Study on the application of comprehensive geophysical prospecting technology for the goaf detection in coal mine

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Abstract. Aiming at the problem that drilling technology is time-consuming and challenging to be used to explore the goaf of a coal mine, a comprehensive geophysical exploration technology is proposed to quickly delineate the goaf. Through the layout of the TEM survey line to survey the development characteristics of goaf in the work area, and then with the help of magnetotelluric sounding method to verify the goaf delineated by TEM, the abnormal area of apparent resistivity obtained by the two methods were basically consistent. And it is consistent with the mining data of coal face. Based on the comprehensive geophysical exploration technology, the problem of multiple solutions of a single geophysical exploration method is solved, which provides technical support for the exploration of goaf in similar projects in this area in the future.

1. Introduction
With rapid urbanization in China, industrial and civil construction land in urban construction often take up the original coal mine goaf. However, due to resource integration, some coal mines have problems such as serious lack of goaf data, unclear boundary distribution, ambiguous goaf water area, and water volume, which seriously threaten the safety of ground engineering. Therefore, find out the distribution characteristics and edge of goaf become an essential basis for auxiliary ground engineering safety [3].

The commonly used exploration techniques of goaf are mainly divided into geophysical exploration and drilling. The control range of drilling is small, the engineering quantity is enormous, and it has certain blindness. At the same time, geophysical exploration can avoid blind drilling, reduce cost, and make drilling more targeted. However, due to the complexity of geological conditions and the multi-solution of geophysical technology in goaf, the geophysical exploration of goaf needs further study.

A single geophysical method often has multiple solutions, which can not accurately determine the distribution characteristics of goaf, while a variety of comprehensive exploration methods can confirm and complement each other, making the final interpretation more accurate [9]. Therefore, to accurately detect the distribution characteristics of the goaf, this paper uses the integrated geophysical exploration technology, which combines the transient electromagnetic method and the magnetotelluric sounding method to analyze the geoelectric response characteristics of the goaf comprehensively. The exploration results of all kinds of ways can be mutually verified, which provides a successful experience for similar geological problems in this area.
2. Comprehensive geophysical technology

2.1. **Working principle of TEM**

The transient electromagnetic method has many advantages, such as accurate positioning, deep detection, and it is not affected by terrain fluctuation, etc. It is widely used in the detection of hidden dangers of embankments [13], water-rich exploration of coal seams, and faults [3-4,10], and goaf detection [5], etc.

The core of TEM is the electromagnetic induction effect of eddy current produced by the underground conductive medium excited by the static magnetic field [6]. Its working principle is that the transmitter sends a periodic square wave current to the rectangular coil lay on the ground. When the current is suddenly interrupted, a step pulse source is formed. The pulse source excites the induced vortex flow field in the underground half-space to prevent the attenuation of the primary domain. When the pulse current is turned off, the eddy current concentrates on the surface near the rectangular coil and then diffuses into the underground half-space. In any later period after cutting off the current, the induced current is in the shape of a multi-layer shell, observing the secondary magnetic field induced by the secondary emission source formed by these current rings on the earth's surface. According to the characteristics of the secondary field attenuation, and through inversion and imaging the electrical structure of the underground medium can be obtained, and the electrical property, scale, and occurrence of the subsurface geological body can be judged. Then the conclusion can be made combined with the comprehensive analysis of geological data to determine the distribution scale and characteristics of goaf [2,7].

During the data interpretation, the induced electromotive force collected by the receiving wireframe is visualized and numerically processed by professional software. Based on the principle of magnetic moment equivalence, the formula of the transient field at the center point of the multi-turn square loop is deduced by TEM as follows [6].

\[
h_z^C(t) = \frac{\sqrt{\pi}NI}{4a} (erf(\theta r) - \frac{2}{\sqrt{\pi}} \theta r e^{-\theta^2 r^2})
\]  

(1)

Assume the equivalent area of the receiving loop is S, and taking the derivative of formula (1) concerning time, the value of induced electromotive force \( V_z^C(t) \) at the center point of the square loop of multiple turns is:

\[
V_z^C(t) = \frac{\pi NIS\rho}{2a^3} (\theta r)^5 e^{-(\theta r)^2}
\]  

(2)

From the expression of θ in formula (1) and (2), the apparent resistivity of the whole space can be deduced:

\[
\rho = \frac{\mu}{4\pi^3 a^2}
\]  

(3)

θ can be solved by (1) and (2) using methods such as translation algorithm, inverse spline interpolation algorithm, and binary search algorithm.

