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A Review of Electrical and Electromagnetic Methods for Coal Mine Exploration in China

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ABSTRACT During the past 20 years, due to the rapid development of China's economy, the amount of coal mining activities has rapidly increased, which has led to a large increase in the number of mined-out areas. Therefore, the role of geophysical exploration in coal fields has changed from the detection of coal resources to engineering geological environmental investigation. The safety, efficiency, and green production of coal mines require more advanced geophysical detection technologies. In particular, the accurate detections of the locations of water-rich mined-out areas, as well as concealed water diversion channels, have become the main focuses of coal electrical methods in recent years. Therefore, electromagnetic methods have become the main means of hydrogeological investigations and deep explorations in mine-out coal areas. In this study, a common DC method was briefly introduced, along with an induced polarization method. Then, three representative electromagnetic sounding methods, including a surface frequency-domain electromagnetic method, time-domain electromagnetic method, surface to air electromagnetic method, and mine electromagnetic method, were respectively introduced.

INDEX TERMS Electromagnetic methods, coal mines, coal resources, mining safety procedures.

I. INTRODUCTION

Geologically, coal measure strata are relatively flat and their structure is relatively simple. The basement of coal measure strata is Ordovician limestone, with high resistance, which is different from the upper strata. The upper interface of Ordovician limestone can be determined by the electromagnetic method, thus the occurrence state of the coal measure strata can be inferred by the same means.

During the 1950s, both direct current resistivity sounding methods and resistivity profiling methods were the main methods used in coal mine resource investigations. For example, these types of methods were used to discover the distributions of hidden coal deposits and tectonics, as well as to determine the shapes and burial depths of coal-bearing basements. As a result, coal electrical methods had successfully contributed to the increase in coal mine resources [1], [2]. During the 1960s, apart from the coal explorations conducted in concealed areas, electrical methods began to be applied in other types of geological and engineering explorations, such as the mapping of Karst, ancient riverbeds, and faults. Moreover, a large number of tests and drilling records have shown that electrical methods had displayed significant advantages in geological mapping, finding hidden coal deposits, detecting faults, mapping karst fissure development zones, and determining hidden water sources.

Then, after the 1980s, coal electrical prospecting began to enter the digital age. With the introduction of globally advanced technologies and equipment; improved adaptability to various working environments; and improvements in the

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reliability of solving the geological problems, China's coal electrical prospecting technologies and abilities had been greatly improved [3].

It has been found that since 2000, the water accumulations in goafs have become a threat to China's coal mine safety production and nearby residents. After the coal mine goaf is filled with water, the apparent resistivity value becomes obviously low. Due to the fact that the electromagnetic method is sensitive to the low resistance target body, and the water-bearing goaf can be delineated by the electromagnetic method. Moreover, seismic exploration has always played a leading role in surface exploration, but in coal mine tunnel exploration seismic exploration is limited in its effectiveness due to the complexity of the exploration environment, and the electromagnetic method can give full play to its own advantages. Therefore, water-rich mined-out areas have become the main targets of coal electrical explorations.

The central and western areas in China are mostly covered by sand or loess, and the surface gullies tend to crisscross. In such situations, the impacts of unstable ground and terrain may seriously restrict the applications of the DC method. As a result, controlled source audio magneto telluric (CSAMT) and the transient electromagnetic method (TEM) have become the main methods used in the detection of mined-out areas.

Traditionally, CSAMT uses square-wave sources to excite transition fields in the Earth, then uses a receiver to receive the primary and secondary field related different frequencies to achieve the purpose of electromagnetic sounding. TEM uses step-wave sources to excite transition fields in the earth. Vortex alternating electromagnetic fields are formed in the earth at the moment of power-off. The attenuation characteristics of the secondary induced electromagnetic fields produced by underground medium over time are then measured, the electrical conductivity and locations of underground inhomogeneous bodies are determined by analyzing the measured signals. In this way, the distribution of underground goafs can be accurately obtained [4], [5]. TEM is sensitive to low resistance water-rich goafs, and has the advantage of convenient construction. As a result, TEM has become the first choice for detecting the water-rich mined-out sections of major mining areas in China [6].

In 2007, Liu and Yue introduced TEM from the ground to the underground areas of coal mines. They had successfully proposed a fan-shaped observation technology for the advanced detection of anomalies in mine roadways. Also, Yu *et al.* [7] summarized the main exploration progress of mine transient electromagnetic method (MTEM). As of 2008, several scientific research institutes and enterprises, including the China University of Mining and Technology, had published many successful cases related to the detection of goaf water using mine TEM. The notable progress made in this research filed had mainly included the following: (1) An analyse of the characteristics of multi-turn small loop devices and their effects on observation results; (2) A clearer understanding of the anomalous response characteristics of typical geological bodies; (3)The establishment of a theoretical basis for the spatial positioning of anomalous bodies; (4) The preliminary grasping of the law of time-depth conversion, which had subsequently provided a theoretical basis for quantitative solutions [8].

