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Effect of Application of Transient Electromagnetic Method in Detection of Water-Inrushing Structures in Coal Mines

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Abstract

Influenced by topographical and geological conditions, it is difficult for research of mine hydrological geophysics to rapidly and accurately detect passages inducing flooding of mines from water-accumulating abandoned mines, to detect precisely small structures causing flooding of mines. Through the study of the key technical difficult problems of the application of transient electromagnetic method(TEM) in hydrogeological exploration in coal mines, the characteristics of TEM such as sensibility to low resistivity, high transverse resolution and high speed have been sufficiently utilized. New inversion technologies have been used to improve the precision of TEM detection. During many rescues of water flooding induced by water inrush in coal mines, TEM has rapidly and accurately located water-inrushing structures in coal mines. It gains time for emergency rescue in coal mines, has significant social and economical benefits. TEM technology has become an important means for water control exploration in coal mines and has optimistic prospect of application.

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Keywords: transient electromagnetic method; coal mine; water control; water-inrushing structure; application; effect

Transient electromagnetic method, shortened as TEM or TDEM is a time domain electromagnetic method. The research on transient electromagnetic method begun in the early 1970's in China. Central South University of Technology (now Central South University), Changchun School of Geology （now Jilin University）, Xi'an Branch of China Coal Research Institute (now Xi'an Research Institute of China Coal Technology and Engineering Group Corp), Institute of Geophysical and Geochemical

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Exploration CAGS, Guilin Research Institute of Geology for Mineral Resources, Central South University of Technology (now Central South University), Xi'an School of Geology (now Chang'an University), Xi'an Jiaotong University, Beijing Institute of Geology for Mineral Resources , China University of geosciences and other institutions have carried out research on TEM theory, methodology and instruments [1~7]. Apart from home-developed instruments, many foreign advanced TEM instruments have been imported. Since recent years, the research on TEM theory and application has become progressively active, apart from the frequent application in Non-ferrous minerals, groundwater, geothermal and geological structures, it has been widely applied in the fields of ensuring safe and high efficient production in coal mines and engineering investigation[2][8~22] .

In hydrogeological exploration in coal mines, earlier TEM could be used only to carry out qualitative or semi- quantitative interpretation, the interpretation precision was relatively low. However, TEM adopts non-grounded loop, so does not have problem of grounding resistance (in many areas where DC electric method can not operate, TEM can work), has little topographic influence and high adaptability, regardless desert or marsh, everywhere it is accessible for men it can work, even for airborne application. Compared to DC electric sounding, TEM takes less time, for a detection point of 1 000 m deep, it takes only 1 to 2 minutes, but the latter takes 40 minutes even longer. At suitable exploration depth, what TEM observe is secondary field(pure abnormal field), it has high sensibility to good conducting geological bodies, high transverse resolution, can improve interpretation precision. Except fewer application in cross-holes, surface to borehole, it is mainly used on surface [2~12][20~22] and underground mines[13~19]. The higher the quantitative interpretation level is, the better the exploration effect. Now it becomes an important geophysical approach for water hazard control in coal mines.

1. Key technical problems in the application of TEM in water hazard control in coal mines

In water control in coal mines, the effect of TEM application is evident in geophysical exploration of mining districts in coal mines, detection of water passages inducing flooding of mine from water-accumulating abandoned mines, high precision detection of water inrushing structures inducing flooding of mines, integrated detection Ordovician limestone water [8~22]. Its own specific exploration method and working technology have been formed. It has become one of the major geophysical approaches for investigation of hydrogeological conditions in most geophysical brigades, special geophysical exploration teams of research institutions, universities and colleges. The working method, engineering design, selection of parameters and interpretation method of TEM influence directly the detection results. The following section will discuss some key technical problems in exploration for water control in coal mines.

