Review Article

Review and Challenges in the Geophysical Mapping of Coal Mine Water Structure

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Generally, the water-bearing structures of coal mines mainly include coal seam, roof, coal seam, floor, and goaf, while the main water-conducting structures include faults, collapsed columns, and collapsed goaf areas. The most commonly used methods for the detection of the above structures include the seismic method, high-density electrical method, controlled source audio-frequency magnetotelluric method, and transient electromagnetic method. Theoretically, the seismic methods have a higher resolution, which can be used to determine the targets’ geometry, but unable to determine whether the target is filled with water, while the electromagnetic methods are capable of this, although with lower resolution. Therefore, it is necessary to adopt the comprehensive geophysical prospecting in the actual field measurement of the coal mine water to guarantee the detection accuracy. Based on this, in the passage, first, we introduced the characteristics of the water-bearing and water-conducting structures and then analyzed the detection results of different methods by examples. Finally, we pointed out that, first, it is essential to develop the mine or airborne methods for the sake of convenience; and second, it is time that we adopt three-dimensional detection technology, multisource and multiresolution detection technology, and electromagnetic big data technology for high accuracy.

1. Introduction

Since the beginning of the 21st century, the coal industry has been booming. Although the coal consumption is decreasing in recent years, the proportion of coal will remain above 55% as of 2025; that is, coal will remain a foundation supporting the sustained and rapid development of China’s national economy [1–3]. However, with the deep buried conditions of coal seams in China, more complicated, high crustal stress conditions [4–7], and sharply changed gradients [8] not only lead to detection difficulties [9] but also render the coal mining difficult for the severe mining disturbances [10] and the increased disasters such as coal and gas outbursts, rock bursts, and water inrushes [11–13]. Therefore, how to coordinate the contradictions between complex mining environmental conditions, safe efficient mining practices, and green mining, which is the demand of China’s development strategies for industrial structure transformation and upgrading [14], has become a significant challenge in deep coal mine production activities [15]. Among these issues, the most challenging disaster is water damage, which may frequently occur due to unknown hydrogeological conditions in effluent water areas and goaf areas. Therefore, it is urgent that we determine the hydrogeological conditions of the mine in advance, such as shallow old mine goaf water areas, roof water, and deep Ordovician limestone water accumulations [16–18].

Actually, the hydrogeological conditions of coal-bearing strata include the combination characteristics of lithofacies and lithological features; geological tectonism after the formation of the coal layers; and the present physical geographical environmental conditions [19, 20]. These conditions determine the strength of the water filling processes within a mining area, as well as the types of potential mine water
damage. Coal mine water mainly includes groundwater and old kiln water, among which the groundwater can be divided into pore water, fissure water, and karst water types, according to the interstitial properties of water-bearing rock [21, 22]. Furthermore, the coal mine water-conducting structures mainly include structural fault zones, contact zones, water-conducting collapsed columns, fractures caused by mining activities, poorly closed water-conducting boreholes, karst collapses, and skylights [23, 24].

At present, the most commonly used methods in coal mine water detection mainly include seismic method and electromagnetic methods. Seismic exploration is a high-resolution method commonly used to detect geological anomalies such as faults, goaf areas, and collapse columns in coal-bearing formations, thus providing scientific guidance for safe and efficient mining [25]. Unfortunately, it cannot ensure whether the anomaly is filled with water. In addition, seismic exploration is not suitable to portray the complex geological structures of small-scale coal seams, such as collapse columns and small faults.

Electromagnetic exploration technology is another one of the main methods used in coal mine water detection at present [26–28], due to its high resolution, sensitivity to low resistance body, simple construction, and high efficiency. However, with the increase of coal mining depth, mining intensity, mining speed, and mining scale, multilayer low-resistivity abnormal bodies are often formed in different depths in the same plane, which leads to new challenges in the application of electromagnetic exploration. First of all, different scales, mining methods, and roof and floor treatment methods will affect the structure of the goaf, further resulting in many changes in the electromagnetic characteristics of the goaf. Second, the superimposition and interaction effect of the electromagnetic fields of the multilayer abnormal bodies make it difficult to distinguish and separate the electromagnetic signals. Finally, the low-resistivity mined-out stagnant water area is often an electrical shielding layer, making it difficult to obtain the deeper electromagnetic signal. For these reasons, developing new geophysical prospecting methods or improving the aforementioned measures should be our priority at present, to improve the effects of coal mine water detection.

2. Geological and Geophysical Models of Water-Bearing Layers

2.1. Hydrogeological Conditions of the Basement of Primary Coal-Bearing Strata. Ordovician limestone is the most water-rich stratum in northern China. However, the water content levels of limestone with different lithologic combinations may vary greatly (Figure 1). For example, for the continuous limestone formation types (thick or medium-thick limestone) located at the bottom layers of layered cave formations, regional karst water-rich zones may be found [29–32]. However, in the limestone and dolomite interbedded formation types with thicknesses of 1–2 m, it is generally not very large karst caves, but selective bedding karst gaps that may be found [17, 33]. Furthermore, under the conditions of limestone intercalated with dolomite (or dolomite type), karsts will develop in the limestone formations. However, there will be very few karsts in the dolomite, which is known to be relatively waterproof [9, 34, 35].

