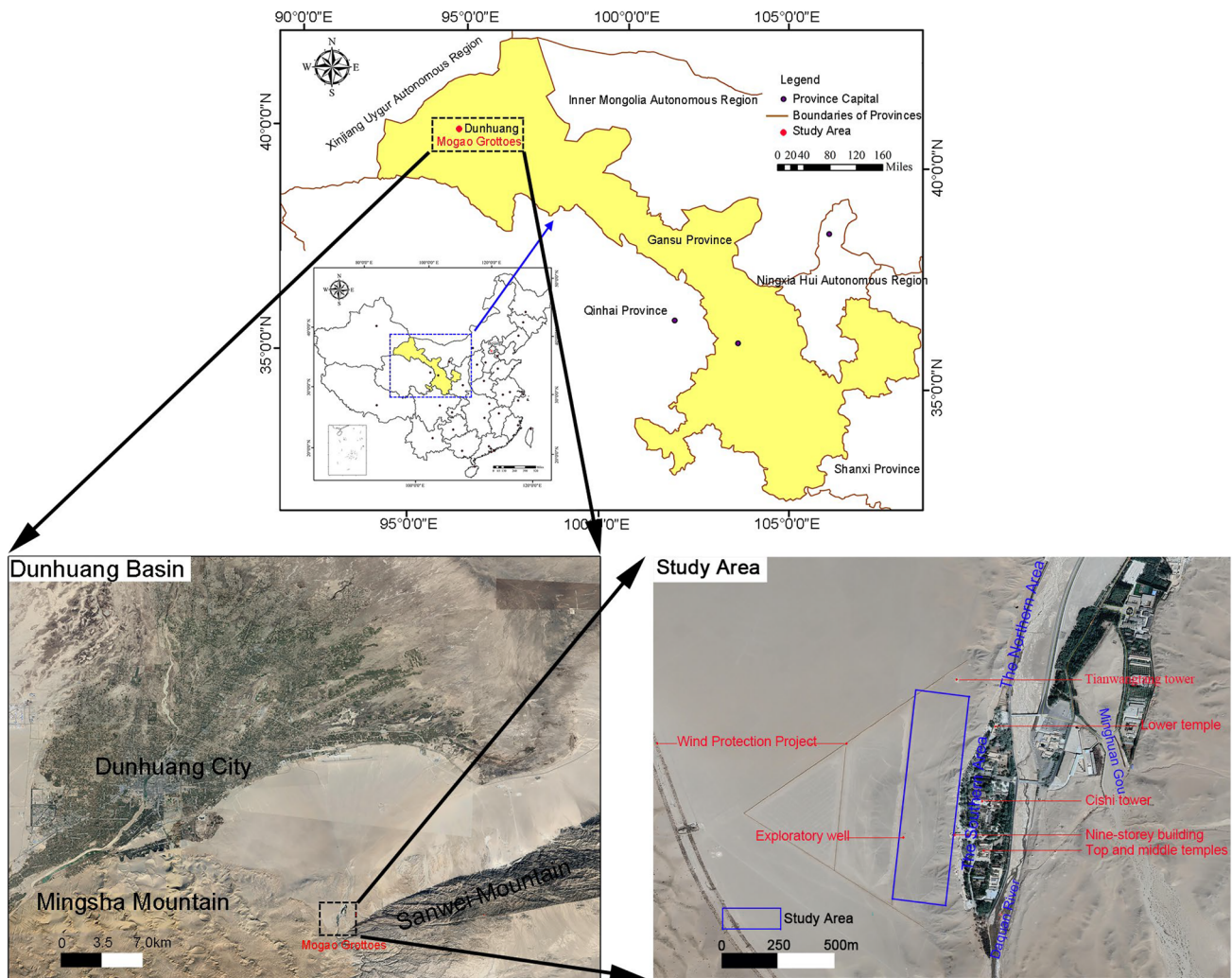

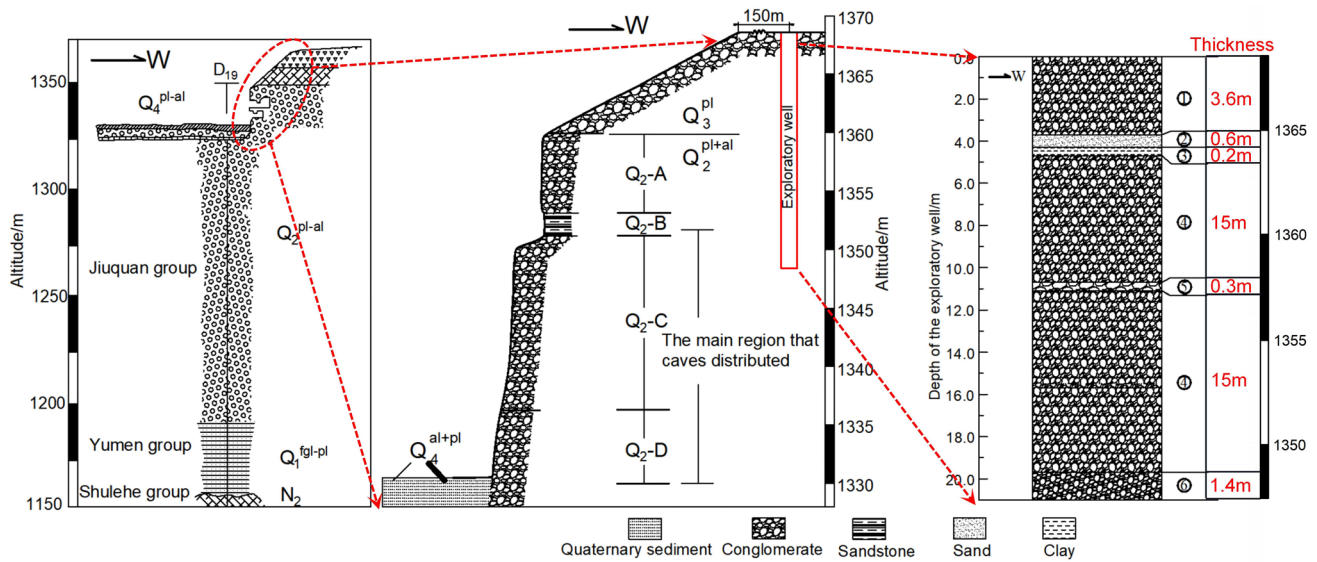**Fig. 1** Location map of the study area

Fig. 2 Typical geological profile of the cliff of Mogao Grottoes (Zhang et al. 1996)

size less than 2 cm accounts for about 30.0%. ⑤ Layer: gravel layer of single-grain structure, particles are well sorted, main particle size is 2–6 cm. It is discontinuously distributed in a thin interlayer throughout the strata. ⑥ Layer: gravel layer. It is blocky and hard. The layer which is distributed in the form of multiple layers is uneven in thickness.