2.2. **Working principle of magnetotelluric sounding**

Magnetotelluric sounding mainly uses the natural alternating electromagnetic field as a field source to study the earth's electrical structure. Due to the skin effect of the electromagnetic field, the downward propagation depth of electromagnetic signals with different frequencies is different. When the electromagnetic field is harmonic, the skin depth and wavelength are directly proportional to the resistivity of the rock and inversely proportional to the frequency of the electromagnetic field [8]. With the decrease of electromagnetic frequency, the penetration depth of the electromagnetic field gradually increases, that is, the detection depth gradually deepens. The penetration depth formulas of different electromagnetic fields are as follows [1,11-12].

\[
H = 503\sqrt{\rho_\infty / f}
\]  

(4)
In formula (4), \( H \) is penetration depth (m), \( \rho_s \) is resistivity (\( \Omega \cdot \text{m} \)), \( f \) is the frequency (Hz).

By using electromagnetic instruments on the earth's surface, the electromagnetic signals of natural sources with different frequencies are recorded, and the information obtained can reflect the knowledge of resistivity distribution in different depths of the earth's internal medium [11-12]. By analyzing the resistivity difference between the gob and the surrounding ordinary rock, the distribution characteristics of the coal mining area are defined.

2.3. Geophysical characteristics of goaf in the coal mine

In theory, the resistivity of dry rock is relatively large, but in fact, the pores and fractures of rock always contain water, and with the increase of humidity or saturation of rock, the resistivity drops sharply. The resistivity of different rocks with the same water content is also different because of the different salinity of the water. Therefore, the resistivity of the rock does not depend on the resistivity of the dry rock itself, but mainly depends on the saturation and water mineralization of the rock. Generally speaking, the resistivity of water-bearing fault, rock fracture, and goaf are much less than that of surrounding rocks without water. It is the physical basis for evaluating the water yield of goaf, fault, and aquifer by the electromagnetic method.

Electromagnetic exploration mainly collects electrical characteristic data of the underground medium. Under normal circumstances, the apparent resistivity of coal-measure strata is a middle and high resistivity reaction. Still, its resistivity will change when the coal seam is mined, and the stress state changes. When the goaf is filled with water, its apparent resistivity is reduced. That is to say, the problem of exploring the distribution characteristics of goaf can be transformed into the challenge of finding the abnormal distribution of low resistance in the formation. According to the characteristics of regional electricity, the detection area with TEM apparent resistivity less than 40 \( \Omega \cdot \text{m} \) in the detection area can be divided into goaf.

3. Introduction of engineering examples

3.1. Location and Geological

Hebei Huaxin Special Steel Co., Ltd. integrated into the park reduction, and the upgrading project is located in Dashe Town, Fengfeng District, Handan City. The plan covers an area of about 1475 m in length and 728 m in width.

This area belongs to the southeast of Dashe mine (the former Xuecun mine) in Fengfeng District is a goaf of the coal mine. The coal mining depth is about 200 ~ 450 m below the ground, mainly mining the 2# and 4# coal seams.

In this area, there are only bedrock outcrops in gullies, and the strata are Ordovician middle series, Carboniferous central series and upper series, Permian upper series and lower series, and quaternary system from bottom to top. The coal-bearing strata are Benxi Formation, Taiyuan Formation, and Shanxi formation of Permian in the Carboniferous system, with a total thickness of the bottom coal measures is 185~203 m and an average thickness of 200 m.

2# coal is the thickest layer in the top part of the minable coal seam, with a thickness of 2.3~7.8 m and an average of 5.4 m. The direct proof is deep grey siltstone with a thickness of 4 m~10 m or a very thin fine sandstone mixed with deep grey siltstone. There is no direct roof locally in some parts, and the bottom plate is dark grey siltstone with a thickness of 12 m. The indirect roof is a dark gray tuff sandstone with a thickness of 0~20 m and a grayish-white quartz feldspar sandstone, in some parts, there is a partial pseudo-roof about 0.5 m thick. This exploration is mainly aimed at the goaf formed by 2# coal seams.

3.2. The layout of geophysical survey lines

According to the characteristics of topography, stratum distribution, and target layer depth in the exploration area, the TEM method is mainly used for geophysical exploration in the exploration area. A total of 13 transient electromagnetic survey lines, numbered TEM1~TEM13, are arranged. The grid of
survey lines is 60 m (line spacing) × 20 m (point spacing). It is used to find out the development scale of goaf, delineate the boundary of goaf.

At the same time, two lines (MT1~MT2) of the MT method are arranged, which are mainly used to verify the detection results of the TEM method, optimize the interpretation results of the TEM method, and reduce the multiplicity of geophysical exploration results. The layout diagram of the survey line is shown in Fig.1.

![Figure 1. Layout of survey line in comprehensive geophysical technology](image)

4. Goaf detection

4.1. Results of TEM detection

Since the depth of the target layer is relatively deep, about 450 m, the detection depth of TEM is increased by increasing the emission current and reducing the emission frequency. Before the formal construction, select the area with less human interference in the survey area for test work, so as to check the stability of the instrument, determine the number of turns of transmitting, receiving wireframe, transmitting frequency, and select the construction parameters that can meet the requirements of completing geological task, etc. Through the test, the exploration depth can be reached, and the effect is the best when the emission loop edge is 5 m, and the emission current is 100 A.