2.2. Hydrogeological Conditions of the Covering Layers of Primary Coal-Bearing Strata. The coal seams in China are generally covered with Quaternary loose layers 50 to 200 m in thickness. Previous studies have found that these layers contain two to four layers of pore aquifers on average with strong or weak water content, determined by the genetic types and lithologic associations (marked as “1” in Figure 1). Among those water-bearing layers, the loose bed water-bearing rocks near the bottom of the Quaternary layers have direct influence on the water filling in mines [36, 37]. In particular, the coarse-grained gravel layers, which are known to be rich in water, may potentially affect coal mining production activities, while loose beds with fine lithology, or coarse-grained gravel layers containing muddy material, have weak water-bearing ability, or even may even form water-resistant layers [26, 27].

2.3. Primary Internal Water Sources of the Coal-Bearing Strata. Water-conducting channels within coal mines include structural fault zones, contact zones, water-conducting collapsed columns, fractures caused by mining activities, poorly closed water-guided boreholes, collapsed karst, and “skylights” (marked as “2” in Figure 1). During mining, accumulated water near the coal seams may flow into the mines through the aforementioned channels. This kind of water is generally referred to as mine (pit) water, among which the goaf water is typical. The goaf water refers to the groundwater preserved in the goaf areas or abandoned roadways of both ancient and modern coal mines due to long-term stoppages in drainage and actually can be seen as a source of usable groundwater [38].

3. Geological Model of Water-Conducting Structure

3.1. Tectonic Fault Zones and Contact Belts. Faults can be divided into tensile faults and compressional faults based on their mechanical properties, and different mechanical properties and structural lithology result in the water-conducting capabilities also differing (Figure 2(a)) [39]. For extensional faults, the majority of the fracture surfaces will be open and contain obvious gaps, the fracture belts tend to be filled with breccia, and such loose and porous zones are known to be beneficial to the flow and storage of groundwater [40, 41]. Therefore, tensile faults are good channels for water-conducting and water-flowing actions within coal mines. While as for compressional faults, the fracture surfaces will be almost closed and the fracture belts are often filled with fault gouges [42]. As a result, they are waterproof or weakly water permeable. In addition, due to the blocking of faults, abundant groundwater will be evident on either one or two sides of the faults [43–46].
3.2. Water-Flowing Collapsed Columns. Geologically, the collapsed columns can be divided into two categories according to whether or not they are filled with water (Figure 2(b)). The first is referred to as a non-water-flowing subsiding column. The basement karst caves of such collapsed columns are not developed on a large scale with the collapsed rock fragments filling the caves and the collapsed spaces of the cover [47]. In addition, all caves and fissures among these will be compacted. Therefore, there will be no connection with the water-bearing fissures in the overlying strata. The other category is the water-flowing subsided column. Its basement karst caves are developed on a large scale, and the fillings inside the collapsed column will not be compacted. As a result, the column will be interlinked with several aquifers in the coal seam, floor, and roof areas; that is, it will be an ideal water-conducting channel for coal mine water.

3.3. Collapsed Goaf Areas. The collapsed goaf areas can be divided into three zones, based on the deformation and failure of the strata above the goaf areas [48] (Figure 2(c)). The
first can be described as the caving zone, which refers to the scope of direct roof collapse after a coal mining face has caved in [27]. The number and size of the rock fissures in the caving zone tend to be large; therefore, the caving zone is both water permeable and sand permeable. Another type is the water-conducting fracture zone, which refers to the emergence of a large number of cut layers above a caving zone. The degrees of fracturing and water permeability will change from strong to weak from the bottom to the top of these zones. The last is referred to as the bending settlement

Figure 3: Sketch map of seismic exploration: (a) the reflection method and (b) the refraction method.

Figure 4: Goaf in a time profile (a) and in a transient electromagnetic profile (b).
zone, which includes the entire area from the water-conducting fracture zones to the surface. The rock strata in these zones bend and fall globally, generally with no obvious cracks occurring. Therefore, the zones may be waterproof or poorly water-conducting channels.

4. Geophysical Prospecting for Coal Mine Water

4.1. Seismic Method. Seismic exploration is an important geophysical survey method commonly used to explore
geological structures and locate useful mineral resources based on the elastic differences between strata and rock. Based on the received seismic waves, the seismic method can be mainly classified into the reflection method (Figure 3(a)) and refraction method (Figure 3(b)), of which the reflection method is the most commonly used in the exploration of the above structures.

In the time profile, if the coal seam had not been mined out, due to the characteristics of low density and low velocity, then reflected waves with strong energy would be present, while if it had been mined out, then the reflection waves would appear to be disorderly or even disappear, due to the absorption and scattering of seismic waves by the goaf areas. In addition, due to the goaf areas, strong reflection waves may also be observed; however, compared with the reflection waves of coal seams, they are characterized by time delay, amplitude enhancement, frequency reduction, and continuous phase and energy enhancement, as illustrated in Figure 4(a). However, the seismic waves in collapsed goaf areas will be reflected as weak or disorganized wave energy, with obvious discontinuous or dislocated reflection waves in the same phase axis. These features provide a basis for the identification of goaf areas in time sections [25, 49].

In the case of discontinuous mining of coal seams, or different filling properties in mining roadways (for example, the roadways become filled with mud, water, and gravel, leaving occasional empty holes), then relatively low-
resistivity anomalies will appear locally in the resistivity profiles Figure 4(b).