Climatic and hydrogeological conditions

The Mogao Grottoes are situated in the hinterland of the northwest of China, the most western part of the Hexi Corridor. Affected by high air pressure from Mongolian yearly, the typical arid climate of the Mogao Grottoes is characterized by dry and lack of rain, a large evaporation throughout the year. As shown in Fig. 3, the annual average precipitation is 23.2 mm, but the evaporation capacity is 2483 mm; the average annual evaporation is nearly 60 times of precipitation (Guo 2009).

The average annual relative humidity of air is 32%; the highest relative humidity is 88%, and the lowest relative humidity is 7%. It shows that the precipitation in Dunhuang and Mogao Grottoes is extremely uneven during the year. The precipitation in summer accounts for 58% of the annual precipitation, while precipitation from October to March next year only accounts for 21% (Fig. 3). The air-dry index reaches about 32; the average annual evaporation in Dunhuang was 2486 mm, which was 56.7 times of precipitation. As a consequence, the surrounding rock is quite dry and the water content is only about 0.5–1.5% (Guo et al. 2008). It was also found that the water vapor in bottomed caves derives from the phreatic water (Zhang et al. 2018). The Mogao Grottoes are on the upper edge of the alluvial-proluvial fan where the

Daquan River discharges. Besides, the surface water mainly comes from the Daquan river and the irrigation of trees in front of the caves. Conditions which determine the water in grottoes are complex, involving replenishment of water mainly from runoff of phreatic water and a small amount of atmospheric condensation (Zhang et al. 2018).

Methodology and survey plan

Survey plan

A multi-electrode resistivity survey experiment is conducted to determine the moisture distribution of the
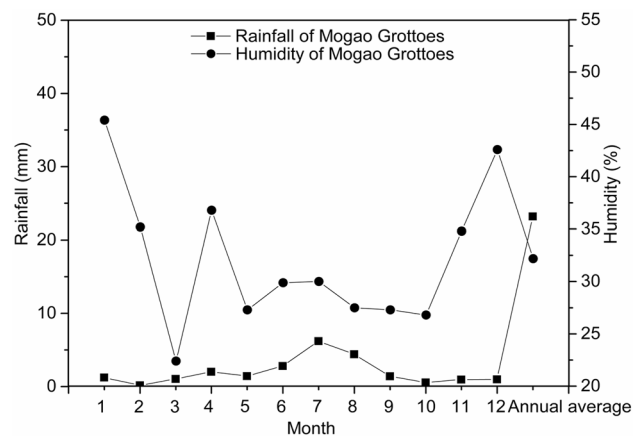

Fig. 3 Average monthly rainfall (mm) and humidity (%) of the Mogao Grottoes

Mogao Grottoes. The resistivity measurements are normally carried out by injecting current into the ground through two current electrodes and measuring the resulting voltage difference at two potential electrodes. The method has been established as very useful in detecting various problems in terms of water and is frequently used in groundwater hazard investigations of grottoes. In this study, two main experimental areas (Fig. 4) are selected: (1) area I, which locates around the exploration well, is chosen as the target area in order to obtain the characteristic resistivity; (2) area II, which locates near the cliff face, is chosen as the primary test area in order to investigate the large-scale moisture distribution of the cliff.

Equipment and survey lines

GeoPen E60M micro-electrode resistivity testing system produced by GeoPen and Wenner array is adopted (Fig. 5). After pre-experiment, appropriate electrode spacing for each survey line is determined. The parameters of the measuring device are given in Table 1. According to the technical specification for the resistivity profiling method (DZ/T 0073–93, 1994), 5 and 8 survey lines are deployed in area I and area II, respectively. There is an artificially excavated exploratory well that is situated 150 m west of cave C96 with a depth of 20 m and a diameter of 80 cm in area I. Since the water content of the well is measured by drying the rock samples, area I is considered a target area to verify the feasibility of the multi-electrode resistivity survey atop the cliff. Survey lines (L_A–L_D) in the area I are deployed perpendicular to each other around the exploratory well. However, survey

lines (L_1–L_8) in area II are deployed based on the terrain and L_1 and L_2 are perpendicular to the orientation of the cliff face approximately. As for L_3–L_8, they are deployed in the gullies of the cliff slope (Fig. 4).

Resistivity features of target area

In applied research, the target area contributes to the interpretation of the final result. In 2008, Shen et al. (2008) made use of the high-density resistivity technique and geophysical prospecting radar to carry out geophysical exploration on several ancient culture layers and target areas of relics in Jinyang. The obtained geophysical characters of target areas have provided a solid foundation for geophysical exploration in the archaeological study on the ancient city relics in Jinyang. So another aim of the target area is to provide geophysical characters for this study.

The water content of the strata of the well is tested, and it shows that the water content of the Mogao Grottoes is very low ($< 1.5\%$), and it is mainly distributed in the range of 0–0.75% (Yang et al. 2017). Moreover, according to the water content test of the samples which are taken from the cliff face, slope, and the exploratory well, the moisture content of the shallow surface of the Mogao Grottoes is also extremely low ($< 2\%$). And it is also indicated that at a certain depth of the slope and platform atop the cliff, the water content of the strata is slightly increased, but rarely exceeds 5%.

Figure 6 shows inversion model resistivity sections of fieldwork conducted in area I in a bid to identify the feasibility of this method and the resistivity characteristics.