In recent years, with the rapid development of electronic technology and computing technology, coal electrical prospecting technology has also been greatly improved. For example, major advancements have been achieved in the areas of geological radar technology; TEM technology; geo-electric imaging technology; CSAMT technology related to data acquisition equipment; electromagnetic imaging technology; 2D and 3D resistivity inversion reconstruction technology; narrow frequency pulse electromagnetic wave reflection technology; and electromagnetic quasi-seismic interpretation techniques. The above-mentioned methods have played important roles in coal explorations, hydrogeology, engineering geology, mine geology, disaster geology, urban geology, and environmental geology.

II. GEOLOGICAL MODEL OF A TYPICAL COAL MINE

China's deep coal strata are known to be complex and diverse, and characterized by strong tectonic stress, severe mining disturbances, and multiple underground hazard sources. These include the high probability of coal and gas outbursts, rock bursts, water inrushes, and other dynamic disasters. Therefore, it is important to select effective methods to coordinate the contradictions between the complex mining environments and safe and efficient mining practices. This has become a major challenge for deep-buried coal resource mining activities. Water damage is one of the main hidden dangers in mine production. Accidents have frequently occurred in coal mine due to the unknown risks of hidden water-rich areas and accumulated goaf water [9], [10]. Electrical sounding method is currently the main methods used for mapping geological structures, searching for mine water inrush channels, and so on. Electrical sounding mainly utilizes in such exploration objects as coal seam faults, collapsed columns, goafs, and so on.

Many fracture structures can be observed in the coal-bearing strata of mining areas, which tend to break and displace the rock masses located near fault areas. This affects the overall integrity of the strata, and channels are often formed for various water-filling sources to pour into the mines in the working areas (Fig.1). In coal measure strata, faults tend to often form fault zones with a certain width. The width and formation of fault zones are related to the drop of faults and the lithology of the two plates. Water inrush from coal-bearing strata is one of the main water hazards in mines. Water inrush in fault zones will result in obvious enhancement of the electrical conductivity, which will be different from the electrical properties of the two fault plates. This makes such areas qualified for electrical explorations.

The term coal seam collapsed column refers to the huge thick soluble rock masses buried in the lower coal strata, which forms very large Karst voids under the action of

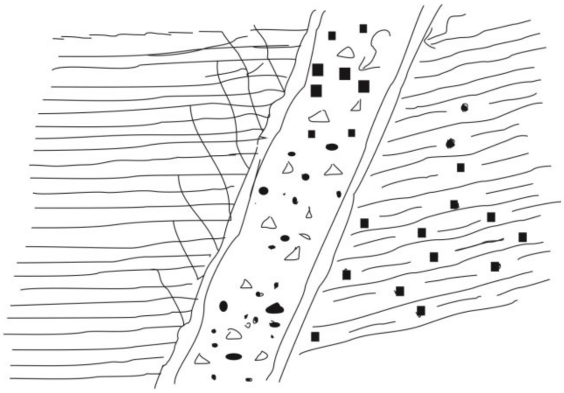

FIGURE 1. Coal seam fault zone.

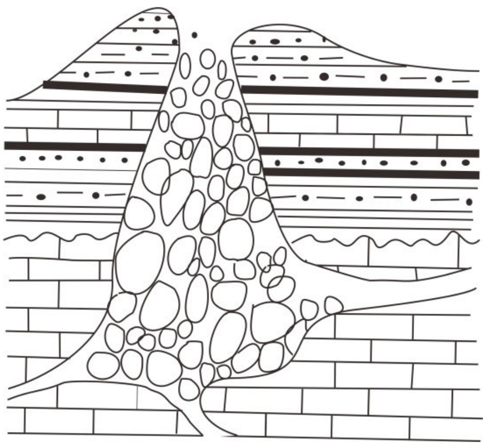

FIGURE 2. Collapsed column of a coal seam.

groundwater corrosion. The effects of gravity cause the overlying rock masses to collapse downward and fill in the dissolution space. Since these formations are similar in shape to columns, they have been referred to collapsed columns, as shown in Fig. 2. The collapsed column can be divided into two types according to their water-filling characteristics: The first is non-water-bearing collapsed column, and the second is water-bearing collapsed column. The collapsed rock masses of the former are filled with Karst caves and caprock subsidence spaces, which lead to the disconnection of each aquifer fissure in the overlying stratum. In such cases, the dissolution process will then terminate, and the collapsed column will lose its water-permeability condition. The fillings in the water-bearing collapsed column are not compacted. Therefore, the vertical hydraulic connections tend to be smooth and several aquifers in the coal seam floor and roof may communicate with each other. This will result in high-pressure groundwater filling the pillar areas, as well as strong karstification. Once water-rich subsidence columns exist in a coal seam, or in its roof and floor, the electrical conductance will be significantly enhanced. As a result, an obvious electrical difference will occur between the coal seam and the surrounding rock masses. This condition will then make it possible to carry out electrical explorations [9].