As for the fault, as it destroys the continuity of the coal seams, the reflection waves in the same phase may be interrupted, split, or merged, or they may even disappear. Additionally, due to the shielding effect of fault, the reflection waves of the footwall are disordered; thus, the shape and occurrence of reflection waves change suddenly. When underground interfaces are complex, stratigraphic interfaces may be interrupted, curved, or uneven; then, other seismic waves such as fault surface waves, diffraction waves, and turning waves may occur (Chen, 2013). Based on these features, not only can we identify the location of the fault but we can also deduce the fault elements like fault plane and fault distance according to the interruption of the reflection waves in the same phase [51, 52], as shown in Figure 5.

Different from the fault almost destroying the continuity of the entire strata within a certain area, the collapsed column only damages part of the layers, but they both cause the continuity, occurrence, and lithology of the area to differ significantly from the normal layers. These form the basis of abnormal seismic waves and provide a means for identifying and determining the collapsed column. The abnormal seismic waves are usually presented as interruptions, distortions, polarity transitions, occurrence mutations, or amplitude attenuation of reflection waves with the same phase (as shown in Figure 6). Meanwhile, they tend to be accompanied by diffraction waves, delayed diffraction waves, and lateral waves, which can be used as the basis for identifying and determining the range and size of a collapsed column [10].

4.2. High-Density Resistivity Method. The high-density resistivity method is actually a resistivity method based on the difference of electrical properties of underground media [54–56], which integrates the electric profiling and electric sounding methods [57]. Similar to the DC method, the direct current I is supplied through electrodes A, B to the earth, and the potential difference between the measuring electrodes M, N (ΔU_{MN}) is recorded, after which the apparent resistivity of the measuring point can be obtained using the formula \( \rho_s = K(\Delta U_{MN}/I) \), where \( K \) is the coefficient of the device. In the field measurement, all electrodes must be placed on each measuring point in the observation section or plane, and then, the instrument automatically utilizes program-controlled electrode conversion device and a microcomputer engineering electrical measuring instrument, to realize rapid and multichannel automatic data acquisition, as shown in Figure 7. According to the arrangement of the electrodes, the high-density resistivity method can be divided into different devices, among which the most commonly used ones include Wenner (Wenner \( \alpha \), Wenner \( \beta \), and Wenner \( \gamma \)), dipole-dipole, pole-dipole, and Wenner-Schlumberger devices [58–60] (Figure 8).

Figure 9 shows an example of goaf detection using the high-density resistivity method. From the figure, we can clearly observe four anomalous areas, among which the two on the right are high-resistivity goaf areas while the left one and the middle one are low-resistivity anomalies. The author infers that the left anomaly is led by the fault, while the middle one is the water-bearing goaf, and the high-resistivity goaf areas are generated by mining in the old kilns and without water filling. That is to say, whether the goaf is filled with water significantly affects the electrical characteristic of the goaf [61].

4.3. Controlled Source Audio-Frequency Magnetotelluric Method. The controlled source audio-frequency magnetotelluric (CSAMT) method is a frequency domain sounding
method with an artificial grounded wire source AB (generally 1-3 km in length). The measuring lines will be arranged parallel to the AB sector-shaped areas with 60° tension angles on either one or both sides. At present, the horizontal electric component Ex and magnetic component Hy are measured by equatorial dipole devices, which are positioned parallel or perpendicular to the source, as illustrated in Figure 10 [28, 62–64]. Due to its strong antinoise ability and relatively high detection efficiency [28, 65, 66], it has been applied in explorations of deeply hidden metal ore bodies, oil and gas structures, and geothermal and hydrologic engineering processes [67].

Figure 11 shows the inversion results and geological interpretation of an actual field measurement of faults using CSAMT. According to the resistivity readings of the profile, the resistivity changed in the horizontal direction at about 2,000 m (survey site number 40) and 3,500 m (survey site number 70), respectively. From this, we can infer that, from west to east, there were two main buried faults (referred to as F1 and F2) with dip angles of approximately 65° across the survey line in the study area. In addition, it can be determined that the fault displacements of F1 and F2 were approximately 230 and 180 m, respectively. As a result, we can conclude that the fault is reflected as a two-dimensional slab which extends deeply downward, and the resistivity changes will be present in the horizontal direction when the fault occurs [68].

4.4. Transient Electromagnetic Method. Completely different from the CSAMT, the transient electromagnetic method (TEM) is a time domain method with the impulse current emitted through ungrounded loops or long grounded wires [45, 69, 70]. The pure secondary field generated by underground media can be measured through receiving coils after the stable currents in the loops or wires have been cut off, as shown in Figure 12(a). The TEM can not only easily penetrate high resistivity layers and remain sensitive to low-resistivity anomalies, but it is also convenient to transport and has higher detection efficiency (Figure 12(b)). Moreover, the grounded wire source TEM has stronger signals in the late time, which is beneficial to deeper explorations. Considering the above features and the low-resistivity characteristic of the water-boring structures, the TEM method, especially with the grounded wire source, has quickly become the preferred method for detecting water-bearing bodies in many coal mines [8, 22, 38, 71].

However, due to the fact that measuring in underground roadways of coal mines is closer to the anomalies, the mine TEM has the advantages of higher resolution, smaller volume effect, lesser influence of host rock, faster measurement ability, and strong portability; thus, it has gradually become a favorite for coal mine geophysical prospecting [72–74]. Figure 13 shows a typical example of the mine TEM Nanling Coal Mine of Yangmei Group of Shanxi Province. It can be seen from the figure that there is a low-resistivity anomaly present in both the seam floor section and seam roof section, and it is deduced that there is a large goaf on the right side of the roadway, which has been verified during the actual mining process.
5. Potential Challenges for Future Geophysical Methods and Technology

Given that in coal mine exploration, the detection conditions and the geological environment have become more complicated, while the detection accuracy, demands, and detection requirements to be more efficient have also become higher, it is urgent that we improve the corresponding geological methods or develop new measures. Based on the above researches, we propose that the geophysical prospecting of coal mine water must be improved by meaning data collecting and processing.