Fig. 4 Deployment of survey lines
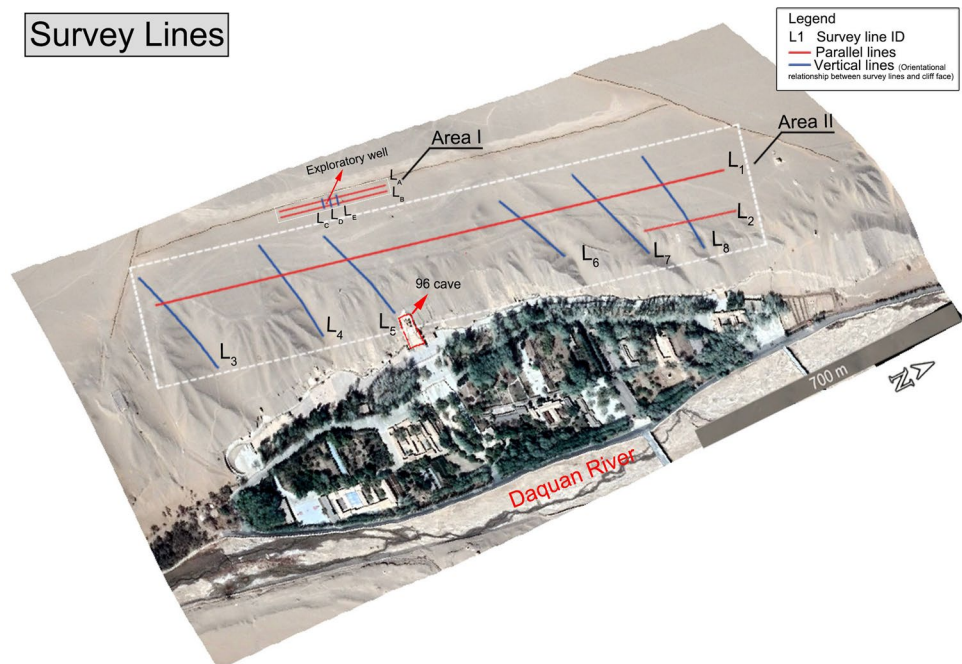
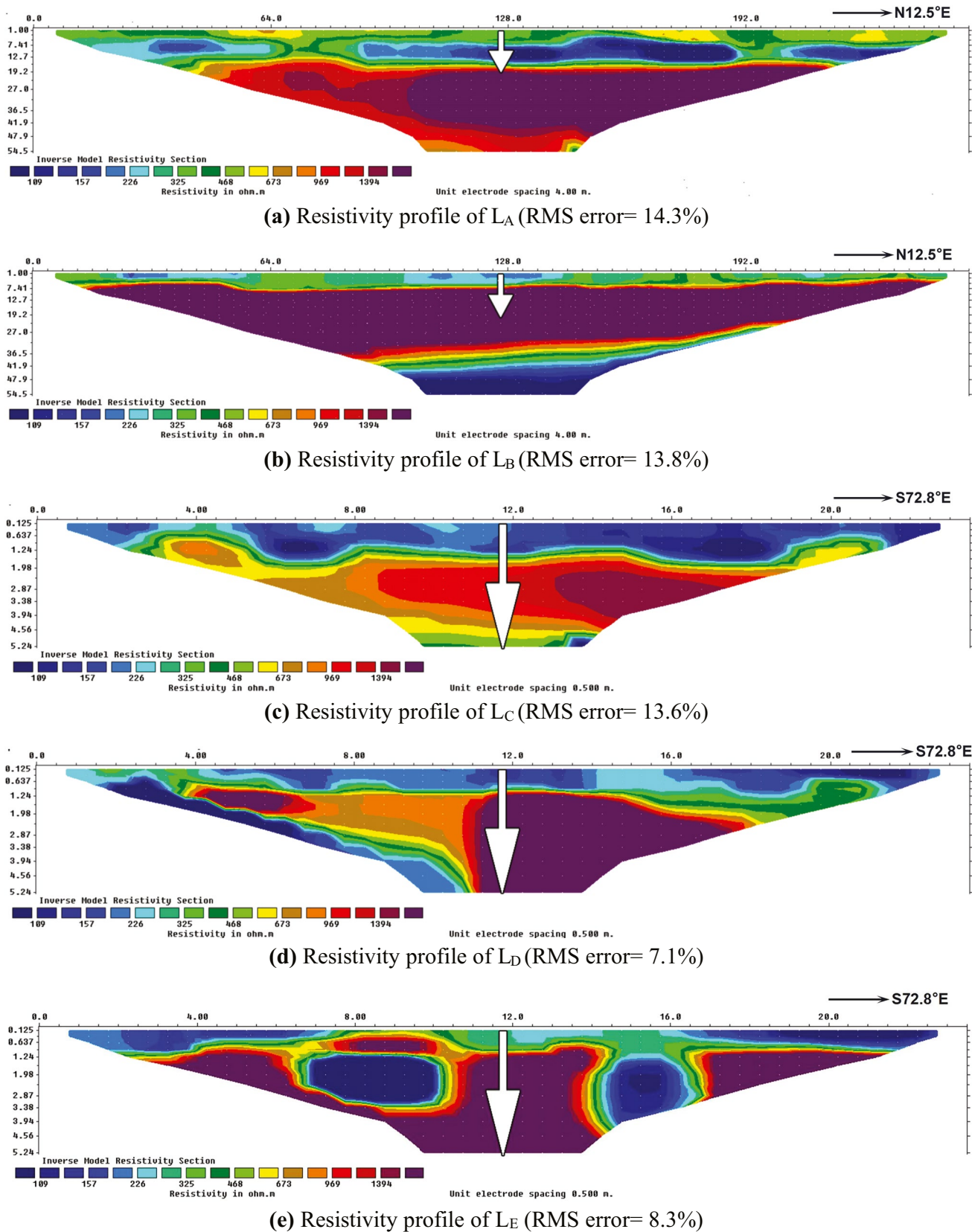**Fig. 5** Multi-electrode resistivity survey system and Wenner array
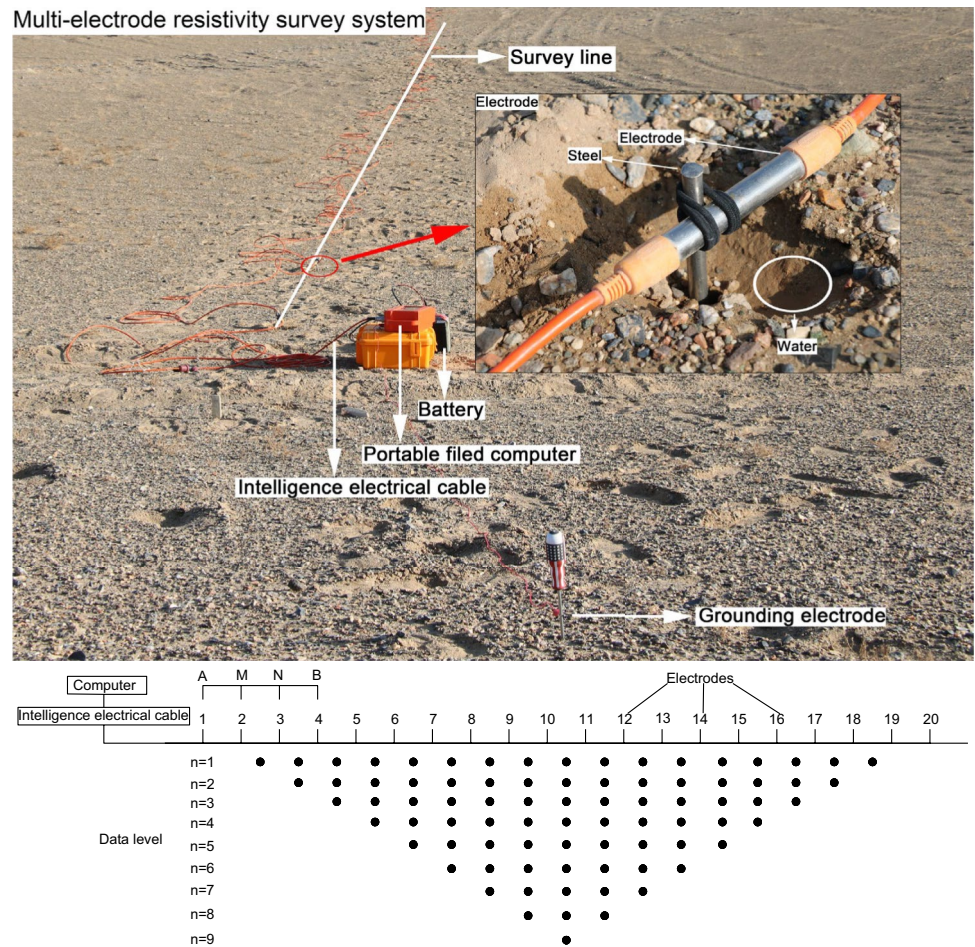
Basically, these figures highlight the features of the moisture distribution where the survey lines were deployed. The vertical resolution of L_A and L_B is 4 m, and the vertical resolution of L_C–L_E is 0.5 m. Figure 6(a), (b) represents the 2D resistivity model sections of L_A and L_B, the inversion results reveal 3 layers: (1) The first resistivity layer from the surface to a depth of about 13 m has a very low resistivity in the range of 90–570 Ω·m. This very low resistivity layer was interpreted as indicating the higher moisture content of the conglomerates; (2) The second layer has high resistivity in the range of 570–1394 Ω·m, which indicates that the moisture content is extremely low in the depth of 13–42 m; (3) As shown in Fig. 6(b), the third resistivity layer has a low resistivity distribution in the range of 50–200 Ω·m at the depth of 42–54.5 m. In order to further identify the distribution of

