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REVIEW

A Review of Geophysical Exploration Technology for Mine Water Disaster in China: Applications and Trends

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Abstract Geophysical exploration can be effective in detecting and monitoring potential sources of coal mine water in-rushes and underground watercourses. Generally, in-mine seismic, DC resistivity, and transient electromagnetic methods are used for such purposes in China. However, such technologies can be influenced by many factors, such as roadways, fissures in the surrounding rocks, and various secondary conditions. Our review of current geophysical methods and tools concludes that further basic research should be carried out on geophysical field propagation in the whole space, data collection methods, and inversion methods appropriate for the special environment of coal mines. Moreover, borehole and roadway space should be designed to incorporate effective geophysical drilling, cross-hole exploration, drilling–roadway exploration, and roadway–roadway exploration. Future hydrogeophysical exploration research should focus on comprehensive geophysical methods combining multi-field synergistic observations with multi-field data integration and automatic monitoring as well as early warning systems for mine water disasters combining real-time processing and analysis of exploration equipment with Internet of Things technology.

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Introduction

Coal mines in China are characterized by great depths, high water pressure at the roof and floor of the roadway, and little geological information about abandoned mines. As a result, mine water inrush is an important factor that impedes mine safety and efficient production (Dong and Hu 2007). A total of 306 water burst accidents killed 1325 people in China during the 11th 5-year plan period (2006–2010). Most of these inrush accidents were due to concealed water-conducting structures and mining-induced fractures that channeled various water sources during roadway excavation and mining (Hu and Tian 2010; Wu et al. 2013a, b). Thus, identifying water-bearing rocks and concealed water-conducting structures, and determining the processes that govern the space distribution and changes around excavated space are critical to preventing water bursts.

It is not enough to rely on traditional geological methods, numerical statistical geological prediction, or drilling and tunneling prospecting. Surface geophysical exploration technologies, such as 3-D seismic, direct current (DC), and transient electromagnetic methods, can provide reliable data on the structural environment and hydrogeological conditions, and are continuously improving, but are still unable to meet the objectives of mine safety and highly efficient production; these require detailed analysis of geological conditions (Danielson et al. 2003). Even with high-resolution 3-D seismic exploration, it is hard to detect secondary faults and other minor geological structures around a narrow coal seam hundreds or even thousands of meters below the earth's surface (Cheng and Shi 2013). Thus, as a fast and nondestructive exploration technology, in-mine geophysical techniques, which rely on close proximity to the exploration target to detect geophysical anomalies, along with strong empirical evidence obtained during exploration and mining, plays an important role in predicting and preventing mine disasters (Liu et al. 2014).

According to the different physical properties being characterized, in-mine geophysical exploration can be divided into seismic, electrical, and electromagnetic exploration technology, along with other methods such as infrared radiation and radon isotope exploration (Fig. 1). Each method has different sub-methods based on the features of the exploration target, measurement parameters, and the spatial position of the observer (Cheng et al. 2014; Lin et al. 2013; Liu et al. 2014). The research and use of in-mine geophysical technologies in China has focused on roadway and coalface excavations where water bursts are most likely and has advanced detection of concealed water-conducting structures. These technologies are also being used for shaft seepage monitoring, backfill grouting detection, roadway lining quality detection, and waterproof pillar exploration (Zhang and Guo 2011). However, these technologies require further improvements in basic theory research, data collection and processing, recording equipment, etc. This paper discusses the application status, existing problems, and development trends of mine geophysical exploration technology related to avoiding water disasters, based on use of seismic, electric, and electromagnetic methods during roadway excavation and coalface mining.

Application of Mine Geophysics for Water Disaster Detection in China

The Mine Seismic Method

Seismic methods analyze the seismic wave velocity, amplitude, frequency, and attenuation to predict the geological conditions ahead of tunneling faces or in the coal panels of the mine. These methods are mainly used to explore for underground watercourses such as concealed water-conducting structures and fissure zones. The most widely used methods are the well-established seismic reflection method, Rayleigh-wave (surface wave) exploration, in-seam (channel wave) seismic survey, and seismic tomography. The seismic reflection method and surface wave survey are often used to detect structures and anomalies ahead of excavation in roadway tunneling faces, while channel wave seismic exploration is based on a transmission observation system, and seismic tomography is mainly used to explore for concealed water-conducting structures in coal panels.

