Ke Ai
ADVANCING RESEARCH
EVOLVING SCIENCE

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.keaipublishing.com/en/journals/geog;
http://www.jgg09.com/jweb_ddcl_en/EN/volumn/home.shtml

Geodesy and Geodynamics

Mapping coalmine goaf using transient electromagnetic method and high density resistivity method in Ordos City, China

*Guiju Wu**, *Guangliang Yang*, *Hongbo Tan*

The Key Laboratory of Earthquake Geodesy, Institute of Seismology, China Earthquake Administration, Wuhan 430071, China

ARTICLE INFO

Article history:
Received 31 March 2016
Accepted 14 April 2016
Available online 30 July 2016

Keywords:
Transient electromagnetic method
High density resistivity method
Coalmine goaf areas
Geotechnical
Electrical

ABSTRACT

The research about subsurface characteristics by using transient electromagnetic method (TEM) and high density resistivity method (HDRM) were already conducted in Ordos. The objective of this research is to detect coalmine goaf areas based on rock resistivity. The data processing using wavelet transform, three point smoothing, RES2DINV and Maxwell processing software to obtain 2D resistivity structure. The results showed that the layers with maximum resistivity values (30–33 Ω m on Line 1, 30–31 Ω m on Line 2, 32–40 Ω m on Line 3) are founded at station 1–7, and 14–20 on Line 1,13–18 on Line 2, and 8–13 and 16–20 on Line 3 which is predicted as goaf layer, and the minimum resistivity values (20–26 Ω m of TEM, 45–75 Ω m of HDRM) at the other layers. This resistivity difference was caused by the geology and characteristics of the study area which is located close by the cleugh with rich coal, so the goaf area distinguishable with aquifer layer and coal seam. The results were also significant accidents and serious destruction of ecological environment.

How to cite this article: Wu G, et al., Mapping coalmine goaf using transient electromagnetic method and high density resistivity method in Ordos City, China, Geodesy and Geodynamics (2016), 7, 340–347, http://dx.doi.org/10.1016/j.geog.2016.04.014.

1. Introduction

From the beginning of the last century, the industrial development has had a negative impact on the exploitation of coalmine forming huge goaf areas. This problem has led to frequent accidents and serious destruction of ecological environment. Therefore, it is urgent to develop goaf detection and comprehensive work. Coalmine goaf detection is to find out the plane distribution and buried conditions underground, which can provide the basis for project safety assessment and disaster management. Recently, the mainly exploration

* *Corresponding author.*
E-mail address: wugjsky@126.com (G. Wu).
Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

ELSEVIER Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.geog.2016.04.014

technologies in goaf are drilling detecting and geophysical detecting, although drilling detecting is the most intuitive and high precision, its project volume is massive, the rate of progress is slow and controlled range is small. So, the goaf detection method is generally given priority to with geophysical exploration, drilling technical method validation is complementary.

Measuring the electrical resistivity of the subsurface is the most powerful geophysical prospecting method in mineral exploration and the main method used for delineating coalmine goaf areas. Time-domain electromagnetic methods which are the subject of this paper, and in particular transient electromagnetic method (TEM) and high density resistivity method (HDRM), are increasingly used for grounded source exploration [1] and subsurface target mapping [2–5], all aspects of coalmine mapping [6–14]. Over the past decades, in particular, TEM and HDRM have been developed to provide early measurements for improved near-surface resolution and to increase the depth penetration.

Because of electrical interference of coal mine, topography affect, detection accuracy and detection depth, a single geophysical method may be problematic for geophysical prospecting. For example, using HDRM explores goaf areas, its effective depth is about 150 m, but if the depth of goaf area is over 150 m, HDRM is apparently ineffective; effective exploration depth of TEM is up to 200 m-500 m, even thousands of meters, but its shallow surface detection capability is weaker than HDRM. Therefore, in this paper, we integrated TEM and HDRM features to map the subsurface structure in Ordos. Fundamentally, the two geophysical methods complement each other. The inversion of data from the two methods is informative in spite of the fact that both methods measure the same physical property of earth. The combination of these two geophysical methods study goaf areas in coal mining areas is very important for the industrial development.

2. Geological setting

The research area is located in Ordos shown in Fig. 1, the terrain is erosion hilly topography and complicated, it is high in north-west and low in south-east. Most of the area is covered by aeolian sand, and gully aspect. The region is semi-arid, semi-desert plateau continental climate, the temperature is different between day and night. Rain is little all the year round, annual precipitation is 194.7–531.6 mm and concentrates in July, August and September, annual evaporation is 2297.4–2833.7 mm. Terrain cutting is severe, and about 50% area is covered by Quaternary aeolian sand and loess, other is bedrock outcropping. The results of drilling reveal that the stratum from old to new is T_3y (Upper Triassic Yanchang formation), $J_{1\text{-}2}y$ (Middle and Lower Jurassic Yan'an formation), J_2z (Middle Jurassic Zhiluo formation), N_2 (Neogene system), Q (Quaternary). T_3y is coal-bearing strata and sedimentary basement, it is not exposed on the earth's surface in this region; $J_{1\text{-}2}y$ is the main coal-bearing strata and exposes in the surrounding valleys, the lithology consists of a set of sandstone, mudstone, sandy clay and coal seam; the main lithology of J_2z is medium grained sandstone and argillaceous or clay cementation, it is relatively loose, its lateral thickness is rather changeable; N_2 is sporadic occurrence; and Q is widely scattered. There is no fault, big fold structure and magmatic rock intrusion in the research area. And the geological structure is simple.