5.1. Data Collecting. Traditionally, the geophysical prospecting of coal mine water is mainly based on 1D or 2D planes. However, due to the complex detection conditions, large interference, weak signals, rapid changes, and large dynamic range of the observed data, it is essential that we carry out and promote 3D detection methods. Taking the seismic method as an example, 3D seismic acquisition technology with wide azimuth and high density can improve the spatial sampling rate and ensure the quality of the original data, which is beneficial to achieving high-accuracy and high-resolution detection.

In addition, affected by the topography and detection conditions, traditional ground geophysical methods are not convenient to implement, and mining methods are interfered with by the mining equipment; hence, developing airborne or semiairborne methods will aid in improving the detection efficiency [75]. Airborne TEM, for example, transmits semisinusoidal pulse currents with specific frequencies into horizontal loop coils around the head [76, 77], wings, and tail of an aircraft and then receives electromagnetic fields at different times during pulse intervals through receiving coils towed in aircraft pods (Figure 14(a)) [78, 79]. Meanwhile, the semiairborne TEM adopts ground emission and airborne receiving processes (Figure 14(b)), thus combining the larger transmitting power of ground TEM and higher detection efficiency of airborne TEM. For these reasons, it can collect an increased abundance of information and reflect the underground geological information more comprehensively, when compared with traditional electrical detection methods [38, 80].

To improve the detection signal, the multisource electromagnetic method is another option. Moreover, to obtain more useful information regarding the underground media, considering receiving multicomponents may be useful too [81–83]. Finally, comprehensive geophysical exploration,
namely, adopting different prospecting methods or the same methods on different workfaces, may also become a trend of coal mine water detection. In any case, obtaining as much useful information as possible remains the sole goal during the data acquisition [84].

5.2. Data Processing. During the past several decades, numerous achievements have been made regarding the data processing and interpretation of both measured data and simulations using different geophysical methods. However, these achievements have not been sufficient to meet the
demands of deep exploration processes with high accuracy and efficiency. Currently, the most commonly data processing is 1D inversion, but unfortunately, it cannot reflect the underground 3D structures precisely. Therefore, in the future, developing multi-information joint inversions under geological structure constraints, electromagnetic big data technology [85], and 3D exploration technology are likely to become the trends. Taking the seismic inversion as an example, OVT processing technology and full waveform inversion are potential technologies of wide azimuth seismic data processing [86–88]. Full waveform inversion makes full use of all kinematic and dynamic information of the seismic data and thus has the ability to depict complex geological structures [53, 89–91].

Regarding the development of electromagnetic big data technology, the high bandwidth technology in big data can make the calculation speed for 3D electromagnetic fields with large amounts of data much faster. Moreover, the analysis theory in big data can comprehensively analyze and match the advantages and disadvantages of various inversion methods, to determine the optimal inversion method for a specific region and problem. The learning and memory functions make the electromagnetic data processing and inversion continuous and inherent. Therefore, introducing new ideas and methods of big data and deep learning theory will further the development of the present electromagnetic detection methods.

Above all, data collecting processes are developing toward acquiring sufficient information that can be used to reflect the underground 3D structures, while the data processing methods will develop so that they can be used to more comprehensively reflect the information from the observed data [92].

6. Conclusions

The existence of coal mine water results in major safety issues in mine production, which may potentially also be harmful to the lives of residents living in mining areas. However, since coal mine water is concealed and has poor spatial distribution characteristics, it has been found challenging to use reasonable and effective geophysical methods to accurately detect and determine the distribution of the water. In recent years, such geophysical methods as seismic methods, transient electromagnetic methods, and high-density resistivity methods have been applied in mine water structure detection processes. However, in practical mining activities, according to the specific geological conditions of the coal mine water structures, it has been necessary to select reasonable methods for exploration by comprehensively considering the characteristics of different geophysical methods, or adopting joint geophysical methods for explorations and interpretation, to obtain ideal detection results.

It has been estimated that with the adoption of 3D multi-azimuth observational technologies in air, ground, sea, seabed, and mine explorations, electromagnetic detection will enter a new era of omnidirectional, multiphysical field joint observations, along with the space-time four-dimensional monitoring of land, sea, air, and mines. Moreover, with further development toward real-time, systematic, intelligent informatization and visualization, major progress will be achieved. Finally, the intersection of the electromagnetic and related disciplines will become imperative, and intelligent and unmanned exploration methods based on big data, deep learning, and cloud computing will become key development fields.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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References

