A new approach for accurate detection of leakage paths from multiple-wenner arrays inverted resistivity imaging in embankment dam

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Abstract. Aiming at the difference of hidden danger identification of embankment dams by different arrays of high-density electrical method, a combined inversion method of wenner data volume is proposed to improve the resolution capability of target. The response characteristics of α, β and γ array to the preset model are presented by constructing the geoelectric model of the dam body and the potential leakage hazard in the contact zone. According to the simulation results, different arrays have different detection effects on the same target and the same array has different detection effects on different targets. β array reflects better effect of low resistance area, and γ array is more suitable for dividing dam body boundary, but both have weak anti-interference ability. In addition, the spatial feature information of the target by multiple-wenner inversion is more for the preset model and can effectively compensate for the limitation of a single array. The inversion results based on a priori model can suppress boundary interference and improve the effective identification of preset hidden dangers and boundary. The field test also shows that the anomaly determined by multiple-wenner inversion technology is highly consistent with the leakage site, which effectively improves the accuracy of hidden danger diagnosis.

1. Introduction
Geophysical methods provide technical services for the investigation of hidden dangers of dams with the characteristics of non-destructive, efficient, and perspective[1]. In particular, the resistivity method is more intuitive and sensitive for the positioning and distribution of weak areas of dam seepage, which guarantees the targeted anti-seepage treatment[2-6]. According to the combination of different measured potential values and current values, the high-density electrical method has derived a variety of detection arrays, and there are differences in the ability of different arrays to recognize the anomaly's recognition accuracy and the characteristics of spatial distribution. Numerical simulation and engineering experiments have also achieved some results in the optimization of the optimal electrode arrays. Numerical simulations are used to compare the resolution and efficiency of 2D resistivity imaging surveys for 10 electrode arrays by Dahlin and Zhou[7] and the GD, PD, DD and SC arrays are strongly recommended for 2D resistivity imaging, and the final choice will be determined by the expected geology, the purpose of the survey and logistical considerations. Sjödahl et al[8] show that the gradient array demonstrates reliable results, and it is suitable for field measurements as it can be used with multi-channel equipment making it very efficient. However, the
2D electrical resistivity survey using the Wenner array is useful for delineating the leakage pathways since leaks generate strong high conductive anomalies[1]. Accordingly, the joint inversion of multi-channel acquisition and full-electric field data has become a trend[9-12].

Considering the efficiency of field work, it is impossible to collect the data volume of every array, the stability and reliability of the inversion results are debatable because of the influence of the measurement accuracy and the external environment of the multi-channel instrument and equipment[13]. Based on the above-mentioned problems in the application of high-density electrical method in the detection of reservoir dam leakage, in order to improve the accurate identification and location of hidden dangers, this paper intends to use multiple-wenner(α, β, γ) arrays inverted imaging technology to deal with the embankment dam resistivity data volume. By constructing the typical geoelectric model of leakage hidden dangers in dam body and contact zone, the response of multiple-wenner arrays and single-array inverted imaging on the spatial characteristics of hidden dangers of two embankments were compared and analyzed, and the inversion results are further improved.

2. Multiple-wenner inverted imaging

High-density resistivity method is based on the electrical conductivity of the differences between rock-soil mass as the research object, according to the established in underground artificial steady current field in the change of space and time as the carrier, based on the data included in the geoelectric data volume for processing, integration and expression. In the data acquisition of high-density electrical method, the combination of different current and potential electrodes forms different arrays. The arrays most commonly used for resistivity surveys were shown in Figure1. And the shape of the contours in the pseudo section produced by the different arrays over the same structure can be very different. So it is necessary to constantly summarize and optimize in field, so as to improve the application effect of high-density electrical method. Two electrodes are selected to inject a current into the dam, and any two potential electrodes are used to measure the voltage. Based on the Ohm’s Law, an apparent resistivity is calculated:

\[
\rho_a = k\frac{AU}{I}
\]

where \(k\) is a geometric factor that depends on the arrangement of the four electrodes.