moisture content of strata around the exploratory well, 3 survey lines are deployed in the perpendicular direction of L_A and L_B, the results of which are shown in Fig. 6(c), (d), and (e). The profiles depicted in Fig. 6(c),(d), and (e) reveal that the resistivity increases with the depth in the range of 0–5.24 m. In addition, the resistivity distribution in the north–south direction within 5.24 m is relatively uneven.

As shown in Fig. 6, the orthographic position of the exploratory well is marked in white along the arrow. Depicted in Figs. 7 and 8, the resistivity is obtained by extracting the data from profiles of L_A–L_E. Therefore, the resistivity changes of the strata around the exploratory well are obtained. Resistivity is uneven, L_A and L_B show lower resistivity at the depths of 9–15 and 17–22 m, respectively. Besides, the resistivity of the L_B profile is generally higher

Table 1 Multi-electrode resistivity survey device

Areas	Area I					Area II							
Survey lines	L_A	L_B	L_C	L_D	L_E	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8
Length/m	240	240	24	24	24	955	189	141	141	141	141	189	189
Electrodes	48	48	48	48	48	48	48	48	48	48	48	48	48
Electrode spacing/m	5	5	0.5	0.5	0.5	5	3	3	3	3	3	3	3

(a) Resistivity profile of L_A (RMS error= 14.3%)

(b) Resistivity profile of L_B (RMS error= 13.8%)

(c) Resistivity profile of L_C (RMS error= 13.6%)

(d) Resistivity profile of L_D (RMS error= 7.1%)

(e) Resistivity profile of L_E (RMS error= 8.3%)

Fig. 6 Resistivity profiles of L_A–L_E in area I, the orthographic position of the exploratory well is marked in white along the arrow

Fig. 7 Resistivity of the exploration well according to L_A and L_B profiles
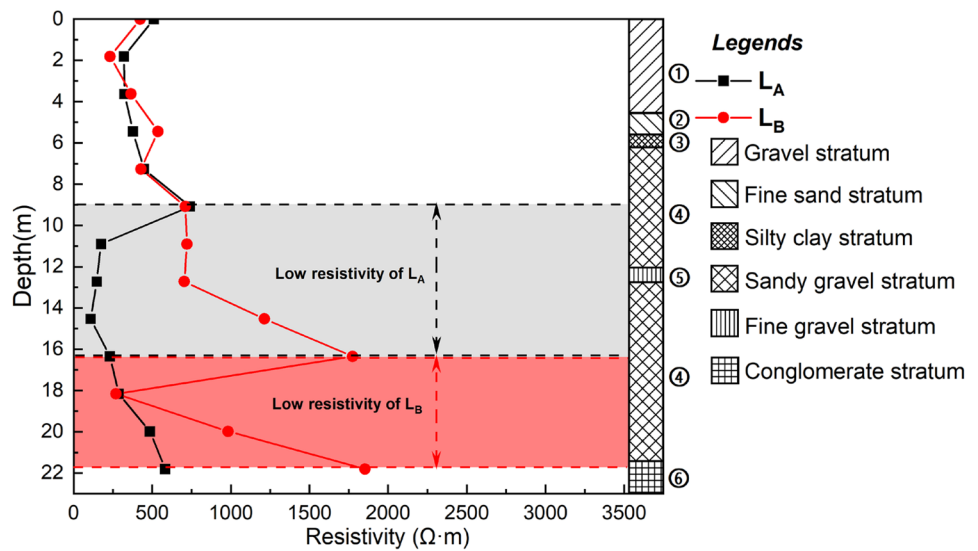
than that of L_A. Figure 8 shows that the resistivity of L_C–L_E basically increases with the depth, but a resistivity decrease could be detected at the depth of 2.75–5.24 m for L_C. In addition, the result, which reveals that resistivity generally increases along the south-north direction in the area I can also be validated.

The water content of different depths and resistivity of the exploratory well profile are shown in Fig. 9. The water content is increasing with the depth, especially in the depth range of 3.5–5.0 m. The water content of strata reaches about 24%, which corresponds to the ③ layer of the well. The ③ layer is defined as a silty clay layer that consists of 60% clay particles. However, it cannot be identified due to the low resolution of L_A and L_B. Conversely, in a depth of about 10 m, a low-resistance layer in the range of 157–226 Ω·m could

be detected. Results from field investigations in the area I demonstrate the efficiency of the multi-electrode resistivity technique in the moisture distribution survey.

