Analysis of response characteristics of comprehensive geophysical prospecting technology in concealed water-bearing structures

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Abstract. The mine transient electromagnetic method and the mine direct current method were used to detect the abundant water at 1,144 m ahead of the track roadway on the 9101 working face in the Chaoyang Coal Mine. Low-resistance abnormal areas indicated by both methods were analyzed comprehensively for early warning of water hazards. The results showed that two low-resistance abnormal areas were indicated by the mine transient electromagnetic method and the existence of a low-resistance abnormal area was indicated by the direct current method. Both methods showed the existence of a low-resistance abnormal area ahead, delineating possible illegal mining areas of old kilns ahead, which were verified by drilling. The methods can indicate the direction for drilling. The case shows that the combination of different geophysical prospecting methods can eliminate their limitations and that comprehensive detection can reduce omissions, which has a good guiding significance for safe mine excavation.

1. Introduction
Coal plays a dominant role in the present stage of energy consumption in China [1]. With the gradual increase of coal prices, efforts have been made to increase the production capacity and accelerate roadway excavation in many coal mines. However, coal mining accidents have occurred frequently. According to statistics, the most frequent accident is the mine water-bursting disaster occurring in the excavation stage [2] mostly due to the failure in advanced detection in the excavation process, which leads to unknown water sources bursting into the mine [3]. Identifying goaf water is the top priority [4]. Great progress has been made in mine geophysical prospecting in recent years under the policy of detection in the case of any doubt or excavation [5]. Many Chinese experts and scholars have carried out relevant research on mine transient electromagnetic [6-8] and direct current methods [9-11] and achieved good detection results.
Different geophysical prospecting methods have their respective advantages and limitations. For example, the mine direct current method based on the point source principle can obtain the resistance value of equipotential surfaces, but it is difficult to distinguish between positive signals and non-positive signals based on the detection results. The transient electromagnetic method is sensitive to the reaction of low resistance objects and has strong direction guidance, but it has higher requirements for the site. We can realize underground fine detection only by making up for the deficiency through comprehensive geophysical prospecting.

2. Comprehensive Mine Detection Method

2.1. Mine Transient Electromagnetic Method

The mine transient electromagnetic method is a detection method based on the electromagnetic induction principle. Generally, ungrounded loops are used to transmit the primary pulsed electromagnetic field to the target layer, and ungrounded loop frames are used to receive the secondary induced eddy current field in the target layer during intermission [12]. The electrical distribution of the target layer can be identified through observation of changes of the secondary induced eddy current field in the target layer.

Figure 1 shows the data analysis method, in which the “smoke ring effect” is used for technical interpretation [13]. The intensity of the transient electromagnetic field formed by the secondary field signal excited by the primary pulse signal can be expressed by the following formula:

$$H_x^*(t) = \frac{P_m}{2 \pi R^3} \left[ \phi(u) - \frac{2}{\sqrt{\pi u e}} \right]$$

Where, $P_m$ is the dipole moment, Aꞏm$^2$; $R$ is the distance from the measuring point to the dipole source, m.

Overlapping loop or central loop devices are generally used for ungrounded loop frames to collect secondary field signals in the construction process with the mine transient electromagnetic method. The side length of loop frames is usually set to about 2m due to the small space in the roadway. The loops are distributed in a fan shape at 180° during detection and collect signals in turn at an interval of 15° from left to right [14], as shown in Figure 2.
2.2. Mine Direct Current Method
The direct current method is a detection method based on observation of the electrical difference in the distribution range of the stratum current field through artificial power supply to rock strata. The potential on any spherical surface with equal radius is equal according to the principle of the electric field of a spherical shell. No matter whether the anomaly is located ahead of the roadway head or in other directions, it will cause the change of the equipotential surface and apparent resistivity. The detection principle is shown in Figure 3. A is the source electrode, B is infinity, and M and N are receiving electrodes. The change of surrounding rocks can be identified through observation of the change law of the current field.