**Figure 1.** Arrangement of the electrodes for some commonly used arrays and their geometric factors.
3. Numerical examples

3.1. Model building
The embankment dam mainly adopts the construction technology of layering and thickening and heightening layer by layer. Under the premise that the filling quality and material are basically uniform, the resistivity of earth-rock dam shows gradual change and uniformity in the running period, and if there is a local weak zone of leakage (high conductivity), the conductivity between materials would be broken. Due to the limited length of the dam top of the mountain reservoir, the influence of the rock foundation (high resistivity) on the bank slope on both banks on the dam is also a factor to be considered in numerical simulation.

Figure 2 is the geoelectric model of typical embankment dam hidden dangers. The specific parameters are as follows: the dam top length is 63 m, the dam height is 20 m, the surface layer is gravel layer within 0.03 m, the electrical resistance is 300 Ω·m, the dam body resistance is 100 Ω·m, and the mountain body resistance is 500 Ω·m. Fig.3 (a)、(b) show typical geoelectric model of leakage hidden danger in dam body and contact zone.

Table 1. Resistivity and estimated geotechnical property ranges of model A and B

| Model name | Distance (m) | Depth (m) | Scale (m×m) | Resistivity (Ω·m) |
|------------|--------------|-----------|-------------|-------------------|
| A          | 30.0         | 7.0       | 3×2         | 10.0              |
| B          | 5.8          | 7.0       | 10×13       | 10.0              |

3.2. Analysis of high-density electrical data
The model uses the FEM algorithm to solve the apparent resistance value of multiple-wenner arrays forward, and adds 1% amount of noise to the calculated data volume. Based on the independent inversion of the data of each wenner array, the data of the wenner data is integrated into a joint inversion. The least square method based on the smooth constraint is used, the smoothness factor is 30, the damping factor is 100, and the number of iterations is 8 times, the error is reduced by 5%, and the RMS 3% is used as the inversion termination parallel condition.

3.3. Inversion of A model
The results of α, β, γ and multiple-wenner arrays inverted resistivity imaging are shown in Figure 3. It can be seen from the figure that the inversion results of different arrays can reflect the existence of low resistance anomaly in the middle part of the dam, and outline the boundary of the dam to a certain extent, indicating that the high-density electrical method is universal in the hidden danger exploration of embankment dam. The middle and low resistance zone is closed in Figure 3(a), the range of the anomaly zone is larger and the depth is shallower than that of the preset model. At the same time, the resistivity is obviously increased from shallow to deep, which shows obvious layered structure. Figure 3(b) represents the inversion results of the wenner β data, the low-resistance area is semi-closed, and its depth is basically consistent with the preset model, but the boundary between the mountain and the dam on both sides is fuzzy. Figure 3 (c) shows that the topographic distribution of the bank slope on...
both sides of the mountain body is good, but the banded continuous distribution of the low-resistance area on the inversion section is troublesome for the identification of hidden dangers. It is necessary to point out that the Wenner $\gamma$ is sensitive to the high resistance structure of the surface layer. The multiple-wenner arrays inverted resistivity imaging shows that the abnormal area is close isolated distribution, which reflects the hidden danger body scale, the position and the buried depth are basically consistent with the preset model, and the shape of the two sides of the mountain is relatively smooth (Figure 3d).

Figure 3. Inversion model section of A dam model

Figure 4. Inversion model section of B dam contact zone model

3.4. Inversion of B model
Figure 4 is the resistivity image obtained from the contact band leakage model calculated by the wenner arrays and the wenner joint inversion. It can also be seen from the results that different arrays can reveal obvious low-resistance anomalies on one side of the dam, and there are also differences in spatial parameter information such as the location, depth, and scale of identifying hidden dangers. Figure 4(a) shows that the horizontal anomaly zone is located in the 10~35m section, which is obviously offset from the preset model horizontal position of 5.8~15.8 m. Compared with Figure 3(a), it can be found that the range of the right mountain body is enlarged to the dam body, and the shape is also distorted, but the anti-interference ability to the shallow inhomogeneous body is strong. The results of the wenner $\beta$ inversion describe the anomalous body well, and the low resistivity anomalous region is in line with the preset model, and shows the tendency of the low resistivity region expanding to the left, and the surface layer of earth and rock has strong interference to the anomalous body. There are many abnormal areas on the inversion section in Figure 4(c), which to some extent interfere with the identification of the target body. The multiple-wenner arrays inverted resistivity imaging makes up for the deficiencies of the various arrays to some extent. The hidden danger area and the right mountain boundary obtained from the inversion are more in accordance with the preset model, and the response to the surface uneven body, but the reflection of the shape and range of the hidden body is not accurate enough.