3. Measuring method theory

3.1. *Transient electromagnetic method*

TEM systems consist of a transmitter instrument, transmitting coil or transmitting wire, receiver coil or antenna, and receiver instrument. Depending on subsurface resistivity, current induced, receiver sensitivity and transmitter–receiver geometry, TEM measurement allows geophysical exploration from a few meters below the surface to several hundred meters of depth (showing in Fig. 2). The method using transmitting coil sends a pulsed magnetic field, and receives induced electromotive force of the secondary eddy-current magnetic field with receiver coil during the intermittent pulse magnetic field, which is to understand the electrical characteristics of underground media. The secondary induced field decay is associated with subsurface conductivity, if the electrical conductivity is better, the secondary field is decreased more slowly, otherwise, the electrical conductivity is worse, the secondary field is decreased more quickly.

The data from field of TEM is induced electromotive force with time. In order to getting resistivity distribution, the induced electromotive force should be converted to apparent resistivity with the following formula,

$$\rho = \frac{\mu_0}{4\pi t}\left(\frac{2\mu_0 S_T S_R}{5t(V(t)/I)}\right)^{2/3}$$

where, $\mu_0 = 4\pi \times 10^{-7}$, S_T is the area of the sending circle, S_R is the area of receiver circle, t is the time of measuring time, $V(t)/I$ is the normalized induced electromotive force what is transient value. Therefore we can detect subsurface distribution characteristics of geological bodies from studying the transient variation with time.

3.2. *High density resistivity method*

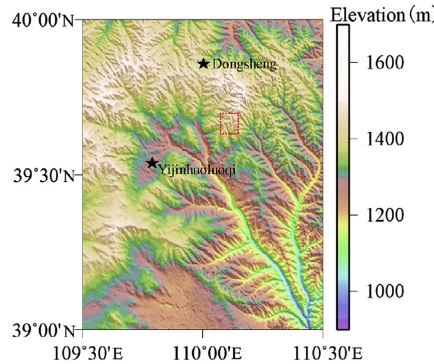
HDRM in working is the same as the conventional resistivity method in principle, the difference is that HDRM in observing is set higher density measured points, the electric poles layout on certain interval measuring points. And in measuring, a number of electrodes are used and they can combine freely between electrodes, which can extract more geoelectric information, the working system diagram is shown in Fig. 3. Actually, HDRM is a many kinds of arrangement of conventional resistivity method, and combines with data automatic processing. Using the following formula we can get the resistivity on each measuring point.

