Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-12, December 2025
DOI: 10.53469/jrse.2025.07(12).13

Application of High-Density Resistivity Method in the Detection of Coal Mine Goafs

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Abstract: ***Aiming at the detection of coal mine goafs beneath transmission lines, this paper investigates the application of the high-density resistivity method using the Wenner array. Geoelectric models representing water-filled (low-resistivity) and non-water-filled (high-resistivity) goafs were constructed, followed by forward modeling and inversion analysis based on the least squares method. The simulation results indicate that this method accurately delineates the boundaries of high-resistivity anomalies. For low-resistivity anomalies, although the inverted depth shows slight thickening, the horizontal location and overall extent are reliably identified. In engineering practice, the inversion profiles of four survey lines revealed distinct low-resistivity anomalies, and the inferred goaf locations were basically consistent with subsequent geotechnical investigation data. This study confirms the effectiveness of the high-density resistivity method (Wenner array) in goaf detection, providing a scientific basis for the site selection and stability evaluation of transmission line projects.***

Keywords: High-density resistivity method, Goaf detection, Wenner array.

1. Introduction

Coal, as a vital energy source, has made tremendous contributions to the development of the national economy since the 1990s [1]. However, large-scale coal mining, coupled with disorderly private mining activities, has left behind a vast number of goafs (mined-out areas). The distribution of most of these goafs remains unclear. Furthermore, the collapse and destruction of goafs exhibit a delayed effect. Once the surrounding rock becomes unstable and fails, it leads to large-scale surface subsidence and ground fissures. This damages surface structures, threatens the safety of residents' lives and property, deteriorates the ecological environment, and poses huge safety risks and potential losses to existing engineering projects. Therefore, it is imperative to find a suitable method to ascertain the location and distribution range of goafs, providing basic data for safety governance.

Currently, goaf detection methods can be categorized into the following types: 1) Geological Survey Method: This mainly involves collecting data combined with field visits and investigations to infer the range of the goaf. This method has low costs and low difficulty, but its results lack a theoretical basis, making it difficult to ascertain the accurate distribution range of the goaf. 2) Geophysical Exploration Method: Utilizing the physical property differences between the goaf and the surrounding rock mass, geophysical methods are used to identify the distribution range of anomalies. This method is non-destructive and has the advantages of high precision and speed, but its disadvantage is the non-uniqueness of the results. 3) Drilling: This involves using a drilling rig to extract soil samples from a certain depth underground to determine the distribution of underground rock and soil layers. This method offers high precision and accurate results, but it is expensive and involves a huge workload for large-area goafs. Therefore, among the above three methods, the geophysical method is the most widely used and suitable one. Geophysical methods used for goaf detection mainly include the High-density Electrical Method, Rayleigh Wave Method [2], Micro-gravity Method, Ground Penetrating Radar (GPR), Radioactivity Method (Radon Measurement) [3], Transient Electromagnetic Induction Technology [4], 3D Seismic Exploration Technology, and Borehole Geophysical Technology (Well Logging). Among them, the High-density Electrical Method is widely used in the investigation of shallow goafs due to its high detection precision and strong anti-interference ability [5].

Based on numerical simulation methods, this paper carries out a study on the detection of coal mine goafs using the High-density Electrical Method. Corresponding geoelectric models were established according to two scenarios: water-filled and non-water-filled goafs. The inversion results were researched and analyzed. Furthermore, the findings were applied to the detection of coal mine goafs in a specific transmission line project, achieving good application results. This proves the feasibility of this method for coal mine goaf detection and provides reference experience for subsequent similar projects.

2. Audio Magnetotelluric Sounding Principle

The High-density Electrical Method is essentially a geophysical exploration technology that integrates the dual characteristics of electrical sounding and electrical profiling. Its implementation involves combining various electrode arrangements with varying electrode spacings. A prominent advantage of this method is that a single deployment of electrodes can support data acquisition tasks involving multiple arrays and multiple levels. Although its field operation efficiency and automation level far exceed those of traditional electrical methods, its theoretical core is consistent with the conventional DC electrical method, both being based on the spatial distribution laws of stable current fields in underground media.

The operation workflow of this method demonstrates a high degree of systematization and automation. Field acquisition begins with the one-time deployment of all electrodes along the survey line. These electrodes are connected to a multi-channel electrode automatic switching system via multi-core cables (or controlled by intelligent switch boxes). Acting as an intelligent bridge between the electrode array and the electrical instrument, this system is responsible for the automatic switching of electrode combinations during the data acquisition process. Once the measurement is initiated, the built-in microprocessor directs a series of automated procedures, including real-time inspection of electrode grounding status, as well as dynamic adjustment and rolling advancement of the measurement array type, electrode spacing, and survey point position. Consequently, it automatically completes data acquisition for the entire survey line and writes the results into the instrument's internal storage in real time. After data acquisition is completed, the data stored in the instrument is exported to a computer. Subsequently, professional software is utilized for format conversion and inversion calculation. Finally, the inversion results are presented in visual forms such as apparent resistivity profiles or slice maps [6].

