Research and Application of In-seam Seismic Survey Technology for Disaster-causing Potential Geology Anomalous Body in Coal Seam

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Abstract: In order to effectively detect potential geology anomalous bodies in coal bearing formation, such as coal seam thickness variation, small faults, goafs and collapse columns, and provide scientific guidance for safe and efficient mining, the SUMMIT-II EX explosion-proof seismic slot wave instrument, produced by German DMT Company, was used to detect the underground channel wave with the help of transmission method, reflection method and transreflective method. Region area detection experiment in mining face had been carried out thanks to the advantage of channel wave, such as its great dispersion, abundant geology information, strong anti-interference ability and long-distance detecting. The experimental results showed that: (1) Coal seam thickness variation in extremely unstable coal seam has been quantitatively interpreted with an accuracy of more than 80% generally; (2) The faults, goafs and collapse columns could be detected and predicted accurately; (3) Experimental detection of gas enrichment areas, stress concentration regions and water inrush risk zone has been collated; (4) A research system of disaster-causing geology anomalous body detection by in-seam seismic survey has been built, valuable and innovative achievements have been got. Series of innovation obtained for the first time in this study indicated that it was more effective to detect disaster-causing potential geology anomalies by in-seam seismic survey than by ground seismic survey. It had significant scientific value and application prospect under complex coal seam conditions.

Key words: in-seam seismic survey technology (ISS), disaster-causing potential geology anomalous body, dispersion feature, mine geophysical prospecting, quantitative interpretation


1 Introduction

China is the world’s top coal producer, consumer, and importer, and it accounts for almost half of global coal consumption. In 2013, China’s raw coal output was 3.974 billion tons, reaching a historical peak. It accounted for 48.3% of the world. After that, although China’s coal production has declined, it still had 3.41 billion tons in 2016, and the world’s share reached 45.7%. In 2017, the coal production has recovered and increased to 3.52 billion tons (National Bureau of Statistics of China (NBS), 2017, 2018). Coal accounts for more than 65% of China's one-off energy consumption structure. Although there has been a decline in recent years, the share is still more than 60%. Due to China’s energy condition of “rich in coal but poor in oil and gas”, coal will be China’s unshakable energy mainstay in the long term (Teng et al., 2016).

Compared with other leading coal producing countries, the geology conditions of coal mines in China are more complicated with more disasters, which resulting in more...
accidents and injuries in mines. Underground mining, used by most of China’s coal mines, accounts for nearly 90% of China’s coal production. While, the output of open pit mining in other major coal producing countries accounts for about 70%. In China, the condition of coal seams in many coal mines are relatively poor, and the coal seam thickness is unstable and among which some is extremely unstable. The goafs left by small coal mines are widely distributed. Also, the small-amplitude faults and the collapse column are also developed. Of the numerous coal mine disasters in China, rock burst, gas outburst in the coal seams and water inrush are posing a serious threat to mine safety production. In this context, coal mining accidents occurs frequently, the death rate of the mines whose production reached million tons is much higher than that of developed countries, and even far higher than that in India (Qi, 2015).

However, the underground accidents can be effectively avoided or the occurrence of it can be reduced in coal mines, and the efficiency of coal production can be improved at the same time if geophysical, geochemical, drilling, and roadway exploration methods can be taken in advance, the violent change zones of coal seam thickness, small faults, collapse columns, goafs, stress concentration area and gas-rich area can be detected and predicted as soon as possible, and take timely safety pre-control measures for potential disaster-causing events such as water inrush risk areas. Geochemical exploration is rarely used in coal mines.

Drilling and roadway exploration are direct and can be described quantitatively, but both two belong to the “view of one-hole or one roadway”, which are with limited-density, high-cost, and sometimes difficult to be constructed. Surface geophysical methods is far away from the target area, and it is greatly affected by the capping and surface conditions, and the precision of exploration is insufficient. Underground geophysical prospecting is close to the target area, which is convenient and efficient. It is widely used in front of roadway or before mining. It will be urgent to find out the disastrous geology abnormal events in and around the coal mining face in order to guide the safe and efficient coal mining scientifically (Teng et al., 2008).

The common underground geophysical exploration techniques in coal mine nowadays include direct current resistivity method (DC method), transient electromagnetic, audio frequency electric perspective, radio wave pit penetration, Rayleigh surface wave, in-seam seismic survey (ISS), seismic P wave, micro-seismic monitoring, ground sound monitoring, mining stress monitoring, electromagnetic radiation and so on. Among which, ISS, DC method, transient electromagnetic and radio wave pothole are more efficient. However, underground geophysical prospecting can be limited by the inherent response of the environment and the method itself. Transient electromagnetic methods and DC method are mainly used for abnormal detection of water accumulation in the mines. But both are interfered by the factors such as roadway accumulation (blotch) water, metal materials, power supply environment, etc., and are also restricted by the whole space environment. With the increase of support strength and the improvement of electrical, mechanization, and automation levels, metal materials are widely used, and it is more and more difficult to eliminate the interference factors, which induce more and more misreporting and underreporting. Radio wave penetration method is mainly used in the exploration of abnormal bodies such as coal seam thickness variation, fault, collapse columns and etc., which is not only easy to be disturbed, but also has multiple solutions, and can only be qualitatively described instead of being quantitatively interpreted. In recent years, although the ISS has been developed rapidly in China, the knowledge of seismic channel wave theory and application method, such as data inversion and image interpretation, is still insufficient, making it difficult to obtain high-resolution information and identify disaster objects in coal seams. Coupled with immature research methods and nonstandard R & D system, the application of ISS has almost stopped developing. In order to make full use of the seismic channel wave and its special frequency dispersion properties, it is necessary to develop the underground seismic channel wave field research on the basis of the ground seismic exploration wave field response, so as to forming a theoretical and technical system that combines both hardware and software, and with the ability to detect potential disaster in coal seams. With the support of the National Natural Science Foundation of China (41130419), demonstration experiments, research and exploration were carried out under the guidance of theory.