$$\rho_s = (\Delta V/I) \times K$$

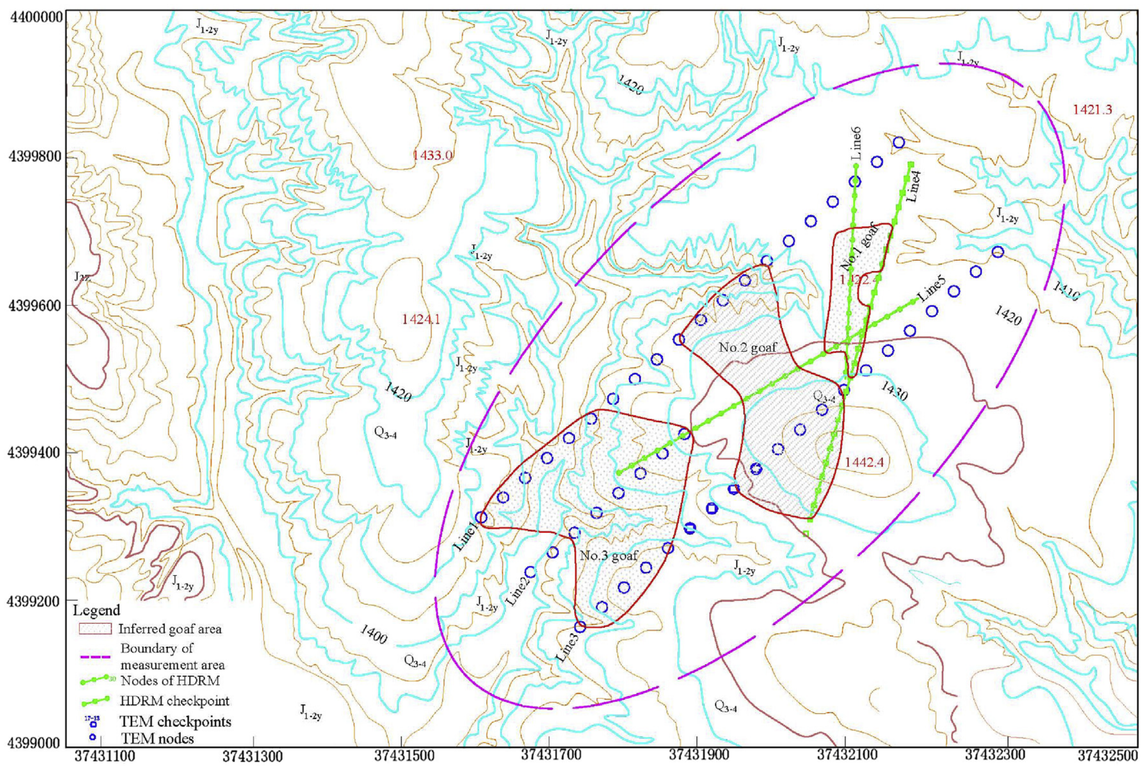
where the K is array coefficient,

$$K = \frac{2\pi}{\frac{1}{AM}-\frac{1}{AN}-\frac{1}{BM}+\frac{1}{BN}}$$

Advantages of using HDRM are: (1) several layouts of the electrodes could be designed and all arrangement detecting electrodes could be finished at one time without any changing



(a)- Location of the research area.



(b)- Simplified geologic map of TEM and HDRM profiles.

Fig. 1 – (a)-Locations and (b)-simplified geologic map of the research area of TEM and HDRM profiles. The research area is located between Dongsheng and Yijinhuoqi. In Fig. 1a, the red dashed box is the research area. In Fig. 1b, the blue circle lines are the measuring lines of TEM (Line 1, Line 2, Line 3). The green lines with dots are measuring lines of HDRM (Line 4, Line 5, Line 6).

or re-arranging; (2) the detecting data can be automatically collected and stored; (3) the result of detecting data could be explained easily [15,16]. In this paper, using comprehensive geophysical prospecting method detected the goaf areas.

4. Data acquisition, processing, and inversion

4.1. *Data acquisition*

The area of the exploration is about 0.21 km^2, two geophysical prospecting methods are used in the study area. The frame of TEM is 120 × 120 m, the excitation frequency is 25 Hz; its observation network is 100 × 40 m, that is to say, the distance of line is 100 m, the distance of nodes is 40 m, there are three measuring lines and 48 nodes. The equipment of HDRM is Pole–Dipole, Dipole (AMN and MNB combination), the length of measuring line is about 1270 m, the number of measuring nodes is 127, average distance of nodes is 10 m. The measuring lines distribution of TEM and HDRM are shown in Fig. 1.

4.2. *Processing*

In this survey, the data of TEM and HDRM need to filter in terms of the detecting. In this paper, the wavelet transform

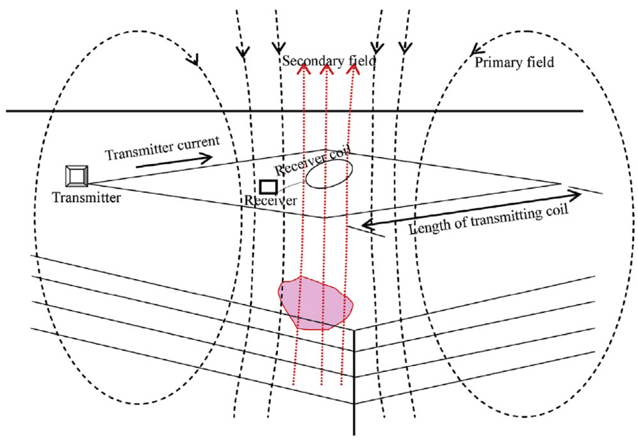


Fig. 2 – Working principle diagram of TEM.

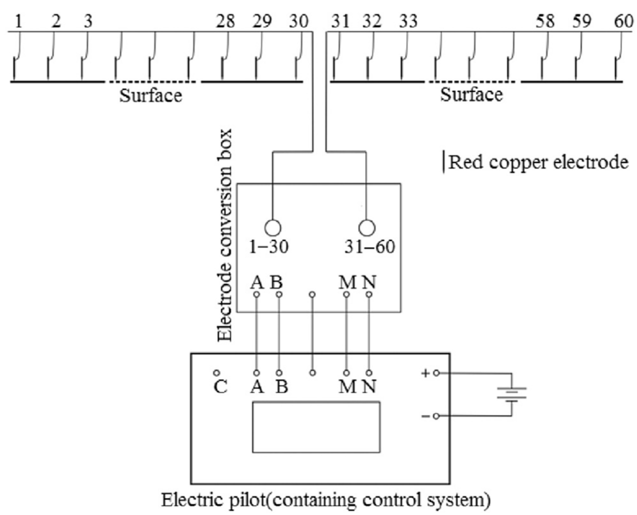


Fig. 3 – HDRM measuring system structure diagram.

