Research Article

Study of Tunnel-Face to Borehole ERI (TBERI) Measurement Configurations and Its Optimization

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Most of the existing electrical-resistivity-based ahead prospecting methods in tunnel use only the tunnel cavity and tunnel face space to locate the water-bearing structures in front of the tunnel. However, due to the limitation of the narrow available space for arranging electrodes in tunnel, this kind of method is difficult to achieve more accurate image for water-bearing structures. The cross-hole electrical resistivity tomography (CHERT) and borehole-to-surface electrical resistivity tomography (BSERT) methods using borehole space have been proved effective means to achieve better images of deep anomalies on the surface. In this paper, the tunnel-face and borehole ERI (TBERI) method in tunnels was studied. To less affect the construction progress, the pole-pole configuration using a single borehole was studied in this paper. Moreover, the configuration is optimized based on the block weighted CR optimization strategy. After considering the data combination, an effective measurement configuration suitable for TBERI detection was formed. To accelerate calculation, some redundant data are removed from the obtained data after proposed block weighted optimization is conducted. By adopting the proposed configuration, the abnormal objects in the target area in the inversion are more accurate. The effectiveness of proposed configuration is verified by numerical simulation.

1. Introduction

In the past two decades, tunnel engineering has developed rapidly in the worldwide. Especially in Southwest China, a large number of roads, railways, and water diversion projects need to rely on tunnels to cross the complex terrains. However, disasters such as water inrush, collapse, and other geological disasters occurred during construction period would threat the construction progress even safety of the constructors. Geophysical prospecting method plays an important role in detecting anomalous bodies [1, 2]. In the field of water-conducting structure detection, the electrical resistivity (ER) method is widely applied because of its high sensitivity to water bodies [3–8]. However, conventional configuration which arrange electrodes on the surface is not close enough to the abnormal body located deep underground. Therefore, electrodes are then arranged in boreholes to obtain data containing more information of the abnormal body located deep underground, which is cross-hole or borehole-to-surface detection. This is an effective way to achieve fine detection of underground low-resistivity bodies [9, 10]. Similarly, for ahead prospecting methods conducting in tunnel environments, the space of ahead drilling borehole can also be used for borehole electrical resistivity (BER) detection.

At present, the cross-hole electrical resistivity tomography (CHERT) is a hot spot in engineering geophysical prospecting especially in the surface electrical detection. However, due to the narrow space in the tunnel, only one single borehole is often used. Therefore, the single-hole ER detection in the tunnel is the focus of our research. Recently, some scholars have conducted systematic research on the single borehole-to-surface ERT (BSERT) method in the surface detection situation. For example, Tsourlos et al. analyse the different types of BSERT configurations through the
sensitivity distribution and the inversion result and conclude that the “in-hole data” is the main cause of symmetric artifacts [11]. They proposed solutions based on data deletion and weighted inversion and to a certain extent solved the problem of symmetric artifacts of the BSERT. Wang and Lin believe that the highly symmetrical distribution of sensitivity is the cause of symmetric artifacts [12]. The balance between detection resolution and the intensity of symmetric artifacts is a key issue in the selection of configurations. They optimized the data of the two configurations for joint inversion and used the weighted MOST method to improve the inversion results, effectively solving the problem of symmetric artifacts. Li et al. proposed the tunnel-face and borehole ERI (TBERI) configuration and applied in a subway tunnel engineering [13]. They proved the effectiveness of this method for detecting water bodies in front of the tunnel.

By adopting the TBERI configuration, more observed data can be obtained by increasing electrodes. However, due to the complex electromagnetic interference of the machine in the tunnel, the quality of the obtained data is uncertain. In order to solve similar problems in surface ERT, Wilkinson et al. proposed the Compare-R (CR) configuration optimization method based on the model resolution matrix of the data set in the surface ERT detection [14]. This optimization strategy can optimize the observation device based on the sensitivity matrix, which can reduce the number of electrodes and basically ensuring the overall quality of the data set, finally greatly reduce the amount of data. This method has been subsequently applied to a variety of electrical detection situations and has been further developed in the past decade [15, 16]. Wilkinson et al. improved the goodness function (GF) of CR method and realized adaptive optimized survey design by introducing block weighting [16]. Uhlemann et al. had made further improvements on this basis [17]. They introduced a weighting factor for electrode placement to achieve combined optimization of both measurement configuration and electrode placement.