Results and discussion

### Resistivity of the cliff body in south-north direction

Resistivity profiles of 8 survey lines in area II are obtained using the Res2Dinv software. Figure 10 shows the inversion model resistivity profiles of these survey lines. The profile depicted in Fig. 10(a) shows the resistivity of the whole cliff body along the south-north direction, it indicates that the cliff has a low resistivity distribution in the range of

Fig. 8 Resistivity of the exploration well according to L_C–L_E profiles
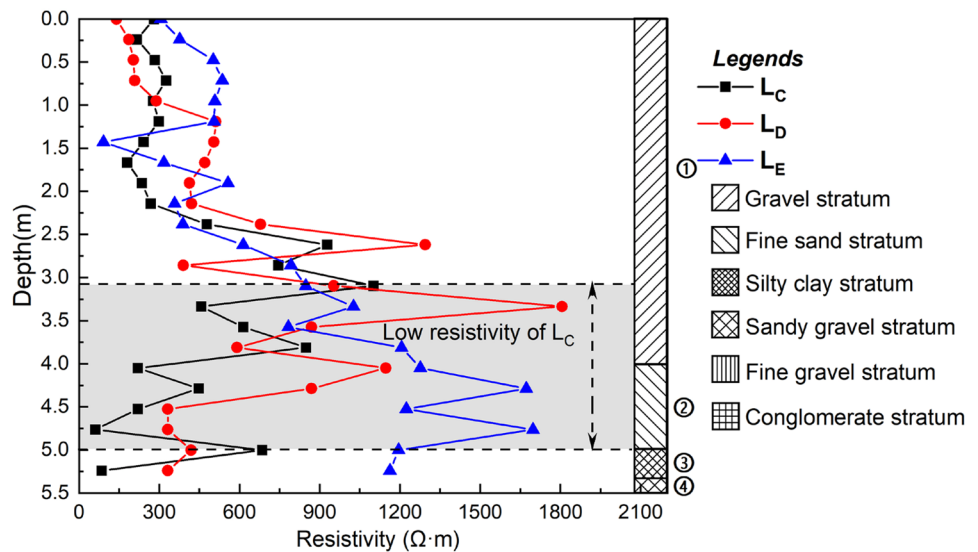
Fig. 9 Water content and resistivity of the exploratory well, resistivity was derived from orthographic position of the exploratory well
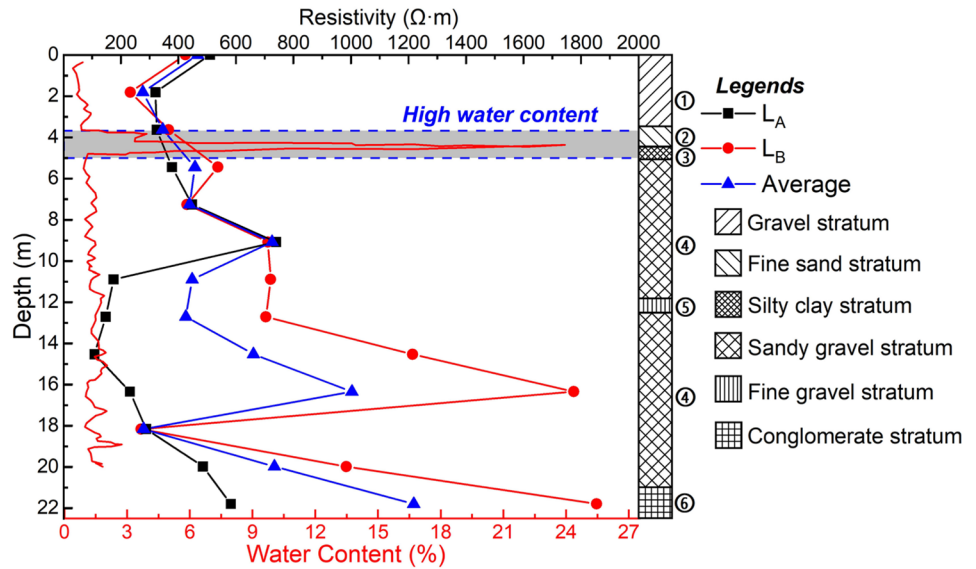

1–300 Ω·m, and a few high-resistivity zones which exceed 1000 Ω·m could be observed. It also indicates the resistivity is not increasing with the depth, and the resistivity of the surface is higher than that of the deep strata. Moreover, the resistivity of the surface is increasing from south to north, which is consistent with resistivity changes in area I. The south end of the profile L_1 shows higher resistivity in the range of 200–800 Ω·m at the depth of 0–45 m. With similar lithology due to the alluvial/diluvial sedimentary environment, the resistivity distribution of L_1 may probably indicate that the moisture content of the cliff body is in an active state.

The profile depicted in Fig. 10(b) shows that the resistivity is decreasing with the depth, and the right bottom of the L_2 profile has a very low resistivity distribution in the range of 1–200 Ω·m. Notably, this low resistivity distribution is found close to a small gully on the north of the profile. There is a high resistivity distribution in the range of 400–1600 Ω·m located on the south of the profile. This result is mainly due to the terrain atop the cliff, since the gully is a runoff area relatively. More water will infiltrate this area, so the resistivity is lower.

Resistivity of the gullies atop the cliff

With the aim to approach the caves as close as possible, 6 survey lines (L_3–L_8) are deployed in gullies atop the cliff. Figure 10(c) shows the resistivity profile of L_3, it indicates that the resistivity is increasing with depth, and the low resistivity zones in the distribution range of 1–300 Ω·m are found in the surface strata. And the resistivity in the eastern part of the surface strata is lower than that of the western part. Besides, a high resistivity zone in a distribution range of 1000–3000 Ω·m could be detected at the depth of

