Research and application of AMT in tunnel hidden goaf under complex conditions

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Abstract. In order to detect the distribution, development scale and shape of mining area in tunnel hidden coal measure strata, and provide intuitive and reliable geological basis for later design and construction, geological mapping combined with audio frequency magnetotelluric method was used for exploration. In this paper, firstly, the characteristics of tunnel hidden goaf and the basic principle of audio frequency magnetotelluric (AMT) method are briefly described; secondly, the key technologies of scientific acquisition and data processing flow of the method are analyzed; secondly, the geological characteristics of goaf under different conditions are analyzed, and the geological models are established for forward modeling; finally, the method is applied in yuchanshan tunnel of Ronglu expressway The results of electromagnetic imaging directly and accurately reflect the distribution position and scale of goaf, and provide reliable basic data for later design. Through theoretical analysis and practical application, the results show that audio frequency magnetotelluric method combined with geological mapping can play an important role in the investigation of tunnel hidden goaf, and can directly reflect the location, shape and other basic elements of goaf, providing more reliable basic data for subsequent investigation and design.

1. Introduction
Goaf, especially the old goaf, is a very complex geological body, which has the characteristics of concealment, complexity and destructiveness. Goaf Collapse causes a series of environmental geotechnical engineering problems, such as ground subsidence, ground water accumulation, road damage, house collapse, bridge instability, etc., which has a great destructive effect on Highway construction.

The principle of route selection of Highway Engineering in goaf is mainly to avoid, and a certain width of safety pillar should be reserved through the non mined area to ensure the operation safety of highway. However, in the areas where mineral resources are widely developed, the influence of goaf cannot be avoided in highway route selection. The
determination of goaf boundary, influence range and stability will affect the formulation of goaf treatment technical scheme, and then affect the selection, optimization and engineering investment estimation of the whole highway scheme. Therefore, the accurate and efficient investigation of goaf is of great significance in the construction of the whole expressway.

Drilling and geophysical exploration techniques are mainly used in goaf exploration of old kilns at home and abroad, supplemented by mining investigation, deformation observation, hydrological test and other means. The drilling method is more intuitive, but it often needs to arrange dense boreholes. Because of the irregularity of small mine mining, it is difficult to accurately explore the scope of goaf by single drilling, and the efficiency is low and the economic investment is large. Therefore, if the geophysical method is used for measurement, and on this basis, a small number of boreholes are properly arranged for verification, the effect of getting twice the result with half the effort will be achieved. Therefore, geophysical method has been widely used because of its advantages of fast, economic and wide detection range.

At present, the geophysical methods for Detecting Goaf mainly include high-density resistivity method, ground penetrating radar, electromagnetic method, seismic method, Rayleigh wave method, inter hole radio wave perspective and so on. Different geophysical methods have their own advantages and disadvantages. For example, conventional electrical method has better detection effect on water cut in goaf, but the detection depth and accuracy are limited; Seismic method can detect deep targets, but the cost is high and the exploration period is long; Ground penetrating radar (GPR) has very high resolution for targets with very shallow depth, but its detection depth is limited. Generally speaking, the geophysical exploration work of goaf, especially in the middle and deep goaf with buried depth more than 100m, has limited optional methods. The audio magnetotelluric method (AMT) is widely used and the technology is relatively mature.

2. Basic principle and main technical characteristics of AMT method

2.1. Fundamentals

In engineering investigation, the equatorial dipole mode is generally selected for scalar acquisition, and the underground power is supplied by the grounding wire arranged in the specified direction. The measuring line is arranged according to the designed observation system, and then the horizontal component electric field ex parallel to the field source and the horizontal component magnetic field hy orthogonal to the field source are collected. According to the collected values of ex and hy, the apparent resistivity $\rho_s$ is calculated by formula (1), and the impedance phase $\varphi_z$ is obtained by formula (2). Finally, the corresponding inversion method is adopted to obtain the apparent resistivity section, and the results are analyzed combined with other data.

$$\rho_s = \frac{1}{\omega \mu} \left( \frac{E_x}{H_y} \right)^2$$

(1)

Impedance Phase:

$$\varphi_z = \varphi_{E_x} - \varphi_{H_y}$$

(2)
2.2. Workflow

2.2.1. data acquisition. In order to ensure the acquisition accuracy, tensor acquisition is used, that is, four electrodes are shared, each electrode forms an electric dipole, and X and Y magnetic rods are arranged vertically with the corresponding electric dipole. The magnetic rod should be as far away from wires, people and houses as possible.

The preamplifier should be placed in the target position, that is, the center of two electric dipoles. The preamplifier should be grounded at least 10m away from the magnetic bar. The specific arrangement is shown in Figure 1.

![Figure 1. Layout of field work collection](image1)

2.2.2. data processing. Data processing is the key link of AMT detection, which is closely related to the accuracy of subsequent data interpretation. The processing steps are as follows: first, preprocess the time series data collected on site, and obtain the virtual and real components and phase data of electric field and magnetic field through mathematical transformation. Then, one-dimensional inversion data are preprocessed and forward model is established to understand the distribution of underground medium resistivity. On this basis, the terrain correction, tensor impedance rotation and other fine processing are carried out, and the appropriate method is selected for 2D inversion. Finally, combined with the geological data and the established forward model, the constraints are added to modify the inversion and gradually approach the real underground geological situation.