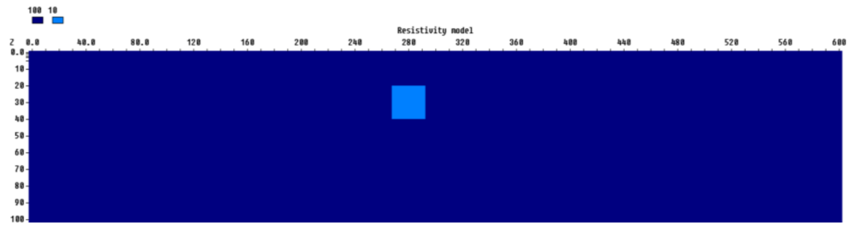
According to different array configurations, the High-density Electrical Method can be classified into the Two-pole (Pole-Pole) array, Three-pole (Pole-Dipole) array, Differential array, Dipole-Dipole array, Wenner array, and Schlumberger array, etc. Each array has its own advantages and characteristics. Among them, the Wenner array is known for its superior effectiveness in detecting goafs. Therefore, the array configuration adopted for the numerical simulation in this paper is the Wenner array.

3. Numerical Simulation

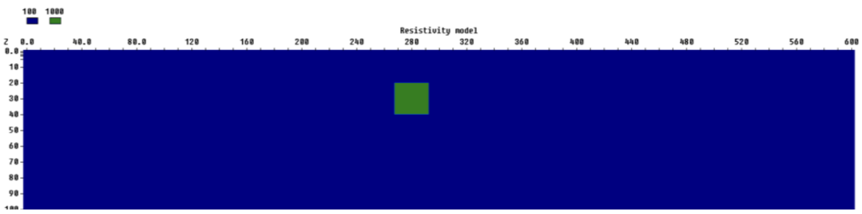
To verify the application effectiveness of the High-density Electrical Method in goaf detection, several theoretical models were established to simulate actual conditions based on the different filling conditions of coal mine goafs. The Finite Element Method (FEM) was employed for forward modeling, while the Least Squares Method was utilized for inversion. Subsequently, the inversion results were analyzed to evaluate the detection effectiveness of this method under various goaf conditions [7].

3.1 Inversion Analysis of Single Models

If the groundwater is abundant and the goaf is filled with water, the electrical characteristics of the goaf manifest as relatively low resistivity, while the surrounding rock manifests as relatively high resistivity. In this scenario, the resistivity of the low-resistivity body is set to 10 Ω·m, and the resistivity of the surrounding rock is set to 100 Ω·m. Conversely, if the goaf is not filled with water (air-filled), its electrical characteristics manifest as relatively high resistivity, while the surrounding rock manifests as relatively low resistivity. In this case, the resistivity of the high-resistivity body is set to 1000 Ω·m, and the surrounding rock remains at 100 Ω·m.The survey line consists of 60 electrodes with an electrode spacing of 10 m, resulting in a total survey line length of 600 m. For both models, the burial depth of the anomaly is set to 20–40 m, with a width of 20 m, located between 270 m and 290 m along the survey line. The two models are illustrated in Figure 1.

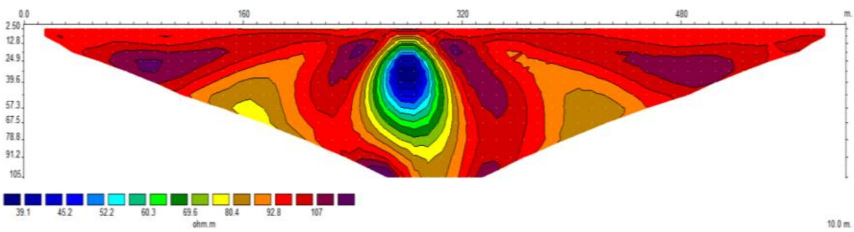


(a) Single low-resistivity model.