method is used. Through the filter is not only eliminate random interference of high frequency, more major is able to effectively filter or suppress jamming signal of TEM and restore the signal change rule, and eliminate and decrease the apparent resistivity curve of three normal device shock of HDRM, which can simplify the abnormal morphology, increase the accuracy of the inference and interpretation. Because some one grounding electrode is bad, or the influence of collecting field is interferential, there will be some mutant points which are need to be processed. The main processing method is deleting these points; owing to the effect of random noise, then using three-points smooth method eliminate it.

In a survey area with mountainous terrain and thick vegetation cover, another problem in TEM and HDRM is the terrain effect caused by uneven topography along the profile, which can add noise to data. Usually, the topography simulation in EM induction is implemented using the finite-element method because triangular elements could allow to precisely model the arbitrary surface. By moving the nodes of triangular or rectangular elements in the vertical direction according to the elevation of the air–earth interface, we can obtain the topographic response of EM induction. In this study, the topography had been integrated into the inversion program to model the terrain effect.

4.3. *Inversion*

The interpretations of the subsurface electric resistivity structure of the Ordos region presented in this paper were based on the HDRM and TEM inversion models and controlled by other available data sets, including drilling and limited geologic data. Interpretation developed from a small range of data sets collected from the region what provides a higher credibility from the HDRM and TEM data. For brevity, we show three profiles of the two geophysical prospecting methods in the survey section.

4.3.1. *The inversion of TEM*

Generally speaking, the values of apparent resistivity of coal strata in ρ_s integration profiles of TEM changes stably, the contours of them are layered distribution and change gently. Otherwise, the contours of apparent resistivity are distortion and deformation. In this article, we can visually distinguish relatively high resistance or high resistance of coalmine goaf from the results of ρ_s integration profiles, and Maxwell processing software is used. Maxwell is one of the world's most mature TEM data processing software, which can be applied to medium, aviation, well a variety of device types of TEM data.

The variation characteristics of the surveyed area from shallow to deep generally are low resistance, high resistance and low resistance. In shallow surface layer, it is mainly quaternary remnants accumulated filth and Malan loess slope, their apparent resistivity is about 24 Ω m; below the first layer, it is yellow thick layered grit of middle and lower Jurassic Yan'an formation, and coal group, their apparent resistivity is about 33 Ω m; when the depth is darker, it is mainly thin layer variegated mudstone and sandy mudstone of upper Triassic Yanchang formation, their apparent resistivity value is relatively low, the average is 10–23 Ω m. If there is without influence of goaf or other geological formation, the apparent resistivity contours change gently on the lateral, it will well reflect the characteristics of the survey area nearly horizontal strata layered distribution.

Fig. 4 is the apparent resistivity composite profile of the TEM of Lines 1, 2, 3. The variation trend of vertical apparent resistivity value is from low, high to low, which is consistent with the actual geological horizon of electrical distribution. The coal strata (purple dotted line on each line) are relative to high resistance layer, the higher resistance anomaly may be mined-out area with no water filling. Three lines are from northeast to southwest across study area, the variation of the coal strata is quite gentle in horizontality, there are also some ups and downs. There are two high resistivity anomaly bodies on Line 1 and Line 3, and one high resistivity anomaly on Line 2, they are distribute between 7 and 11 (the second type of anomaly), 15 an 20 (the third type of anomaly) point on Line 1, between 13 and 18 (the third type of anomaly) point on Line 2, and 8 and 13 (the second type of anomaly) point and 16 and 20 (the third type of anomaly) point on Line 3, their high resistance are 30–33 Ω m on Line 1, 30–31 Ω m on Line