Channel wave is a special type of seismic wave, whose wave field properties are similar to the channel wave propagated in the high and low velocity layer of the earth, but they are not exactly the same. It is a guided wave that only propagated in low-speed coal seam. As only propagating between roof and floor, channel wave is confined in coal seams after many times of total reflection. Thus, channel wave is not easy to “leak”, and it can form strong interference disturbance by interfering other waves. Due to different vibration forms, the channel waves are divided into two types: Love wave and Rayleigh wave (Hu et al., 2013; Pi et al., 2013). Channel waves were first recognized by Evison (1955) in the coal seam of Mangapehi coal mine in New Zealand in 1955. Krey (1963) proved the propagation response of channel waves in the coal seam theoretically and practically, and pointed out its application value in 1963. Channel wave, be of strong anti-interference ability, long propagation distance and obvious frequency dispersion, carries rich information of coal seam, and its roof and the floor (Liu et al., 1993, 1994). The ISS is a coal mine geophysical exploration method for detecting underground geological hazards, such as coal seam thickness variation, faults, collapse columns and etc. By blasting and forming the seismic, it collects and interprets the channel wave. (Liu, 1997) Research of channel wave theory and its instrument development were proceeding rapidly in 1970s at abroad. Germany, the Soviet Union, the United Kingdom, the United States, Hungary, Australia and other countries put the ISS into application and achieved great application results in 1980s (Buchanan, 1978; Krey et al., 1982; Lu et al., 2006; Sun et al., 1998; Wang et al., 2012; Wu et al.,
production enterprises are paying more and more attention continuously to strengthen the production safety, coal China's international image. With a series of measures to water inrush and rock burst are numerous in China, which dangerous mining accidents, such as the gas outburst, output jumped from about 1 billion tons in 2000 to nearly Chinese coal had entered its golden age. China's raw coal growing economies, as well as strong energy demand, Organization (WTO). With the development of rapidly makes the technology in a stagnant state in last 20 years. characteristics in China and difficult to decode, which equipment was cumbersome in construction, complicated ISS encountered bottleneck as the seismic channel wave experiment. In addition, the research and application of ISS was introduced as the seismic channel wave electronic system in data acquisition, inversion, structural characterization, analysis and interpretation, and software, which intend to develop a new approach to explore the potential coal mine hazards by channel wave technology.

2 Development and Application of ISS Technology in China

ISS was introduced in China with the reform and opening-up and the exchange of advanced foreign technology in the late 1970s. In 1978, Chongqing research institute of China Coal Research Institute, Jiaozuo Mining Institute and Weinan Coal Mine Special Equipment and Instrument Factory carried out field tests in coal mines, and the physical model research and equipment research and development. (Sun et al., 1997; Cheng et al., 2009). China University of Mining and Technology has been engaged in channel wave propagation characteristics and numerical simulation experiments developed special processing software as well since 1983. (Yang, 2001; Ji et al., 2012). Xi’an research institute of China Coal Research Institute introduced SEAMEX-85 seismic channel wave instrument and the special software ISS, through which valuable scientific research of collapse columns, faults, scour belt, etc in Datong, Pingdingshan, Kailuan, Xuzhou and other mining areas were obtained. (Liu et al., 2014)

Since early 1990s, when ISS was going to develop in China, the coal market has been in a long-term downturn, and the efficiency of coal mining enterprises has continued to be low. It was hard to actively accept and promote new technologies, and difficult to stop mining for the experiment. In addition, the research and application of ISS encountered bottleneck as the seismic channel wave equipment was cumbersome in construction, complicated in operation, and lack of processing software for coal seam characteristics in China and difficult to decode, which makes the technology in a stagnant state in last 20 years.

In 2001, China became a member of the World Trade Organization (WTO). With the development of rapidly growing economies, as well as strong energy demand, Chinese coal had entered its golden age. China's raw coal output jumped from about 1 billion tons in 2000 to nearly 4 billion tons in 2013, accounting for about 50% of the world's share (Wu et al., 2018). However, some extremely dangerous mining accidents, such as the gas outburst, water inrush and rock burst are numerous in China, which not only caused heavy losses and casualties, but affected China's international image. With a series of measures to continuously strengthen the production safety, coal production enterprises are paying more and more attention to geophysical exploration in detecting and predicting potential geological anomaly events, forecasting potential hazard factors, reducing safety risk, and improving production efficiency. Due to its advantages in the detection of coal seam thickness drastic changes, faults, collapse columns, etc., ISS has been paid attention to once again by scientific researchers and field technicians in coal mines. (Hu et al., 2013).

Although the ISS technology has the advantages in underground mine detection, it is complicated to operate, making it difficult to identify and interpret the wave field with the technology. (Feng et al., 2015; Ji et al., 2014; Pi et al., 2013). To do a better job in ISS, a solid knowledge of seisimology, and a rich knowledge of mine geology are needed, as well as a good grasp of the on-the-spot situation of coal mines. It is necessary not only to realize scientific layout and strict construction under the condition of fully understanding mining face conditions and clear detection targets, but also to take site optimization and fine-tuning construction scheme into consideration. We can perform operation accurately on the spot, collect and identify data carefully and select channel wave information to compare with the geological information exposed on the spot, inverse fitting and scientific interpretation, and carry on verification in order to continuously improve the detection level.