4. Discussion

4.1. Optimization of single-array inverted
From the above results of different arrays of high-density electrical method and their joint inversion, it can be seen that it is universal to identify the hidden danger body and the boundary between the dam body and the mountain by using the difference of resistivity, and the simulation results show that it is theoretically feasible to detect the hidden danger of embankment dam by using the ground resistivity. But it can also be seen that the responses of different arrangement forms to the same model are different. In Figure 3 and Figure 4, the spatial parameter information of the hidden body and the boundary between the dam body and the mountain are obviously different, indicating that the structure of the geological is biased by different arrays. In addition, the same result is also reflected from the perspective of the same array to different models. Compared with Figure 3 (c) and Figure 4 (c), the wenner $\gamma$ recognizes the contact zone model significantly better than the dam model. In summary, if a single array is used to detect the hidden dangers of the earth dam body and the contact zone, the
Wenner β is preferred, and the wenner γ has better identification effect on the boundary of dam body and mountain, but their anti-interference ability is relatively weak.

4.2. Multiple-wenner arrays inverted resistivity

Because of the inherent defect of a single array reflecting the target body in a one-sided way, the multiple-wenner arrays inversion is to improve the accurate identification of geological by integrating data from different arrays. It can be seen from Figure 5 that when the number of electrodes is 64 and the number of recording layers is 21, the amount of single-wenner data is 651, while the amount of multiple-wenner arrays data reaches 1953(Fig.1). Because of the obvious increase of data points in different depths, the longitudinal resolution of inversion results is improved. The core buried depth of the hidden danger body in the joint inversion profile is 7.0 m in Figure 3(d), which accords with the preset model center depth of 8 m, and the deviation rate is 12.5%, which is much smaller than the inversion result of a single array, and the boundary division between the mountain and the dam is also better. To some extent, the floating range of resistance reflects the approximate degree of inversion results to the preset model. The maximum and minimum values of resistance obtained by multiple-wenner arrays inversion are the largest, in which the difference between the extreme values of A model is 102Ω·m, and the difference between the two extremes of B model is 120Ω·m. It can be seen that the multiple-wenner arrays inversion results are closer to the resistance range of the preset model. In summary, the joint inversion technique can effectively improve the longitudinal resolution and the variation range of resistance value of hidden danger of embankment dam.

4.3. Correction of inversion results

From the results of numerical simulation in Figure 3(d), the resistivity of 89Ω·m is the lower limit, and the hidden danger zone is judged to be 29~34m, which is enlarged from the horizontal position of the preset model by 30~33m, but the hidden region obtained by multiple-wenner arrays inversion has the deviation of range and position at the same time in Figure4 (d). The results of multiple-wenner arrays inversion are obviously improved compared with those of a single array, but considering that the combined data volume is still affected by the path and region of electric field line propagation, the location and range of the abnormal region are expanded or shifted compared with the preset model. Therefore, in order to improve the accurate identification of hidden danger area and boundary, reducing the interference of the geological structure of the dam to the target body becomes the key. In order to eliminate the influence of embankment dam structure on hidden body, the ratio of hidden danger model resistivity (\(\rho_n\)) and dam structure model resistivity (\(\rho_0\)) obtained by multiple-wenner arrays inversion is calculated.

\[
\eta = \frac{\rho_n}{\rho_0}
\]

Where \(\eta\) is a correction coefficient and is dimensionless.

Figure 6 (a) is the inversion image of the mean model of the existing dam structure, in which it is obvious that the dam structure has an impact on the dam body segment, resulting in low resistivity anomaly in the homogeneous model, which brings interference information to the accurate identification of hidden dangers in the dam body. Fig.4(d)、5(d) were calculated by using the ratio to obtain Figure 6(b)、(d). The range of the abnormal body in the middle of the dam was obviously reduced, and the coincidence degree of the transverse position with the preset model was improved, but the longitudinal depth was too deep in Figure 6(d). The modified model shows that the size, depth and shape of the abnormal body have been greatly improved in Figure 6(d), which improves the identification reliability of the hidden body. The corrected resistivity distribution is also more consistent with the default model in Figure 6(e) and (e). In a word, by establishing the basic form of the dam model and using the ratio method to eliminate the influence of the background model, the identification effect of hidden dangers can be improved, which will become the key to accurately identify hidden dangers of the dam.
5. Field example