1.1. Technical problems needed to pay attention to in TEM hydrogeological geophysical exploration in coal mines

1.1.1. Device (method) selection

The device of commonly used near TEM sounding devices include electric dipole source, magnetic dipole source etc. In exploration for water control in coal mines, aquifers are often layered and located at depth of less 800 m. generally central loop device is selected. It is characterized by the best coupling with target layer, little influence of sides and horizon inclination, so the parameters of the detected layer is relatively accurate.

1.1.2. Principle for selecting side length of transmitting coil

The amplitude of anomaly of ore body depends on the dimension, sharp and conductivity of ore body. Whiting defined side length of loop, the amplitude of anomaly increases with the side length of loop, finally reaches certain saturation value, and the extent of anomaly increases correspondingly （transverse resolution of abnormal body becomes poor）. On the other hand, with the increase of side length, the interference of side geological bodies increases, in the same time the intensity of exterior interference （natural electric field and industrial electricity）and geological noises（electric conductive overburden, surrounding rocks and fractured zone）increases also. Therefore side length which reaches the value of $0.8V_{max}$ is the optimal side length. The result of simulation experiment has indicated that when L/h=0.9~1.5， the obtained response is bigger than $0.8V_{max}$(note：$_{max}$ is the maximum value of response signals, L is side length of loop, h is the maximum depth of target layer or target ore body）. Therefore side length $L \leqslant$h is recommended for conventional hydrogeological exploration in coal mines.

1.1.3. Principle for selecting detection grid

The detection grid depends on whether the geological task is reconnaissance or detailed exploration, generally for area reconnaissance, detection grid is selected as: line interval×point interval=L×L/2~ L/4. While for area detailed exploration the detection grid is selected as: L/2~L/4×L/6~ L/10. In order to efficiently detect water-bearing and conducting geological structures influencing coal production and to ensure safe production in coal mines, structures to detect in coal mines are relatively small, TEM often adopts area detailed exploration or local fine exploration. Therefore the detection grid is denser than that speculated in regulations.

1.2. Key technical problems in actual exploration of water-inrushing passages

1.2.1. Central loop is selected as the working device

1.2.2. Principle for selecting detection grid in detection area

This kind of exploration is high precision exploration with target, for concrete water-inrushing point and passage, the designed detection grid must have 3~5 detection point within a known abnormal body. It is required that in the profile point interval and observation can reflect clearly and completely the details of the anomaly, the extent of geophysical detection must over twice bigger than that of the known geological abnormal body. Therefore such a detection grid can be densified according to actual situation.

1.2.3. Principle for selecting time window and data acquisition mode

The depth range of target strata or geological abnormal bodies must located in the middle of the time window, the acquired data should not be the data collected by the past 20 channels. High density acquisition mode, for example 40~100 channels of log equal interval, and acquisition of high density arithmetic equal interval should be used, so as to prepare for the fine interpretation in the next stage.

1.3. Reliability assessment method of data acquired in field

For conventional hydrological geophysical exploration, the data quality can be checked and assessed following "Technical regulations for surface transient electromagnetic method". For high precision exploration of concrete water-inrushing passages, there are higher requirements, i.e. the data of the target depth must be checked by repeated detection. When there is no position error, the root mean square relative error must be less than 4%（it is 5% in the regulations） to ensure the reliability of data acquired in the field.

1.4. Inversion interpretation method

In the past, TEM data interpretation used mostly qualitative analysis of measured ρ_τ curves, pseudo ρ_τ section and iso- ρ_τ plane, as well as semi quantitative interpretation method by defining related interface on the basis of the turning point on $S_\tau(h_\tau)$ or $S_\tau(t)$ curves. These methods are far from meeting the actual need of safe production in coal mines.

For high precision exploration of concrete water-inrushing passages, more precious inversion interpretation methods are needed. At present, two dimensional inversion technology is not quite mature, one dimensional inversion interpretation method can be used(relatively mature), for example one dimensional inversion of non-linear least square，one dimensional inversion of pseudo-MT Bostick, one dimensional “smoke ring” rapid inversion etc[1][3][4] to interpret anomaly of low resistivity. Then, spatial extraction technology of low resistivity anomaly resulted from inversion(equivalent to secondary inversion interpretation) is used to sever abnormal body of low resistivity, finally to form spatial distribution map of abnormal body(for example profile along a survey line or a survey point, plane at a depth), which can meet the requirement of high precision exploration.