Yima Coal Mine is the mine with complex geological background and serious underground disasters in China. Its coal seam stability is poor, the small geology structures and small goaf are widely distributed. It is threatened by coal and gas outburst, rock burst and water inrush (Le et al., 2013); Coal seam thickness change zone, structural zone, goaf, etc., main geological factors that causing potential disasters in coal mines, are closely related to rock burst, coal and gas outburst, mine water inrush, and other disasters in mines. To effectively detect the geological anomalies that caused mine disasters potentially, Yima Coal Industry Group Co., Ltd. first introduced the SUMMIT-ⅡEX type explosion-proof seismic channel wave instrument produced by DMT of Germany in 2009. After that, many research institutes, such as Hebei Coal Research Institute, Heilongjiang Longmuy Mining Group Co., Ltd., Jinzheng Anthracite Mining Group, and China University of mining and technology, and et al., purchased the SUMMIT-ⅡEX channel wave seismonagraph as well, and carried out the technology application and related scientific research. (Wang et al., 2012; Lian et al., 2015)

In order to promote the advancement of ISS, and better serve the safe production in coal mines, the Institute of Geology and Geophysics of the Chinese Academy of Sciences has taken the lead to a cooperative program called “five parties from the two countries” (the other four are Henan Yima Coal Industry Group, Institute of Geology, China Seismological Bureau, Institute of Geographical Science and Resources, Chinese Academy of Sciences, German DMT Corporation, respectively), which is sponsored by the national NSF of China (Characterization of coal mine underground disaster events and seismic channel wave field-variation of coal seam thickness and detection of faults and goaf, No. 41130419). Since then, scientific research team, the typical in-site conditions, and the advanced equipment have been strongly tied to form a combination of
production, study and research, which involves industry and university as well as domestic and international integration, and have been carried out a series of field experiments and innovative applied research. The team has carried out mathematical-physical simulation and developed some softwares. It carried out 69 times of ISS tests, which accurately predicted geological anomalies of underground potential disaster events and guided coal mine safety production scientifically. The team solved the difficulty of quantitative detection of extremely unstable coal seam thickness and improved its inversion method with an accuracy of more than 80% in mining face test. The precision detection of fault distribution and drop, goaf area, and collapse column is completed. For the first time, the ISS technique has been applied to the detection of in-situ stress concentration area, gas enrichment area, floor water inrush risk area and region area (including 2 mining faces), etc., and the near-orthogonal fault detection test has been carried out in the coal mining face of plateau coal mine with elevation of 3584 m. The trials have yielded valuable insights and exploratory results (Lian et al., 2017). Meanwhile, Jincheng Anthracite Mining Group, Hebei Coal Research Institute also achieved certain results in the aspect of collapse columns, geological structures. Many R & D enterprises, such as Xi’an Research Institute of China Coal Research Institute, have also made gratifying achievements in equipment localization, miniaturization and radio conversion (Cheng et al., 2013). Nowadays, the main site for the application and research of ISS technology has been transferred to China, forming a system of ISS which combines the theory, method, technique, software, inversion and interpretation.

3 Quantitative Detection of Coal Seam Thickness

The sudden change of coal seam thickness may lead to the occurrence of disaster events in underground coal seam, therefore, it is important to find out its occurrence and quantity.

3.1 Dispersion characteristics of coal seam thickness variation

The coal seam thickness is controlled and influenced by factors such as the fluctuation of the deposition substrate, the scouring of the river, the transformation and the superposition of the later tectonic events. The occurrence conditions of the coal seams in some coal fields in China, with large variation coefficient, belongs to the unstable and extremely unstable coal bed, or even the “chicken nest coal”. Both the coal seam thickness variation zone and the coal-rock junction zone are high occurrence areas of outbursts, such as gas burst, rock burst, water inrush, roof accident, etc., which is the key to determine the mining face selection and mining method, and the key to safe and efficient coal mining. As is the focus of mine safety, variation at coal seam thickness is one of the important problems to be solved in underground geophysical exploration of coal mines (Li et al., 2017).

The influence of coal thickness variation on the dispersion characteristics of channel wave is very obvious. The main frequency band of the Love-wave moves towards the low frequency with the coal seam thickness increasing, while the wave velocity corresponding to the same frequency decreases (Ji et al., 2011). It is a negative correlation between the thickness of coal seam and the propagation velocity of channel wave under the selected frequency, that is, the velocity of channel wave decreases with the increase of coal seam thickness as shown in Fig. 1 (Feng et al., 2018a, 2018b). Therefore, the average thickness of coal seam, coefficient of variation, and the detection purpose should be considered comprehensively when selecting the frequency for wave velocity imaging. If the coal seam of the mining face is thin, it is necessary to circle out the non-mining section. When guiding the safe production and providing the basis for the reconstruction of the mining face, a higher frequency-velocity image should be selected as shown in Fig. 1a. In this case, the velocity of channel wave is sensitive to the thin coal reaction, and the best resolution can be obtained (Yang et al., 2010). Conversely, the low-frequency is used for imaging as shown in Fig. 1b.