In mine seismic reflection, an observation system is laid out in the tunneling face of the roadway or behind it to detect any hidden geological structures ahead of the

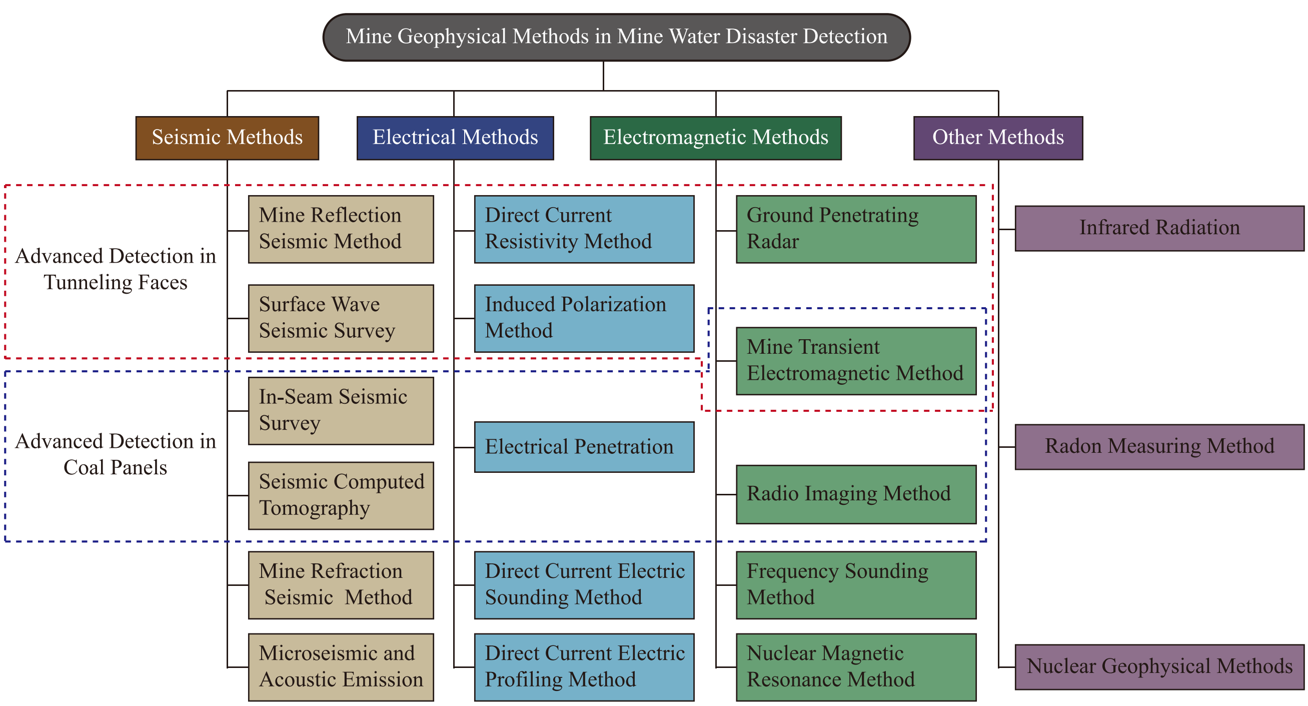

Fig. 1 Main in-mine geophysical methods for water disaster detection in China

tunneling face that might induce water disasters. Compared with Rayleigh wave exploration, seismic reflection can explore to greater depths with higher precision. Since the spatial form of underground roadways is similar to that of tunnels, some tunnel seismic reflection prospecting methods were first used in mines, such as the tunnel seismic prediction method developed by Amberg Measuring Technique Ltd, Switzerland (Dickmann and Sander 1996), horizontal seismic profiling by OYO Corporation, Japan (Inazaki et al. 1999), tunnel reflection tomography by NSA Engineering, USA (Otto et al. 2002), and the integrated seismic imaging system developed by the GFZ Research Center, Germany (Borm et al. 2003). Comparing mining and transport tunnels, there is a difference in geological conditions, roadway size, and the relationship between the excavation and stratum space. In particular, roadways in coal seams are generally parallel to the stratum, causing some of the seismic waves to show geometric propagation characteristics of guided waves. The wave fields in mine roadways are also more complex, including body waves, surface waves, acoustic waves, and guided waves. To investigate the geologic features of coal mines, Chinese scholars have introduced reflected-wave tunnel seismic prediction (RTSP), mine seismic prediction (MSP), and multi-wave and multi-component seismic exploration (Liang and Song 2009; Shen et al. 2009; Zhang et al. 2007). Considerable progress has also been made in seismic data processing and imaging. Mine seismic reflection method can now explore the lithologic interface and tectonic zone about 100 m ahead of the roadway. Given this exploration range and its high resolution, mine seismic reflection is sensitive to geological anomalies, especially faults. However, the narrow observation space inside a roadway and the effect of multiple reflections in the 3-D rock mass can make data processing and data interpretation difficult.