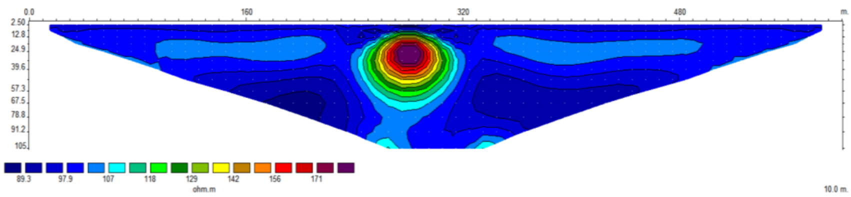


(b) Single high-resistivity model.

Figure 1: Single models.



(a) Inverted apparent resistivity profile of the single low-resistivity model.



(b) Inverted apparent resistivity profile of the single high-resistivity model.

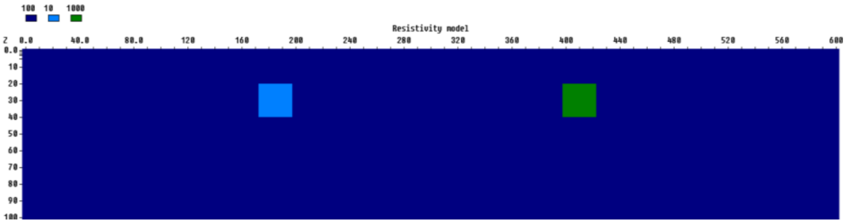
Figure 2: Inversion results of the single models.

The corresponding apparent resistivity profiles were obtained for both models after multiple iterative inversions. Analysis of the inverted apparent resistivity profile for the single low-resistivity model (Figure 2a) reveals that the resistivity distribution effectively highlights the characteristics of the low-resistivity target. The center of the low-resistivity anomaly is located between 270 m and 290 m along the survey line, at a burial depth of 20 m to 48 m. Regarding the depth, the top interface of the anomaly is delineated quite accurately, while the bottom interface appears slightly thickened; however, this does not affect the overall assessment of the low-resistivity body. Overall, both the burial depth and width of the low-resistivity model fall within the inferred range of the anomaly's depth and central width.

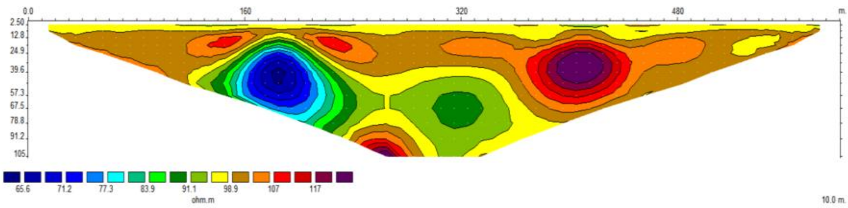
Analysis of the inverted apparent resistivity profile for the single high-resistivity model (Figure 2b) shows that the resistivity distribution effectively highlights the characteristics of the high-resistivity target. The center of the high-resistivity anomaly is located between 270 m and 290 m along the survey line, at a burial depth of 20 m to 40 m. The determination of the anomaly's extent is accurate in terms of both depth and width. Overall, both the burial depth and width of the high-resistivity model fall within the inferred range of the anomaly's depth and central width.

3.2 Inversion Analysis of the Complex Model

In practical engineering projects, multiple goafs may coexist simultaneously. Therefore, a complex model was established in which both a low-resistivity anomaly and a high-resistivity anomaly appear within the same stratum, aiming to investigate the detection effectiveness of this method for complex goaf scenarios. As shown in Figure 3(a), the resistivity of the low-resistivity body was set to 10 Ω·m, the surrounding rock to 100 Ω·m, and the high-resistivity body to 1000 Ω·m. The survey line consisted of 60 electrodes with an electrode spacing of 10 m, resulting in a total line length of 600 m. The low-resistivity anomaly was positioned between 175 m and 195 m along the survey line, while the high-resistivity anomaly was positioned between 400 m and 420 m. Both anomalies had a burial depth of 20 m to 40 m and a width of 20 m.



(a) The complex model



(b) Inverted apparent resistivity profile of the complex model

Figure 3: The complex model and its inversion results

The apparent resistivity profile obtained from the inversion of the complex model is shown in Figure 3(b). The analysis indicates that the resistivities of both the high- and low-resistivity bodies are distinctly different from that of the surrounding rock, and the shapes of the anomalies are well highlighted. The center of the low-resistivity body is located between 168 m and 202 m along the survey line, at a burial depth of 20 m to 46 m. While its width shows a slight increase, the delineation of the top interface is relatively accurate; although the bottom interface appears somewhat thickened, this does not affect the overall assessment of the low-resistivity body. Overall, both the burial depth and width of the low-resistivity model fall within the inferred range of the anomaly's depth and central width.

