Application of Surface-To-Roadway TEM for detecting deep aquifer in Coal Field, an example from North China

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Abstract

Transient electromagnetic methods (TEM) are effective tools for the hydrogeological investigations of coal mines. However, the traditional ground-based and underground-based TEMs typically fail to detect the deeply buried water-bearing bodies in the majority of coal mines in northern China, where the quaternary overburden is generally thick and many aquifers exist. In the present study, a surface-to-roadway TEM was proposed which utilized grounded-wire sources to transmit signals with large moments on the surface, and required receivers which had the ability to record signals with high resolution in underground mining roadways. First of all, the proposed device was introduced. Subsequently, a synthetic model was established based on the existing information of Zhuxianzhuang coal field in Anhui Province, China, along with the analysis of forward and inversion results. Finally, the acquisition and processing of field data were conducted. Both the synthetic and field results demonstrated the feasibility and superiority of the proposed method. The deeply buried aquifers were able to be better characterized by the surface-to-roadway configuration than the ground-based surveys.

Introduction

The water-bearing bodies within coal mines may be caused by underground aquifers, voids, limestone karsts, collapse columns, or water-flowing faults (Dong and Hu, 2007; Gui and Lin, 2016). During open cut and underground mining activities, the presence of water-bearing bodies may potentially lead to unexpected water inrushes and mining fatalities (Moebs and Sames, 1989; Wu, 2014; Polak et al., 2016). Therefore, sound knowledge of any existing water-bearing bodies, including their locations and how far they extend in and around operating mines, is critical for safe coal mining operations.

Electromagnetic methods have been proven to be effective ways for investigating the hydrogeological conditions of coal mines (Danielse et al., 2003; Hatherly, 2013). Among the available electromagnetic methods, transient electromagnetic methods (TEM) are currently the most commonly used method in the field (Kaufman and Keller, 1983; Fitterman and Stewart, 1986; Xue and Yu, 2017). In essence, TEMs are ground-based. That is to say, the transmitters and receivers are both located on the Earth's surface. Ground-based TEMs are widely used in coal fields around the world. In particular, TEMs have been successfully used in the northwestern China, where the coal seams are generally shallowly buried and the surrounding strata are relatively resistive (Xue et al., 2013; Lu et al., 2017; Xue et al., 2018). However, in northern and central China, the buried depths of coal seams tend to be generally large and the overlying conductive Quaternary strata is very thick (Pan et al., 2005; Zheng et al., 2008; Chen et al., 2015). In addition, in some areas of China, it is also important to investigate the water-filled karsts in Ordovician or Carboniferous limestone layers, which are usually buried at great depths (Zhou et al., 2015). In previous investigations, it has been found to be difficult for ground-based TEMs to probe sufficiently deep to identify water-bearing bodies in low-resistivity environments (Spies and Parke, 1984; Yan et al., 2006).

Therefore, in order to address the above-mentioned issues and obtain high resolution for deeply buried small anomalies, fully underground TEMs were developed in China (Yu, 2001; Tan, 2009). These types of
TEMs place both the transmitting and receiving coils underground. For example, they are placed directly on the working faces or under the roofs or above the floors in mining roadways, for the purpose of detecting nearby water-bearing bodies. Due to the fact that the transmitters and receivers are much closer to their targets, the resolution of underground TEMs can be greatly improved (Jiang et al., 2007; Xue et al., 2007; Li et al., 2014; Chang et al., 2016). However, due to the narrowness of mining roadway spaces and the requirements of explosion-proof transmitters, the sizes of the transmitting coils, as well as the transmitting current intensities, are both limited. As a result, the amplitudes of the signals tend to be weak and the detection ranges quite short (no more than 60 m) (Sun et al., 2012; Cheng et al., 2014). Moreover, the diffusion of the transient electromagnetic fields in the full-space containing roadways is more complex when compared to half-space models (Krivochieva and Chouteau, 2002; Jiang et al., 2007; Yu et al., 2017), and there remains a lack of quantitative inversion technology for these types of configurations (Yu et al., 2008; Liu et al., 2014; Yan et al., 2019).