10–20 m. It also shows that the resistivity of strata in the gully is lower, which means the moisture content is higher. Profile L_4 depicted in Fig. 10(d) reveals that the resistivity of the profile is low with a distribution range of 1–260 Ω·m, and meanwhile the resistivity of the strata located in the gully has a low distribution range of 1–100 Ω·m. In general, the resistivity is increasing with depth. A relatively high resistivity zone with a distribution range of 200–260 Ω·m has been detected at beginning of the gully. Figure 10 shows the resistivity profile of L_5, which is also deployed in the gully. The result shows a low resistivity between 1 and 200 Ω·m. In addition, a relatively high resistivity zone in the range of 500–2500 Ω·m is detected. There is no exception that the resistivity of the strata in the gully is still quite low and the strata located in the beginning part of the gully share higher resistivity. The resistivity of profile L_6 is represented in Fig. 10(f). It shows that the resistivity of the gully is still low with a distribution range of 1–100 Ω·m. A relatively low resistivity zone, which has a distribution range of 1–150 Ω·m is located at a distance of 60–80 m, at a depth of 5–20 m. The surface strata located in the distance of 0–60 m and at a depth of 0–10 m have a higher resistivity in the range of 250–500 Ω·m. Nonetheless, the resistivity of profile L_6 is low in general. The resistivity of profiles L_7 and L_8 are depicted in Fig. 10(g), (h), except for a few zones, which have high resistivity, the general resistivity is in a low distribution range of 1–200 Ω·m. Different from L_3–L_6, whole survey lines of L_7 and L_8 are deployed in the gully atop the cliff. In consideration of the high resistivity zones, there is an obvious high resistivity with a distribution range of 500–2000 Ω·m that could be detected in profile L_7. As for L_8, 3 high resistivity zones have been presented in the profile with the obvious distribution range of 500–1500 Ω·m located in the distance of 140–165 m.
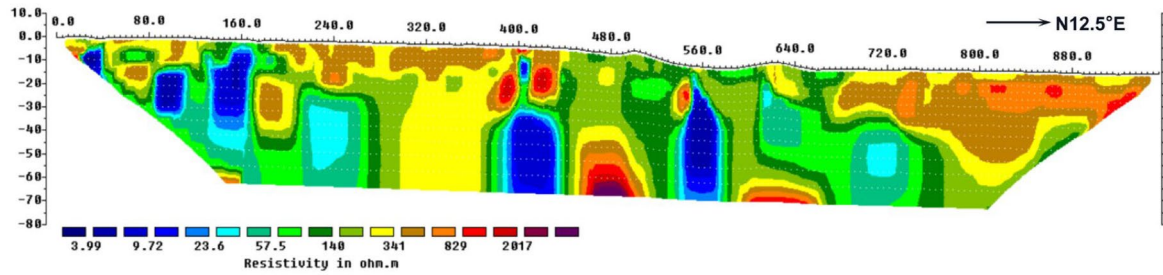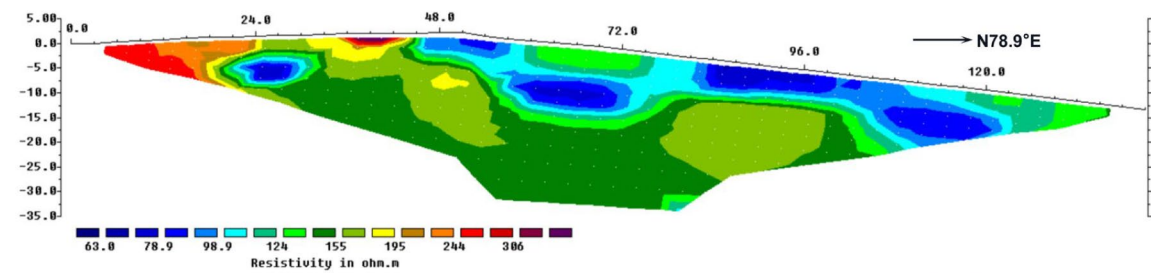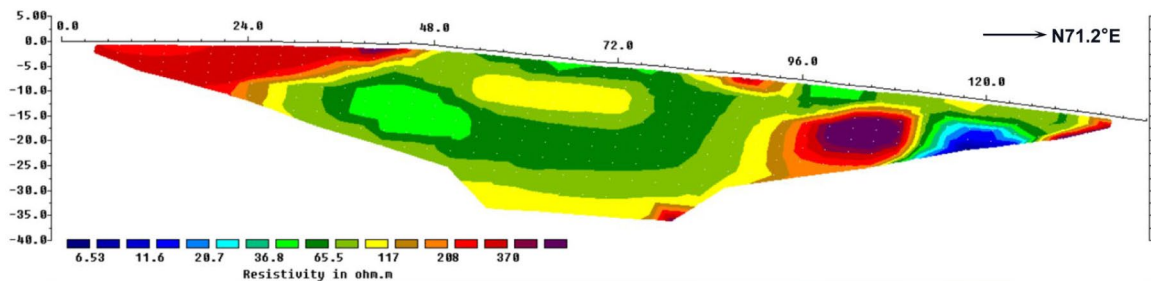
(a) Resistivity profile of L_1 (RMS error= 9.6%)
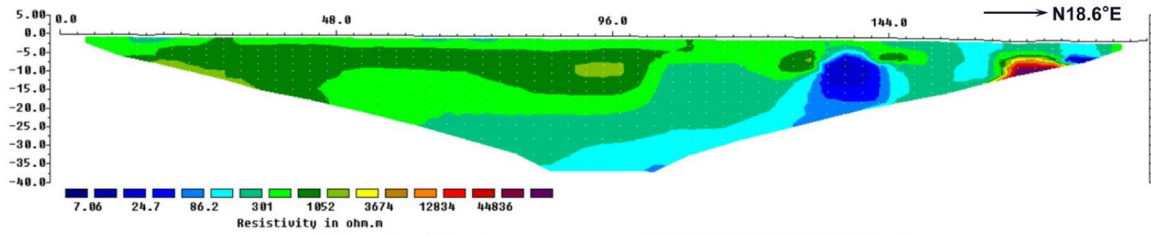
(b) Resistivity profile of L_2 (RMS error= 5.7%)
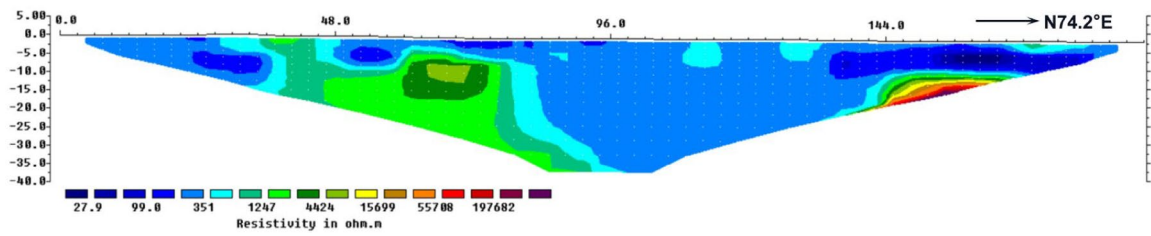
(c) Resistivity profile of L_3 (RMS error= 6.5%)

(d) Resistivity profile of L_4 (RMS error= 14.7%)

(e) Resistivity profile of L_5 (RMS error= 14.8%)

Fig. 10 Resistivity profiles of L_1–L_8 in area II

(f) Resistivity profile of L_6 (RMS error= 10.3%)

(g) Resistivity profile of L_7 (RMS error= 11.8%)

