Application of Three-Dimensional Electrical Resistivity Tomography in Archeological Prospection

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Abstract. As the important part of historical relics, ancient architectural sites contain an amount of cultural information, which are of great significance for the future development of mankind. But improper prospection methods will lead irreversible damage to the existing architectural sites. Therefore, appropriate detection methods have significant meaning in archeological prospection and cultural relic protection. At present, there are many methods to explore ancient architectural sites, among which three-dimensional electrical resistivity tomography (ERT) methods are gradually popularized, because of its advantages of non-destructive, high efficiency, economic and deep prospection. But there are too many electrode arrays, such as Wenner array, Schlumberger array, dipole-dipole array and pole-pole array. First, this paper briefly introduces the application status of ERT. Then, a simple geoelectrical model is constructed, and the inversion results are obtained with different arrays. The comparison of the inversion results for 4 electrode arrays shows that the dipole-dipole array gives the highest resolution. And, a more complex geoelectric model is constructed and compared with the results of the inversion. The results show that conclusions have a good consistency. And, this paper shows that Wenner method and Schlumberger array have high resolution in archeological prospection.

1. Introduction

Human civilization has continued for thousands of years, and ancient humans have left rich historical relics in various forms for future generations. These historical relics record important information such as the intellectual status, technological development, and education level of the ancestors, which are of great significance for the future development of mankind. However, improper prospection methods will cause irreversible damage to existing historical relics. Therefore, appropriate detection methods have significant meaning in archeological prospection and cultural relic protection.

Commonly used geophysical detection methods include transient electromagnetic method (TEM), ground penetrating radar (GPR), magnetic method, electrical resistivity tomography (ERT), and so on [1–3]. Meanwhile, these geophysical detection methods have their own advantages and disadvantages [4]. Among them, the TEM has advantages of deep detection depth, strong anti-interference ability and high lateral resolution [5,6]. However, the TEM Method is easily affected by metal objects such as bronzes, ancient weapons, ancient coins and so on, which are easily found in archeological site [7]. This feature limits the application of TEM in archeological prospection to some extent. GPR is high resolution and high efficiency but data are easily affected by surface objects. Therefore, special algorithms must be used to reduce the interference during prospection. Magnetic method has high efficiency in large-scale archaeological sites, but it suffers more interference, and can only provide
two-dimensional information in the detection area, and lack information along the depth direction. So, it is usually combined with other geophysical methods to explain data. And compare to other geophysical prospection, ERT is adopted in this paper because of its characteristics of large amount of data acquisition, automation of data acquisition process, low cost and higher efficiency.

Until now, Su et al. use the ERT to survey the ancient ditch in Sanxingdui, Guanghan City, Sichuan Province [8]. The inclination and trend characteristics of the ditch were measured and verified. Dai and Xie detect a tomb area in Jiangxi Province, and successfully determines the specific location of the tomb through the inversion results, which provided an important basis for the complete excavation of the tomb [9]. Rory et al. use ERT survey to estimate the depth of sediment at the Romuald’s Cave site [10]. Papadopoulos et al. compared the effectiveness of two- and three-dimensional inversion results and detect the archeological site of Sikyon and Europos in Greece [11].

Particular, compared to Two-dimensional ERT, Three-dimensional have the advantage of high accurately results and help to explain the image [12]. This paper will take Three-dimensional ERT to analyze. Nowadays, with the development of the instruments and the maturity of inversion software, ERT has widely used in archeological prospection [13–14].

In archeological prospection, the most suitable electrical resistivity array should be selected according to different geological conditions. Common electrical resistivity array types consist of Wenner inline, dipole-dipole, pole-pole inline and Schlumberger inline. In order to study the differences among different array types, this paper compares inversion results and geoelectric models.

2. Numerical simulation of ancient architectural sites
Numerical simulation includes forward modeling and inversion method. And, there are many forward modeling methods, such as finite-difference methods, finite-element methods, integral equation method, and boundary element method. Several forward modeling methods have their own advantages and disadvantages, among which finite-element methods are favored for its fast calculation speed, small memory consumption, and fast calculation speed. In this paper, the finite-element methods are used for forward modeling. The least-squares inversion methods have the advantages of small memory consumption and fast calculation speed when processing large amounts of data, which is used in this paper. The flow chart of numerical simulation is as shown as Figure 1.

![Figure 1. The flow chart of numerical simulation.](image-url)
2.1. Numerical simulation of ancient architectural sites with simple structure

Most of the ancient architectural sites are no longer complete, especially for the underground buildings, which are represented by the unclear of the site boundaries and the lack of roof. The restoration drawing of architectural sites is shown as Figure 2. Based on the restoration drawing and common resistivity value, the paper creates a simple geoelectric model shown as Figure 3. The green area stands for rooms and front pillars, and the blue area stands for soil media.

![Figure 2. Restoration of architectural sites.](image)

![Figure 3. Simple geoelectric model.](image)

Based on the current situation of ancient buildings, the parameters of geoelectric model are set as follows: 1024 electrodes are set within 31m×31m square in the simulation field making up a 32×32 grid with 1 m horizontal spacing between the electrodes. And 0.5m between each data point. The resistivity is 10Ω·m and 100Ω·m for the surrounding soil and the ancient architectural site, respectively. The size of the ancient building site is 19m×13.5m. The burial depth of architectural sites is in the range of 1m to 5m. The distributed of geoelectric model along the depth is shown in Figure 4.