Another potential way to improve the resolution for deep targets is to use surface-to-underground TEMs, in which the transmitters are located on the surface in order to excite strong signals, and the receivers are located underground in order to obtain EM fields with high signal-to-noise ratios (SNR) (Dyck, 1991). The traditional art of this configuration is the surface-to-borehole TEM (Boyd and Wiles, 1984; Bishop et al., 1987). Many previous studies and applications have demonstrated the advantages and potential of deep mineral exploration activities (Eaton and Hohmann, 1984; Eadie, 1987; Irvine, 1987; Lane, 1987; West and Ward, 1988; Augustin et al., 1989; Newman et al., 1989; Zhang and Xiao, 2001). Therefore, based on previous findings, it was possible in this study to place receivers in an underground roadway to form a surface-to-roadway TEM. The frontier research had been completed by Li et al. (2016) and Jiang et al. (2019), in which a surface-to-underground TEM device was developed by deploying a large rectangular loop source on the surface and a receiving coil in the mining roadway. The feasibility and superiority of this configuration when applied to the detection of deeply buried water-bearing bodies were well proven by the aforementioned researchers’ synthetic modeling and field applications. However, the majority of the previous studies and applications regarding surface-to-underground TEMs were based on loop sources, and very little has been published regarding research based on grounded-wire sources (Chen et al., 2017a; Wu et al., 2017; Chen et al., 2019). It is currently known that TEM surveying processes with grounded-wire sources can potentially reach greater depths and higher sensitivity to resistive targets than surveys conducted using loop sources (Spies, 1989; Skokan and Adersen, 1991; Strack, 1992; Poddar, 1996; Chen et al., 2015; Chen et al., 2017b; Levi and Goldman, 2017). In addition, it has been confirmed that long wire sources are more suitable for profile observations than the rectangular loop sources. Therefore, this study considered that it would be very meaningful to propose a surface-to-underground TEM method based on grounded-wire sources at this time.

In this research investigation, a surface-to-roadway TEM was developed using a grounded-wire source. The synthetic and field results from Zhuxianzhuang coal mine in China showed significant improvements in the resolution of the deeply buried water-bearing bodies when compared to traditional ground-based TEM results.
Survey Area

The Zhuxianzhuang Coal Field is located 13 km southeast of Suzhou City in China's Anhui Province. The coal field is covered by the Cenozoic loose strata layers with thicknesses ranging between 246 m and 260 m. The strata which were revealed during previous drilling activities include Ordovician, Carboniferous, Permian, Jurassic, and Quaternary strata, among which the coal bearing strata were determined to be the Carboniferous and Permian. At the current time, the main workable coal seam within the survey area is No. 8 coal seam, with an occurrence depth of approximately 600 m. A diagram of the stratum is shown in Fig. 1.

The Zhuxianzhuang Coal Field aquifers are composed of Cenozoic loose aquifers, Jurassic aquifers, Permian sandstone aquifers, Taiyuan Formation limestone aquifer, and Ordovician limestone aquifers. Among those, the Cenozoic loose aquifers were divided into four aquifers and three aquifuge from top to bottom as follows: The three aquifuge were mainly composed of clay with an average thickness of 80 m. Each were considered to be a regional distribution stable aquifuge, which effectively blocked the vertical hydraulic connections between the upper one, two, and three aquifers and the lower fourth aquifer. Due to the special locations of the Quaternary aquifer, it was the main source of the mine water and the water in the subsidence area. The fifth aquifer (Jurassic) was located roughly parallel to the No. 8 coal seam, and its abundance was determined by the karst development degree. Based on previous research findings, it was considered that the karst in the northeastern section of the coalfield was extremely developed. However, it was uneven, and filled with mud, calcite, gypsum, and other materials. Therefore, due to the uneven distribution of the karst, the water yields of the different sections had varied, and increased with the increasing thicknesses of the conglomerate from south to north. The Permian coal seams were determined to be composed of mudstone, fine sandstone, and sandstone, and characterized with undeveloped fissures. Therefore, the water-bearing capacity was weak, which made it difficult to divide the aquifers. The limestone karst aquifer of the Taiyuan formation was approximately 140 m thick in total, in which the water yield capacity was dependent on the development degrees of the karst fissures. It was found that, according to the pumping data of four holes in the area, the water yield capacities of the shallow outcrops were generally strong, while those of the deeper areas (300 m) was generally weak. That is to say, there was an obvious vertical zoning observed. In addition, due to the high levels of the water tables of the aquifers, parts had been affected by faults, and the aquifer had become thinner. This situation was considered to be a major threat to the mining activities in the No. 10 coal seam. The main strata and aquifers in the survey area are detailed in Table 1.
### Table 1
Formation stratigraphy of the survey area based on drilling data

