

# Study On In-Seam Wave Response Characteristics of Reflection in Fault Bearing Coal Seam of Shuangliu Coal Mine

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## Research Article

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# Abstract

In order to study the response characteristics of reflected trough in-seam wave in fault bearing coal seam, find out the geological structure of coal mine, and ensure the scientific and safe mining of coal mine, the physical property parameters of coal and rock samples of No.3 Coal Seam in Shuangliu Coal Mine were determined, and the three-dimensional numerical analysis model of homogeneous isotropic medium was established. The full wave field forward modeling of elastic wave equation was carried out by using the finite difference method. In this paper, the dispersion curve of No.3 Coal Seam in-seam wave detection in Shuangliu Coal Mine is studied. The results show that under the geological conditions of Shuangliu Coal Mine, the dispersion curves of in-seam wave are obviously different when the coal thickness is 1m, 3m, 5m and 8m; The dispersion curve of reflected in-seam wave in goaf is disordered, which is obviously different from that of normal coal; The Airy phase velocity of in-seam wave in No.3 coal seam of Shuangliu Coal Mine is about 1000 m/s, and the dominant frequency is 140 Hz. The conclusions are as follows: the formation of in-seam wave in the mining area is related to the direct roof and floor, but not to the indirect roof and floor; When the wave velocity difference between the roof and floor is large, the better dispersion response of Airy phase.

## 1 Introduction

With the continuous expansion of the scale of production in the coal industry and the increase in mining depths, coal mine safety has received more and more attention, and finding out the geological conditions of coal mines is a prerequisite for ensuring safety. In-seam wave exploration has been gradually applied to coal mine geological exploration in recent years. It is a kind of seismic exploration method. Its imaging definition is high, and it responds well to smaller geological anomalies (Hu et al. 2013; Li et al. 2016). Through in-seam wave seismic detection, the geological anomaly can be detected. Targeted drilling in the area not only saves time and effort, but also saves costs. Therefore, the in-seam wave seismic exploration method has been well applied in most mining areas across the country (Yang et al. 2020; Li et al. 2019; Pi et al. 2013). Many scholars have conducted numerical simulation research on in-seam wave detection in coal mines and analyzed its dispersion characteristics, which have important guiding significance for in-seam wave detection in coal mines (Lu et al. 2016; Jiang et al. 2018; Du et al. 2017). In this paper, the physical parameters of coal and rock samples in Shuangliu Coal Mine are measured, and the obtained data is used to establish a three-dimensional numerical simulation model, carry out forward simulation, and study the in-seam wave response characteristics, which will provide a theoretical basis for the future in-seam wave detection in the mine and surrounding areas.

## 2 Principles Of In-seam Wave Exploration

### 2.1 In-seam wave formation process

In-seam wave is a type of seismic wave. Because the coal seam density is lower than the surrounding rock density, the wave conduction velocity in the coal seam is low. The density and velocity ratio of coal to

surrounding rock is about 1:1.5~1:3, the interface between coal seam and roof and floor is a wave impedance interface (He et al. 2017; Ji et al. 2019). When the seismic source releases energy in the coal seam, except for a small amount of energy scattering, most of the energy propagates in the coal seam and overlaps each other, interfering with each other to form an in-seam wave (Yang et al. 2011; Wang et al. 2018; Su et al. 2020). In coal seams, seismic waves of different types and frequencies interact to form in-seam waves. Therefore, the wave velocity of the in-seam wave has a functional relationship with the frequency, which means that the in-seam wave is a dispersion wave.

## 2.2 In-seam wave exploration method

There are two main methods for in-seam seismic method in underground coal mines: in-seam wave transmission method and in-seam wave reflection method. The in-seam wave transmission method refers to arranging the seismic source and the geophone on the inner side of different roadways in the survey area, one roadway excites the seismic source, and the other roadway receives the in-seam wave signal. The in-seam wave transmission method is relatively simple to detect, with a large detection range and high accuracy, and the later data processing and analysis is relatively easy, and it can also provide basic data information for the reflected in-seam wave (Ji et al. 2012). The in-seam wave reflection method detection refers to the arrangement of the seismic source and the geophone on the inner side of the same roadway in the survey area. When passing through the geological anomaly, a part of the in-seam wave is reflected back to the position of the geophone, that is, the in-seam wave reflection signal is received (Hu et al. 2020; Zhao et al. 2019). Due to the influence of the thickness of the coal seam, the horizontal position of the fault, the size of the geological anomaly, the physical properties of the rock mass in the horizontal direction, and the frequency of the in-seam wave, compared to the in-seam wave transmission method, the reflection method is complicated and has large errors, and the energy is relatively weak (Zhao et al. 2019).