In this paper, the optimization of measurement configuration of TBERI was studied. First, a measurement configuration of TBERI is proposed based on the application research of Li et al. [13]. Then, the TBERI measurement configuration is optimized based on the block weighted optimization method, and the optimized configuration is verified by one numerical simulation. Next, the optimization algorithm is introduced in the second chapter. Then, the results of block weighted optimization is shown in chapter 3 through the distribution image of the model resolution matrix. Finally, the effectiveness of the proposed method is verified by the inversion simulation results of the two anomalies.

2. Methodology

2.1. TBERI Measurement Configurations. TBERI is proposed to make full use of the tunnel face and forward drilling space. As shown in Figure 1(a), the size of the tunnel is assumed to be 9 m × 7 m with shape of horseshoe, and a 30 m long advance borehole was drilled in front of the tunnel face. Figure 1(b) shows the specific arrangement of electrodes on the tunnel face. The electrodes are divided into 7 rows; the spacing between each row is 1 m, and the distance between electrodes in the row is also 1 m. There is a 0.5 m gap between the electrode array and the upper and lower boundaries of the tunnel, and a total of 45 electrodes are arranged on the tunnel face. The electrodes in the borehole are arranged at equal intervals of 1 m, with a total of 30 electrodes.

It has to be noted that the pole-pole configuration was mainly discussed in this paper. Based on the configuration of A-M (A is located on the tunnel face, and M is located in the borehole) introduced by Wang and Lin [12], the AM configuration was additionally discussed (all electrodes are located in the borehole); these two kinds of configurations are as shown in Figure 2. The A-M configuration can obtain 1,350 data, and the AM configuration can obtain a maximum of 435 data without considering the reciprocity of the electrodes. Combining the two pieces of data forms the basis for the next configuration optimization, the comprehensive data set \( S_c \). Although Tsourlos et al. have clearly pointed out that the in-hole data like AM configuration is not recommended [11], Wang and Lin believe that a balance should be struck between symmetric artifacts and resolution (however, they also exclude in-hole data) [12]. In the following content, the reason why we consider AM configuration will be explained.

Apparently, the AM configuration data is a kind of “in-hole data.” This type of data has the typical characteristics of symmetrical distribution of sensitivity, which makes it difficult to perceive the orientation information of anomalies. This is also the cause of symmetrical artifacts. However, due to the full use of the drilling space, this type of data is sensitive to the depth information of the anomaly and is necessary for ensuring the deep detection capabilities of BSERT. Therefore, Wang and Lin recommended to combine different configuration data in order to improve the inversion result [12]. To verify the conclusion in tunnel environment, a numerical test is conducted. A \( 4 \times 4 \times 4 \) m\(^3\) block with resistivity of 10 \( \Omega \)·m is assigned at a distance of 2 m from the borehole and 4.5 m from the tunnel face. Figure 3 shows the least-squares inversion results of different configurations (A-M or A-M + AM). It can be seen that although the addition of AM results in symmetry artifacts, the resistivity of the anomalies located deep in front of the tunnel face can be easily seen. Therefore, the AM configuration was considered to obtain a better inversion result.