The center of the high-resistivity body is located between 395 m and 423 m along the survey line, at a burial depth of 20 m to 42 m. Its burial depth is determined quite accurately. Although the width is slightly enlarged, it does not affect the overall assessment of the high-resistivity body. Overall, both the burial depth and width of the high-resistivity model fall within the inferred range of the anomaly's depth and central width.

Analysis of the above results reveals that in the complex model, the significant difference in resistivity between the high- and low-resistivity bodies caused mutual interference. Compared to the inversion results of the single models, the inferred ranges of the anomalies increased to a certain extent. However, the burial depths and widths of the model bodies generally remain within the inferred ranges of the anomalies' depths and central widths. This demonstrates that high-density electrical resistivity tomography using the Wenner array configuration has excellent application effectiveness for goaf detection.

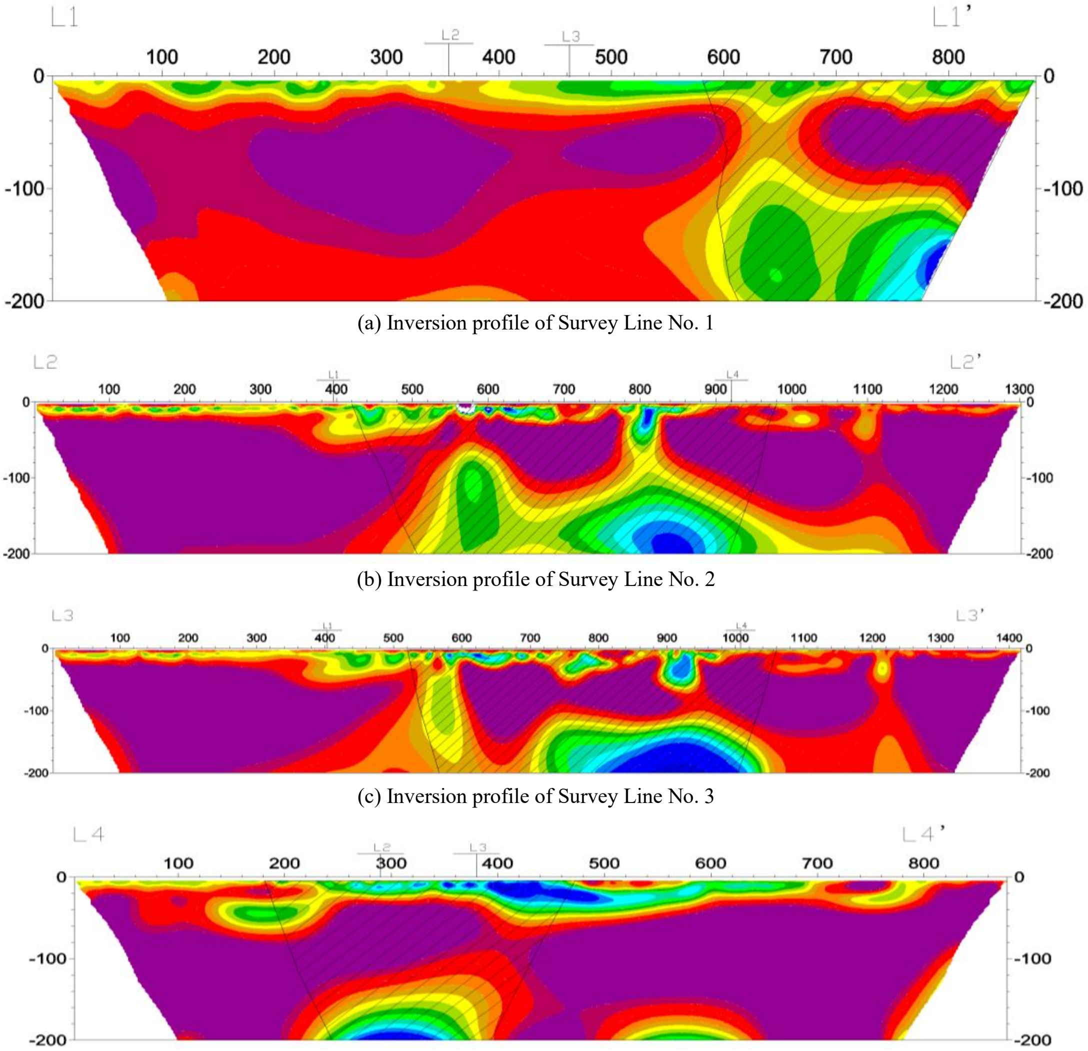
4. Engineering Case Study

4.1 Survey Line Layout

Based on the anomalous response characteristics and geoelectric field distribution patterns reflected by the goaf detection models discussed above, this paper presents a practical application in a coal mine goaf exploration project for a transmission line engineering project. The survey area has a well-developed drainage system. The overburden consists of cohesive soil in the upper part and a sand layer in the lower part, while the exposed rock strata are sandstone with locally intercalated thin coal seams. There are significant electrical differences between the strata, providing the necessary geophysical prerequisites for using the resistivity method to detect goafs.