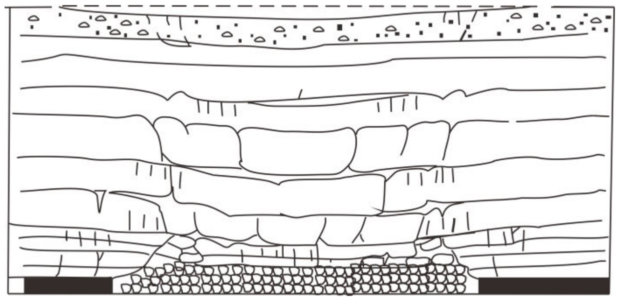

FIGURE 3. Mined out area of a coal seam.

It is known that mining goafs will be formed after a coal seam has been mined out. The changes in the stress conditions cause the propagation characteristics of the geophysical field to become altered. The overburden strata in a goafs will collapse and fall, forming bending zones, fracture zones, and collapsed zones in vertical direction, as illustrated in Fig. 3. After a large number formation of these types of goafs, the roofs of the coal seams will become deformed, and then collapse under the influence of the overlying strata and self-weight. Under typical conditions, low resistance changes in the local depression of the apparent resistivity isoline will be observed. Furthermore, as local water-rich goafs form in the coal seam and its roof and floor rock strata, the electrical conductivity will be significantly enhanced, and a significant electrical difference will be formed between the goafs and the surrounding rock masses. These types of resistivity difference create opportunities for electrical explorations [6], [11].

III. DIRECT CURRENT PROSPECTING METHOD

The direct current (DC) prospecting method is based on the electrical conductivity difference of rocks (ore) in prospecting crusts. The method can be used to solve various geological problems through the observation and examination of the distribution laws of stable artificial electric current fields [12], [13]. The DC method is mainly used in geological mapping; coal prospecting; hidden geological structure detection (for example, faults, collapsed columns, karst, and so on); mine water inrush channels mapping; coal seam scour zone delineating; and so on. In accordance with the different geological tasks and geoelectrical conditions, different types of devices can be used for DC prospecting in coalfields. Also, the construction methods are flexible and diverse.

A. GROUND DIRECT CURRENT SOUNDING METHOD

For the ground direct current sounding method, based on the conductivity difference between rock and ore, specific artificial steady current fields are first established using power electrodes (A or A, B). Then, in accordance with the potential difference between the measuring electrodes (M, N), and the relative positions between the electrodes, the apparent resistivity can be calculated. On this basis, the occurrence state and influence range of the geological anomalies in an exploration area can be accurately deduced.

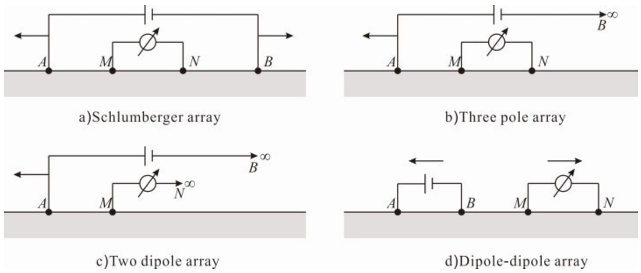

FIGURE 4. Different DC electric sounding devices.

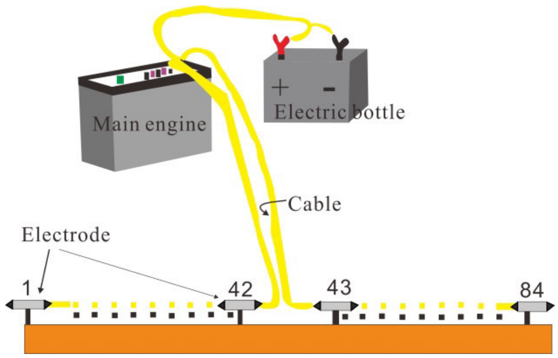

FIGURE 5. High density resistivity device.

When using the aforementioned method, power electrodes (A, B) are used as transmitters in order to excite current to the underground. Then, measuring electrodes (M, N) are used to measure the potential difference between two points in the earth. The electrodes and measured points are moved according to the selected distance sequences. A diagram of the specific device is shown in Fig. 4.

B. GROUND HIGH DENSITY RESISTIVITY METHOD

The high-density resistivity method is a multi-device and multi-offset method which combines the functions of sounding and profiling [14], [15]. This method can perform multi-device data acquisitions with one pole distributions and highlight abnormal information by calculating the ratio parameters. The main characteristics are as follows: (a) Once the electrode layout was completed, it will not be required to move the electrodes in the field measurement; (b) Then, using an electrode switch, the scanning and measuring of the various electrode arrangements could be realized, and abundant geo-electric section information could be obtained; (c) When compared with the traditional resistivity methods, the ground high density resistivity methods have the advantages of low construction cost, high efficiency, abundant geological information, and convenient interpretations. The specific device diagram is shown in Fig. 5.