2.2. Block Weighted CR Optimization Strategy. The optimization strategy will be briefly introduced in this part; detail content could refer to Tsourlos et al., Uhlemann et al., and Wilkinson et al. [11, 17, 18]. In the generalized inversion theory, the model resolution matrix \( \mathbf{R} \) can be defined by the following formula [19]:

\[
\mathbf{m}^{\text{fit}} = \mathbf{R} \mathbf{m}^{\text{true}},
\]

where \( \mathbf{m}^{\text{fit}} \) and \( \mathbf{m}^{\text{true}} \) are simulated model and real model, respectively. The model resolution matrix quantifies the resolved degree of each grid. If each grid is perfectly resolved then \( \mathbf{R} = \mathbf{I} \) [14]. For ease of calculation, after
linearization, $R$ can be calculated by the following formula [20]:

$$R = (J^TJ + C)^{-1}J^TJ,$$  \(\text{(2)}\)

where $J$ is Jacobian matrix and $C$ is the regularization matrix [21]. The CR strategy is based on the calculation of $R$, selecting a subset $S_b$ (the base set) from $S_c$. Although $S_b$ contains less data, its model resolution value is similar to $S_c$. The complete flow chart of optimization progress is shown in Figure 3. In this progress, the goodness function (GF) is the key point to controlling the optimization process. It determines which data will eventually be selected into $S_b$. The calculation formula of GF is as follows [14]:

$$GF = \frac{1}{m}\sum_{j=1}^{m} \frac{R_{t,j}R_{b,j}}{R_{t,j}},$$  \(\text{(3)}\)

where $R_t$ is the resolution of the base set plus the test configuration and $R_b$ is the resolution of the base set. In each iteration of optimization, the single or multiple configurations with the highest GF value will be selected to be added to the base set. In order to add artificially controllable factors in the optimization process, Uhlemann et al. and Wilkinson et al. improved the calculation formula of GF [17, 18]:

$$GF = \frac{1}{mw_{c}^\beta}\sum_{j=1}^{m} \frac{\omega_{t,j}^\beta R_{b,j}^{\beta}}{R_{t,j}^{\beta}},$$  \(\text{(4)}\)

where $\omega_t$ is the so called block weighting factor while $\omega_c^\beta$ is the weighting factor for electrode selection. In this paper, $\omega_t$ was mainly considered because there is no need in this study to produce an “extremely focused” measurement configuration in TBERI. Therefore, $\beta$ is set to 0, and $\omega_c^\beta$ will not work in the formula. In the subsequent numerical simulations, the depth range of the anomaly is assumed to be known based on the borehole information (for example, a low-resistivity body exists between 10 and 15 m). Based on this, the weighting factor $\omega_t$ of the grid within the range of 10-15 m will be set to 1, while other grids will be set to 10$^{-12}$.

3. Numerical Simulations

3.1. Optimization Simulation. Firstly, an array optimization experiment was conducted, using the block weighted CR optimization strategy. A $15 \times 15 \times 30$ m$^3$ cube zone is
arranged in front of the tunnel face as the target as shown in Figure 4. The target zone is close to the borehole and the tunnel face. In the target zone, the weight factor $w_t$ is set to 1, while the other zone is $10^{-12}$. In this optimization, the comprehensive data set is the collection of all AM and A-M data. The electrode arrangement has been described in detail in Section 2.1. Under this electrode arrangement, the comprehensive data set could contain up to 1090 data. The initial data set is a set of data obtained by single data selected arbitrarily. After each optimization iteration is completed, 30 optimal data with the largest $GF$ value will be added to the base set. The number of iterations is selected according to detecting requirement of the optimized configuration. In this paper, the optimization iteration process continues until there are more than 390 data in the base set.

Figures 5(a)–5(d) show the change process of the relative model resolution during the optimization iteration. Under the influence of the weighting factor in the $GF$ formula, the optimization strategy tends to give priority to increasing the model resolution in the 0–15 m area in front of the tunnel face. It can be seen from the figure that the optimization strategy is to increase the model resolution of all grids in the range of 0–15 m overall, although half of the grids in this area have a weighting factor of $10^{-12}$. For the area in 15 m to 30 m on the $Z$ axis, the model resolution is obviously lower, which shows that the weighting factor plays a role in the optimization process. Figures 5(e) and 5(f) show the comparison of the model resolution of the base set and comprehensive set. The model resolution of the base set is symmetrical distributed, and there is almost no asymmetric distribution although it has the difference in weight factors.