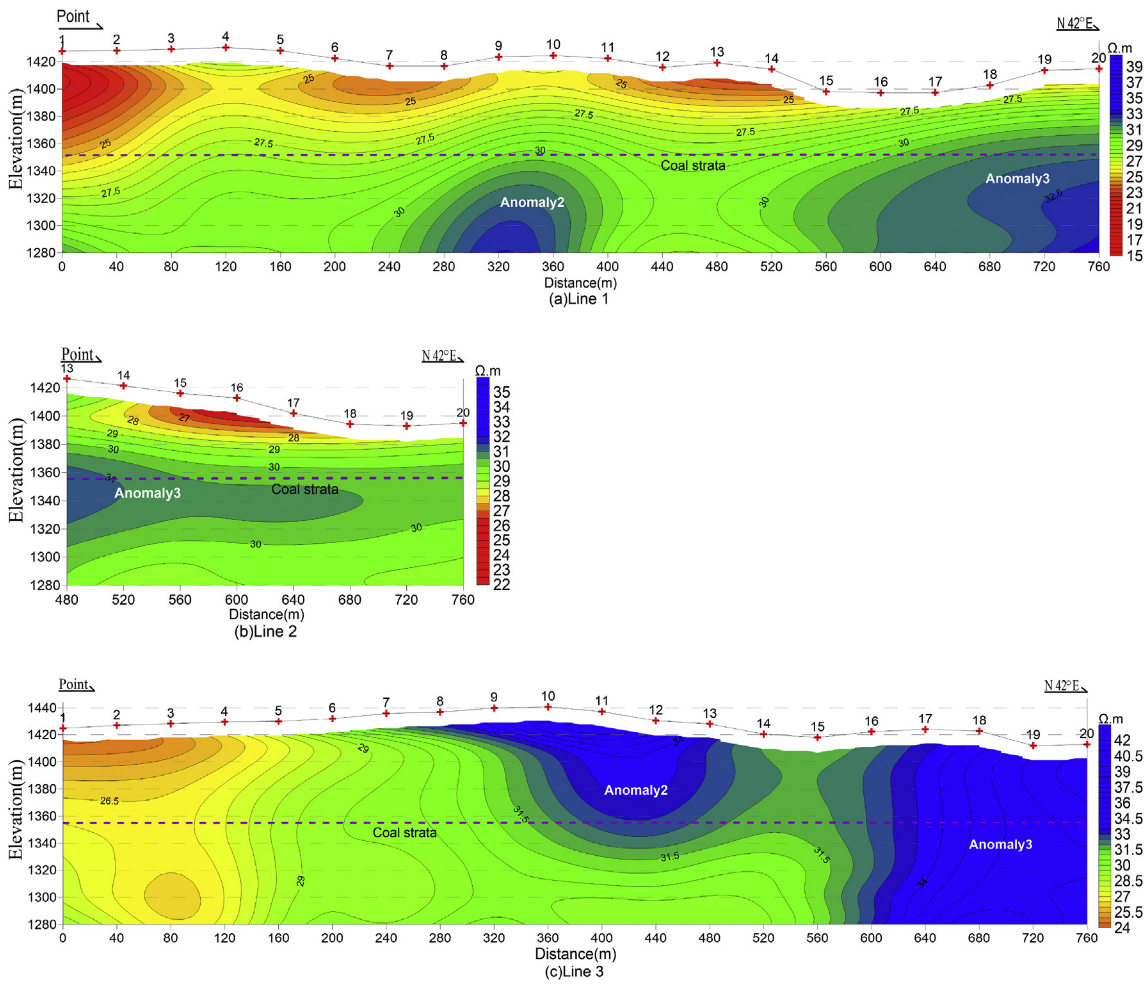


Fig. 4 – Apparent resistivity composite profiles of the TEM of (a)-Line 1, (b)-Line 2, (c)-Line 3.

2, 32–40 Ω m on Line 3, respectively. They are all relatively high resistivity anomaly, and their distribution ranges are big and obvious, and their amplitude is strong. Comparing with the result of drilling, the anomaly is corresponding with the northwest edge of roadway known extension direction, thus we speculate that the anomaly should be relatively large mined-out area. The detail information of anomaly points is shown in Table 1.

4.3.2. *The inversion of HDRM*

The result of HDRM ρ_s shows that the electric changes of coal strata have some regularity in the absence of coalmine goaf area or other tectonics effects, that is to say, the apparent resistivity values change stable, the contour of the apparent resistivity is bedded distribution and change flat; on the contrary, when there are influence of coalmine goaf area or other geological formation, apparent resistivity contour is distorted, deformed. The goaf will be shown low resistance when it is filled with water; the mined area will be shown high resistance when it is not filled with water. The color ρ_s profiles can intuitively display the mined areas of the low and high resistance. In this paper, the inversion soft of RES2DINV is applied. The RES2DINV programs use the smoothness-constrained Gauss–Newton least-squares method inversion technique to produce a 2D model of the subsurface from the apparent resistivity data alone. This program has been optimized for the inversion of large data sets. And four different techniques for topographic modeling are available in this program.

In the ρ_s profiles shown in Fig. 5, the blue rectangle dashed lines mark out the coalmine goaf of high resistance and there are using uniform numbers, which is convenient for abnormal comparative analysis on the sections. In the study, the same color classification standard is not used, and anomaly threshold selection is not unified, it is due to the area is a larger part of the surveyed area, line arrangement of span is also bigger, and the surface and the geological formation condition is different, the apparent resistivity values change

Table 1 – Profile anomalies and properties of TEM.