[1] X. X. Shi, S. Yan, J. M. Fu, and M. S. Chen, “Improvement for interpretation of central loop transient electromagnetic method,” Chinese Journal of Geophysics, vol. 52, pp. 1931–1936, 2009.
[2] J. W. Teng, “Some important scientific problems in current lithospheric physics research in China,” Applied Geophysics, vol. 4, no. 1, pp. 66–72, 2007.
[3] S. Yan, G. Wang, T. G. Shen, and X. Z. Zeng, “Detection depth of transient electromagnetic method for A-type layer,” in 2006 7th International Symposium on Antennas, Propagation and EM Theory, pp. 922–925, Guilin, China, 2006.
[4] O. Aydan, “The inference of crustal stresses in Japan with a particular emphasis on Tokai region,” in Rock Stress, pp. 343–348, CRC Press, 2003.
[5] Y. J. Pang, H. Zhang, H. H. Cheng et al., “The modulation of groundwater exploitation on crustal stress in the North China plain, and its implications on seismicity,” Journal of Asian Earth Sciences, vol. 189, p. 104141, 2020.
[6] L. Tannock, M. Herwegh, A. Berger, J. Liu, and K. Regenauer-Lieb, “The effects of a tectonic stress regime change on crustal-scale fluid flow at the Heyuan geothermal fault system, South China,” Tectonophysics, vol. 781, p. 228399, 2020.
[7] G. Zulauf, “Structural style, deformation mechanisms and paleodifferential stress along an exposed crustal section: constraints on the rheology of quartzofeldspathic rocks at supra- and infrastructural levels (Bohemian Massif),” Tectonophysics, vol. 332, no. 1-2, pp. 211–237, 2001.
[8] G. Wu, G. Yang, and H. Tan, “Mapping coalmine goaf using transient electromagnetic method and high density resistivity method in Ordos city, China,” Geodesy and Geodynamics, vol. 7, no. 5, pp. 340–347, 2016.
[9] Y. S. Pan and Z. H. Li, “Analysis of rock structure stability in coal mines,” International Journal for Numerical and Analytical Methods in Geomechanics, vol. 29, no. 10, pp. 1045–1063, 2005.
[10] H. T. Zhang, G. Q. Xu, X. Q. Chen et al., “Groundwater hydrogeochemical processes and the connectivity of multilayer
aquifers in a coal mine with karst collapse columns,” *Mine Water and the Environment*, vol. 39, no. 2, pp. 356–368, 2020.

[11] F. P. Cui, W. Qiang, Z. Shuai, N. A. Wu, and J. Yuan, “Damage characteristics and mechanism of a strong water inrush disaster at the Wangjialing coal mine, Shanxi province, China,” *GeoFluids*, vol. 2018, Article ID 3253641, 2018.

[12] M. Li, J. X. Zhang, W. Q. Zhang, A. Li, and W. Yin, “Numerical simulation of water–silt inrush hazard of fault rock: a three-phase flow model,” *Rock Mechanics and Rock Engineering*, vol. 55, no. 8, pp. 5163–5182, 2022.

[13] J. Y. Chen, J. W. Teng, and J. Badal, “Constraining the anisotropy structure of the crust by joint inversion of seismic reflection travel times and wave polarizations,” *Journal of Seismology*, vol. 13, no. 2, pp. 219–240, 2009.

[14] W. H. Ao, W. H. Huang, C. M. Weng et al., “Coal petrology and genesis of Jurassic coal in the Ordos Basin, China,” *Geoscience Frontiers*, vol. 3, no. 1, pp. 85–95, 2012.

[15] Y. Gao, X. T. Kang, G. Huang, Z. Y. Wang, M. Tang, and L. J. Gelius, “Forecasting the hydraulic properties of fault rocks in underground mining areas covered with thick unconsolidated layer,” *GeoFluids*, vol. 2021, 15 pages, 2021.

[16] X. Gao, X. T. Kang, G. Huang, Z. Y. Wang, M. Tang, and Y. T. Wang, “Research and application of in-seam seismic survey technology for disaster-causing potential geology anomalous body in coal seam,” *Acta Geologica Sinica-English Edition*, vol. 94, no. 1, pp. 10–26, 2020.

[17] G. Xue, W. Chen, and H. Zhong, “Mapping coal-beds water-filled zones by using SOTEM,” in *International Workshop and Gravity, Electrical & Magnetic Methods and their Applications*, pp. 482–485, Chengdu, China, 2015.

[18] Q. Xue, J. L. Cheng, N. N. Zhou, W. Y. Chen, and H. Li, “Detection and monitoring of water-filled voids using transient electromagnetic method: a case study in Shanxi, China,” *Environmental Earth Sciences*, vol. 70, no. 5, pp. 2263–2270, 2013.

[19] Q. Xue, S. Yan, L. J. Gelius, W. Y. Chen, N. N. Zhou, and H. Li, “Discovery of a major coal deposit in China with the use of a modified CSAMT method,” *Journal of Environmental and Engineering Geophysics*, vol. 20, no. 1, pp. 47–56, 2015.

[20] D. Halabowski, I. Lewin, P. Buszynski et al., “Impact of the discharge of salinised coal mine waters on the structure of the macrinovertebrates communities in an urban river (Central Europe),” *Water, Air, and Soil Pollution*, vol. 231, no. 1, 2020.

[21] Q. H. Ma, J. J. Cao, and Y. T. Wang, “Study on wide stripe mining based on the principles of overlying strata spatial structures and yield coal pillar,” in *International Conference on Mine Hazards Prevention and Control Qingdao*, pp. 219–225, People’s R China, 2007.

[22] C. S. Xiong and X. X. Zhai, “Mechanism of seam floor water inrush in a special geological structure zone and its application to water control in coal mining,” in *International Symposium on Mining Science and Safety Technology Jiaozuo*, pp. 194–198, People’s R China, 2007.

[23] Z. Yao, X. Li, T. Wu, L. Yang, and X. Liu, “Hybrid-fiber-reinforced concrete used in frozen shaft lining structure in coal mines,” *Materials*, vol. 12, no. 23, p. 3988, 2019.