When the geological conditions are more complicated, the combined detection method of in-seam wave transmission and reflection can also be adopted. This method requires high site conditions and equipment, and the construction cost is also high. However, it has the comprehensive advantages of transmission and reflection detection. The in-seam wave information obtained by the detection is comprehensive, and the accuracy of the judgment of geological anomalies is high.

## 3 Characteristic Numerical Simulation Of In-seam Wave

The propagation speed of the in-seam wave has a functional relationship with the frequency, and the Airy phase with high frequency and large amplitude existing in the in-seam wave group velocity dispersion curve is the most important feature of the presence and strength of the in-seam wave signal (Yang et al. 2020). The main factors influencing the in-seam wave dispersion characteristics are the thickness of the coal seam, the degree of gangue, the degree of difference between the physical parameters of the coal seam and the surrounding rock, and the lithological characteristics of the roof and floor (Zhao et al. 2019; Gao et al. 2020).

The No.3 Coal Seam coal seam and roof and floor rock samples of Shuangliu Coal Mine were selected for related parameter testing to provide basic information for detection, data inversion, and result interpretation. The statistical results of the rock wave velocity test under no-load conditions are shown in Table 1. By comparison, it is found that the sequential changes of the ratio of P-wave and P-wave velocities with different lithologies are basically consistent with the sequential changes of lithological P-wave velocities. Since the seismic wave velocity of the rock formation is directly proportional to the density of the rock formation, the following table shows that the density of the coal seam in this area is compared with the density of the roof and floor rocks, that is,  $V_P \text{ coal} : V_P \text{ mud} \approx 1:1.36$ , so this area has the conditions for in-seam wave formation.

Table 1  
Test results of rock wave velocity under unloaded condition

Lithology	P-wave velocity / $\text{m}\cdot\text{s}^{-1}$	S-wave velocity / $\text{m}\cdot\text{s}^{-1}$	$v_p/v_s$
Coarse sandstone	3562.64 ~ 4269.13	2701.67 ~ 3007.90	1.28 ~ 1.44
	3897.08	2891.81	1.35
Medium sandstone	3971.20 ~ 4194.94	2784.44 ~ 3059.08	1.37 ~ 1.43
	4053.25	2896.07	1.40
Fine sandstone	3366.10 ~ 4021.14	1858.91 ~ 2788.02	1.40 ~ 2.14
	3675.45	2276.84	1.77
Argillaceous sandstone	2777.16 ~ 3080.25	1751.52 ~ 1770.87	1.57 ~ 1.76
	2928.70	1761.19	1.66
Too limestone	5346.49 ~ 6943.80	2672.65 ~ 3445.10	1.56 ~ 2.35
	6355.61	3059.97	2.13
Austrian limestone	3977.73 ~ 5201.57	1893.06 ~ 2593.99	2.01 ~ 2.12
	4771.74	2312.98	2.07
No.3 Coal Seam	2144.40	1340.97	1.6

The No.3 Coal Seam coal seam and roof and floor rock samples of Shuangliu Coal Mine were selected for related parameter testing to provide basic information for detection, data inversion, and result interpretation. The statistical results of the rock wave velocity test under no-load conditions are shown in Table 1. By comparison, it is found that the sequential changes of the ratio of P-wave and P-wave velocities with different lithologies are basically consistent with the sequential changes of lithological P-wave velocities. Since the seismic wave velocity of the rock formation is directly proportional to the density of the rock formation, the following table shows that the density of the coal seam in this area is compared with the density of the roof and floor rocks, that is,  $V_P \text{ coal} : V_P \text{ mud} \approx 1:1.36$ , so this area has the conditions for in-seam wave formation.

Using the obtained coal and rock sample parameters, using Norsar and Tesseral 3D numerical calculation software, using coal seam thickness and roof and floor lithology as variables, a three-dimensional numerical analysis model is established and forward simulation is performed. The model is set to a homogeneous and isotropic medium, and the finite difference method is used to perform a full-wave field forward simulation of the elastic wave equation. The size of the model is 100 0 m × 500 m (length × width), the length, width and height of the model grid are all 1 m, and the height of the model is determined according to the actual plan. There are 20 seismic sources and geophones, the shot spacing and the track spacing are both 20 m, the sampling length is 1000 ms, and the sampling rate is 0.1 ms. The excitation source is a Rake wavelet spherical source with a dominant frequency of 200 Hz. Regarding the influence of changes in coal seam thickness and roof and floor lithology characteristics on the in-seam wave seismic response characteristics, the transmission method is used to arrange the observation system in the numerical simulation, which is more conducive to the study of the regularity of its response characteristics.