3.2 Detection of coal seam thickness variation in Huaxing Coal Mine (HCM)

Geology background and observation systems. The 15200 blasting mining face of HCM has a strike length of 1054 m and a tendency of 225 m. The average thickness of coal seam is 2.2 m (ranges from 0.2 to 7.8 m), and the coefficient of variation is 73%, which is an extremely unstable coal seam. Before the channel wave detection, the mining face has been mined about 320 m. The HCM reformed this mining face simply based on the variation of coal seam thickness inferred from the roadway disclosure information, leading to the scrapping of 600 m reconstructed roadway and increasing of production cost about 3 million yuan. The mining face is divided into three sections by the middle lane and the connection lane. To figure out the coal seam thickness variation, the three sections are regarded as different survey areas (Survey Area A, Survey Area B, Survey Area C) to detect the coal seam thickness by ISS technology as shown in Fig. 2. The channel wave signal collected in the mining face is of poor quality, in which only 26% of the wave phase is clear and the dispersion curves are continuous. In order to obtain the best resolution of 1.5m thickness coal seam as shown in Fig. 1a, the 185 Hz channel wave is selected, and the group velocity of the data in Area A is calculated, and then by adopting the method of CT tomography, the velocity distribution map of at 185 Hz in 15200 mining face of area A is obtained, as shown in Fig. 3.

The velocity map is based on the actual coal seam thickness and channel wave tomography. The contour of the wave velocity of 1250 m/s is formulated as the contour of the coal thickness of 1.5 m as shown in Fig. 4, where the “velocity-coal seam thickness” curve is fitted by the fourth-order polynomial. The five thin-coal areas with a thickness of less than 1.5 m can be distinguished in Fig. 3 and Fig. 5. The predicted location of the roadway in the thin-coal area is basically consistent with the actual exposure in Fig. 5. Among the 120 measured coal thickness data collected in area A, 101 out of them accord with the forecast results. Although 19 of them are slightly
different, the deviation is less than 0.5 m, and the prediction accuracy is 84%. If the allowable deviation is ±0.2 m, the prediction accuracy can reach 96%. The coal mining face has been reformed scientifically, and there is no abandoned roadway since then, according to the test results of ISS in the survey area. After more than two years of mining, the production of raw coal is about 0.67 million tons, and the ash in raw coal is effectively reduced and the heat generation increased by 5%–6%, with a direct economic benefit of more than 20 million yuan. Thus, ISS can scientifically guide the production of coal mining with remarkable economic profits.

3.3 Coal seam thickness variation detection in Yian Coal Mine (YCM)

The average thickness of 11061 fully mechanized coal face in YCM is 4.5m (ranges from 0.4 to 8m), and the coal seam is unstable. 748 channel wave data are collected during the data acquisition of the mining face, and 696 channels are selected. Compared with the coal seam in HCM, the coal seam in YCM is much thicker, and it is advisable to choose lower frequency image as shown in Fig. 1b. The tomography was performed with a frequency of 125 Hz, and then the wave velocity distribution map of the working surface was obtained (Fig. 6a). Combined with the actual coal seam information exposed by the roadway, the coal thickness and the channel wave velocity are fitted, and the contour of the coal seam thickness at the mining face is obtained (Fig. 6b). According to the prediction results, the coal seam thickness and the channel wave velocity of the 11061 mining face have the following corresponding relationship:

![Fig. 1. Dispersion curves of Love mode channel wave.](image1)

(a) Frequency-velocity curve of thin coal seam; (b) frequency-velocity curve of thick coal seam.

![Fig. 2. ISS observation system in 15200 mining face of area A.](image2)

![Fig. 3. Velocity distribution of channel wave in 15200 mining face.](image3)

![Fig. 4. Fitting curve between coal seam thickness and channel wave velocity.](image4)
Where $h$ represents the thickness of the coal seam, the unit is m, and $v$ represents the wave velocity of the groove, and the unit is m/s. The comparison between the prediction results and the measured coal seam thickness are shown in Fig. 7. It shows that the accuracy of the prediction result in Area A, B, C is 90%, 84%, 89%, respectively, and the overall prediction accuracy is 86%. If the allowable
deviation is ±0.2 m, the prediction accuracy can be increased to 92%. The results of ISS effectively guide the production of the mining face safely and efficiently.

3.4 Summary of ISS in coal seam thickness variation

I. ISS technology can realize the quantitative interpretation of coal seam thickness change in coal mining face, and it has better effect on detecting thickness of unstable or extremely unstable coal seam.

II. The lower frequency channel wave is suitable for wave velocity imaging if the coal seam is thick. On the contrary, when the coal seam is thin, it is appropriate to use higher frequency for wave velocity imaging. The contour map of channel wave velocity can be transformed into the contour map of coal seam thickness according to the negative correlation between wave velocity and coal seam thickness.

III. In order to improve the accuracy of interpretation, the coal seam thickness should be interpreted based on the contour map of channel wave velocity, where it should be fully combined with the coal seam information exposed in the roadway of the mining face.

IV. The interpretation of coal seam thickness by ISS can be used to guide the reconstruction of coal face, the safe mining, and the coal production efficiency, which not only ensure the safety mining, but also brings a lot of economic profits.

4 Small Faults Detection

ISS is adopted in underground coal mine as the size of fault and fracture zone in coal seam is small that geophysical exploration on surface are difficult to identify.

4.1 Set-up for small faults detection

The faults will cause the formation fracture and dislocation in the coal seam, which destroy the original integrity of the coal seam, and some even form "push, slip, squeeze" in coal seam causing coal seam thickness change violently. Therefore, the faults in coal seam bed will not only increase the difficulty of coal mining, but also lead to rock burst, coal-gas outburst, water inrush and roof-fall accidents.

While the channel wave propagating along the coal seam at the differential interface of the isometric impedance of the fault, the reflection of channel wave will occur when it is used to detect the fault in coal seam bed (Yang et al., 2012). Based on the propagation velocity of channel wave and the time when the reflected wave reaches the geophone, the position of fault (reflection interface) can be detected. If the fault fall is greater than the coal thickness, the channel wave will be blocked, forming a blind receiving area by transmission method. The channel wave signal will be weaker than the normal area when the scale of fault is smaller than the coal thickness. The location of the fault and fault throw can be predicted by integrating the disclosed fault, the thickness of coal seam, and the intensity of channel wave signal. The ISS can be used to detecting faults inside coal mining face by transmission method, or faults on either side of roadway by reflection method. Moreover, it will get much precise detection of the faults in the coal mining face when combining transmission method and reflection method together.