In the direct current method, a stable field is generated with the point source. The formulas are expressed as [15-16]:

\[ \mathbf{j} = \frac{\mathbf{E}}{\rho} ; \ \text{div} \ \mathbf{j} = 0 ; \ \mathbf{E} = -\nabla U \]
Where, $E$ is the electric field intensity; $\rho$ is the resistivity and $j$ is the current density. According to above formulas,

$$\text{div} \left( \frac{1}{\rho} \text{grad} U \right) = 0$$

In a homogeneous medium, $\rho$ is a constant. Therefore, $\text{div} \text{grad} U = \nabla^2 U = 0$

Three-level devices are generally used in the construction process with the mine transient electromagnetic method, with the distance between the source electrode A and the head being 14 m and the interval among the three source electrodes A being 4 m. The spacing between the receiving electrodes M and N is 4 m. Mobile measurements are taken for 30 times, and the detection distance is about 100 m.

3. Example Applications

3.1. Geology

The primary mineable coal bed of the Chaoyang Coal Mine in Jincheng, Shanxi is 9#, where there are many illegal mining areas of old kilns, posing safety hazards to roadway excavation and the layout of the working face. For effective understanding of ambient conditions, comprehensive geophysical prospecting was carried out at 1,144 m ahead of the track roadway on the 9101 working face. The roof lithology of the roadway is medium-fine sandstone and silty mudstone, and the floor lithology is sandy mudstone and mudstone. The coal bed is relatively stable with an average coal thickness of 2 m.

3.2. Detection with Mine Transient Electromagnetic Method

Figure 4 shows the fan-shaped pseudo-section of apparent resistivity in advanced detection. According to the figure, there are two areas with relatively low apparent resistivity, and the boundary line of apparent resistivity in low-resistance abnormal areas is $20 \, \Omega \cdot m$. The low resistance area on the left side of the roadway is located in the section between detection angles $30^\circ$ and $90^\circ$, with a depth of about $50 \, m$. It is presumed to be the water accumulation area of old kilns with illegal mining. The low resistance area on the right side of the roadway is located in the section between detection angles $0^\circ$ and $80^\circ$, with a depth of about $40 \, m$. It is presumed to be the water accumulation area of old kilns with illegal mining.

3.3. Detection with Mine Direct Current Method

Figure 5 shows the advanced detection with the mine direct current method. According to the figure, there is a conspicuous abnormal area with relatively low resistance at 52 m–60 m ahead of the head.
The apparent resistivity of the abnormal area is less than 50 Ω·m. According to analysis, there is a water accumulation area of old kilns with illegal mining in the section.

3.4. Verification
The mining party set advanced boreholes according to the comprehensive geophysical prospecting results. It has been verified that the borehole set at an azimuth angle of 90° and with a depth of about 45m had water flow at a rate of about 10m³/h; the borehole set perpendicularly to the right side of the roadway, at an azimuth angle of 180° and at 65m had water flow at a rate of about 10m³/h. The results of drilling verification are basically consistent with the analysis of comprehensive geophysical prospecting results.

4. Conclusions
Both the mine transient electromagnetic method and the mine direct current method for advanced detection can detect water hazards ahead, if any, facilitating effective pre-warning and advanced prediction of water hazards.

The transient electromagnetic method is obviously superior to direct current method in terms of accuracy. When there are multiple water-rich areas around, the former can indicate low-resistance anomalies in different directions at the same time, while the latter only shows anomalies in some section. Blindness exists in the guidance of the direct current method for drilling, while the transient electromagnetic method can reduce drilling workload when providing guidance on drilling.

Comprehensive detection can realize comprehensive analysis, comparison and verification of multiple parameters, eliminate the multiplicity of solution, improve the accuracy of geophysical prospecting, reduce omission of abnormal areas and eliminate the limitations of a single geophysical prospecting method.

The drilling verification has demonstrated that although advanced detection can predict the water-rich area ahead, it can only be qualitative, but cannot identify the type of water hazards and the amount of water precisely which need to reply on subsequent geological work.

Acknowledgements
The author gratefully acknowledges the funding by the National Natural Science Foundation of China (51704162, 51804162).

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