[24] J. Z. Zhu, Y. Liu, Q. M. Liu et al., “Application and evaluation of regional control technology of limestone water hazard: a case study of the Gubei coal mine, North China,” *GeoFluids*, vol. 2021, 15 pages, 2021.

[25] R. Q. Huang, Z. Wang, S. P. Pei, and Y. S. Wang, “Crustal duc- tile flow and its contribution to tectonic stress in Southwest China,” *Tectonophysics*, vol. 473, no. 3–4, pp. 476–489, 2009.

[26] J. R. Zhao, X. K. Zhang, F. Y. Wang et al., “North China subcraton lithospheric structure elucidated through coal mine blasting,” *Chinese Science Bulletin*, vol. 54, no. 4, pp. 669–676, 2009.

[27] G. Carlson, M. Shirzaei, S. Werth, G. Zhai, and C. Ojha, “Seasonal and long-term groundwater unloading in the central valley modifies crustal stress,” *Journal of Geophysical Research - Solid Earth*, vol. 125, article e2019JB018490, 2020.

[28] W. Qiao, W. P. Li, X. Zhang et al., “Prediction of floor water disasters based on fractal analysis of geologic structure and vulnerability index method for deep coal mining in the Yanzhou mining area,” *Geomatics, Natural Hazards and Risk*, vol. 10, no. 1, pp. 1306–1326, 2019.

[29] Q. Xue, W. Chen, J. L. Cheng et al., “A review of electrical and electromagnetic methods for coal mine exploration in China,” *Ieee Access*, vol. 7, pp. 177332–177341, 2019.

[30] L. Gao, X. T. Kang, G. Huang, Z. Y. Wang, M. Tang, and X. Shen, “Experimental study on crack extension rules of hydraulic fracturing based on simulated coal seam roof and floor,” *GeoFluids*, vol. 2022, 12 pages, 2022.
[40] E. V. Kalinin, O. S. Barykina, and L. L. Panasyan, “Mathematical-numerical modeling of tectonic fault zone (Tadzhikistan),” in 12th International IAGG Congress, pp. 91–93, Torino, Italy, 2015.

[41] G. B. Zhang, W. Q. Zhang, H. L. Wang, S. W. Cao, Y. Wu, and Z. Wang, "Research on arch model and numerical simulation of critical water and sand inrush in coal mine near unconsolidated layers," Geofluids, vol. 2020, 12 pages, 2020.

[42] S. C. Zhang, B. T. Shen, Y. Li, and S. Zhou, "Modeling rock fracture propagation and water inrush mechanisms in underground coal mine," Geofluids, vol. 2019, 15 pages, 2019.

[43] S. Pucci, N. Palyvos, C. Zabci, D. Pantosti, and M. Barchi, "Coseismic ruptures and tectonic landforms along the Duizce segment of the North Anatolian fault zone (Ms 7.1, November 1999)," Journal of Geophysical Research - Solid Earth, vol. 111, no. B6, 2006.

[44] E. H. Rutter, R. E. Holdsworth, and R. J. Knipe, "The nature and tectonic significance of fault-zone weakening: an introduction," Geological Society, London, Special Publications, vol. 186, no. 1, pp. 1–11, 2001.

[45] L. Tsotsorkov, D. Nikolaov, and A. Kostov, "Work of mining machines in fault tectonic zones for the conditions of Assarel mine," in Proceedings of the 20th International Mining Congress and Exhibition of Turkey, No 133, pp. 277–283, Ankara, Turkey, 2007.

[46] F. Yuan, C. Z. Song, S. F. Lin et al., "Analysis of the tectonite types and tectonic deformations of Wenji area in the northern Feidong part of the Tan-Lu fault zone," Acta Petrologica Sinica, vol. 36, no. 2, pp. 601–620, 2020.

[47] H. Guo, H. Q. Wang, S. Q. Chen, and Z. R. Wu, "Cause analysis and prevention of hole collapse by water injection and dust removal in Qi Panjing coal mine," Geofluids, vol. 2020, 8 pages, 2020.

[48] H. X. Lin, F. Yang, Z. Z. Cao, Y. Wang, and X. jiao, "Disastrous mechanism of water discharge in abandoned gob above the stope in mining extra-thick coal seam," Geofluids, vol. 2021, 10 pages, 2021.

[49] Y. S. Liu, J. W. Teng, T. Xu, Y. H. Wang, Q. Y. Liu, and J. Badal, "Robust time-domain full waveform inversion with normalized zero-lag cross-correlation objective function," Geophysical Journal International, vol. 209, pp. 106–122, 2017.

[50] Q. Chen, R. Y. Qian, S. L. Chang, M. Jiang, and G. B. Zhang, "Acquisition method study of 2D reflection seismic short profile through WFSD-1 in main faults of Wenchuan earthquake," Chinese Journal of Geophysics-Chinese Edition, vol. 54, pp. 2060–2071, 2011.

[51] R. Di Stefano, C. Chiarabba, L. Chiaraluce et al., "Fault zone properties affecting the rupture evolution of the 2009 (Mw 6.1) L’Aquila earthquake (Central Italy): insights from seismic tomography," Geophysical Research Letters, vol. 38, article L10310, 2011.

[52] E. Roland, D. Lizarralde, J. J. McGuire, and J. A. Collins, "Seismic velocity constraints on the material properties that control earthquake behavior at the Quebrada-discovery-Gofar transform faults, East Pacific Rise," Journal of Geophysical Research - Solid Earth, vol. 117, no. B11, 2012.