### 3.1 Response characteristics of in-seam wave to coal seam thickness

According to the geological conditions of the mine, select the physical parameters of coal and rock as shown in Table 2, with the thickness of the coal seam as a variable (1 m, 3 m, 5 m, 8 m), the top and floor thickness of the model were selected as 50 m respectively, and a three-dimensional "roof-coal-floor" 3-layer symmetrical level was established. The three-dimensional numerical analysis model of the medium is shown in Fig. 1. The physical parameters of the model are shown in Table 2.

Table 2  
Table 2 Physical parameters of coal and rock

Lithology	P-wave velocity /m·s <sup>-1</sup>	S-wave velocity /m·s <sup>-1</sup>	Density /kg·m <sup>-3</sup>
Coal seam	2000	1200	1400
Mudstone	3000	1800	2100

The format conversion and Gabor change processing of the seismic wave information received in different coal thicknesses are performed, and the characteristics of the in-seam wave dispersion curve under different coal thickness conditions are obtained as shown in Fig. 2. It can be seen that the thickness of the coal seam has an obvious influence on the development of the in-seam wave: it is difficult to form an in-seam wave on the working face with a coal thickness of 1 m, and the reflected wave reception time and frequency are basically linear. After analysis, it is a S-wave of the coal seam; the coal thickness is 3 m. When the coal thickness is 5 m, the in-seam wave has obvious characteristics; when the coal thickness is 8 m, the in-seam wave develops poorly again.

### 3.2 Response characteristics of in-seam wave to roof and floor lithology

A three-dimensional numerical analysis model of a homogeneous medium with different roof and floor lithology levels is established (Fig. 3). The forward numerical model scheme is shown in Table 3, and the physical parameters of the model are shown in Table 4. When the coal seam thickness is 5 m, the in-seam wave dispersion characteristics under different roof and floor conditions are shown in Fig. 4. It can be seen that when the direct roof and floor are mudstone with the same lithology, the in-seam wave is not affected by the change of the double-layer roof and floor. The development characteristics of the in-seam wave are the same as the frequency dispersion characteristics of the single roof and floor of mudstone in 3.1. It shows that the number of roof and floor rock layers has no effect on the formation of in-seam wave, and is only related to the lithology of the direct roof and the direct bottom.

Table 3  
Forward numerical model scheme

Plan	Lithology of the roof	Top plate thickness/m	Coal seam thickness/m	Floor lithology	Thickness of bottom plate/m
Plan1	Sandstone/mudstone	25/25	5	Mudstone/Sandstone	25/25
Plan2	Sandstone/mudstone	25/25	5	Sandstone/sandstone	25/25
Plan3	Sandstone/limestone	25/25	5	Mudstone/Sandstone	25/25

Table 4  
Physical parameters of coal and rock mass

Lithology	P-wave velocity /m·s <sup>-1</sup>	S-wave velocity /m·s <sup>-1</sup>	Density /kg·m <sup>-3</sup>
coal seam	2000	1200	1400
sandstone	3500	2200	2650
Mudstone	3000	1800	2100
Limestone	6500	2700	2800

### 3.3 Analysis of simulation results

Through the analysis of the response characteristics of in-seam wave to coal thickness and roof and floor lithology in Shuangliu Coal Mine, the following results are obtained:

(1) The thickness of the coal has obvious influence on the characteristics of the in-seam wave dispersion curve. The in-seam wave has the characteristics of dispersion. The frequency of the in-seam wave decreases with the increase of the thickness of the coal seam, while the coal thickness basically has no effect on the Airy phase velocity of the in-seam wave. In the numerical simulation, the frequency of the Airy phase is higher than that of the measured results. The analysis is mainly due to the fact that the frequency of the seismic source selected by the simulation is inconsistent with the frequency of the actual explosive source. According to the working face length of 200 m, the time for the geophone to receive the

in-seam wave is about 200 ms, and the calculation shows that the in-seam wave velocity is about 1000 m/s.