The seismic transmitted wave method generates seismic source explosions in a roadway and records the seismic waves in other roadways of the coal panel. The vibration signals received are divided into different wave groups according to their travel times. Pressure waves (P-waves), which are characterized by low amplitude and high frequency, arrive first. Shear waves (S-waves) are the second to arrive, with their higher amplitude and lower frequency signals. Channel waves are the slowest, and have the highest amplitude and high frequency signals (Fig. 2a). The seismic velocity tomography of these three wave groups can be used to detect structures, coal thickness changes, and areas of stress concentration and gas enrichment in the coal panel (Cardarelli and Cerrto 2002; Zhang and Liu 2006). Traditional P-wave and S-wave tomography are based on the theory of minimum time and mainly reflect the conditions of the roof and floor of the seam, while the tomography of the channel waves, which are specific to coal seams, can provide more direct information about the seam itself. The geological profile of a coal seam typically shows a low-velocity layer that forms a physical “waveguide”. Multiple total reflections from the top and bottom interfaces of the seam trap some of the wave energy inside the coal seams and the neighboring rocks. Because this energy does not dissipate much, it can propagate long distances and its wave characteristics are easy to identify (Krey et al. 1982; Yang et al. 2009). The vibration components of the channel waves with their different frequencies and propagation velocities create a dispersion pattern that reflects the characteristics of the roof and floor lithology, coal seam thickness, coal seam density, and structures in the panel (Fig. 2b) (Ji et al. 2012; Räder et al. 1985). Thus, through tomography studies, we can obtain seismic parameters, such as the propagation velocity of channel waves with different frequency and energy attenuation (Ford et al. 2010); using inversion, the structural development, coal thickness changes, and areas of stress concentration can also be modeled (Yang et al. 2014).

The mine seismic method boasts high precision, long exploration range, and sensitivity to locating geological structures. However, it is also delicate and easily affected by many factors, particularly the seismic source and the geophone coupling used for data acquisition. Sensors arranged on the roadway surface or in boreholes can be affected by the excavation damage zone, sound waves, and other construction machinery vibration, which can make it difficult to acquire high quality data and can reduce detection accuracy. In addition, in gassy mines, a high-energy explosive source is typically not allowed, so a low-energy hammer source is usually the only option.

The Mine Direct Current Method

While seismic exploration can distinguish between wave impedance interfaces (velocity × density), it is not sensitive to water saturation of the coal and rock mass. The difference in water content is more easily detected by measuring electrical properties, since it typically changes the spatial distribution of the electric field (artificial or natural). The mine DC method uses changes in the electrical property parameters, such as the medium’s conductivity, dielectric properties, and polarization characteristics, to analyze the medium’s lithology, water content, and structural development. This approach has been used in China for 50 years. The introduction of high-density electrical methods in the late 1980s improved the results of water content measurements in rock strata and the prediction of water inrush from coal mine floors (Liu et al. 2005).

However, mine safety exploration focuses more on the distribution of water bodies and water movement within the unexploited areas ahead of the tunneling face and the