Figure 6 shows the value of the average relative model resolution during iteration. The solid purple line represents the change in the average relative model resolution in the
target zone, and the red dotted line represents the change in the average relative model resolution in the whole zone. The average relative model resolution of the target zone is always greater than that of the whole zone. After 13 iterations, the average relative model resolution of the target zone reached about 0.85, while the whole area only reached about 0.7. This shows that the weighted optimization strategy can give priority to improving the model resolution of the target zone.

3.2 Inversion Simulation. In this section, three inversion simulations are calculated to compare the performance of the data set before and after optimization in the inversion. The first column of Figure 7 shows the model schematic diagrams of the three simulations. In the first simulation, a $4 \times 4 \times 4$ m$^3$ block with resistivity of 10 $\Omega$ m is assigned at a distance of 2 m from the borehole and 5 m from the tunnel face, and the low-resistance block is located in the target zone. In the second simulation, the low-resistance block of
the same size is set at a distance of 2 m from the borehole and 20 m from the tunnel face and is no longer in the target zone. In the third model, two low-resistance blocks were arranged inside and outside the target zone, and the size of the blocks is the same as the last two models. The resistivity of mentioned blocks above is $10 \, \Omega \cdot m$, and the background resistivity is $1000 \, \Omega \cdot m$. Three-dimensional least-squares inversion method with smooth constraints was used for inversion imaging. The forward simulation data used for inversion has been added with a certain degree of noise, and the noise application method can be referred to Bellmunt et al. [9]. The selection of noise-related parameters is related to Wang and Lin [12]. The iteration is terminated when the RMS value is less than 5%, and the number of iterations for each simulation is between 5 and 6 times. The second column is the inversion results using the comprehensive set, and the third column is the inversion results using the optimized measurement configuration. The centers of the low-resistance blocks are all located on the $X = 0 \, m$ section, so the inversion results with the two-dimensional slice image of the $X = 0 \, m$ section are also shown.

As shown in Figures 7(b) and 7(c), for the anomalous body located near to the tunnel face, the value of resistivity in the inversion result is more approach to the forward model. It is probably because the model resolution of the grid near to the tunnel face is higher than that of far grid. Because the optimized configuration uses less data than the original comprehensive configuration, some artifacts appear in the inversion results. Nevertheless, the resistivity value of the artifacts is much less than the anomalous bodies. Therefore, the optimized configuration is able to image the anomalous bodies. As shown in Figures 7(e) and 7(f), the location of the anomalous body is accurately imaged. As shown in Figures 7(h) and 7(i), both the anomalous bodies are imaged accurately. Similarly, the resistivity value of anomalous body near to the tunnel face is closer to the forward model than the farer one.

In the first simulation, the inversion results of the comprehensive set and the optimized data set are similar to each other, and both produce a certain degree of symmetrical artifact. In the second simulation, for the block located outside the target zone, the optimized data set showed a “blurred” imaging effect. In the third calculation example, when two blocks exist at the same time, the optimized data set can image the blocks in the target zone well but can only roughly image the block outside the target zone.

4. Discussions

Model resolution is one of the standard to evaluate the detecting ability of a configuration. Therefore, an optimization strategy could help select configuration pertinently. In the optimization simulation, selected one side of the borehole within the range of 0-15 m is selected as the target zone to get better inversion result within this area. In our thought, the distribution of resolution should be symmetrical because the model resolution on the side where the target zone is located is higher than the other side. However, the result obtained is an almost symmetrical model resolution distribution. We believe that this phenomenon is caused by the “in-hole data.” As discussed by Tsourlos et al. and Wang and Lin [11, 12], the sensitivity of “in-hole data” is symmetrically distributed, and it has the same sensitivity to the grid at any angle around the borehole. Therefore, it is reasonable to speculate that the influence of “in-hole data” on the model resolution is also symmetric. Since we have considered
“in-hole data” in the comprehensive set, these data will inevitably be selected into the base set during the optimization process. This results in a symmetrical distribution of the resolution of the optimized model. Although it is impossible to achieve accurate block weighting optimization in the range of 0-15 m, this algorithm still effectively distinguishes two regions in the depth direction. This is reflected in that the model resolution in the 0-15 m area is significantly higher than the 15-40 m area. At the same time, for specific engineering condition, the area of the target zone could be selected according to the demand.