C. DIRECT CURRENT RESISTIVITY METHOD FOR MINE

In this method, the measuring points of the mine DC resistivity method are arranged along underground mine roadways. The movements of the electrodes will determine the working principles of the mine resistivity method. The arrangements of the electrodes will determine the resolution and

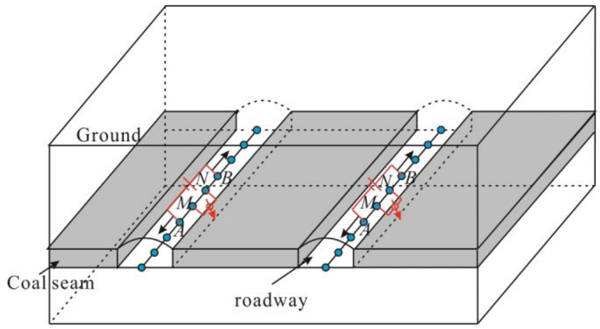

FIGURE 6. Coal layer floor surrounding an underground roadway.

electrical response characteristics of the mine resistivity method. Meanwhile, the relative positions between the exploration targets and the measuring points will determine the pole positions of the mine resistivity method. The basic principle of the DC resistivity method for mine is similar to that of the ground DC resistivity method. However, the mine direct current resistivity method collects data in underground roadways, and the DC field is distributed throughout the entire space. Therefore, in accordance with the different types of electrical devices and the nature of the geological problems to be solved, the direct current resistivity method for mine can be currently subdivided into roadway roof, floor electrical sounding method; layer sounding method; direct current advanced exploration method; direct current perspective method, and so on. The specific device diagram is shown in Fig. 6.

D. DIRECT CURRENT AUDIO ELECTRICAL PERSPECTIVE METHOD FOR MINE

It has been determined that the electrical difference among various underground rock masses will affect the distribution of the artificial electrical fields. Therefore, based on this, DC audio electro-perspective method can solve hydrogeological problems by measuring the distributions of artificial electric fields using specific instruments in underground mines. Due to the ''absorption'' effects of the conductors, the current density will decrease and the apparent conductivity will increase at corresponding receiving positions in mining roadways. Then, when compared with the solid medium, the water medium in the mine will be characterized by low resistance. In other words, when fissures occur and water storage has formed in the strata, those sections will show the characteristics of low resistivity. In the present study, the water-bearing structures were simulated as local anomalous bodies with good conductivity. Then, the water volumes and water containing anomalies were detected through the electrical field induced by the point power. It was found that when compared with the host rock, the abnormal parts of the aquifer structures were highly conductive. Generally speaking, the magnitudes of the water inflow will be positively correlated with the abnormal variations in the apparent conductivity. For example, the higher the apparent conductivity and the greater the anomaly range are, the larger the formation water-bearing

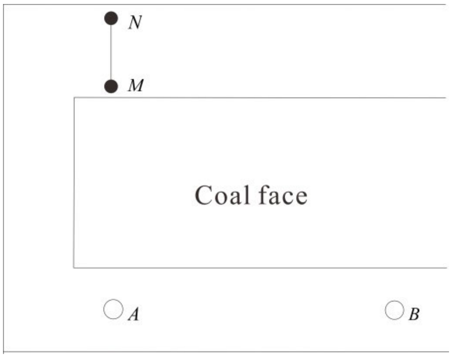

FIGURE 7. Audio frequency electric perspective working device.

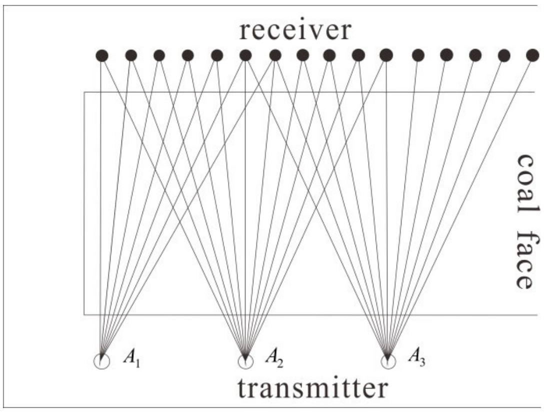

FIGURE 8. Audio electrical fluoroscopy measurement device.

capacity will be when the vertical structures of the formations are the same and the horizontal structures are relatively homogeneous.