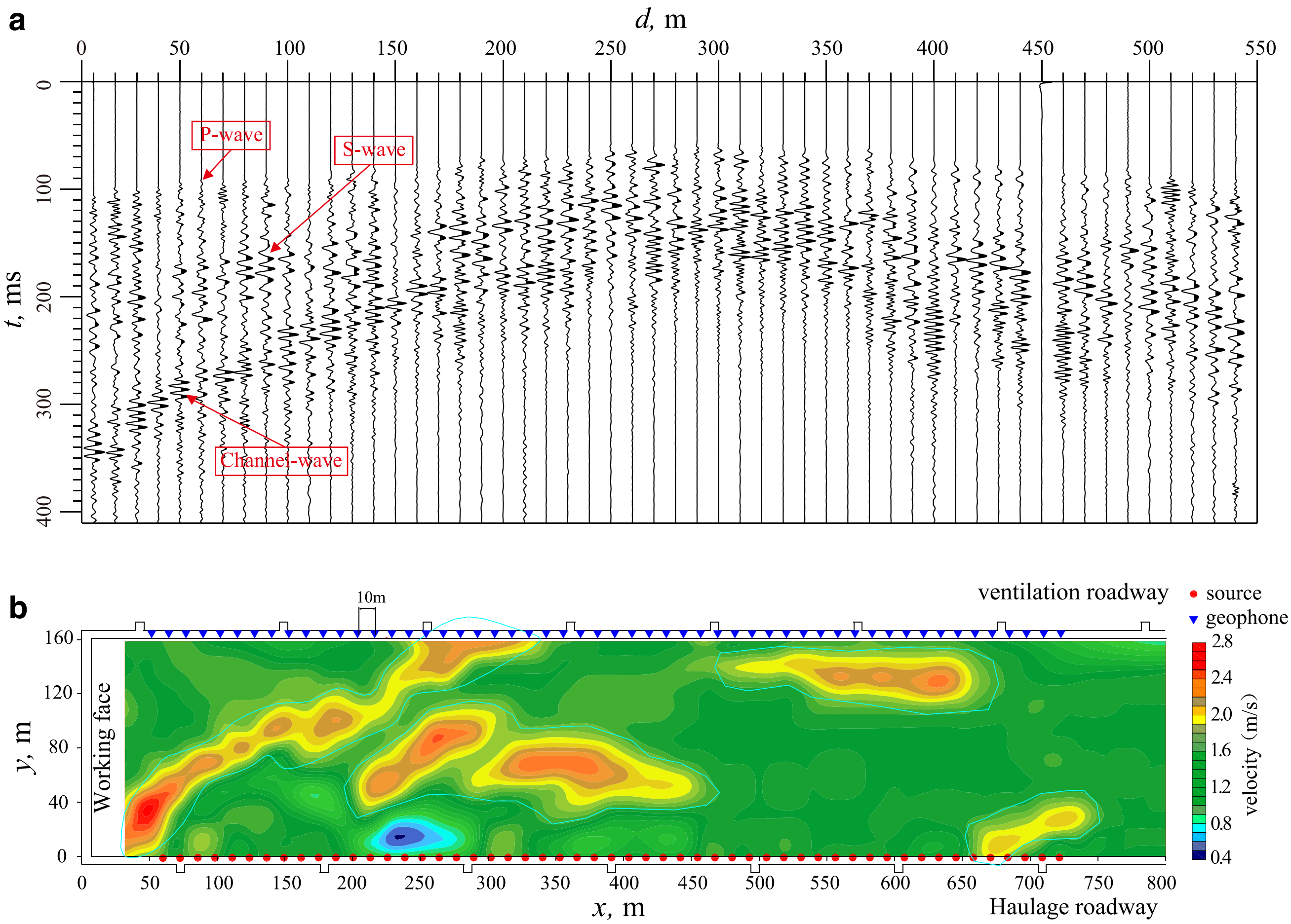

Fig. 2 Transmission wave seismic exploration: **a** measured seismic record—the direct P- and S-waves and channel waves can be distinguished by their travel times and frequencies; **b** channel wave tomogram at a constant frequency of 105 Hz—the *orange* and *yellow areas* are influenced by faults or show where the coal seam thickness decreases; the wave velocities in these areas are nearly twice that in the regular coal seam (the *green areas*)

roof and floor of the working face. Hence, DC resistivity (DC advance exploration) and electric tomography technology have been more widely used in the last two decades. At the same time, use of the induced polarization, charge, and self-potential methods have contributed to the DC method and expanded its use for advanced geological prediction (Li et al. 2011).

The DC method of advanced exploration in a tunneling face includes the DC three-electrode method, DC focusing method, and DC induced polarization (Binley and Kemna 2005; Han et al. 2010; Ruanet al. 2009; Qiang et al. 2010). Based on differences between the observation systems, Chinese scholars have proposed the use of a 2 point-3 electrode resistivity exploration method. Its geometry intersection theory is based on the 3 point-3 electrode and seven-electrode exploration systems and examines the effect of the roadway in the entire space. This method has a detection distance of more than 100 m, and is sensitive to high water content ahead of the tunneling face (Han et al. 2010). However, DC source fields have low sensitivity to anomalous bodies ahead of the tunneling face, and are greatly affected by open space, which compromises the exploration distance and interpretations, which remain controversial (Cheng and Shi 2013).

The DC resistivity method is an important tool for exploring the geologic conditions of roadways ahead of excavation and investigating the development of fracture fields during mining (Bevc and Morrison 1991; Liu et al. 2010, 2014; Wu et al. 2013a, b). Figure 3 shows the DC resistivity method being used to monitor the development of a fractured and caving zone in the roof of the working face. Dynamic exploration is being carried out using a measuring electrode device that is fixed in an elevation borehole drilled towards the working face.

Electric tomography is an important subset of the DC method that has seen improvements in recent years. It uses underground techniques similar to those of seismic tomography, usually measuring emission currents and potentials