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Average thickness (m)</th>
<th>Lithology</th>
<th>Aquifer</th>
<th>Water abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>260</td>
<td>Grit, clay, and silt</td>
<td>1 to 4</td>
<td>Good</td>
</tr>
<tr>
<td>J</td>
<td>120</td>
<td>Semi-cemented brecciform sandstone and mudstone</td>
<td>5</td>
<td>Uneven</td>
</tr>
<tr>
<td>P</td>
<td>400</td>
<td>Sandstone, mudstone and coal</td>
<td>6 to 7</td>
<td>Weak</td>
</tr>
<tr>
<td>C</td>
<td>180</td>
<td>Limestone, mudstone, and coal</td>
<td>8</td>
<td>Uneven</td>
</tr>
<tr>
<td>O</td>
<td></td>
<td>Limestone</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

### Surface-to-roadway Tem Configuration

The method which was proposed in this study is illustrated by Fig. 2. A grounded-wire source was placed on the surface and supplied with a bipolar current with a duty cycle of 50%. Receiving sensors were placed in the subsurface roadway in order to record the electromagnetic fields. It was necessary for the transmitter to be located parallel with the roadway as far as possible. The length of the source was generally several hundred meters to 2 km, and the horizontal distance between the source and roadway was suitable within several hundred meters. The sensor were small loops or magnetic probes used for recording magnetic responses (induced voltage) in three directions (x, y, z), or several electrodes were used to receive the electric field signals in the direction along the roadway. The construction of this method was basically similar to that of ground-based devices (Chen et al., 2015), with the exception that the receivers were placed in a subsurface mining roadway.

### Synthetic Modeling

#### Synthetic model

The main purpose of this exploration was to investigate the water yield capacities of the 5th aquifer of the Jurassic and the 8th aquifer of the Carboniferous. Prior to conduct the field measurements, this study first carried out 1D forward simulation and inversion processes. Then, based on the results, the differences between the ground and underground observations were analyzed and the superiority of underground observation was obtained. Firstly, according to the distributions of the strata and aquifers in the survey area (Fig. 1 and Table 1), a synthetic layered model were established as shown in Fig. 3. The resistivity of the two aquifers is $10 \, \Omega \cdot m$ and the thickness is 50 m, the top interface depths are 200 m and 700 m respectively. The roadway depth is 450 m, and their height and resistivity are both ignored in this
study, as shown in Fig. 3a. The length of the source is 1 km, and the length of the survey line is also 1 km, 500 meters away from the source (offset), as shown in Fig. 3b.

1D modeling and inversion

The parameters of 1D forward modeling were as follows: The transmitting current is 1 A, the time window was between 1 ms and 100 ms, including 41 time channels, and only the vertical induced electromotive force (dBz/dt) was calculated. 51 survey points were calculated with interval of 20 m for both surface and roadway survey lines. The forward modeling results of three points (x = 0 m, x = 250 m, x = 500 m) are shown in Fig. 4. It can be seen that when the observation point is located underground (dotted line in Fig. 4), the response of the secondary field rises first and then decreases after reaching a maximum value. The rising part indicates that the maximum value of horizontal underground induced current has not spread to the observation point (Chen et al., 2020). After about 10 ms in this case, the observed responses of underground and surface basically coincide.

Then the 1D Occam's inversion (Constabl et al., 1987) was carried out to the forwarding responses of both surface and roadway cases. The maximum depth of inversion model was set as 1000 m, the thickness of the first layer was 5 m (increasing by 1.05 times), and the number of fitting times was set as 10. It should be noted that due to the oscillation of the early stage of underground observation response, as shown in Fig. 4, only the responses after 0.1 ms for underground conditions were inverted. The inversion results of a selected point (x = 500 m) were shown in Fig. 5. It shows that the inversion results of both cases can reflect the electrical structure of the synthetic model, reveal the both low-resistivity aquifers, especially for the shallow one, where the inversion depth and resistivity are basically the same. However, when the depth is greater than 300 m, the resistivity of the two results are gradually different, the roadway-based one is closer to the real value. This difference can be seen more clearly in the profile results as shown in Fig. 6.