In this work, the high-density electrical resistivity tomography profiles were laid out in a grid pattern ("#"-shape). A total of four long profiles were established with an electrode spacing of 10 m. Each long profile was composed of multiple individual segments. Finally, the data from each segment were spliced together to form a single long profile for integral inversion. Splicing the profile data allows for the comparison and delineation of anomalies across the entire survey line, making interpretation more convenient and reducing certain errors. Profiles No. 1 and No. 4 have a total length of 900 m and run in a north-south direction. Profile No. 2 has a total length of 1300 m, and Profile No. 3 has a total length of 1400 m; both No. 2 and No. 3 run in an east-west direction.

4.2 Interpretation of Results



(a) Inversion profile of Survey Line No. 1

(b) Inversion profile of Survey Line No. 2

(c) Inversion profile of Survey Line No. 3

(d) Inversion profile of Survey Line No. 4

Figure 4: Inversion results of the survey lines

Figure 4 presents the inversion results for the four survey lines. Overall, the resistivity is relatively high with well-defined stratification and a fairly uniform distribution. Based on a comprehensive analysis of the regional geological data, the detailed interpretations are as follows:

In the inversion profile of Survey Line No. 1 (Figure 4a), the surface layer exhibits low resistivity and is inferred to be the overburden, with a thickness of approximately 10 m. The underlying layer shows higher resistivity and is inferred to be sandstone. In the range of 600–900 m along the profile (shaded area), a significant resistivity anomaly appears. An anomalous low-resistivity body is observed at a depth of approximately 130 m and below, with resistivity values ranging from 1 to 18 Ω·m. It is inferred that this low-resistivity anomaly represents a coal mine goaf that has been filled with groundwater following underground mining.

In the inversion profile of Survey Line No. 2 (Figure 4b), the surface layer similarly shows low resistivity, inferred as the overburden (~10 m thick), while the lower part is high-resistivity sandstone. A significant resistivity anomaly occurs between 420 m and 920 m along the profile (shaded area). An anomalous low-resistivity body appears at a depth of about 110 m and below, with values between 1 and 18 Ω·m. This anomaly can be detailed into two distinct zones: the low-resistivity body at 560–600 m exhibits slightly higher resistivity than the body to its right, which is attributed to the likelihood that this section is filled with a mixture of water and rock (caved material); the low-resistivity anomaly at 760–

900 m is inferred to be a water-filled coal mine goaf.

In the inversion profile of Survey Line No. 3 (Figure 4c), the surface layer is low-resistivity overburden (~10 m thick), overlying high-resistivity sandstone. A significant anomaly is found between 520 m and 1060 m along the profile (shaded area). The low-resistivity body appears at a depth of about 120 m and below, with values of 1–18 Ω·m. Similar to Line No. 2, this can be divided into two zones: the body at 540–580 m has slightly higher resistivity than the one to its right, suggesting a mixture of water and rock filling; the anomaly at 780–1020 m is inferred to be a water-filled coal mine goaf.

In the inversion profile of Survey Line No. 4 (Figure 4d), the surface layer is inferred as the overburden (~10 m thick) with low resistivity, overlying high-resistivity sandstone. A significant resistivity anomaly occurs between 180 m and 450 m along the profile (shaded area). An anomalous low-resistivity body is observed at a depth of approximately 140 m and below, with resistivity values ranging from 1 to 18 Ω·m. It is inferred that this anomaly represents a coal mine goaf filled with groundwater.

5. Conclusions

1) Through forward and inverse modeling of the goaf numerical models, the geoelectrical response characteristics of different filling materials in the goaf were summarized and analyzed. This provides a theoretical basis for the detection and analysis of goaf characteristics.

2) In conjunction with the engineering case study, low-resistivity anomalies were identified in the inversion profiles of all four survey lines. The burial depth of the goaf roof and its approximate spatial distribution were preliminarily inferred. Verification using subsequent geological survey data confirmed that the actual conditions were largely consistent with the inferred locations of the anomalies.

3) Due to the inherent limitations and local non-uniqueness of the high-density resistivity method, it is recommended to employ a combination of multiple exploration methods in practical work. This integrated approach ensures that the geological interpretation results are closer to the actual subsurface conditions.

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