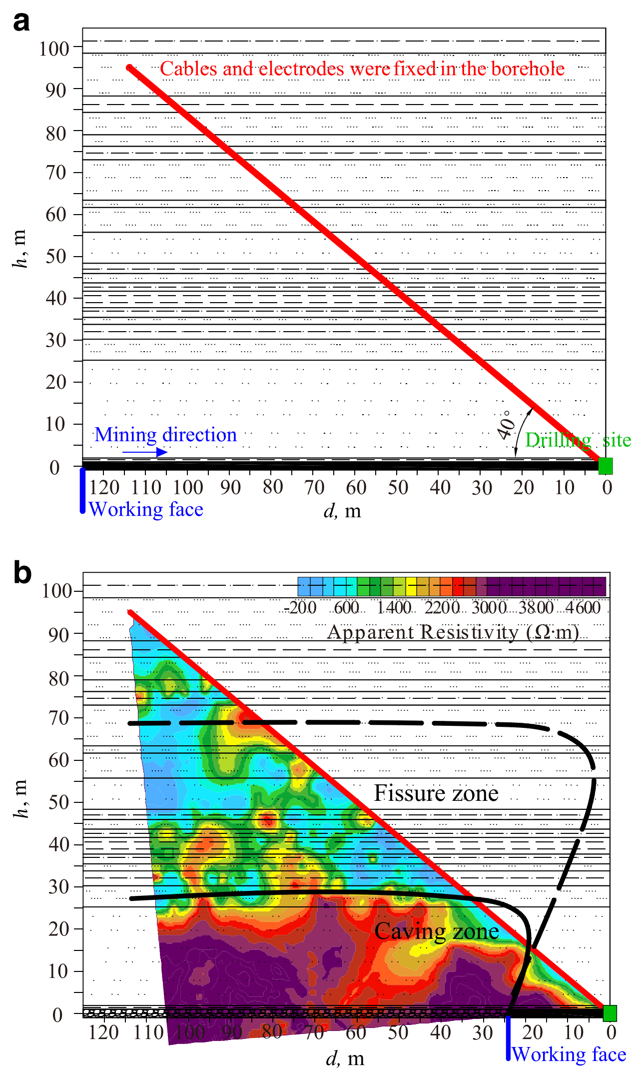

Fig. 3 Observation system of dynamic exploration and apparent resistivity profile of the roof. Cables and electrodes were placed in a borehole that was drilled at an angle of 40°. Then the borehole was sealed by grouting and the roof failure characteristics were monitored during mining. The caved roof of the working face and fissures led to reduced resistivity after stoping

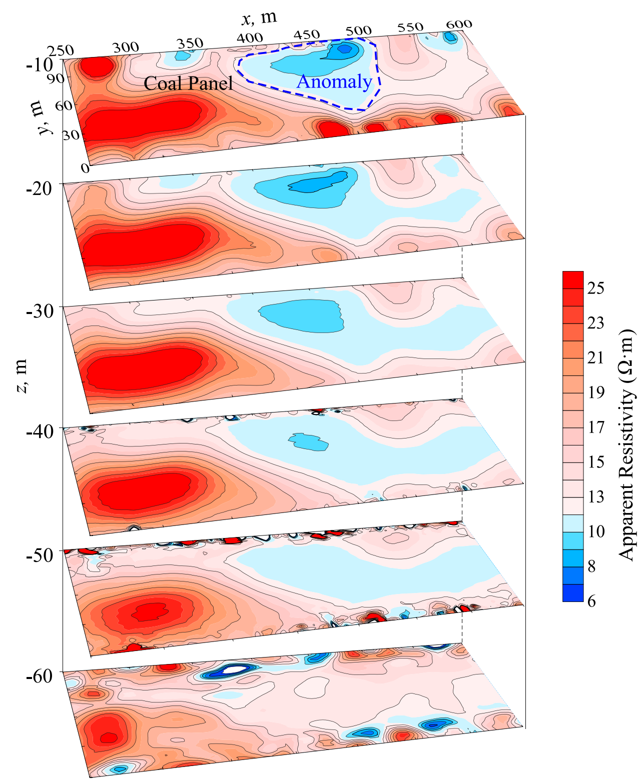

Fig. 4 Apparent resistivity section of the DC penetration method for subsided column detection in a coal mine panel floor

between adjacent roadways or between boreholes in the panel. Two-electrode and three-electrode methods are often used and inversion analysis is often conducted along the electric streamline and equipotential surfaces (Gélis et al. 2016). With various observation methods, electric tomography can achieve DC penetration of the roof and floor of the panels as well as layer penetration along the coal seams (Han and Shi 2000; Li et al. 2010; Liu et al. 2009). In addition, with the advantages of large exploration distance, information about various characteristics, many inversion parameters, and sensitivity to low-resistivity bodies, this approach is very useful for finding water-bearing structures in the roof and floor of the working face and evaluating their water content. Figure 4 illustrates how the DC penetration method is used to explore for water flowing in a subsided column in the floor of a mine panel. The distribution and forms of water-bearing structures can clearly be seen from the apparent resistivity sections at different depths.

The mine DC method boasts high resolution in the shallow part of the exploration area and is highly sensitive to water. However, if the geoelectric anomalies are superimposed in a random direction and the roadway is nonconductive, the resulting geoelectric field will be inhomogeneous and complicated. It is then difficult to locate the geoelectric anomalies, especially in DC advanced detection, since low-resistivity anomalies in other directions can be mistaken for being in front of the tunneling face.