This project uses CUGTEM-8 transient electromagnetic instrument for resource exploration. Both the transmitting and receiving coils are square with a side length of 5 m, in which the number of turns of the transmitting coil is 2, and the number of turns of the receiving coil is 32. Power supply current range is 100 A, power supply pulse width is 10 ms. After the inversion of transient electromagnetic data, a total of 13 apparent resistivity profiles were obtained. Due to the limitation of space, the most typical sections Line TEM7 and Line TEM12 are selected to be described in this paper. The orientation of the part is 42.5 degrees, with the northwest-southeast direction.

As shown in Fig. 2(a), the cold color represents low resistivity, and the warm color represents high resistivity. It can be seen from the figure that there is a relatively low resistivity body at the depth of 0~50 m, which is mainly caused by the clay layer covered by the quaternary system on the surface. The line about 320 ~ 500 m in horizontal direction and vertical direction of about 450 m, about 650 m in horizontal direction and vertical direction is about 350~400 m, at the level of 800~1100 m and the vertical direction about 350~400 m shows relatively low resistance reaction. The resistivity is between 20-40 Ω·m. It is speculated that there are cavities in the coal mine after mining. It is speculated that there is a cavity in the coal mine after mining. With the accumulation of time, the roof and floor are broken, which leads to the hydraulic connection between the strata. The water slowly penetrates into the cavity. In addition, the carbon component contained in the coal mine has good conductor characteristics, so it shows a low resistivity resistance reaction, which is judged as an abnormality of the goaf. The abnormality number of the goaf is Y1~Y3.
As shown in Fig. 2 (b), it can be seen from the figure that there are totally four low resistance abnormal areas Y1 ~ Y4 in the survey line (circled with red solid line in the figure), the resistivity is between 20 ~ 40 Ω·m, so it is speculated that the survey line is an abnormal goaf with weak water yield.

4.2. Results of magnetotelluric sounding

There are many factors causing low formation resistivity. In order to verify that the low resistivity detected by TEM is indeed the reaction of water filling in goaf, magnetotelluric sounding method is adopted to verify the transient electromagnetic results. Two magnetotelluric sounding lines are arranged at line TEM7 and line tem12, and two apparent resistivity profiles 2 (c) and 2 (d) are obtained.

As shown in Fig. 2(c) and 2(d), there are intermittent and incoherent beaded low-resistance bodies between 100~1100 m in profile and 250~400 m in depth. These abnormal areas of low resistivity bodies may be caused by water fillings and carbon components in the goaf. The resistivity anomalies detected by this method are all low resistivity anomalies, and they are basically consistent with the anomalies delineated by TEM in horizontal position and vertical depth, which shows that the goafs delineated by the two methods is accurate and reliable.

![Figure 2](image)

**Figure 2.** Comparison of TEM and magnetotelluric sounding results.

4.3. Plane distribution law of goaf

In this data processing, four planar graphs with depths of 400 m, 350 m, 300 m and 250 m are made according to the profile of the apparent resistivity of each survey line, so as to show the plane distribution range of goaf more intuitively.

As shown in Fig. 3, there are 6 corresponding abnormal areas of low resistance in 400 m, 350 m and 300 m depth, numbered as LR1~LR6. By analyzing its characteristics, it can be found that the abnormal area of apparent resistivity is in the middle low resistance reaction, with resistivity between 20-80 Ω·m. It is speculated that it is an abnormal area of goaf with weak water content. The development scale of goaf becomes smaller with the shallowness of depth. When the depth is 250 m, there is no obvious abnormal area of apparent resistivity, indicating that the depth of 250 m is outside the influence range of coal mining.

According to the low resistivity abnormal area delineated by apparent resistivity on the plane, its location and shape are basically consistent with the information of the coal face collected by geology, which shows that it is feasible to detect the goaf in this area by using transient electromagnetic method.
Figure 3. TEM apparent resistivity plan. (a) apparent resistivity plan of TEM at 400 m depth; (b) apparent resistivity plan of TEM at 350 m depth; (c) apparent resistivity plan of TEM at 300 m depth; (d) apparent resistivity plan of TEM at 250 m depth.

5. Conclusion
The comprehensive geophysical exploration method combining TEM and magnetotelluric sounding is an important technical means to explore the goaf of coal mine. Comprehensive analysis of the response sensitivity of the two methods to different physical quantities of underground media can eliminate the interference and solve the shortcomings of multiple solutions of a single geophysical method, so as to accurately delineate the distribution characteristics and plane distribution position of goaf.

Limited by the electromagnetic method itself, its resolution of the shallow anomalies is low. In the later work, we should strengthen the research on reducing the blind area depth of electromagnetic method to avoid the undetermined shallow anomalies.

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