2. Effect of the application of TEM method

2.1. Effect of detection of passages inducing flooding of mines by water-accumulating abandoned mines

Flooding accident which was caused by water from abandoned mine and induced the most heavy casualties in Chinese history: on 7 August 2005 in Daxing mine of Xingning City, Guangdong Province , a huge water penetration accident occurred [20]，more than 15 million t water from a abandoned mine flooded the mine in 1.5 h, 123 underground miners all lost life.

Hydrogeological generalities: the extent of flooded mine was from-420 mto+262 m，6 km long along strike. Because the water-isolating pillar of the mine had been destroyed by abandoned small mines， the mine, abandoned small mines and the surface were connected, so precipitation on the surface infiltrated directly into the mining district. It was estimated that the static water volume in the mine was over 15 million m3, predicted dynamic water volume was about 2 000 m3 / h. The elevation of the main shaft mouth was +282 m，the coal seams were mined by three levels below -290 m, the lowest mining level was 420. The surface elevation of the mountainous area is +350 m~+390 m，the depth of the target horizons was 550 m~700 m.

Task for geophysical exploration: emergency rescue, fast exploration of water-penetrating passage in water-isolating pillar within the key section at level -180 m~-290 m, analysis and inferring of the position of the potential water-penetrating passage, providing scientific basis for blocking the passage.

Design of geophysical exploration: central loop device was used, with safety-ensuring pillars as the center, within a area of 900 m×200 m, 9 lines were put with point interval of 10~20 m and line interval of 25 m. Transmission frame was 600 m×800 m，data were acquired by 30channels, and PROTEM67 made in Canada was used.

The detection was undertaken by Xi’an Branch of China Coal Research institute(with assistance of Beijing Ouhualian Science & Technology Ltd., Institute of Geology and Geophysics of Chinese Academy of Science, and others) and accomplished in 5 days. Within the detection extent, only one abnormal area was found. The eastern boundary of the abnormal area was the thrust fault F16（a boundary fault）, it was inferred that the fractured zone of F16 and coal seam with high dip（>50°）induced water penetration after fall of water-isolating pillars to form a water-abundant area— the unique abnormal area of water-penetrating passage. Its distribution regularities were : within level-180 m~-290 , the passage was upside down speaker wider and wider downwards, the most narrow section was about 90 m（near lines 7~9）, horizontal width was about 140 m, the widest section was about 140 m（near lines 4~7）. See Fig.1. According to comparison to result that the expert team dealing with the accident inferred from known geological data, the geophysical result was considered completely correct.

2.2. Effect of hydrological geophysical exploration in mining district of coal mine

In 13th mining district(north) of Gaocheng mine, the major mined seam was seam II_1 . It's roof was a huge nape(a sliding structure) [21]. According to known data, fractures were relatively developed in the roof , overlaying interbedded sandstone and mudstone, contained a lot of water. This fracture water and confined water in the floor of seam were very unstable and hazardous for driving of roadway and mining of working face. Every year water bursting and inrushing occur in several working faces, the sever ones flooded working faces , causing heavy economic lose.