The Mine Transient Electromagnetic Method

Heavy equipment and low work efficiency have restricted use of the mine DC method. In contrast, non-contact AC methods have recently emerged, represented by the mine transient electromagnetic method (MTEM), the radio imaging method (RIM), and ground-penetrating radar (GPR). The RIM has been widely used for detecting geological anomalies in coal panels due to its sensitivity to such structures (Emslie et al. 1975; Holloway et al. 2000;

Wu et al. 2010). However, a conflict is emerging between the low transmission power of the explosion-proof instrument and the increasing width of coal panels. Also, the need for three-dimensional detection of the structure's spatial location and water abundance delays further development of this method. High-resolution GPR has contributed a lot to backfill grouting detection, roadway lining quality detection, and coal barrier delineation; however, its exploration range is limited (Neal 2004; Singh 2015; Villain et al. 2015). With signals reaching longer distances, low-resistivity sensitivity, and efficient equipment systems, the MTEM is gradually becoming the main tool for such hydrogeological exploration.

The MTEM uses a non-contact coil to produce a primary field around the mining space, and observes changes in the secondary field induced by bodies of inhomogeneous electrical properties in the coal and rock mass between intervals. By analyzing the recorded fields, the geoelectric characteristics with depth can be obtained, which can be used to derive the required geological information and hydrologic distribution within the range of the technology. The China University of Mining and Technology first introduced the use of MTEM into coal mines and studied the transient electromagnetic field distribution, developing the equipment (turn-off time, transmitted power, and transmitting coil loop numbers), time-depth conversion method, and so on (Cheng et al. 2013; Li et al. 2012; Yu 1999). As a non-contact exploration technology, it also has good exploration directivity. It can be used to detect concealed water-bearing structures ahead of the roadway and to determine anomalous areas with low resistivity around the coal panel, such as water in a sandstone roof, limestone floor, or abandoned mine (Hu et al. 2014; Yu et al. 2007). Figure 5 shows the results of MTEM analysis for exploration of a permeable fault ahead of the roadway. It can be seen from the apparent resistivity profile that the exploration distance using this method can reach over 100 m and that it is very sensitive to water-bearing structures. However, due to the turn-off time of the equipment, this method also has blind areas in the shallow part of the exploration area (axis: 0–10 m).

The MTEM has advantages in detecting water content in a stratum. It is directional, flexible, and sensitive to water. However, it is not easy to extract an effective signal under the strong interference of rails, bolts, and electrical equipment in the roadway. Currently, non-screened coils are mostly used in mines, which makes it difficult to distinguish anomalies in front of and back of the mined areas. In addition, MTEM magnifies the volume of low-resistivity anomalies, which causes the detection point to deviate from the actual location.

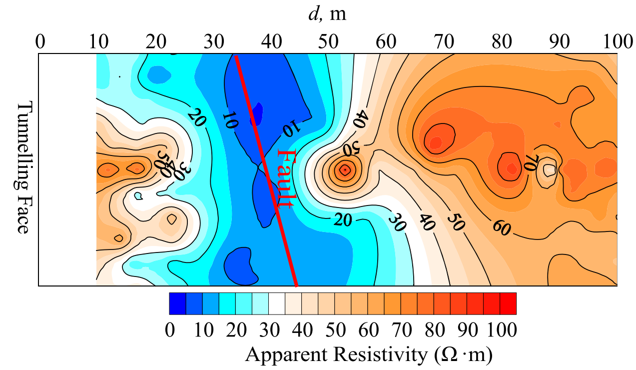

Fig. 5 Apparent resistivity profile of water-bearing fault ahead of the roadway. The low apparent resistivity area represents a water-bearing structure ahead of the tunneling face (axis: 25–45 m). Beyond this area, the contour lines of apparent resistivity change gradually, rising to high values, indicating that the rocks in these areas are mostly uniform and contain little water

The Integrated Mine Geophysical Method

The use of a single geophysical method always has certain limitations. The volume effect of the electrical and electromagnetic methods and the insensitivity of the seismic method to water content mean that one single method is unable to determine both the exact position and the water content of geologic targets. The integrated mine geophysical method (IMGM) combines the use of various methods and parameters. Moreover, comprehensive exploration can analyze the forms and hydrogeological characteristics of geological anomalies from different perspectives (Hamdan et al. 2010; McGrath et al. 2002). Using the IMGM means that a number of methods are used to complement each other and verify results, reducing the limitations and multiplicity of a single geophysical method (Cheng and Shi 2013; Liu et al. 2014). For instance, the mine DC resistivity method has high resolution in shallow target detection and can overcome the shortcomings of the blind zones of the MTEM. The combination of seismic and electric or electromagnetic methods can provide comprehensive information on a structure's position and water content. MTEM has been combined with the mine DC and reflected seismic methods in exploration of the tunneling face. In addition, combining the seismic wave method with the DC or electromagnetic methods has achieved good results in predicting structure-related water disasters in coal panels; however, these integrated methods have not been promoted in due to their cost and the amount of data collection and analysis required. Figure 6 shows how the IMGM was used to detect a subsided column in a mine panel floor. The results of the three methods agreed and complemented each other and were used to determine the location and water-bearing properties of the collapsed column.