Unipolar (power supply) -dipole (receiving) device is used in mine electrical perspective construction. That is to say, the transmitting electrode (power supply electrode A) is laid at equal distance on one side of a roadway, while the other transmitting electrode (power supply electrode B) is arranged at a relatively infinite distance. As a result, one side of a working face will correspond to a power supply point, and then a pair of electrodes (receiving electrode M, N) will be located along the roadway, as shown in Fig. 7. When such a device is used for construction purposes, the connection line will be vertical to the roadway direction. The aforementioned working device is detailed in Fig. 7.

For Audio Electrical Fluoroscopy, the emitter will be located at one point in one roadway, and the receivers will be located within a certain range of the corresponding points in another roadway. This will effectively form a sector on the plane, as shown in Fig. 8. Therefore, from a spatial perspective, a rectangular strip will be formed to repeatedly measure all of the power supply points. Also, the measuring network density will include a 50 m distance of the power supply points and a 10 m distance of the receiving points. Then, observations will be made in the sector symmetrical section of another roadway which corresponds to each launch point in order to ensure that each unit in the survey area has a

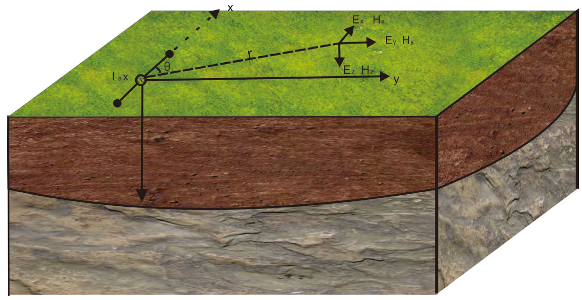

FIGURE 9. Electromagnetic frequency sounding observational device.

coverage of more than three emission-receiving rays. At this point, the power supplies and receptions of the roadways will be exchanged. This type of observation strategy has been found to effectively eliminate the noise outside the detection area; highlight the impacts of the anomalies in working faces; and improve the accuracy of the interpretation results.

IV. FREQUENCY ELECTROMAGNETIC MERHODS FOR COAL MINE

A. GROUND ELECTROMAGNETIC FREQUENCY SOUNDING METHOD

In the early 1960s, frequency sounding methods were introduced from the former Soviet Union. In 1967, China began to develop this type of method, and their first electromagnetic frequency sounding instrument was developed in 1971. The instrument was equipped with 30 frequency points, from 3906.25 Hz to 0.17 Hz. It was a single-channel, dual-frequency points instrument. Moreover, it contained both a transmitter and receiver, and the transmitter had a maximum supply current of 10 A and a transmission power of 8 kW, as shown in Fig. 9. Then, between 1972 and 1973, the Xi'an Coalfield Geological Exploration Research Institute of the Ministry of Coal took the lead in the field of experimental electromagnetic frequency measurements. As a result, studies were conducted in various coal fields, with the main geological object being the fluctuations of high resistivity basement surfaces. These new methods were found to have many advantages, such as: high efficiency; large exploration depths; good resolution; flexible devices; convenient construction parameters; minimally influenced by topographical conditions; strong ability to penetrate high resistivity layers, and so on. Therefore, from 1976 to 1982, Chinese researchers developed intensive learning electromagnetic frequency sounding technology; formed electromagnetic frequency sounding boards and single component interpretation method of electric fields; and studied the topographical effects of the phase conversion of electromagnetic frequency sounding and correction technology.

B. CONTROLLED SOURCE AUDIO MAGNETOTELLURIC METHOD

Controlled source audio magnetotelluric (CSAMT) method is an artificial source frequency domain sounding method which has been developed based on the audio magnetotelluric

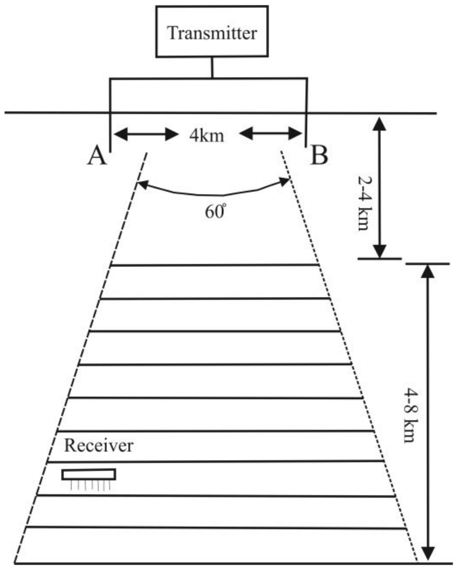

FIGURE 10. CSAMT field site arrangement.

method (AMT) [16]. Since CSAMT was launched in the 1980s, China has achieved many strong geological results in the explorations of deeply concealed metal ore bodies, oil and gas structures, geothermal and hydrological engineering projects. The main features of CSAMT are as follows:

(1) By using controlled artificial field source, the signal intensity will much greater than those of the natural fields. Therefore, the method has strong anti-noise abilities; (2) The measured parameter is the ratio of the electric field to the magnetic field, which can potentially reduce the outside random interference and the influences of the terrain conditions; (3) Based on the principle of the skin depth of electromagnetic waves, electrical sounding in different depths can be carried out by changing the frequency, which potentially improves work efficiency. The electromagnetic sounding of seven physical points can be completed simultaneously by one launch, and the exploration depth can reach 1 to 2 km.