[53] F. S. Meng, G. Zhang, Y. P. Qi, Y. D. Zhou, X. Q. Zhao, and K. B. Ge, "Application of combined electrical resistivity tomography and seismic reflection method to explore hidden active faults in Pingwu, Sichuan, China," Open Geosciences, vol. 12, no. 1, pp. 174–189, 2020.

[54] S. Rochdane, M. Elgettafi, A. El Mandour et al., "Contribution of electrical resistivity tomography in the study of aquifer geometry and groundwater salinization of eastern Haouz and upstream Tassaout domain, Morocco," Environmental Earth Sciences, vol. 81, no. 4, 2022.

[55] Z. Song, Q. Y. Zhou, D. B. Lu, and S. Xue, "Application of electrical resistivity tomography for investigating the internal structure and estimating the hydraulic conductivity of in situ single fractures," Pure and Applied Geophysics, vol. 179, no. 4, pp. 1253–1273, 2022.

[56] M. X. Su, K. Cheng, H. Y. Li et al., "Comprehensive investigation of water-conducting channels in near-sea limestone mines using microtremor survey, electrical resistivity tomography, and tracer tests: a case study in Beihai City, China," Bulletin of Engineering Geology and the Environment, vol. 81, no. 5, 2022.

[57] M. Metwaly and F. AlFouzan, "Application of 2-D geoelectrical resistivity tomography for subsurface cavity detection in the eastern part of Saudi Arabia," Geoscience Frontiers, vol. 4, no. 4, pp. 469–476, 2013.

[58] M. H. Loke, J. E. Chambers, D. F. Rucker, O. Kuras, and P. B. Wilkinson, "Recent developments in the direct-current geoelectrical imaging method," Journal of Applied Geophysics, vol. 95, pp. 135–156, 2013.

[59] K. P. Panda, A. Upadhyay, M. K. Jha, and S. P. Sharma, "Mapping of late-stage zones using 2D electrical resistivity tomography survey in parts of Paschim Medinipur, West Bengal, India: an approach for artificial groundwater recharge," Journal of Earth System Science, vol. 129, no. 1, p. 129, 2020.

[60] A. Sendros, M. Himi, R. Lovera et al., "Electrical resistivity tomography monitoring of two managed aquifer recharge ponds in the alluvial aquifer of the Llobregat river (Barcelona, Spain)," Near Surface Geophysics, vol. 18, no. 4, pp. 353–368, 2020.

[61] Q. Chen, S. Zhang, S. L. Chang, B. Liu, J. Liu, and J. H. Long, "Geophysical interpretation of a subsurface landslide in the southern Qinshui basin," Journal of Environmental and Engineering Geophysics, vol. 24, no. 3, pp. 433–449, 2019.

[62] Z. X. Liu, G. Q. Xue, and L. B. Zhang, "Comparison and analysis on effective observation area of tensor CSAMT by numerical simulation method," Chinese Journal of Geophysics, vol. 60, pp. 3278–3287, 2017.

[63] P. E. Wannamaker, "Tensor CSAMT survey over the sulphur springs thermal area, Valles caldera, New Mexico, United States of America, part II: implications for CSAMT methodology," Geophysics, vol. 62, no. 2, pp. 466–476, 1997.

[64] P. E. Wannamaker, G. W. Hohmann, and S. H. Ward, "Magnetotelluric responses of three-dimensional bodies in layered earths," Geophysics, vol. 49, no. 9, pp. 1517–1533, 1984.

[65] C. H. Lin, H. D. Tan, W. W. Wang et al., "Three-dimensional inversion of CSAMT data in the presence of topography," Exploration Geophysics, vol. 49, no. 3, pp. 253–267, 2018.

[66] X. D. Luan, Q. Y. Di, H. Z. Cai, M. Jorgensen, and X. J. Tang, "CSAMT static shift recognition and correction using radon transformation," IEEE Geoscience and Remote Sensing Letters, vol. 15, no. 7, pp. 1001–1005, 2018.

[67] M. Zhang, C. G. Farquharson, and C. S. Liu, "Improved controlled source audio-frequency magnetotelluric method apparent resistivity pseudo-sections based on the frequency and frequency-spatial gradients of electromagnetic fields," Geophysical Prospecting, vol. 69, no. 2, pp. 474–490, 2021.
[68] C. T. Yu, S. L. Chang, Y. Han, J. S. Liu, and E. G. Li, “Characterization of geological structures under thick quaternary formations with CSAMT method in Taiyuan City, northern China,” Journal of Environmental and Engineering Geophysics, vol. 24, no. 4, pp. 621–628, 2019.

[69] N. O. Kozhevnikov and E. Y. Antonov, "Magnetic viscosity effect on TEM data of an array with a fixed transmitter loop," Russian Geology and Geophysics, vol. 59, no. 6, pp. 690–696, 2018.

[70] G. Q. Xue, S. Yan, and N. N. Zhou, “Theoretical study on the errors caused by dipole hypothesis of large-loop TEM response,” Chinese Journal of Geophysics-Chinese Edition, vol. 54, pp. 2389–2396, 2011.

[71] G. Q. Xue, W. Y. Chen, Z. J. Ma, and D. Y. Hou, "Identifying deep saturated coal bed zones in China through the use of large loop TEM,” Journal of Environmental and Engineering Geophysics, vol. 23, no. 1, pp. 135–142, 2018.

[72] J. H. Chang, B. Y. Su, R. Malekian, and X. J. Xing, "Detection of water-filled mining goaf using mining transient electromagnetic method,” IEEE Transactions on Industrial Informatics, vol. 16, no. 5, pp. 2977–2984, 2020.