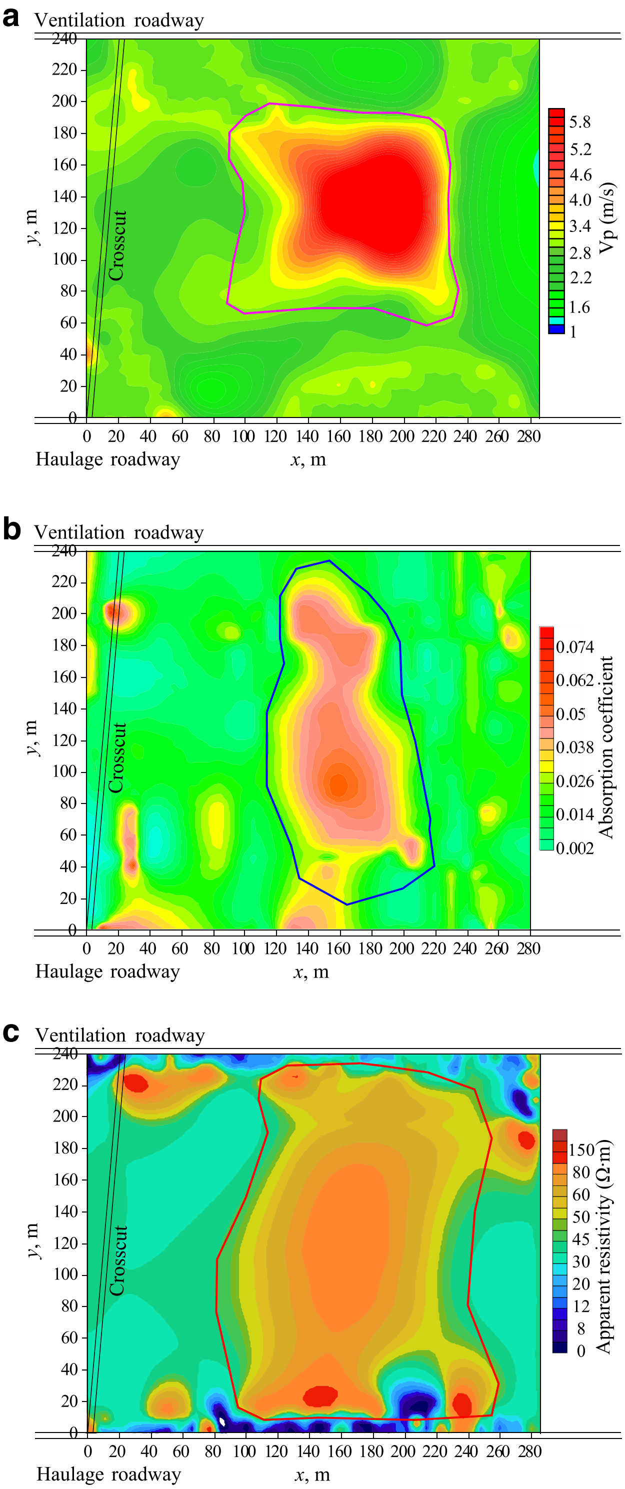

Fig. 6 The application of integrated mine geophysical exploration technology in collapsed column detection in the floor of a coal panel: **a** seismic CT; **b** radio imaging; **c** DC penetration. Even though the DC penetration method magnifies the abnormal area because of its volume effect, the anomalous locations of the three geophysical methods correspond well. The characteristics of high-speed and high-resistivity indicate that the rocks contain little water in this area

Current Trends in Mine Geophysical Exploration for Mine Water Disasters

Although mine geophysical exploration in China has been successful in preventing and controlling mine water disasters, most of the progress in this field was made by large-scale introduction and promotion of techniques and equipment; the focus has been on practical applications while the theoretical basis has been largely ignored. Therefore, many of the techniques applied are experimental. The incomplete theoretical basis and unclear aim of whole-space exploration has produced a gap between exploration precision and the demands raised by the geological conditions, coal safety, and high efficiency. Therefore, effort should be directed towards researching the basic geophysical theories in the whole space, new techniques and methods, precise data processing, equipment development and improvement, and water disaster online early warning systems.