5.1. Location and geology
The rainfall collecting area of a reservoir is 2.0 km, the main stream is 1.2 km long, and the storage capacity is 180,000 m³. It is a small (2) type reservoir mainly for drinking water and irrigation, with an irrigation area of 450 mu. In 2014, reinforcement measures were implemented for the dam, including the use of split grouting technology for the dam body, and the use of contact section cement grouting for the foundation zone. However, there are still obvious leakage phenomena at the dam foot, with a leakage volume of 1.2L/s, and the water is lipid. To clarify the cause of dam leakage is the premise of disease control, and blind measures to prevent seepage have a negative effect. In order to find out the cause of dam leakage, the parallel electrical method is used to detect hidden dangers. The field electric measuring line is arranged on the anti-seepage section of the dam crest and extends to the mountain on the right bank. The electrode spacing is 2m, and a total of 52 electrodes are arranged. The two-dimensional resistivity data can be collected using a recently developed multi-electrode resistivity meter system WBD-1 parallel electrical method.

5.2. Results
Figure 7 was obtained by Res2dinv. During the survey, the reservoir level of the reservoir was 4m from the top of the dam, and the height difference of the extension line on the right bank was 4m. It can be seen from Fig.8 that when the number of inversion iterations is 7, the RMS error is 3.3, indicating that the inversion results theoretically achieve a better approximation effect on the dam structure. The inversion resistivity section shows an obvious binary structure model of the dam. The resistivity of the dam body is relatively low and distributed in layers. The resistivity changes in the vertical and horizontal direction are smooth, and there is no obvious closed low-resistivity anomaly area. Terrain features two abutment batholith form basically, on the left side of the vertical resistivity on more violent change, may be associated with this rock mass slope is bigger, the right side of the batholith slope is relatively smooth, but the measuring line 50~80 m segment appear at the bottom of the low resistivity anomalies, and the abnormal area is half closed to deep and on both sides of the extension, concluded that the area section of rock mass for dam feet a significant leakage of the main parts. In addition, the toe leakage position is located directly below the measuring line at 50~52m, which is basically consistent with the position judged.
To further verify the reliability of multiple-wenner arrays results, drilling holes ZK1 and ZK2 were drilled on the measuring line 52m and 82m respectively. The drilling results showed that the hole depth of ZK1 was 44.3 m, of which the batholith depth was 24.7 m, and the average permeability to the hole depth of 34.1 m was 17Lu. The drilling depth of the ZK2 borehole is 25.9 m, in which the batholith depth is 9.6 m and the average permeability from the ZK2 bore hole to the hole depth 17.4 m is 31Lu. It can be seen from the water pressure test that the shallow rock mass of the two boreholes is moderately permeable, indicating the effectiveness of multiple-wenner arrays inverted resistivity imaging. It should be pointed out that since the reservoir dam engineering geological longitudinal profile and rock resistivity values have not been measured, the multiple-wenner arrays inverted resistivity imaging have not been corrected by ratio, but the results can be used to identify the causes and locations of reservoir leakage.

6. Conclusions
High-density electrical method is an effective technique for the diagnosis of embankment dam leakage. Among them, the β array is better at finding the low-resistance abnormal area inside the dam, and the γ array has better identification effect on the boundary between the dam and rock mass, but their anti-interference ability is lower than that of the α array. The multiple-wenner arrays inverted resistivity imaging effectively circumvent the differences of different arrays detection results and data fusion arrays more body improve horizontal resolution of dam hidden dangers, the use of the inversion results based on the initial geoelectric model correction technology, reduce the mountain structure on the interference of dam leakage hidden trouble, and effectively improve the ability to distinguish the shape and scale of hidden dangers. Based on the prior model, the correction of inversion results is based on the construction of the known structure shape of the dam rock and soil mass. However, most of the engineering applications lack basic geological data, and only numerical simulation is discussed in this paper. It is necessary to deeply carry out the geoelectric field inversion technology including the dam shape, so as to make the exploration results more accurate and truer.

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