4.2 Detection of faults in coal seam of Yunding Coal Mine (YCM)

The prediction results of 3D seismic surface exploration in YCM shows that Fault 12 is parallel to the 11100 mining face and about 40 m above the track roadway of mining face. The extension length of the fault is about 400 m, and the fault throw ranges from 0 to 11 m. The YCM is mine threatened by water inrush from the Ordovician limestone Aquifer in the floor and coal-gas outburst. Other mines in the same coal field ever happens coal-gas outburst and water inrush in which fault is one of the main causes of disasters. The seismic channel wave reflection method is used in this detection. Through the data acquisition and pretreatment, the high frequency channel wave phase of 350–550 Hz is extracted. Through velocity analysis, the optimum dynamic correction velocity is 1100 m/s, through enveloping, superposition the superposition...
section of the common center point is obtained and the continuous strong reflection seismic phase in the stack section is predicted as the location of fault development (Fig. 8). As showed in Fig. 8, the deviation between the fault location shown by drilling and its prediction position by ISS is less than 5m. By continuous drainage and aquifuge grouting, the threaten of the fault to face is successfully defensed until the 11100 mining face finished mining.

4.3 Detection of faults in Xinyi Mine

Xinyi Coal Mine is facing serious mining hazards. It is not only threatened by gas outburst, but also be harmed by Ordovician pressure aquifer of limestone on the coal floor. Moreover, fault is one of the most serious geological factors in this mine. The coal seam average thickness in 12040 mining face is 5.0 m (rang from 0.5 to 10.6 m) with a simple geological structure. The false roof of the mining face is carbonaceous mudstone, whose thickness is stable and about 0.6 m. The lower part of the first roof is mudstone and sandy-mudstone with an average thickness of 5.8 m, and the upper is a medium-grained quartz sandstone with an average thickness of 14.2 m. During the mining, the track lane of the mining face revealed a high-angle ordinary fault with a drop of 2.2 m and an inclination of 75°. But its extension length and distribution direction need to be further explored in order to improve the precision of the coal seam floor grouting and coal-gas controlling, which contributes to avoiding water inrush and gas outburst. As shown in Fig. 9, channel wave transmission detection can predict the extension of fault to the interior of the face by about 60 m by analyzing the clear degree of the channel wave ray and the seismic phase produced by seismic source on both sides of the fault. That is to say, if the coal seam thickness is stable, and not be destroyed by structure, the channel wave is with good quality, the dispersion curve is easy to identify, and the shape is complete and continuous. In contrary, once the coal seam thickness is unstable, and be destroyed by structure, the channel wave is with poor quality, the dispersion curve is hard to identify, and even cannot be identified. By analyzing the map of channel wave velocity inversion in Fig. 10, the extension is predicted as about 50 m. Based on the comprehensive analysis of the interpretation results, it is predicted that the strike of the fault is 70°, and the length of extension to the inner face ranges from 50 to 60 m. The actual extension length of the fault to the inner mining face is 53 m, which is associated with the prediction result of ISS.

4.4 Effect of ISS on faults in coal seam

Faults in coal seams can be effectively identified by ISS technology. When the fault is located in the adjacent area outside the coal face, it is better to use the reflection wave method to detect the fault. However, if the fault is in the face interior, it is suitable to use the transmission wave method, the reflection wave method, or to combine the two together. The reliability of the channel wave interpretation and prediction can be improved by synthetic analysis of raw data, seismic phase, reflection phase, data acquisition quality and velocity, etc. However, there are still some technical difficulties in detecting the multi-component faults.

Fig. 8. The fault location comparison between ISS prediction and drilling.

Fig. 9. Channel wave quality distribution in 12040 mining face.
5 Goaf Detection

After unordered coal mining, many coal seam goaf areas are left behind, which will cause serious disasters to the subsequent secondary coal mining.

5.1 The harmfulness of goaf and water inrush event

The coal mines in China reached about one hundred thousand in the 1990s, most of which were small and underground coal mines. By the end of 2017, the number had dropped to about 7000. However, the closure of these coal mines left a large area of goaf that filled with water. Out of profits, the mining of coal resources were with a greater arbitrariness, combing with weak technical strength and unclear-marked mining and water accumulation, making it difficult to accurately grasp the goaf and the scale of accumulated water, which will pose a serious water hazard to the nearby large-scale mining mines. For example, on August 7, 2005, water inrush accident occurred in Daxing Coal Mine in Meizhou, Guangdong Province, which resulted in 121 deaths or whereabouts unknown; on December 2, 2005, 42 people died in Xinansigou Coal Mine, Henan Province; on March 28, 2010, Shanxi Wangjialing Coal Mine water inrush accident, resulting in 153 people trapped, and 38 deaths. These serious water inrush accidents are all caused by water in the mined-out areas left by small coal mines.

5.2 Detection of goaf water of Xinan Coal Mine

About half of the east wing of Xinan Coal Mine was submerged by Xiaolangdi Reservoir, and there were thousands of small coal mines left over in different periods in shallow coal seams, of which 42 small coal mines were directly located within the flooded area of Xiaolangdi Reservoir. It not only causes the water in the small mines in the east wing of the mine to be connected with the reservoir water, but also poses a great threat to the mine safety. As once the goaf water collapses, the consequences are inconceivable. In order to “liberate” the shallow coal resources and ensure the production and mine safety, the seismic channel wave reflection method is used to detect the goaf in the shallow adjacent areas at the mining faces of 15050 and 15060 respectively. No strong reflection phase was found within 200 m of the survey area as shown in Fig. 11. Combined with the results of surface transient electromagnetic survey, it was concluded that the mining face could be safely produced. Then, under the safe condition, more than 1 million tons of the coal resource could be “emancipated”, whose economic value is about 800 million yuan.