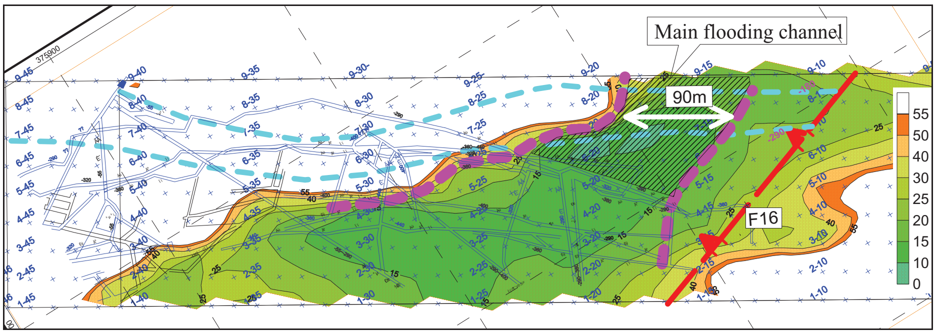

Fig.1. Plane of anomaly of low TEM apparent resistivity

Task for geophysical exploration: (1)To detect mainly the planar distribution extent of water-abundant zone of roof aquifer and water-conducting structures for seam II_1(within 120 m above the seam); (2) to detect the planar distribution extent of water-abundant zone of floor aquifer and water-conducting structures for seam II_1(within 30 m below the seam); To analyze qualitatively the distribution regularities of water-abundant zone in detection area. The depth of the target horizon was 280m~480m。

Design of geophysical exploration: central loop device was used, the density of detection grid was 50 m×25 m， survey lines were approximately perpendicular to the strike of major structures. The transmission frame was 450 m×450 m，data were acquired by log equal interval 20 channels, the frequency of power was 6.25Hz，V5 made in Canada was used.

The detection found that coal seam II_1 and the upper strata had water-bearing section with different water abundance, of them the interval at 100~120 m above the seam had the largest scale and biggest intensity of water abundance, followed by the interval near the seam. Production verified that water inrush occurred when excavation went into geophysically abnormal area(see Fig.2). At 5 locations of the roof, 1 location of the floor, 1 location and 1 location of water drainage entry in roof water inrushes occurred successively, water inflow ranged from 40 to 120 m^3/h， the position of water inrushes coincided completely with geophysical data. The mine operator did not believe at the beginning, trusted completely geophysics, on the basis of geophysical data, arranged again reasonably working faces, avoiding effectively further water inrush and ensuring safe production.

2.3. High precision detection effect of water-inrushing structures inducing flooding of mine

A water inrush occurred on 1 March 2010 in air return entry (level +870) in floor of seam 16 in the front of excavation heading in Luotuoshan mine of Shenhua Wuhai Energy Co. Ltd16 [22], the peak water inflow was about 72 000 m^3/h. it was the second largest water inrush in Chinese history of water inrush in coal mines, the mine was flooded during short time, causing 32 deaths and 115 injured.

Hydrogeological generalities: in Luotuoshan mine field the major coal bearing strata are Upper Carboniferous Taiyuan Formation（C_{2t}）and Lower Permian Shanxi Formation（P_{1s}）. Groundwater recharge from surface water is poor, generally coal measures and overlying sequences contain little water, only local places with developed fractures contain a little bit more water. Underlying Ordovician limestone is rich in water. The elevation of water level of Ordovician limestone aquifer is +1259.21～+1269.49 m. The water pressure of Ordovician limestone that the floor of the air return entry of 16^{th} seam bears is over 4.1MPa. There is 34 m from 16^{th} to Ordovician limestone, no complete impermeable bed exists. Ordovician limestone may be the major source for water recharge in the mine.

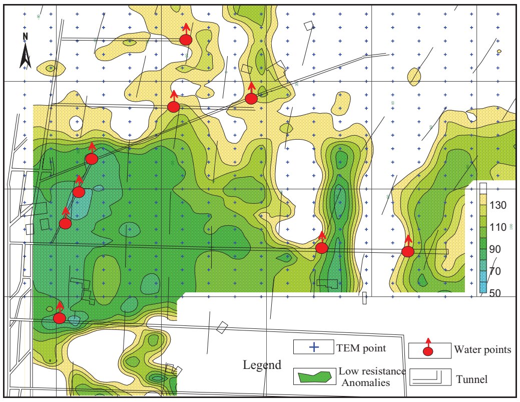

Fig.2. Plane of anomaly of TEM low apparent resistivity in 13thmining district of Gaocheng mine

Task for geophysical exploration: to conduct emergency rescue, according to the distribution features of geophysical abnormal area, to analyze the nature and the position of water-inrushing passage. The detection depth was not less than 530m（100 m inside Ordovician limestone）; to interpret and predict other potential geophysical abnormal bodies in the area.