Generally speaking, the lengths of the grounded-wire used in CSAMT range between 1 and 3 km, and alternating current with frequency f will be supplied to generate alternating electromagnetic field. Under normal conditions, the measuring lines will be arranged parallel to AB within sector-shaped areas with 60 degrees tension angle on one or both sides. At present, equatorial dipole devices are mainly utilized to measure the horizontal component Ex, which is positioned parallel to the source, and the magnetic field component Hy, which is located orthogonal to the source. This study's field site layout is shown in Fig. 10.

V. NEW TRANSIENT ELECTROMAGNETIC METHOD

TEM is a time-domain artificial source electromagnetic method based on the principle of electromagnetic induction [17], [18]. There are many types of ground loop TEM devices, such as overlapping loop device, central loop device, dipole device, large fixed loop device, ground electrical source transient electromagnetic method, ground-space transient electromagnetic method, and mine transient electromagnetic method.

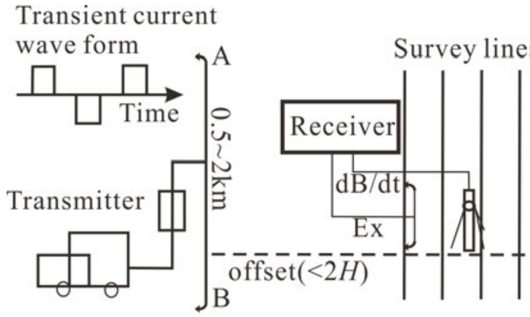

FIGURE 11. Construction layout for the SOTEM.

A. SHORT-OFFSET TRANSIENT ELECTROMAGNETIC METHOD (SOTEM)

Recently, based on the traditional long-offset transient electromagnetic method (LOTEM), a new type of transient electromagnetic device, i.e. short-offset transient electromagnetic method (SOTEM), was proposed [19], [20], [4]. In this new method, 500 to 2,000 m grounded wire is used as the source to supply bipolar rectangular step current with a strength of 10 to 40 A. The signal observation area is within less than 2 times the detection depth (Fig. 11). However, unlike the LOTEM, which uses continuous waveform excitation and observes total field responses at a large offset (generally 3 to 8 times the detection depth), the SOTEM observes pure secondary field response in a small offset. On one hand, the SOTEM has the ability to improve the signal-noise ratios. On the other hand, it reduces the influence of volume effects, thereby greatly improving the accuracy of the processing results. In practical field work, the derivatives of the vertical magnetic field component over time (induced voltage), along with the component of the horizontal electrical field, are generally observed. One transmitter can cover a wide range of measuring points. Therefore, in mountainous areas in particular, the arrangement of the grounded wire source is more convenient.

According to the theory of transient electromagnetic field, the measurement of the pure secondary field during pulse turn-offs in the field can achieve the near-source large depth detections of electrical source transient electromagnetic [21]. Therefore, when using single pulse waveform and observing pure secondary field after the pulses have been turned off, the self-field and radiation field can be separated, making the deep detection abilities of short offset possible. Then, after examining the spectrum of single pulse, it can be observed that the amplitude and frequency of the step pulse will be inversely proportional, and the low frequency harmonics will be dominant. Therefore, the separation of the primary field and secondary field can potentially ensure that the small offset observations have the capability of deep sounding. The majority of the existing ground transient electromagnetic

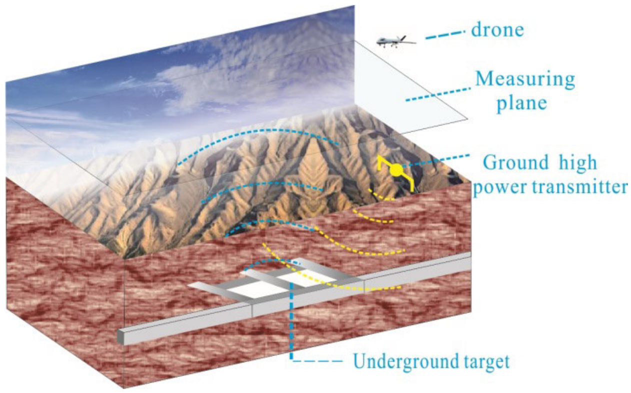

FIGURE 12. Ground-airborne transient electromagnetic method.

instruments use bipolar step waveforms for selection. It has been found that by using these waveforms as the excitation sources, and observing the pure secondary field at the interval between the switching off of the positive and negative power supplies, near-source deep explorations can be realized.