5.3 Goaf water detection in a coal mine in Shanxi Province

There is a large area of goaf in a coal mine area in Shanxi province. Goaf water is the main risk of coal mining, and the adjacent Wangjialing coal mine has caused a particularly serious death accident due to the outburst of goaf water. There is a suspected goaf in the 32111 mining face of the mine, and the position and water accumulation are unknown. In order to scientifically guide the exploration and discharge of water and eliminate the threat of water outburst, the abnormal region of wave field is identified by combining transmission wave method with...
reflected wave method through wave field analysis under the guidance of seismic channel wave field theory (Fig. 12). It is suggested that the superimposed area of the abnormal area should be taken as the focus of water inrush exploration. Of the dozens of water exploration boreholes constructed in the mine, 5 of them were detected water accumulation in the goaf. 5 outlet boreholes were located in the abnormal area of ISS or in the edge of the abnormal area. 3 of them are in the superposition area of the determined wave field anomalies, and the other 2 are also close to the superposition region (Fig. 12).

5.4 Effect and problems of ISS application in goaf water

I. The application of ISS in underground goaf detection of coal mine has obvious effect.

II. In order to achieve more precise results, mathematical-physical simulations and more field tests are needed to study the anomalous characteristics of seismic channel waves (including non-water-filled or water-filled conditions) when they encounter mined-out areas in the course of propagation. The characteristics of absorption, velocity and spectrum of the reflected wave field should be studied in an innovative way.

III. The combination of seismic channel wave with surface 3D earthquake, high density seismic and transient electromagnetic exploration, and underground electrical geophysical exploration can obtain a more accurate detection of goaf.

6 Collapse Column Detection

In coal mining, it may lead to water inrush and other mining disasters that result in heavy casualties or property losses when blindly exposed or approached to the collapse column without coal seam thickness detection and prediction.

6.1 Collapse column water inrush in coal seam

Collapse columns are widely distributed in coal mines in China. In some mining areas, hundreds of collapse columns are exposed by a single coal mine. Collapse column is one of the main factors that cause the coal mine inrush accident. Water inrush from collapse column, connecting Ordovician Limestone Karst confined aquifer and the floor of coal seam, happened in 2171 mining face, Fangzhuan mine, Kailuan, on July 2nd, 1984, is peculiar in the history of world mining. Its largest outflow value was up to 2053 m³/min, and direct economic losses were over 400 million Chinese Yuan (Yin et al., 2004).

Both Shanxi Jincheng anthracite mining group Co., Ltd and Yima Coal Industry Group Co., Ltd. have ever used the transmitted and reflected wave method, combined the two methods together to detect the collapse column, and cooperated in the exploration and interpretation. However, the interpretation result of the seismic channel wave method is generally superior to that of other geophysical exploration methods based on the validation data.

6.2 Collapse column detection in Chengzhuang Coal Mine (CCM) of Shanxi Jincheng Anthracite Minging Group Co., Ltd

In CCM, ISS is used to detect the development of collapse columns in the area ranging from cut hole to 600m from it in mining face 5308. Out of 899 dispersion curves, 494 curves with continuity and travel time reliability were selected to pick up travel time at 180 Hz, and the velocity distribution of the channel waves in the detection area were plotted by tomographic imaging. One low velocity region in the channel wave velocity map is predicted to be an oval collapse column with a long axis of 90 m and a short axis of 48 m as shown in Fig. 13. It also shows that the long axis and the short axis are 98 m and 52 m respectively in actual coal mining, which are consistent with the predicted size and position, and the occurrence of the collapse column is similar as well.

It shows that the theory and technology of ISS can be effectively used to detect the location, scale and occurrence of collapse columns which pass through coal seams or affect the occurrence of coal seams.

7 Stress Concentration Zone Detection

The stress concentration zone in coal seam is the high-risk area of disaster event.

7.1 Rock burst originated from stress concentration

The rock burst, caused by the instantaneous release of elastic deformation energy contained in coal and rock
mass, has the characteristics of sudden occurrence, intense material movement and great destructive power, which seriously threatens the safety of coal mine and is easy to cause serious accidents of mass death and injury. On January 20, 1960, the Coalbrock North Coal Mine in South Africa suffered a serious rockburst accident, resulting in 432 death. And the underground damage area was up to 3 million square meters (Li, 2003). Mines in more than 20 countries, including China, have suffered from rock burst disasters (Pan et al., 2013). China is one of the countries with serious damage caused by rock burst in mine, and more than 100 mines have been hit by rock pressure disaster. Yima coalfield, with serious rock burst, has occurred more than 100 times (Xu et al., 2015), resulting in more than 30 death, and the damage at the site was extremely serious as well (Fig. 14).

It is generally believed that rock bursts may occur under high in-situ stress condition. Seismic P wave was mainly used to detect the high stress concentrations at the coal face by the transmission method. By analyzing the image of velocity distribution of P wave, it can be concluded that the region with high wave velocity is the relatively concentrated area of in-situ stress with a high-risk of rock bursts (Lian et al., 2017). Yima Coal Industry Group Co., Ltd. was the first coal mine to use the channel wave seismograph to detect the in-situ stress concentration area at coal mining face. By comparing the result with that of the in-situ stress detector (PASAT), a new understanding has been developed in the detection of stress concentration regions.