Number of line	Abnormal position (dot) and serial number	Inferring nature
Line 1	7–11 (second type anomaly), 14–20 (third type anomaly)	Coalmine goaf
Line 2	13–18 (third type anomaly)	Coalmine goaf
Line 3	8–13 (second type anomaly), 16–20 (third type anomaly)	Coalmine goaf

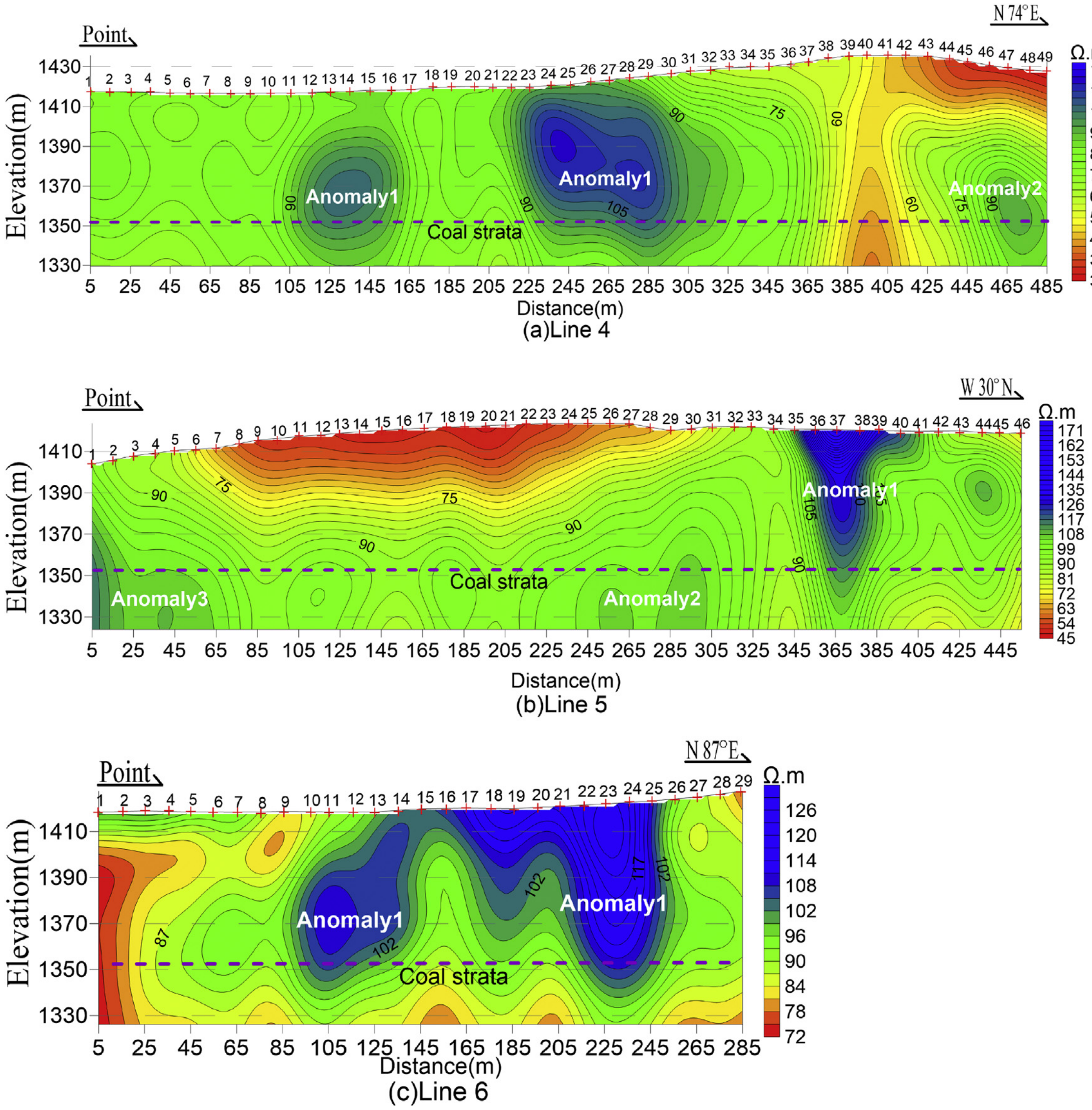


Fig. 5 – Apparent resistivity composite profile of the HDRM of (a)-Line 4, (b)-Line 5, (c)-Line 6.

is bigger. The different depth of the old empty area will lead to the difference of resistivity, If using the same color classification standard and anomaly threshold explains and analyzes the occurrence situation of old empty area, it will cause missing.