B. GROUND-AIRBORNE TRANSIENT ELECTROMAGNETIC METHOD

On the basis of the electrical source method, Nabighian and Macnae (1991) proposed a ground-airborne TEM, in which electrical sources or loop sources are laid on the ground in order to transmit a high-moment transient electromagnetic field. Then, the signals are collected using probes carried by airborne devices. This method adopts a three-dimensional measurement method of global, high-density, and sweeping surfaces (Fig. 12). When compared with the airborne transient electromagnetic method, it has been found to have a higher signal-to-noise ratio, and its working mode is relatively safe. In addition, since the transmitter is located on the surface, the transmitting power and exploration depth are larger. Therefore, this method is more suitable for the needs of deep prospecting. Furthermore, when compared with the ground transient electromagnetic method, since the measuring devices are located in the air, the working efficiency is greatly improved. Due to these advantages, the ground-airborne transient electromagnetic method has great potentials for applications in swamps and mountainous areas where conventional TEM cannot be carried out.

C. TRANSIENT ELECTROMAGNETIC METHOD FOR MINE

Mine TEM is applied in underground roadways of coal mines using multi-turn small loop devices. When compared with ground TEM, this type of method not only has the advantages of higher resolution, smaller volume effect, fewer influence of host rock, faster measurement abilities, and increased portability, but can also be used to solve mine geological problems which cannot be addressed using mine DC method. These problems include accurate detections of water-bearing structures in the roofs and floors of working faces; advanced prospecting of roadways with limited lengths, and so on [22]. The specific device is detailed in Fig. 13.

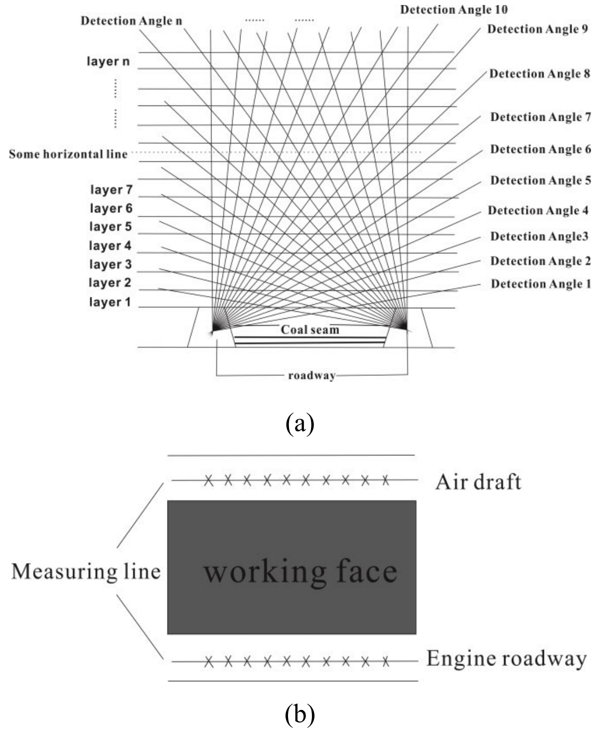

FIGURE 13. Schematic diagram of a transient electromagnetic detection device for mines. (a) Schematic diagram of the vertical line cross-section observations and detections. (b) Schematic diagram of the survey line layout.

D. INTRODUCTION OF COMMONLY USED COAL ELECTRICAL METHOD EQUIPMENT

At the present time, PROTEM, V8, GDP-32 II, Terra TEM and EH4 instruments are widely used. The details of these instruments are as follows:

The PROTEM Transient Electromagnetic Instrument is a time domain electromagnetic instrument developed by the Canadian company Geonics, which has a large market share of such instruments worldwide. It has experienced several updates since it was first produced. Currently, PROTEM47, PROTEM47HP (underground water exploration system), PROTEM57, PROTEM67, and PROTEM67HP (enhanced type) are still widely used.

The V8 Instrument is a multi-functional (MT, AMT, CSAMT, TDEM, FDEM, TDIP, SIP, and all types of resistivity methods) system developed by the Phoenix Geophysical Company of Canada. This device is currently widely used in oil and gas explorations, geothermal explorations, groundwater surveys, crustal and seismic research, active fault research, mineral surveys, and environmental engineering surveys, along with other fields. The V8 Instrument has also been applied in oilfields, coalfields, and railways, as well as other systems worldwide.

The GDP-32II Instrument is a multi-channel receiver of the fourth generation for controllable source and natural field source electrical and electromagnetic detection. It was produced by the Zonge Engineering Company of the United States. It is characterized by having almost all its electrical measurement functions in the middle and low frequency bands. Its electrical measurement methods mainly include DC, TDIP, FDIP, CR, CSAMT, AMT, MT, TEM, and NanoTEM. Therefore, it can be widely used in solid mineral explorations, engineering geophysical explorations, and oil and gas explorations. In addition, it is expected to be adopted in the future for environmental geological surveys and monitoring projects.