7.2 In-situ stress concentration area detection in Gengcun Coal Mine (GCM)

The average depth of 12230 mining face in GCM is 550

Fig. 13. Collapse column comparison between ISS prediction and actual.

Fig. 14. The photos of damaged roadway after the accident.
which has the potential danger of rock bursts. The test area is 400 m in the middle section of the mining face. Released from a same seismic source, the channel wave and P-wave were collected by the SUMMIT-Ⅱ EX channel wave seismograph, and the P-wave was collected by the PASAT in situ stress detector. In the upper roadway, 40 shot points were designed with a spacing of 15 m; the lower roadway was designed with 25 SUMMIT-Ⅱ EX channel wave wave seismographs, with a spacing of 15 m and a hole depth of 2 m. The PASAT in situ stress detector was placed next to it. There are 24 detection points with a spacing of 15 m. The detector and the wall anchor were connected by screws. The shots are fired one by one, and the two sets of instruments receive seismic signals simultaneously in the lower lane. After data processing, inversion and tomography, PASAT type P-wave velocity map (Fig. 15), SUMMIT P-wave velocity map (Fig. 16) and SUMMIT channel wave velocity map (Fig. 17) were respectively characterized.

The comparison of the imaging results of the SUMMIT-Ⅱ channel wave velocity distribution map and the P-wave velocity distribution map and the PASAT P-wave velocity distribution map shows that the high-speed regions of the three are different, but they have higher similarities and large overlaps (Fig. 18). The overlapping area is located in the range of 130 to 190 m outward from the cutting hole of the lower lane and extends to the inside of the working surface by 37 m, so it is inferred to be the stress concentration area of the working surface.

There is a wide range of overlap between the high-speed region of SUMMIT-Ⅱ channel wave and the high speed area of P wave of PASAT in-situ stress detector. There is a normal fault with 8.5 m fault throw in the overlap area, and the fault and its vicinity are usually stress-concentrated areas. When drilling in this section, the coal and rock powder amount is large, and it is easy to shrink holes.

From the above detection results, it can be seen that:
(1) The high-risk area of rock burst can be predicted by detecting the stress concentration area of rock burst mining face by ISS.
(2) The combination of seismic channel wave and P wave is used to detect the stress concentration area in coal mining face, better prediction results can be obtained.

8 Detection of Gas Enrichment Area

8.1 Gas in coal mine
Gas is the first killer of coal mines. Once coal-gas outburst, gas explosion and other gas accidents occur, which can easily cause serious casualties and property losses. On February 14, 2005, 214 people were killed and 30 were injured in Liaoning Sunjiawan mine gas explosion accident. On October 31, 2016, 33 people were killed and 1 were injured in Chongqing Jinshanggou coal mine gas explosion accident.

In-situ stress concentration zone, complex and staggered structural zone, coal seam thickness variation zone and other sections are easy to form "gas bag", which is the key to prevent gas accident. ISS has obvious effect on the detection of geological hazards abnormal region such as in-situ stress concentration zone, complex and staggered structural zone, coal seam thickness variation zone, etc. (Feng et al., 2017). Therefore, it can be used to detect gas enrichment areas and guide the prevention and control of mine gas disaster.

8.2 Gas enrichment area detection in Xinan Coalfield
In Xinan coalfield, the Shanxi Formation, with a thickness from 0 to 18.88 m and an average thickness of 0 to 4.0 m, is mainly mined. At present, 5 pairs of production mines, including Xinyi, Yian and Xinan, are all in danger of coal and gas outburst, and gas prevention and
control is the most important task in coal production of each coal mine. The transmission method of seismic channel wave is used to detect the gas enrichment area in the 6 selected mining faces. The contour map of the channel wave velocity and the measured gas content contour map obtained by the inversion are compared and analyzed (Fig. 19). It is found that there is a correlation between the wave velocity of the channel wave and the change of the gas content:

1. If the coal seam thickness is stable, the gas content is generally higher in the section with higher velocity of channel wave.
2. The gas content is generally higher in the zone where channel wave velocity change rapidly, or in the zone with high and low velocity interphase distribution.
3. The gas will be higher where the low speed wave

Fig. 18. Comprehensive result by joint-detecting of channel wave and P-wave.

![Fig. 18. Comprehensive result by joint-detecting of channel wave and P-wave.](image1)

Fig. 19. Comparison between channel wave velocity and gas content.

![Fig. 19. Comparison between channel wave velocity and gas content.](image2)
area is surrounded by high speed wave.

9 Detection of Floor Water-irruption in High Risk Area

9.1 Coal mining safety and bottom plate bearing karst aquifer threat
Karst water in coal seam floor is one of the major coalmine hazards in China’s coal mines. Once the coal seam floor pressure karst water inrush, it probably leads to the submersion of coal face, mining area, and even the mine or other serious underground water inrush accidents, sometimes cause casualties as well. For example, on September 2, 2003, a Cambrian limestone karst aquifer water inrush accident occurred in Fenjin Coal Mine, Yichuan County, Henan Province. The water inrush quantity reached 9800 m$^3$ in 20 minutes, resulting in the death of 16 people.

At present, mines mainly use transient electromagnetic method (TEM), DC method, high density resistivity method, audio frequency electrical perspective to detect the risk of water inrush from the floor aquifer. Generally, the region with low apparent resistivity is regarded as the suspected water-rich area, and then the risk of water inrush is predicted based on factors like apparent resistivity, the water inrush coefficient and so on. Though effective, these methods are susceptible to metal materials, power supply, water and other factors. With the powerful supporting and the development of mechanization of mine roadway, and the extensive use of metal materials, it is difficult to detect with a complete power outage, which leads to the increase of false alarm and false report. Therefore, an attempt has been made to combine the seismic channel wave detection results with the electrical detection results in order to improve the reliability of the prediction of water inrush risk from the coal seam floor (Li et al., 2013).