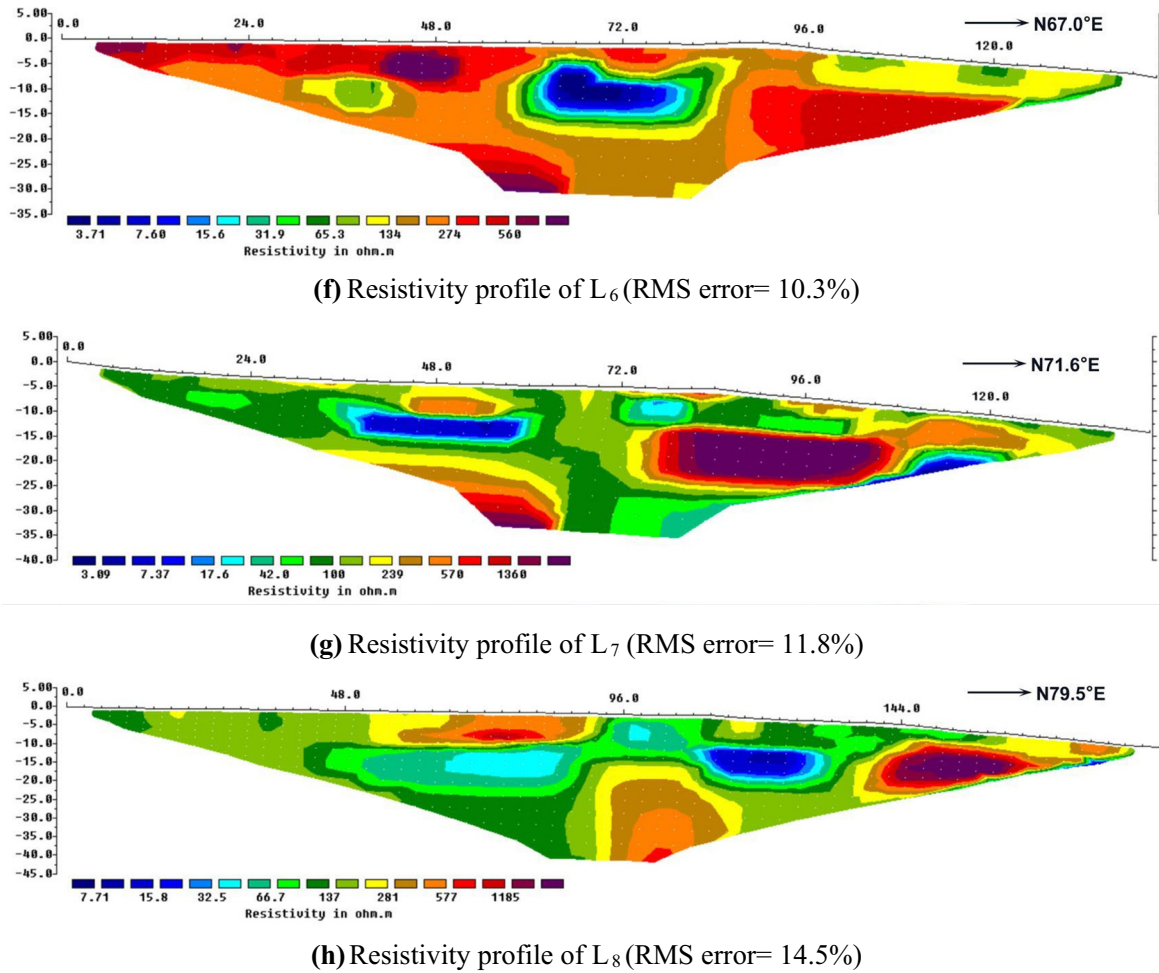**(h)** Resistivity profile of L_8 (RMS error= 14.5%)

Fig. 10 (continued)

As shown in Figs. 6 and 10, RMS errors of resistivity profiles obtained by Res2dinv are in the range of 5.7–14.8%. Although the right data processing, including removing bad data points and using appropriate inversion parameters, models, and topography correction, has been applied, considerable RMS errors can also be detected in this study. The field test should be taken into account. Ground resistance is high for the loose surface, which is mainly consisted of pebbles and sand. We tried to pour abundant water around the steel, but little effect on the RMS errors is obtained. Salt solutions and the field test under rainfall conditions might be useful ways to improve the data quality in this area. Nevertheless, the resistivity profiles in this study can be still used as an indication of the moisture distribution characteristics of the cliff of Mogao Grottoes.

The effect of gullies on moisture distribution

Abundant precious murals have been preserved in Mogao Grottoes, but they are suffering from deterioration. There are many typical diseases, including flaking, net cracks, disruption, detachment, paint loss, and blister, as well as black smudges and graffito. Many of them can be connected to the accumulation and migration of soluble salt caused by water transformation. The water is confirmed as one of the most serious threatening factors to the safety of murals. Guo (2009) made use of the multi-electrode resistivity method in the investigation of the moisture at Mogao Grottoes. It shows that there is no free water within the depth of 100 m from the surface of the cliff top. And the moisture could be transformed into deep strata, which may cause salt diseases. Considering the existing studies, a large-scale investigation of the cliff is needed. The result shows that the resistivity of the inside cliff is low in a general distribution range of about 1–300 $\Omega \cdot m$. Especially, the resistivity distribution in gullies atop the cliff is even lower, indicating higher moisture content. As shown in Fig. 11, the dashed black boxes indicate the gullies where the survey lines (L_3–L_8) are located. The resistivity profiles show that the resistivity of strata in gullies is always lower, and rainfall will concentrate and permeate

**Fig. 11** Gullies atop the cliff of Mogao Grottoes
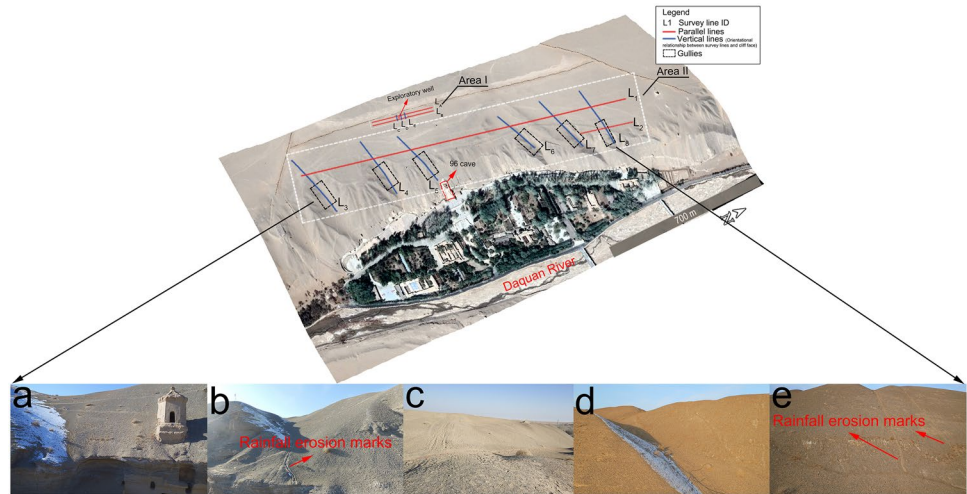
due to the terrain, so the caves excavated in the cliff, which is near the end of gullies, may suffer from more serious deterioration, particularly for the caves distributed in the upper layer. Obvious rainfall erosion marks (Fig. 11(b), (e)) can be detected in these gullies as well. Besides, in winter there will be some snow in gullies (Fig. 11(a), (b), (d)), the temperature will increase over time and the moisture resulting from the melting snow will keep migrating into the cliff. Thus, on the whole scale of the cliff, upper caves which are excavated around these gullies should be paid more attention to diseases induced by moisture.