Data Acquisition

This study's underground data acquisition was carried out in an abandoned horizontal mining roadway with a buried depth of approximately 400 m and a NE strike. As shown in Fig. 5a, the length of the entire survey line measured 500 m with a point distance of 20 m, and only the vertical induced voltage was observed by a receiving probe with an effective receiving area of 4000 m². As shown in Fig. 7b, the grounded-wire source was arranged along a nearby north-south road on the ground, with a length of 750 m. The current was 16 A, the basic frequency was 2.5 Hz, and the transmitting and receiving instrument was V8 system from the Phoenix Company. In addition, another ground-based survey line was set up at the projection of the roadway on the surface, which was the same length (500 m) and had the point distance (20 m). The distances between the two ends to the source were 370 m and 240 m, respectively, as illustrated in Fig. 7b. In addition to different observation positions, the above-mentioned parameters used at the ground and roadway sites were consistent. This study first collected the data in the mining roadway and then on the ground. However, it should be noted that in the underground observations, the
receiver was required to start on the ground, and then its GPS was locked before it was transported to the mining roadway.

Figure 8 details several of the original observational data results from the measuring points. As can be concluded from the figure, the signals with high signal-to-noise ratios had reached approximately 40 ms, which indicated that only weak noise had exited in the survey area, and that the interference levels of the ground and underground data were basically the same. Therefore, based on the results of previous investigations, it was assumed that the noise had mainly originated from the surface transmission lines and underground coal mining activities. However, the impacts were relatively low due to the large distances between the sources and the measuring points. This study still considered the noise influence in the inversion process, even though there was no need to adopt any filtering or denoising methods for the original data. Furthermore, the data from the mining roadway had displayed the same trends as the numerical simulation results.

Data Interpretation

In the current investigation, 1D Occam’s inversion was carried out for all of the observed data in the mining roadway and on the surface using the same inversion parameters. The inversion results confirmed that all of the observational data had fit well, among which the fitting residual of the ground-based data was between 1.29% and 9.47%, and that of roadway data was between 1.96% and 10.06%. Subsequently, the inversion results of six measuring points with 100 m intervals were taken as this study’s examples, as shown in Fig. 9.

It was obvious that the electrical structures of the shallow stratum within the 400 m range reflected by the ground-based and roadway-based inversion results were basically consistent. For example, both had existing obvious low resistivity layers, which corresponded to the fourth aquifer in the Quaternary which was widely distributed in the survey area. Meanwhile, clear differences had occurred below 400 m. It was observed that the resistivity of the ground inversion results had decreased and its value was very small, while that of the roadway inversion results first decreased and then increased, showing a relatively high resistance at the bottom. According to the geological and existing drilling data of the survey area, limestone stratum of the Carboniferous and Ordovician were present below the 700 m depth, in which the resistivity was relatively high. It was determined in this study that the reason for the low resistivity in the ground-based inversion results was the limitation of the detection depths, which was related to the insufficient observation time and the low resistivity of the shallow layers.

As shown in Fig. 10, 2D cross-sections were drawn based on the ground-based and roadway-based inversion results, in which the detection results of the two configurations of the geoelectrical structures were shown more clearly. As can be seen in the figure, the detections of the geoelectrical structures of the shallow stratum (within 500 m) obtained by the two devices were basically the same. The resistivity of the stratum shallower than 100 m was approximately 50 \( \Omega \).m, which represented the Quaternary sedimentary layer. The lower conductive layer was approximately 5 to 10 \( \Omega \).m, which represented the
fourth aquifer in the Quaternary. Also, a relatively high resistance stratum with discontinuous transverse resistivity was observed, which was nearly 400 m thick. This represented the Jurassic and Permian strata. Among those, the resistivity between points 0 and 140 m were relatively low and connected with the fourth aquifer in the upper part, which revealed that the fifth aquifer of the Jurassic in the site had strong water yield capabilities. As illustrated in Fig. 5a, there were fractured structural characteristics observed (marked as F in Fig. 10b), which had led to fracturing and formations of water diversion structures and rich water channels. Moreover, there was an obvious low resistance anomaly observed under the roadway near the 400 m point. This anomaly was deduced to be related to the water filling of the karst fissures in the underlying limestone stratum. However, the ground-based inversion results failed to reflect its lower boundary.