![Figure 4. The distributed of geoelectric model along the depth.](image)

In order to compare the results of different arrays, we use SURFER software to draw the resistivity horizontal slice the depth of the resistivity horizontal slices with Wenner array, dipole-dipole array, pole-pole array and Schlumberger array are selected as 2.93m, 2.05m, 2.96m and 2.93m, respectively. The slices are shown in Figure 5.

As shown in Figure 5, the resistivity horizontal slice with Wenner array can basically reflect the structure of underground buildings, but resolution is low. And the result through dipole-dipole array has the highest resolution and accurately reflects the actual model. At the meantime, the slice of Schlumberger array also has high resolution. Dipole-dipole and Schlumberger arrays show better images than pole-pole and Wenner array. Three-dimensional profile by dipole-dipole array is shown as Figure 6.

The maximum detecting depth of dipole-dipole array is about 9m. And the detecting depth of Wenner array, pole-pole array, and Schlumberger array are 5m, 20m, and 8m, respectively. The pole-pole array can be used to detect deep archeological sites, and the depth of Wenner array is shallow.
All in all, pole-pole array has the deepest detecting depth. dipole-dipole array gives the highest resolution and best image.

![Figure 5.](image1)

**Figure 5.** The resistivity horizontal slices with different array, which is under simple structure. (a) Wenner array. (b) Dipole-dipole array. (c) Pole-pole array. (d) Schlumberger array.

![Figure 6.](image2)

**Figure 6.** Three-dimensional profile by dipole-dipole array.

2.2. Numerical simulation of ancient architectural sites with complicated structure

In the above, the paper analyzed the results of the simple structural geoelectric model, and demonstrated that dipole-dipole array and Schlumberger array can reflect the actual situation well. However, the architectural sites often have more complex structures. Based on the structure of ancient architecture, shown in Figure 7, a complex geoelectric model, which is represent for building group, is constructed. Distribution along the depth of architectural are shown as Figure 8.
Figure 7. Existing ancient architecture.

Figure 8. Geoelectric model along different depth with complicated structure.

(a) Wenner array  (b) Dipole-dipole array

(c) Pole-pole array  (d) Schlumberger array

Figure 9. The resistivity horizontal slices with different array, which is under complicated structure. (a) Wenner array. (b) Dipole-dipole array. (c) Pole-pole array. (d) Schlumberger array.

The parameters of geoelectric model are set as follows: 1024 electrodes are set within 31m×31m square in the simulation field making up a 32×32 grid with 1 m horizontal spacing between the electrodes. And 0.5 m between each data point. The resistivity of the surrounding soil is still 10Ω·m, the resistivity of the ancient architectural site wall is same with 100Ω·m. The size of the ancient
building site is 19m×18.5m. Considers the burial depth of ancient architectural sites, and the burial depth of architectural sites is still in the range of 1m to 5m. The depth of the resistivity horizontal slices by Wenner array, dipole-dipole array, pole-pole array and Schlumberger array are 2.93m, 2.71m, 2.96m and 2.93m, respectively. The resistivity horizontal slices with different array are shown as Figure 9.

As shown in Figure 9, the resistivity horizontal slices with dipole-dipole array still have the highest resolution, while the slices of Pole-pole array and Wenner array have low resolution in shallow exploration area. As for Schlumberger array, it basically reflects the geoelectric model. This result has good consistency with results above. Particular, all the slice from Figure 9 have clearly boundary, it may due to the exterior wall is thicker than inner wall. In some extent, we can speculate the relative size of wall thickness through the resistivity horizontal slice. The slice of dipole-dipole has clearly boundary for inner wall. In the future, dipole-dipole array can be taken to detect the architectural sites.

3. Conclusion

The ERT is widely used in archeological prospection, because of its non-invasive, low cost and high efficiency. First, this paper briefly introduces the current situation of the application of three-dimensional ERT in archeological prospection. Based on the ancient architecture, this paper uses numerical simulations to compare the resolution of three-dimensional ERT for 4 electrode arrays of Wenner, dipole-dipole, pole-pole and Schlumberger. Two synthetic geoelectric models, simulating underground archeological structure, are used to examine the imaging capabilities of these arrays. The conclusions are summarized as follows:

(1) All electrode arrays can basically reflect the geoelectric model. It shows that three-dimensional ERT has a well applicability in the detection of underground architectural sites.

(2) For the simple geoelectric model, the resolution of dipole-dipole array is the highest. The pole-pole array detects deepest, while the depth of dipole-dipole array and Schlumberger array is moderate, and that of Wenner array is shallow. The resistivity horizontal slice by dipole-dipole array can accurately reflect the boundary of the simple geoelectric model.

(3) For the complicated geoelectric model, the resolution of dipole-dipole array is still highest. As for Schlumberger array, it can basically reflect the boundary of geoelectric model too. Due to the clearly boundary of slices, we can speculate the relative size of wall thickness through the resistivity horizontal slices.

(4) All in all, through the result of numerical simulation, the dipole-dipole array can be taken in actually archeological prospection. Well, the pole-pole array is more suitable for relatively deep sites.

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