The inversion result verifies the optimization effect. For anomalies in the target zone, the optimized data set basically retains the sensitivity to this zone, and the inversion results before and after optimization are basically the same. For anomalies after 15 m, due to the lower optimized model resolution of this zone, the inversion result of the optimized data set is obviously inferior to the inversion result of the comprehensive set. Through this optimization method of measurement configuration, we can greatly reduce the amount of data while preserving the model resolution of the target zone.

It has to be noted that the number of iterations is selected according to subjective demand. A method based on data set and resolution matrix should be proposed to the balance between calculation effectiveness and accuracy of the inversion result to evaluate the optimization progress objectively. The effectiveness of proposed strategy should be verified in field test.

5. Conclusions and Outlook

In this paper, a single-hole electrical resistivity detection method TBERI and two pole-pole configurations suitable for tunnels are proposed to obtain accurate inversion result. However, symmetrical artifacts appear in the inversion result of AM configuration. This confirms that the azimuthal information can only be retrieved by the potential electrodes...
arranged on tunnel face. Therefore, a comprehensive configuration including a single-hole electrical resistivity detection method TBERI and two pole-pole configurations is proposed. Then, block weighted CR optimization strategy is proposed to optimize the configuration for accurate and effective inversion. Based on the comprehensive set composed of A-M + AM configurations, about 60% of the data and achieved an average relative model resolution of 80% in the target zone are streamlined. Through three sets of inversion simulations, the effectiveness of this optimization method is verified: the imaging effect in the target zone is basically retained, while the imaging effect outside the target zone is weakened.

It has to be noted that only initially considered pole-pole configurations are considered in this paper. However, in the research of Wang and Lin [12], they have fully considered the tripole or quadrupole configurations. This will be what we will further study and discuss in TBERI in the future. In addition, this paper carried out a preliminary attempt on the pole-pole configuration of the measurement configuration optimization strategy and verified its effectiveness. In the follow-up study of the tripole or quadrupole configurations, as the amount of data will increase exponentially, it will be necessary to study its data reduction and optimization methods.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors have no conflicts of interest to declare.

Authors’ Contributions
Dr. Zhengyu Liu did the instruction and revision work of this paper. Mr. Wei Zhou and Mr. Lichao Nie completed the design of electrode arrangement and measurement configuration of the TBERI method in this paper. Mr. Yongheng Zhang carried out the work of writing this paper. Mr. Yonghao Pang and Mr. Zhao Dong carried out the block weighted optimization of the TBERI measurement configuration. Mr. Zhimin An and Mr. Chuanyi Ma carried out the calculation work of the numerical examples in this paper.