Basic Research on the Whole Space Geophysical Theoretical System

Because of the lack of comprehensive theoretical studies, analogue simulations, and field testing of the coal mine environment, whole space distribution has been assumed in most mine geophysical exploration studies and the data processing is based on "half-space," which means that the propagation of geophysical fields are restrained by a plane. This compromise can lead to deviation of the exploration results (Cheng and Shi 2013). Therefore, a more extensive theoretical model should be established and theoretical studies on whole space geophysical field propagation should be carried out, focusing on the coal mine environment, e.g., roadway space, zones of broken rock surrounding the roadway, and roadway supporting conditions. Additionally, numerical and physical simulations of the entire geophysical field should be conducted with anisotropy and nonlinearity and three-phase coupling of solid, liquid, and gas. Research programs should also include studies to optimize observation systems and data collection methods in the roadway, suppress jamming and separation, and improve precise imaging technology of potential disaster sources. At the same time, the combined use of various geophysical methods including seismic methods, electric methods, and electromagnetic methods should be further developed, and different disciplines such as petrophysics and geology should be introduced to transform the geophysical exploration results from tangential graphs of direct geophysical parameters to wider geological interpretation (Cimino et al. 2007; Elwaseif et al. 2012). For example, in the commonly used intersection observation system in MTEM, stacking of the seismic data can be used as a reference to calculate the apparent resistivity, which can decrease the volume effect of the MTEM signal to a certain degree (Hu et al. 2014).

Synergistic Observation and Coupling Analysis of Integrated Geophysical Fields

Integrated geophysical methods are more precise than single methods and can avoid the incompleteness of single parameter interpretation. However, comprehensive geophysical exploration is not simply an accumulation of geophysical methods, but a reformation of the entire exploration system including collection methods and equipment, data processing, and comprehensive data interpretation. For example, synergistic observation of the seismic wave, electric, and electromagnetic fields can provide important criteria for early warning parameters in active exploration for and passive monitoring of mine water disasters. With regard to recording equipment, instruments that integrate the recording of various geophysical parameters including seismic, electric, and electromagnetic parameters should be researched and developed. The network parallel electrical method is one example (Zheng and Liu 2008). The concept of multi-channel acquisition in seismic exploration can be developed for parallel data collection in the DC method including networking protocol and intelligent electrodes. Such a device could collect seismic, DC method, and MTEM data independently while synchronizing their time scale. With respect to data fusion, research is needed on the joint inversion of the MTEM and DC methods with similar properties and joint inversion of seismic, electric, and electromagnetic methods with different properties (Bennington et al. 2015; Hamdan et al. 2013; Khalil et al. 2013).

Studies on New Mine Geophysical Methods in Boreholes and Roadway Space

At present, most of the geophysical data from mines are observed and obtained in narrow roadways, which restricts the layout of observation systems, results in limited and incomplete information, and affects the accuracy of the results. Roadway service and drilling required for coal mine safety can be used to expand geophysical observation space. Spaces such as rock and coal roadways, hydrological boreholes, and gas drainage bores should be designed to enable effective geophysical detection, cross-hole geophysical exploration, drilling–roadway geophysical exploration, and roadway–roadway geophysical exploration. Combining these spaces with existing observation zones could create a 3-D observation system that would improve exploration of underground watercourses on different scales, from fissures to large structures.

Real-Time Monitoring and Online Early Warning of Mine Water Disasters

Geophysical exploration of potential water disasters in China is capable of detecting potential problem sources and underground watercourses, but passive monitoring of water bursting factors and modeling of concealed sources and processes are still in the developmental stage. Because large quantities of data are measured and transferred, existing mine geophysical equipment consists mainly of wired equipment with large storage capacities, whereby data is collected on site and then processed and interpreted above ground. This results in an early warning lag time. Therefore, it is imperative to strengthen real-time monitoring of mine water disasters and improve early warning technology. Research areas include observing conditions during predicted in-rush events, real-time monitoring of water burst factors, dynamic analysis of water burst data, processing and transfer of the results, and timely decisions and feedback of expert systems. In addition, it is necessary to study automatic monitoring of potential mine water disaster areas and early warning systems, combining the exploration equipment for real-time processing and analysis with Internet of Things technology.

Conclusions

1. Mine geophysical technology is the main tool to detect concealed water-conducting structures and assess the water content of rock mass. Some comprehensive exploration technological achievements have been made in exploration of tunneling faces, such as are the mine seismic method, mine DC resistivity method, and mine transient electromagnetic method. Specialized geophysical technologies have been developed for use in mine structures and for water disaster exploration in panels; these include in-seam seismic surveying, seismic CT, direct current penetration, mine transient electromagnetic method, and radio-wave penetration. They have played an important role in controlling and preventing water disasters.
2. Facing the particular environment in the coal mine, much effort should be directed to researching basic whole-space geophysical theories, new techniques and methods, precise data processing, equipment development and improvement, and water disaster online early warning systems. Further studies should be conducted to improve the precision of the seismic and electrical sources used in disaster exploration, including studies on the foundation for a geophysical theoretical system covering the whole space of the roadway, studies on integrated geophysical methods with multi-field syner-

gistic observations and joint inversion, and studies on 3-D observation systems and new methods of drilling–roadway space. In addition, for effective mine water disaster monitoring and early warning, equipment armed with real-time processing and analyzing functions should be implemented in potential disaster areas, combined with Internet of Things technology. Mine hydro-geophysical exploration development should be focused on active detection of the sources of water disasters while passively monitoring water bursting factors.

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