![Figure 2. Data processing chart](image2)

3. Geological characteristics and forward modeling of goaf
According to the different filling characteristics of unfavorable geological bodies, a theoretical model for the simulation of concealed unfavorable geological bodies is established. In order to reduce the influence of terrain on the resolution of the model, a horizontal terrain model with a width and height of 400m is established. The cavities of unfavorable geological bodies are represented by regular circles with a diameter of 50m. The resistivity value of the background area is set to 500 \( \Omega \cdot m \). The resistivity value of cavity in poor geological body with mud filling and rich water is 50 \( \Omega \cdot m \). The resistivity value of cavity without filling or half filling is 2000 \( \Omega \cdot m \). In order to study the theoretical detection depth of the audio frequency magnetotelluric method for detecting the hidden unfavorable geological body with a diameter of 50m, the underground buried depth of the cavity is designed to be 300m, as shown in Figure 3.

![Figure 3. theoretical test model of concealed unfavorable geological body](image)

The purpose of numerical simulation is to establish the resolution of audio magnetotelluric data to the model under a certain buried depth by establishing different forms (with or without filling) of a certain scale of concealed unfavorable geological body. The forward bandwidth of the theoretical model is 10K ~ 10Hz, and the forward results of the model are shown in Figure 4.

It can be seen from the forward modeling results that under the theoretical conditions, the audio magnetotelluric sounding method has a certain resolution ability for the regular abnormal body with a diameter of 50m and a buried depth of about 300m, which also provides a theoretical support for the next interpretation work.
4. Application example

4.1. Overview of the study area

The research area is a control project Yuchan mountain tunnel from Rongchang (Yuchuan boundary) to Luzhou section of Guang'an Luzhou expressway of G8515 line, and passes through the coal mine area with two wings of Gufo mountain anticline distributed in the north-east direction, and there is coal seam goaf area, which has a great control effect on the selection and design of the route scheme. The formation lithology is mainly coal bearing deposits of Xujiahe Formation in the upper Triassic system, mainly composed of gray quartz sandstone, feldspathic quartz sandstone, thick layer sandstone, thin layer sandstone and siltstone, with mudstone, coal seam and lenticular siderite layer. It is of great significance to find out the distribution of the hidden goaf for the route selection and the follow-up work.

4.2. AMT survey line layout and field physical parameters

In order to detect the distribution of hidden goaf in the tunnel, AMT is arranged along the yuchanshan tunnel. EH-4 magnetotelluric instrument is used. The distance between measuring points is mainly 30m, and some key areas are densified to 20m.

In order to understand the electrical parameters of the work area, the electrical parameters were measured. Through data analysis, it can be seen that the resistivity of surface block and gravel soil is generally less than 150, relatively complete rock mass \( \rho_s > 1500 \ \Omega \cdot m \), broken, water bearing or karst strongly developed rock mass presents low resistivity abnormal response, under normal conditions \( \rho_s < 800 \ \Omega \cdot m \), there is a certain difference in resistivity between broken and water bearing rock mass and intact rock mass; The fault fracture zone is relatively broken and contains water, and it is a low resistivity zonal extension in high resistivity background, which has the physical premise of AMT exploration. According to the empirical statistics and analysis of geophysical inversion results in this area, the apparent resistivity values of tunnel rock mass are obtained (Table and table 2).

| Stratigraphic lithology                          | Kanya apparent resistivity \( \rho_s (\Omega \cdot m) \) |
|-------------------------------------------------|------------------------------------------------------|
| Extremely broken, goaf or water rich rock mass  | \( \leq 200 \)                                       |
| Broken or water bearing rock mass               | 200 ~ 800                                            |
| Relatively broken rock mass                     | 800 ~ 1500                                           |
| Relatively complete rock mass                   | \( \geq 1500 \)                                      |
4.3. Achievements and explanations

Figure 5. Geophysical exploration results of Yuchanshan tunnel

The inversion results (Fig. 5) show that: the resistivity contour lines of three sections of tunnels (BK144+015 ~ +290, BK144+515 ~ +730, BK146+040 ~ +280) are in the form of low resistance depression. It is speculated that the rock mass in this section is broken and rich in water. According to the coal seam position indicated in the special report of goaf, combined with the actual resistivity form, the possibility of Goaf Collapse Area in these three sections of tunnels is relatively large, and it has a great impact on the tunnel body. There may be Goaf Collapse Area under the BK145+000 tunnel body, which has great damage to the tunnel rock mass structure, and it is difficult to deal with later.

The electromagnetic results have obvious effect on the response of goaf and coal measure strata in this tunnel. It also verifies that the electromagnetic exploration after the key technology processing can be applied to the detection of tunnel goaf through appropriate modeling analysis.

| Line position | Main unfavorable geological conditions of tunnel body | Influence degree | The difficulty of treatment |
|---------------|---------------------------------------------------|-----------------|----------------------------|
|               | Fault fracture zone goaf                          | Fault           | Fault                     |
|               |                                                    | fracture zone   | fracture goaf zone        |
| Line B        | 2 places                                          | 4 places        | very                      |
|               |                                                    |                 | very great                |
|               |                                                    |                 | difficult                 |

5. Epilogue

In this paper, AMT imaging technology is used in the investigation of hidden goaf in highway tunnel, and its method principle, main characteristics, key technology and other aspects are described.

According to the characteristics of tunnel hidden goaf, a suitable model is established and numerical simulation is carried out. The results show that AMT method has a good response to the hidden goaf with large buried depth.
Through the application of engineering examples, it shows that AMT method can be accurate and clear imaging in the tunnel hidden goaf, and has obvious reaction to the fault and other adverse geology, which proves the effectiveness of this method in highway tunnel exploration, and can also be popularized and applied in related fields, with wide practical value.

AMT method is greatly affected by current. In the process of exploration, the magnetic rod should be far away from the high voltage line, otherwise it will produce abnormal interference and affect the interpretation results. The next step focuses on the suppression and shielding measures of high voltage lines.

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