Terra TEM was developed by the Monex Geosopeg Company of Australia. The SIROTEM-II instrument, which was developed in 1977, has advanced indicators such as multi-channels, transmitting and receiving, four superimposing options, and setting the sky suppression file. The SIROTEM-III, which was developed in 1990, is a compact, lightweight instrument with a digital transmitter and a receiver which has the ability to work with an external high-power transmitter. This system was continuously improved and updated until the Terra TEM series was introduced. The Terra TEM utilized the most advanced computer chips and touch screen displays. Then, based on 24-bit ADCs, the TerraTEM24 was developed in 2016. It has a multi-channel configuration, in which each channel is independent and data acquisition can be carried out at the same time. Also, by implementing its automatic gain function, the 24-bit resolution can be expanded to 32 bits. In addition, a built-in transmitter or external transmitter can be set up to expand the application scope of the TerraTEM24 system and improve work efficiency.

The EH4 Continuous Conductivity Profile is a new concept conductivity tensor instrument which was developed by EMI Company of the United States. This company is well known for manufacturing high resolution seismographs. The EH4 instrument utilizes the principle of magnetotelluric measurements and sets up a special artificial electromagnetic wave emitter. This type of wave emitter includes a pair of crossed antennas which serve as magnetic dipoles in the X and Y directions. The antenna is portable and is only used for the power supply of ordinary automobile batteries. The instrument is specially used to compensate for the electromagnetic interference harmonics in the quiet areas of magnetotelluric fields, and in the vicinity of several hundred Hz, by transmitting frequency ranges from 500 Hz to 100,000 Hz.

VI. UNDERSTANDING THE FUTURE DEVELOPMENT OF ELECTROMAGNETIC METHODS

China's electrical prospecting of coal-fields began in the early 1950s. Major progress was made in the period of 1970s to 1980s. Then, by the 1990s, with the introduction of digitization, coal electrical prospecting technology had made great progress. Subsequently, an integrated mode of design, acquisition, processing, and interpretation had gradually formed, accompanied by the submissions of important research results.

In the future, research will focus on such concepts as ''large depths, high precision, full spaces, and full fields''; strengthen the basic theoretical research; further develop and improve the basic theories of underground full-space physical fields [23]; and improve the development of full-field detection technology with electrical sources [24]. Also, increased attention will be given to the development of new technologies and methods [25], [26], and further examinations will be conducted regarding the following important areas: Multi-components; arrays; multi-coverage and wide-area observational methods; vector synthesis development; multi-parameter joint interpretation; constrained inversion of geological conditional boundaries and other potential integrated geosciences information; and the strengthening of joint analyses processes between other geophysical methods in order to improve the fine processing of obtained data. In addition, the development of portable, high-power, multi-functional, intelligent, and high-resolution flameproof instruments will be enhanced, along with the use of superconducting probes to collect data and the embedded real-time processing and interpretation of display systems. These future strides will be of major significance for the improvements of fine detection.

VII. CONCLUSION

Coal resource is one of the energy and mineral resources in the word. It almost accounts for 25% of the world's primary energy consumption. At present, coal also is China's basic energy. In recent years, driven by the rapid development of the national economy, China's coal production and consumption showing a rapid growth momentum. Geophysics accordingly plays an important role in coal resource exploration. For a long time, seismic exploration played an important role in coal resources exploration. Coal electromagnetic method was only an important supplementary means.

From the turn of the century, due to the rapid development of China's construction, the amount of coal mining activities has rapidly increased, which has led to a large increase in the number of mined-out areas, especially water-rich zone. Therefore, electromagnetic method exploration in coal fields became major tool in coal mine hazard investigation, as well as concealed water diversion channel.

The DC method was formerly used for surface exploration, while now it is mainly used for coal mine tunnel exploration. Coal mine production is a dynamic mining process. It is a good direction to use geophysical methods for dynamic monitoring in the mining process [27], [28]. For example, related scholars use network parallel direct current resistivity method in roadway or borehole to monitor mining fissures and water diversion channels [29].

Transient electromagnetic method is mainly used for surface water-bearing goaf detection and underground advanced detection. As the detection environment and actual terrain become more and more complex, it is necessary to develop ground-to-air electromagnetic for fast exploration. At the same time, due to geological structure and electromagnetic noise, new technologies, such as multi-components; multi-coverage and wide-area observational methods; vector synthesis development; multi-parameter joint interpretation; constrained inversion, as well as high performance electromagnetic detection equipment, are urgently needed for research and development. These future strides will be of major significance for the improvements of fine detection.

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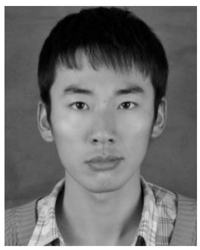

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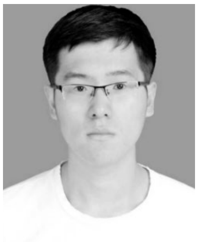

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