[73] B. Y. Su, J. C. Yu, C. X. Sheng, and Y. L. Zhang, "Maxwell-equations based on mining transient electromagnetic method for coal mine-disaster water detection,” Elektronika ir Elektrotechnika, vol. 23, pp. 20–23, 2017.

[74] P. Wang, M. X. Li, W. H. Yao, C. Su, Y. Wang, and Q. Wang, "Detection of abandoned water-filled mine tunnels using the downhole transient electromagnetic method,” Exploration Geophysics, vol. 51, no. 6, pp. 667–682, 2020.

[75] J. Lin, G. Q. Xue, and X. Li, "Technological innovation of semi-airborne electromagnetic detection method,” Chinese Journal of Geophysics, vol. 64, pp. 2995–3004, 2021.

[76] Y. M. He, G. Q. Xue, W. Y. Chen, and Z. B. Tian, “Three-dimensional inversion of semi-airborne transient electromagnetic data based on a particle swarm optimization-gradient descent algorithm,” Applied Sciences, vol. 12, no. 6, p. 3042, 2022.

[77] X. Wu, G. Q. Xue, Y. Zhao, P. F. Lv, Z. Zhou, and J. J. Shi, "A deep learning estimation of the earth resistivity model for the airborne transient electromagnetic observation,” Journal of Geophysical Research -Solid Earth, vol. 127, no. 3, 2022.

[78] Y. X. Li, T. K. Qiang, and J. T. Tang, "A research on 1-D forward and inverse airborne transient electromagnetic method,” Chinese Journal of Geophysics, vol. 53, pp. 751–759, 2010.

[79] L. F. Mao, X. B. Wang, and W. J. Li, "Research on 1D inversion method of fix-wing airborne transient electromagnetic record with flight altitude inversion simultaneously,” Chinese Journal of Geophysics, vol. 54, pp. 2136–2147, 2011.

[80] X. Wu, G. Q. Xue, P. Xiao, J. T. Li, L. H. Liu, and G. Y. Fang, "The removal of the high-frequency motion-induced noise in helicopter-borne transient electromagnetic data based on wavelet neural network,” Geophysics, vol. 84, no. 1, pp. K1–K9, 2019.

[81] Y. J. Li, X. D. Meng, W. M. Huang, Y. Q. Wu, and G. Li, “3D numerical modeling of induced-polarization grounded electrical-source airborne transient electromagnetic response based on the fictitious wave field methods,” Applied Sciences, vol. 10, no. 3, p. 1027, 2020.

[82] X. Li, Y. Y. Zhang, X. S. Lu, and W. H. Yao, "Inverse synthetic aperture imaging of ground-airborne transient electromagnetic method with a galvanic source,” Chinese Journal of Geophysics, vol. 58, pp. 277–288, 2015.

[83] Y. Y. Zhang, X. Li, W. H. Yao, Q. Q. Zhi, and J. Li, “Multi-component full field apparent resistivity definition of multi-source ground-airborne transient electromagnetic method with galvanic sources,” Chinese Journal of Geophysics-Chinese Edition, vol. 58, pp. 2745–2758, 2015.

[84] W. G. Zhang, J. Y. Ching, A. T. C. Goh, and A. Y. F. Leung, "Big data and machine learning in geoscience and geoengineering: introduction,” Geoscience Frontiers, vol. 12, no. 1, pp. 327–329, 2021.

[85] H. Grandis and Sungkono, "Modified symbiotic organisms search (SOS) algorithm for controlled-source audio-frequency magnetotellurics (CSAMT) one-dimensional (1D) modelling,” Journal of Earth System Science, vol. 131, no. 1, 2022.

[86] C. L. Wu, B. Feng, H. Z. Wang, and T. Z. Wang, "Three-dimensional angle-domain double-square-root migration in VTI media for the large-scale wide-azimuth seismic data,” Acta Geophysica, vol. 68, no. 4, pp. 1021–1037, 2020.

[87] L. Y. Zhang, A. Li, and J. G. Yang, "Data processing of a wide-azimuth, broadband, high-density 3D seismic survey using a low-frequency vibroseis: a case study from Northeast China,” Exploration Geophysics, vol. 51, no. 6, pp. 652–666, 2020.

[88] S. X. Zhang, J. L. Sheng, and M. D. Xing, "A novel focus approach for squint mode multi-channel in azimuth high-resolution and wide-swath SAR imaging processing,” Ieee Access, vol. 6, pp. 74303–74319, 2018.

[89] Z. K. Wang, S. C. Singh, and M. Noble, “True-amplitude versus trace-normalized full waveform inversion,” Geophysical Journal International, vol. 220, no. 2, pp. 1421–1435, 2020.

[90] P. Zheglova and A. Malcolm, "Vector-acoustic full-waveform inversion: taking advantage of wavefield separation and dealing,” Geophysics, vol. 85, no. 4, pp. R409–R423, 2020.

[91] H. J. Zhu, J. D. Yang, and X. Y. Li, "Azimuthal anisotropy of the North American upper mantle based on full waveform inversion,” Journal of Geophysical Research - Solid Earth, vol. 125, no. 2, p. 125, 2020.

[92] C. Serele, A. Perez-Hoyos, and F. Kayitakire, “Mapping of groundwater potential zones in the drought-prone areas of South Madagascar using geospatial techniques,” Geoscience Frontiers, vol. 11, no. 4, pp. 1403–1413, 2020.