Origin of moisture in the cave

First and foremost, it should be pointed out that the resistivity can partially characterize the moisture distribution of the cliff (Keigo et al. 2015). Hence, combined with the result suggested by Guo (2009), Li et al. (2011), and Li et al. (2013a, b), four potential origins of moisture in downward

and lateral directions are displayed in the profile depicted in Fig. 12: ① rainfall infiltration, ② moisture from the air, ③ evaporation from irrigation of shelterbelt in front of Mogao Grottoes and Daquan River, and ④ the evaporation of the infiltrated water in the shelterbelt. A multi-electrode resistivity survey carried out in front of C45, C72, C85, and C108 by Guo (2009) shows that the resistivity of lower strata in front of the caves is lower after the irrigation of the shelterbelt, and the moisture migration induced by related evaporation can be inferred. Guo (2009) also suggested that the moisture in the gully will migrate toward the cliff face after the rainfall. Moisture migration trends are speculated in these areas, and more serious diseases of murals can be detected. Correlations between neighbor survey lines are depicted in the 3D resistivity profile (obtained by using Surfer) in order to estimate the main characteristic of moisture distribution inside the cliff body. Figure 13 shows that resistivity profiles can match well with each other. Moreover, four potential danger areas, which may be caused by the

Fig. 12 Moisture source of caves at Mogao Grottoes (modified from Li et al. 2013a, b)
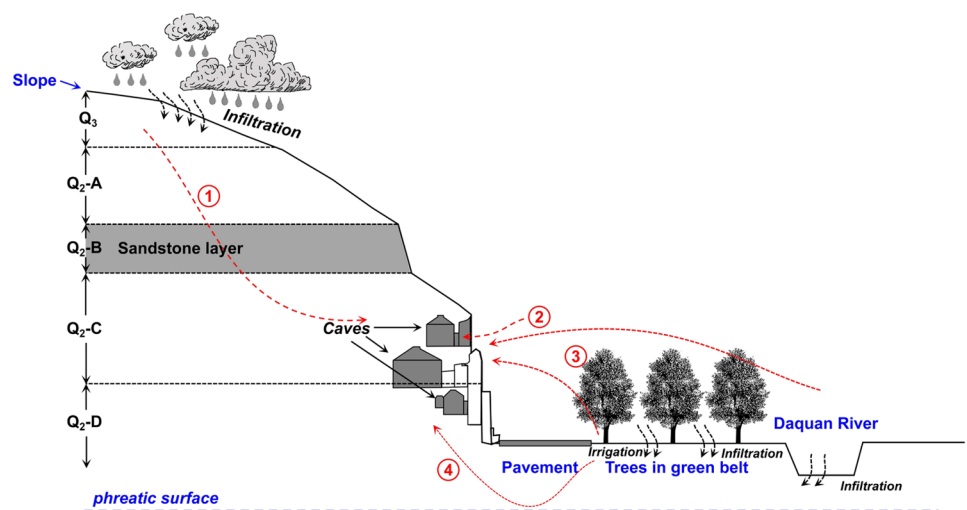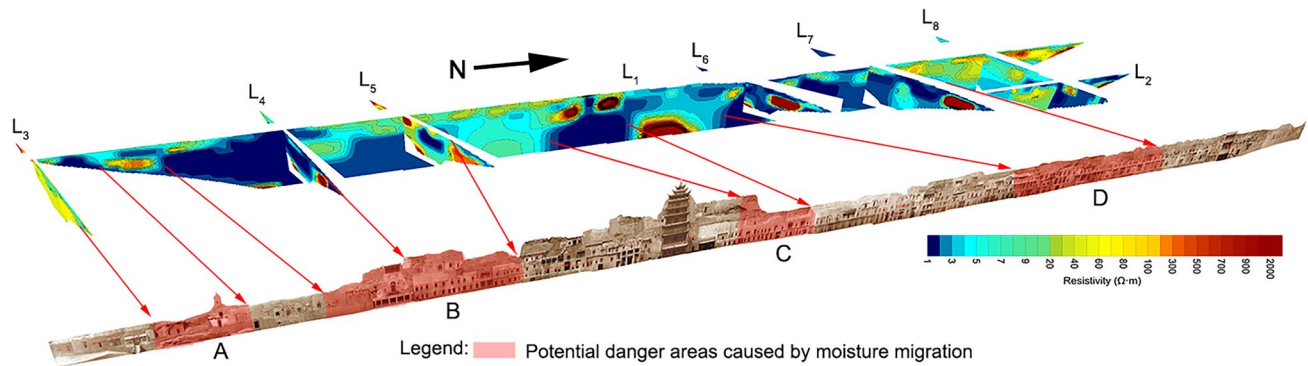
Fig. 13 Potential danger areas caused by the moisture migration

moisture migration, can be summarized as A, B, C, and D. Resistivity, which indicates higher moisture content, is in the range of 1–100 Ω·m for these areas. Comprehensively, more attention should be paid to murals in caves that are distributed in these four potential danger areas during the preservation process.

Conclusion

By multi-electrode resistivity investigation atop the cliff of the Mogao Grottoes, the following conclusions can be drawn:

1. In area I, by making a comparison with the water content of the exploratory well, we ultimately find that the cliff body can be divided into 3 layers based on the resistivity:(1) strata with low resistivity at the depth of 0–13 m; (2) strata with high resistivity at the depth of 13–42 m; (3) strata with low resistivity at the depth of 42–54.5 m. The method is demonstrated efficient in moisture investigation in the Mogao Grottoes. And the known target area with certain water content will help to achieve more distinct interpretation results. However, the resolution needs to be carefully considered because the thin layer cannot be identified distinctly.

2. The resistivity profiles of survey lines deployed in area II show that the resistivity of the inside cliff is low in a general distribution range of 1–300 Ω·m. Resistivity profiles of L_2–L_8 well confirmed the results of L_1, especially at intersection points. It shows that the resistivity of the gullies is lower, which could arouse the salt disease of murals caused by water, especially for upper caves distributed around the end of gullies. In general, the resistivity of the cliff inside is low, with higher resistivity in the surface strata and lower in the deep

ones. The strata that have lower resistivity are considered to have higher moisture content. Considering the resistivity is quite low in gullies, salt disease of murals inside the caves that are excavated into the cliff around these gullies will be more serious. Thus, more concern should be paid to mural diseases in these caves.

3. Based on the comprehensive resistivity results of the cliff body, four potential danger areas (A, B, C, and D) on the cliff face caused by the moisture migration could be summarized. Moreover, intensive horizontal migration of moisture will finish their move on the surface of murals, and the deterioration of murals would also be fiercer.

In conclusion, the multi-electrode resistivity survey has well performance in the moisture distribution investigation of the cliff of the Mogao Grottoes. More research about the accurate relationship between moisture content and resistivity should be carried out in order to further study the moisture content and migration, specifically, under seasonal rain conditions.

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