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References
[1] S. Li, B. Liu, X. Xu et al., “An overview of ahead geological prospecting in tunneling,” Tunnelling and Underground Space Technology, vol. 63, pp. 69–94, 2017.
[2] S. Li, R. Liu, Q. Zhang, and X. Zhang, “Protection against water or mud inrush in tunnels by grouting: a review,” Journal of Rock Mechanics and Geotechnical Engineering, vol. 8, no. 5, pp. 753–766, 2016.
[3] S. Li, B. Liu, L. Nie et al., “Detecting and monitoring of water inrush in tunnels and coal mines using direct current resistivity method: a review,” Geotechnical Engineering, vol. 7, no. 4, pp. 469–478, 2015.
[4] B. Liu, Q. Guo, S. Li et al., “Deep learning inversion of electrical resistivity data,” IEEE Transactions on Geoscience and Remote Sensing, vol. 58, no. 8, pp. 5715–5728, 2020.
[5] Y. Pang, L. Nie, B. Liu, Z. Liu, and N. Wang, “Multiscale resistivity inversion based on convolutional wavelet transform,” Geophysical Journal International, vol. 223, no. 1, pp. 132–143, 2020.
[6] M. H. Loke, J. E. Chambers, D. F. Rucker, O. Kuras, and P. B. Wilkinson, “Recent developments in the direct-current geoelectrical imaging method,” Journal of applied geophysics, vol. 95, pp. 135–156, 2013.
[7] A. Revil, M. Karaulis, T. Johnson, and A. Kemna, “Some low-frequency electrical methods for subsurface characterization and monitoring in hydrogeology,” Hydrogeology Journal, vol. 20, no. 4, pp. 617–658, 2012.
[8] Y. Rubin and S. S. Hubbard, Hydrogeophysics Vol 50, Springer Science & Business Media, 2006.
[9] F.Bellmunt, A. Marcuello, J. Ledo, and P. Queralt, “Capability of cross-hole electrical configurations for monitoring rapid plume migration experiments,” Capability of cross-hole electrical configurations for monitoring rapid plume migration experiments, vol. 124, pp. 73–82, 2016.
[10] K. Leontarakis and G. V. Apostolopoulos, “Laboratory study of the cross-hole resistivity tomography: the model stacking (MOST) technique,” Journal of Applied Geophysics, vol. 80, pp. 67–82, 2012.
[11] P. Tsourlos, R. Ogilvy, C. Papazachos, and P. Meldrum, “Measurement and inversion schemes for single borehole-to-surface electrical resistivity tomography surveys,” Journal of Geophysics and Engineering, vol. 8, no. 4, pp. 487–497, 2011.
[12] H. Wang and C.-P. Lin, “Cause and countermeasures for the symmetric effect in borehole-to-surface electrical resistivity tomography,” Journal of Applied Geophysics, vol. 159, pp. 248–259, 2018.
[13] S. Li, S. Xu, L. Nie et al., “Assessment of electrical resistivity imaging for pre-tunneling geological characterization - a case study of the Qingdao R3 metro line tunnel,” Journal of Applied Geophysics, vol. 153, pp. 38–46, 2018.
[14] P. B. Wilkinson, P. I. Meldrum, J. E. Chambers, O. Kuras, and R. D. Ogilvy, “Improved strategies for the automatic selection of optimized sets of electrical resistivity tomography measurement configurations,” Geophysical Journal International, vol. 167, no. 3, pp. 1119–1126, 2006.
[15] F. M. Abdullah, M. H. Loke, M. Nawawi, and K. Abdullah, “Improving the resolution of 3-D resistivity surveys along the perimeter of a confined area using optimized arrays,” Pure and Applied Geophysics, vol. 176, no. 4, pp. 1701–1715, 2019.
[16] P. B. Wilkinson, M. H. Loke, P. I. Meldrum et al., “Practical aspects of applied optimized survey design for electrical resistivity tomography,” Geophysical Journal International, vol. 189, no. 1, pp. 428–440, 2012.
[17] S. Uhlemann, P. B. Wilkinson, H. Maurer, F. M. Wagner, T. C. Johnson, and J. E. Chambers, “Optimized survey design for electrical resistivity tomography: combined optimization of measurement configuration and electrode placement,” Geophysical Journal International, vol. 214, no. 1, pp. 108–121, 2018.
[18] P. B. Wilkinson, S. Uhlemann, P. I. Meldrum et al., “Adaptive time-lapse optimized survey design for electrical resistivity tomography monitoring,” Geophysical Journal International, vol. 203, no. 1, pp. 755–766, 2015.

[19] W. Menke, Geophysical Data Analysis: Discrete Inverse Theory, Academic press, 2018.

[20] M. H. Loke and R. D. Barker, “Least-squares deconvolution of apparent resistivity pseudosections,” GEOPHYSICS, vol. 60, no. 6, pp. 1682–1690, 1995.

[21] M. H. Loke, I. Acworth, and T. Dahlin, “A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys,” Exploration Geophysics, vol. 34, no. 3, pp. 182–187, 2003.