Design of geophysical exploration: the maximum depth of the target horizon was 600 m. Central loop was used, the density of detection grid was 10 m×10 m, data were acquired by log equal interval 100 channels, Canadian V8 was used. Table 1 showed the major working parameters.

Xi’an Branch of China Coal Research Institute undertook and accomplished the detection task in 5 days. High density TEM technology was used to conduct fine detection of the area of 800vm×200 m nearby the water-inrushing point. As the result, it was found: 1）inside Ordovician limestone at the detection extent there existed an abnormal nearly northeast—southwest zone of low resistivity, it was inferred as a strong runoff zone inside Ordovician limestone, and the extent of water-abundant abnormal area in Ordovician limestone tended to increase downward; 2）Nearby water-inrushing point, the abnormal area of low resistivity extended from the top of Ordovician limestone to coal measures, locally crossover 16th seam to nearby the floor of seam 9, locally the width of the anomaly was less than 20m(as shown in Fig.3).

Verification: borehole Z2-1 had a fall through of 12.5 m at depth of 409.5 m～422 m, according to analysis, the position of the fall through was a void cave at the top of water-inrushing collapsed column. The horizon of 16th seam at this place was 414 m～421.8 m, the horizontal distance from the position of the fall through in borehole Z2-1 to the air return entry of 16th seam was 4.8 m. it was verified that water inrush in entry of 16th seam was induced by local collapse of strata(local collapsed column), the source was Ordovician limestone water.

Table 1. TEM major parameters

Device type	Central loop
Number of channels	100
Stimulating frequency	8.33Hz
Stacking number	500(variable)
Loop frame	600m×600m
Area of reception coil	100m^2
Transmitted current	21A
Adopted system	Canadian V8

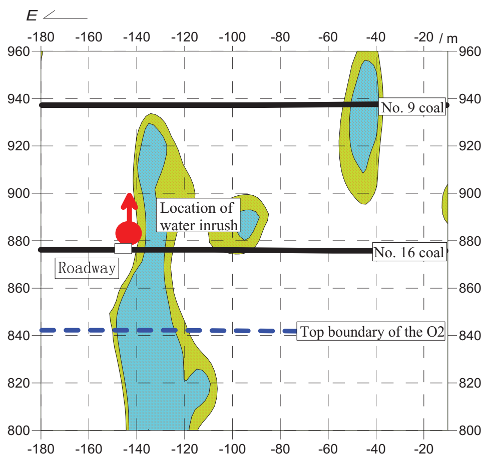

Fig.3. Section of anomaly of low TEM apparent resistivity (along point 17)

3. Conclusion

Transient electromagnetic method observes directly pure secondary field, eliminates the influence of primary field in frequency domain method, is characterized by high sensibility to bodies of low resistivity, higher transverse resolution(it can resolve water-conducting structures of over 400 m deep and dozen m transversely wide), little topographic influence and fast operation. It can rapidly and accurately accomplish detection to locate water-inrushing structures, to save time for emergency rescue during flooding accident in coal mines.

Since recent years, the effect of application has been evident in surface detection of water-inrushing passage inducing flooding of mines by water-accumulating abandoned mines , high precision detection of small water-inrushing structures inducing flooding of mines, integrated detection Ordovician limestone water, hydrogeological exploration of mining district of relatively large area(including water-bearing fault, karst, water-inrushing and conducting passage, water conducting or bearing collapsed column), transverse resolution of surface exploration has only error of one point interval, the depth of conventional exploration is up to 1 000 m. The technology has optimistic prospect of application in hydrogeological exploration in Chinese coal mines.

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