Fig. 5 is the apparent resistivity composite profile of the HDRM of Lines 4, 5, 6. There are very obvious high resistance anomalies between 11 and 17 point on Line 4, its high resistance is 90–102 Ω m, between 35 and 39 point on Line 5, and between 10 and 25 point on Line 6, their high resistance is 105–120 Ω m, what is the first type of anomaly. The first type of anomaly is very noticeable, but the range is not big, the shape is strip on Line 5, it may be caused by roadway or local coalmine goaf. There are the second kink of high resistance anomalies between 46 and 49 point on Line 4, between 24 and 31 on Line 5, and the third type of anomaly is between 1 and 7 point on Line 5, their high resistance are 90–102 Ω m, 102–110 Ω m, 90–105 Ω m, respectively. These two kinds of anomalies are obvious and their ranges are big, they should be large mined-out area. The detail information is shown in Table 2.

Electrical prospecting itself has a certain volume effect, the high resistance abnormal area does not directly reflects the distribution pattern of mined-out area on the profiles, the anomaly reflects the width and depth of the mined-out area information is uncertain, and the forward and inversion

Table 2 – Profile anomalies and properties of HDRM.

Number of ine	Abnormal position (dot) and serial number	Inferring nature
Line 4	11–17,23–30 (first type anomaly), 46–49 (second type anomaly)	Coalmine goaf or roadway
Line 5	1–7 (third type anomaly), 35–39 (first type anomaly), 24–31 (second type anomaly)	Coalmine goaf or roadway
Line 6	10–25 (first type anomaly)	Coalmine goaf or roadway

technology is not yet mature, therefore, this paper combines two electrical prospecting methods to determine the abnormal area. And the direction of measure lines are perpendicular to the main roadway of goaf, part of the goafs are relative, therefore, using continuous tracing line can be carried out to determine the distribution and extension of the mined-out area on each measure line.

5. Integrated interpretation

The research integrates the goaf interpretation results of TEM and HDRM, the high resistance abnormal areas are shown in each apparent resistivity profile, and combining the well up and down control chart and relative geological, drilling data, and the characteristics of the room and pillar cola mining area deduce the distribution and range of goal or roadway and map the inferred goaf plane figures. In Fig. 1, the filling areas with grey dotted lines are inferred ranges of mined-out area. In apparent resistivity profiles of TEM and HDRM, the goaf number is corresponding to the number of high resistance abnormal area, for example, the third type of anomaly is corresponding to the No.3 mined-out area, which is convenient for analysis.

In the research area, there are three inferred coalmine goaf areas or roadway. The No.1 goaf is controlled by the first type of anomaly, and on Line 4, Line 5 and Line 6 of HDRM reflects, respectively. The anomalies are obvious, their amplitudes are strong, but their scales are small, this anomaly should be a past small coalmine goaf.

The No.2 goaf is reflected on Line 1 and Line 3 of TEM. The second type of anomaly is noticeable on the three measure lines, and the scale of the anomaly is larger, in terms of the well up and down control chart, it is known roadway in northwest, and corresponding to the extension direction of the roadway. The surface cracks and collapse can be seen nearby the 11 point on Line 4 and the 9 point on Line 2 of TEM, so the anomaly should be caused by large mined-out area.

The distribution area of the No.3 goaf is big, it is mainly controlled by the third type of anomaly, and on Line 1, Line 2 and Line 3 of TEM reflects respectively, the anomaly is obvious and its scale is large. The existing roadway extends to the abnormal area range. The surface collapse can be seen nearby the 19 point on Line 3. That is to say, this anomaly is a large area goaf.

In addition, it is worth noting that mining space is relatively small when the roadway is tunneled, and its abnormal range and amplitude is also relatively weak. But other geological phenomena may cause the similar anomaly, which will bring interference for inferred analysis.

6. Discussion and conclusion

The interpretation of electromagnetic exploration data follows the principles from the known to the unknown, from the node to the line, from the line to the surface, from the simple to the complex, and combines with the known geological, drilling and hydrological data to analyze and infer.

Because the survey area is undulating terrain, it limits the construction site of the HDRM and also adds the difficulty of the data interpretation. Therefore, this research combines the advantages of HDRM and TEM to determine the structure of about one hundred meters of the summit area. In this area, the coal mining method is room-pillar or tunnel mining, the collapse of coal goaf mostly did note occur after mining. In theory, when the coal seam is worked out, a certain scale of inflatable space will form in such a short time what causes the electrical property of the corresponding formation is different from the surrounding rock electric property. At the same time, when the coal goaf is intact and without water, the coal goaf is high resistance layer; and when the goaf collapse and basically fills without water, it is also high resistance layer. On the contrary, it will be low resistance layer, and will become lower and lower with the deepening of the goaf water salinity and collapse degree.

The abnormal number is the same in the results of HDRM and TEM profiles. In this research, the maximum sounding depth of HDRM is about 100 m, which is vulnerable to be effected by the shallow surface layer, uneven body and terrain what will lead to the distribution of the superficial electric property is heterogeneous, but all these do not affect the interpretation of the deep abnormal high resistance. Although the terrain condition does not limit the TEM measure, the vertical volume effect is relatively larger, which is easily affected by the low resistivity layer and causes the deep electric property become low.