The inversion results below about 600 m all indicated extremely low resistivity levels due to the insufficient detection depths of the ground-based observations. As a result, it was impossible to determine the geoelectrical changes below the Permian strata due to the ground-based observational methods losing adequate detection ability in the deeper strata. Meanwhile, the underground inversion results reflected the deep Carboniferous and Ordovician limestone strata with high resistance, and the ranges of the two low resistance abnormal areas. It was found that according to the inversion results of the roadway observations, it could be assumed that a fault zone on the left of the survey line had influenced the larger areas in the vertical direction, then formed a fracture zone which penetrated the fourth aquifer in the Quaternary, the fifth aquifer in the Jurassic, and the eighth aquifer in the Carboniferous. Subsequently, a large water-enrich area was formed, which is marked as A1 in Fig. 10b. Moreover, the low resistance area on the right of the survey line displayed an independent water rich area (A2), which was caused by the water-filled karst fissures in the limestone strata.

Finally, there were two issues which should be noted in this study's investigations. For example, the low resistivity anomaly areas in the inversion results were purposely enlarged, and the actual water-enriched areas may have been much smaller than those illustrated in Fig. 10. In addition, the electromagnetic method adopted in this study was found to have poor results in delineating the formation boundaries, which needed to be constrained by the known geological and drilling data. There was an obvious vertical high resistance zone in the shallow part between points 100 to 200, which was observed to be larger in the cross-section of ground-based observations. This had resulted from an underground airway at a depth of approximately 50 m. In summary, it was revealed that the aforementioned shallow local inhomogeneous body could potentially have a certain impact on the observational data and processing results of the shallow layers. However, it would have much weaker impacts on the deeper underground roadway observational results (Chen et al., 2017a).

**Conclusions**

In the vast areas of northern and central China, the buried depths of coal seams tend to be generally deep, with thick conductive Quaternary overburden. In addition, there are known to be many underground aquifers. Due to the shielding influences of conductors, the detection depths and accuracy levels of
traditional ground-based TEMs are limited. Therefore, it has been difficult to achieve good detection results in previous hydrological surveys. In the present study, a surface-to-roadway TEM configuration was developed by locating receivers in roadways of widely existing coal mines and transmitting on the surface based on grounded-wire sources. It was observed that the surface transmitters had the ability to provide larger magnetic moments. Furthermore, the receivers in the roadways could not only achieve observation points closer to the targets, but also had the ability to largely avoid the electromagnetic and geological interference on the surface. In this study, 1D forward modeling and inversion processes were carried out for the proposed method, and then applied to the Zhuxianzhuang Coal Field of Anhui Province. The results of the numerical simulations and in-situ application confirmed that the proposed surface-to-roadway TEM had significantly improved the resolution of the deeply buried water-bearing bodies in the study area.

References


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Figures
Figure 1

Generalized strata of the survey area
Figure 2

Sketch map of the surface-to-roadway TEM, in which a grounded wire was placed on the surface as the transmitter, and magnetic or electrical sensors were placed in the subsurface roadway as the receivers.

Figure 3

Synthetic model (a) and layout of Transmitter- Receivers (b)
Figure 4

1D forward modeling results of three observation points (x=0 m, x=250 m, x=500 m)
Figure 5

Comparison of inversion results at single site (x=500 m)

Figure 6

Comparison of profile inversion results

Figure 7
Layout of the field applications: (a) Planar diagram of the mining roadway; (b) Survey lines and transmitter on the surface

![Diagram of mining roadway and survey lines](image)

Figure 8

Measured raw data curves of several survey sites: Upper panel indicates the surface data; and the lower panel indicates the roadway data
Figure 9

1D Occam’s inversion results for several survey sites
Figure 10

Depth-resistivity sections based on 1D ARIA inversion: (a) Results of the surface data; (b) Results of the roadway data