9.2 Detection of Ordovician aquifer water inrush risk in Xinan Coal Mine
In Xinan Coal Mine, the thickness of the aquiclude of the coal seam floor in 13151 mining face was with an average of 45.7 m, and there is a risk of water inrush due to the water pressure of 3.0 MPa, (Li et al., 2015). Before mining, TEM and ISS were both carried out in the mining face. As shown in Fig. 20, an electrical low resistance zone was delineated in the lower lane according to the results of TEM. There were three high-speed zones in the distribution map of channel wave velocity in mining face. The high-speed zone is usually caused by stress concentration or coal seam thinning, while the coal seam thinning is closely related to the development of floor structure. By comprehensive analysis, the overlap area of high speed area and low resistance area was predicted as the floor water inrush high risk area, and this was verified by four drilling holes as shown in Fig. 21. Due to the incomplete bottom grouting, the floor water inrush occurred in the predicted high-risk area on January 16, 2012, with a maximum instantaneous water inflow of 700 m$^3$/h.

It is shown that the combination of ISS and TEM can be used to detect the water abundance in the floor of coal seam, which can better predict the water inrush risk of the floor.

10 Detection of Region Area

10.1 Detection of region area beneficial to design coal mining face scientifically
Before working in the coal mining face, the geophysical exploration should be carried out in the area that composed of several mining faces, even half or the whole mining area, to detect the geological structure, the coal seam thickness variation, collapse columns, goaf distribution, and the mining risk prediction areas. It is of great significance to the scientific design of mining face, safe and efficient excavation, and reasonable management of mining. However, geophysical exploration is rarely carries out in region area. Thus, based on the long propagation distance of channel wave, it can be used in the regional detection of abnormal bodies of underground disaster events.
10.2 Region area detection in Yunding Coal Mine

Yunding Coal Mine is close to the western boundary fault of Xinan coalfield, where the structure of the mine field is developed, and the thickness of coal seam varies greatly. In Fig. 22, based on the mine-return air roadway and the belt roadway completed in 12010 mining face, the channel wave transmission method is used to detect the thickness of coal seam and the development of faults in the region area formed by the designed 12010 and 12030 mining faces, which provides a scientific basis for the design of the two mining faces, roadway drivage, and coal mining. In Fig. 22, based on the coal seam thickness information in exposed area, the inversion velocity image of channel wave detected in region area of the two mining faces were transformed into coal seam thickness map, in which the coal seam area with thickness less than 1.5 m is predicted (Fig. 22). According to the coal seam thickness map, the mine 12010 and 12030 mining faces were designed scientifically and the roadway excavation of mining face was arranged. When the track roadway and cutting hole of 12010 face are formed, in order to compare the detection effect with the region area, the channel wave transmission method is used to detect the 12010 coal mining face again. As shown in Fig. 23, a thin coal area with the thickness of less than 1.5 m has also been identified for a single mining face as well. In both surveys, no faults were found.

The 12010 mining face has finished the mining now. Compared with the actual situation, the results of ISS is associated with the exposing situation in the mining, which shows that the detection results of the region area of the two mining faces are basically in accordance with those of the single mining face. However, Fig. 24 shows that the detection and prediction effect of a single mining face is better than region area detection, which indicates that the effective resolution of the channel wave will be decreased with the increase of detection distance.

11 Innovation and Suggestion

Guided by the theory of seismic channel wave, the systemic research, lasted more than 7 years, carried out 69 experiments of high-precision ISS and high-resolution data acquisition in coal mines. For the first time, systematic and innovative achievements and important progress have been made in detecting abnormal bodies of geological hazard events in coal seams.

11.1 Innovation

(1) The variation in thickness of the coal seam can be effectively detected by seismic channel wave field theory and its detection technology. The geological anomalies, such as faults, collapse column, the location, occurrence, and scale of goaf, which may lead to underground disasters, are detected and discovered accurately in coal seams.

(2) ISS presents boundary field abnormal response in the exploration of stress concentration zone, gas enrichment area and water inrush area, which can act as a role of early warning.

(3) Seismic channel wave, P-wave, S-wave and other geophysical prospecting methods such as
microearthquake, TEM, DC resistivity survey, surface geophysical exploration are combined for a multi-element and comprehensive analysis, which can better interpret the channel wave field and detect the potential disastrous geological anomaly in coal seams.

(4) The theory and method of ISS for underground disaster events are defined, and an independent interpretation system is formed in the aspects of observation system, data acquisition, inversion imaging software and so on. The first batch of measured data and maps of a series of typical disaster events have been obtained and the practice of coal mine production has been effectively guided by scientific interpretation.

The results obtained by this research and the formation of seismic channel wave field characteristic detection systems are initiative at home and abroad. It has laid a solid foundation for detection, early warning and prediction of geological anomalies of underground disaster events in coal mine and it open up a new field.

11.2 Suggestions

Different from the characteristic of the seismic wave field in surface exploration (seismic wave propagates in infinite half space), seismic channel wave field (propagated in low speed channel with high speed media) has the characteristics of obvious dispersion and rich information. The theory is clear, the logic is strong, and the conclusion is reliable, and it fully shows that the ISS has a good function and potential for the exploration of abnormal geological bodies in underground coal seams. Therefore, it is suggested that the relevant departments should continue to give high attention and strong support in order to form an industry-academy-research trinity platform for ISS of disaster events detection in underground coal seams in China, which will make new contributions to the safety production and healthy development of China's coal industry.

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