There are three measure lines of TEM and HDRM, the results of these profiles show that three coal goaf areas exist, at the same time circle their distribution and extension direction, the goaf areas are uniformly distributed in the range of the research region. In this study, the two geophysical prospecting methods are used. The characteristics of the two methods and the exploration results show that HDRM in framing high resistance coal goaf has more advantages compared with TEM. Therefore, in the region of the terrain condition permit should lay out HDRM measuring line as much as possible. If the conditions are fit for HDRM construction area, then use TEM to explore.

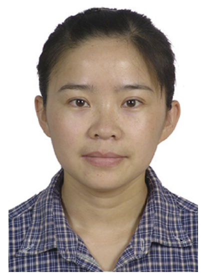
Acknowledgement

This work is supported by the Institute of Seismology Foundation, China Earthquake Administration (201326126).

REFERENCES

[1] Gunderson Brian M, Newman Gregory A, Hohmann Gerald W. Three dimensional transient electromagnetic responses for a grounded source. Geophysics 1986;51(11):2117–30.
[2] Cheesann SJ, Edwards RN, Chave AD. On the theory of sea-floor conductivity mapping using transient electromagnetic system. Geophysics 1987;52(2):204–17.
[3] Xue GQ, Elzein Mohammed EA, Guo WB. The response of large-loop transient electromagnetic method. Univ Afr J Sci 2010;1(1):1–17.
[4] Xue GQ, Yan YJ, Cheng JL. Research on detection of 3D underground caves based on the TEM technique. Environ Earth Sci 2011a;64:425–30.

[5] Xue GQ, Yan YJ, Li X. Control of wave-form dispersion effect and applications in TEM imaging technique for identifying underground objects. J Geophys Eng 2011b;8:195–201.
[6] Xue Guoqiang, Li Xiu, Di Qingyun. The prospecting of TEM in theory and application. Prog Geophys 2007;22(4):1195–200 [in Chinese].
[7] Wang Shanxun, Yang Wenfeng, Zhang Weimin, Wang Beizhan. Application of TEM to detecting coal goaf. Chin J Eng Geophys 2012;9(4):400–5 [in Chinese].
[8] Guo Chun, Liu Baizhou, Bai Denghai. Prediction of water disasters ahead of tunneling coal mine using continuous detection by UW TEM. Seismol Geol 2006;28(3):456–62 [in Chinese].
[9] Liu Shucai, Liu Zhixin, Jiang Zhihai. Application of TEM in hydrogeological prospecting of mining district. J China Univ Min Technol 2005;34(4):414–7 [Chinese].
[10] Yan Liangjun, Xu Shizhe, Hu Wenbao, Chen Qingli, Hu Jiahua. A rapid resistivity imaging method for central loop transient electromagnetic sounding and its application. Coal Geol Explor 2002;30(6):58–61 [in Chinese].
[11] Xin Sihua, Song Rencheng, Yang Jianjun, Liu Wei. Application of high density electric surveying in coalmine gob area investigation. Coal Geol China 2008;20(1):59–61 [in Chinese].
[12] Li Yaoguo, Douglas W Oldenburg. Approximate inverse mappings in DC resistivity problems. Geophys J Int 1992;109:343–62.
[13] Dahlin Torleif, Bernstone Christian, Loke Mong Hong. A 3-D resistivity investigation of a contaminated site at Lernacken, Sweden. Geophysics 2002;67(6):1692–700.
[14] Shima Hiromasa. 2-D and 3-D resistivity image reconstruction using alpha centers. Geophysics 1992;57(10):1270–81.
[15] Robert E Grilnm, Gary R Olhoeft, Kate Mckinley, Joseph Rossabi, Brian Riha. Nonlinear complex-resistivity survey for DNAPL at the Savanah River site A-014 outfall. J Environ Eng Geophys 2005;10(4):351–64.
[16] Dong J, Zhai P, Zhang Z, Mou Y. Application of high density resistivity method in detection of base water body in coal mine working face. Sci Technol Eng 2008;16(6):1550–2.



Guiju Wu, Assistant Researcher. Phone: +86-153-3716-2960.

Education: 2004 B.S. Computer Science and Mathematics, Yangtze University, Jingzhou, China; 2008 M.S. Geodetection and Information Technology, China University of Geosciences, Wuhan, China; 2010.10–2011.4 Visiting Scholar. Virginia Polytechnic Institute and State University, Blacksburg, USA; 2012 Ph.D. Geodetection and Information Technology, China University of Geosciences, Wuhan, China.

Professional Appointment: 2012.07-present Assistant Researcher at Institute of Seismology, China Earthquake Administration.

Research interest: Gravimetry and analysis of gravity temporal change/signal; Forward and inversion of electromagnetism and gravity; Gravity, magnetic and electrical data processing and their interpretation.