(2) When the top and bottom lithological wave speeds are close, the influence on the frequency of the in-seam wave Airy phase is small. When the top and bottom wave speeds differ greatly, the dispersion response of the Airy phase increases, but the amplitude is small. Different roof and floor lithology combinations have no obvious influence on the in-seam wave velocity, and the in-seam wave velocity is still about 1000 m/s.

Through the relevant parameter test of No. 3 coal seam and roof and floor rock samples of Shuangliu Coal Mine, it provides basic information for detection, data inversion and result interpretation. According to the simulation results, the response characteristics of in-seam wave under different geological conditions in Shuangliu Coal Mine are mastered, which provides a theoretical basis for further research on the reflection of in-seam wave in fault-bearing coal seams in Shuangliu Coal Mine.

## **4 Achievement Verification**

### **4.1 Overview of the working face**

The 23(4)09 working face of Shuangliu Coal Mine is adjacent to the mine boundary on the east side. There is a known goaf near the mine boundary and gangue is contained in the coal seam. On the west side is the 23(4)11 working face which is preparing to stop. It is No.3 Coal Seam, the coal seam structure is relatively simple, the average coal thickness is 3.5 m. In this survey, the 23(4)11 working face was used as the test object to understand the development characteristics of the reflection in-seam wave, and the 23(4)09 working face was used to detect the influence of the goaf or the gangue layer on the development of the in-seam wave.

### **4.2 Observation system layout**

The area of 0.2 km\*0.7 km on the west side and 0.2 km\*1.7 km on the east side of the tailgate in the 23(4)11 working face of Shuangliu Coal Mine is used as the reflection in-seam wave detection area. The shot spacing and track spacing are both 10 m. The distance is 5 m, 200 g mine latex explosive is used as the explosive, and the blast hole is 2 m deep. 70 shot points and detector points are arranged on the west wall, 170 shot points and detector points are arranged on the east wall. The observation system is shown in Fig. 5.

### **4.3 Data processing and analysis**

After AGC gain and band-pass filtering are performed on the more typical original seismic single shot records collected on site, the signals collected by the 40th and 41st shots are shown in Fig. 6. It can be seen that the P-wave, S-wave, in-seam wave and reflection in-seam wave of the two shots are well developed, but the signal-to-noise ratio is average. The sound wave interference shown in figure a appears in the multi-shots. After analysis, it may be caused by the noise interference generated by the equipment

in the working face. The frequency band is relatively wide and the signal is obvious, it is difficult to filter, which will have a certain impact on the later drawing and interpretation.

The spectrum of the in-seam wave is usually used to analyze the spectral difference between the in-seam wave and the P-wave and the S-wave, and the narrowband filter can be used to extract the Airy phase or separate the P-wave and the S-wave. It can also extract the P-wave, S-wave and the in-seam. The spectral characteristic parameters of the wave are used for CT imaging. By analyzing the spectrograms of P-wave, S-wave, and in-seam wave, it is found that their peak frequencies are 78 Hz, 80 Hz, and 140 Hz, it can be seen that the difference is quite obvious. Therefore, the 120–180 Hz frequency band is selected for filtering in the in-seam wave exploration in this area, which can achieve the purpose of highlighting the effective signal of the in-seam wave and suppressing other interference waves.

The most fundamental feature of in-seam wave is the phenomenon of dispersion. The velocity and structure information of the roof and floor and coal seams can be seen through the dispersion characteristics of the in-seam wave. Through the dispersion analysis, the existence of the in-seam wave can be explained, and the coal seam can also be detected. Abnormal structures in the structure and working surface. According to the existing geological data and the obtained experimental data, the theoretical calculation of the in-seam wave dispersion curve is shown in Fig. 7. Based on the multiple filtering of single-track record, the groove wave dispersion curve obtained by extracting the group velocity and phase velocity curve from the measured groove wave record is shown in Fig. 8. The Airy phase velocity and dominant frequency of the in-seam wave at 23(4)09 working face are similar to the results calculated by the theoretical model. Therefore, the Airy phase velocity of the in-seam wave is determined to be 100 0 m/s and the dominant frequency is 140 Hz. Since the 23(4)11 working face is located at the boundary of the mine, there is a goaf near the coal seam and gangue is partially contained in the coal seam. Therefore, the in-seam wave dispersion characteristics are obviously different from the normal coal body. The characteristics are: the in-seam wave energy is weak and discontinuous, the energy of P-wave and S-wave (high-speed area) even exceeds that of in-seam wave, which is messy and irregular, the main frequency range of in-seam wave is slightly higher than that of normal coal body, and the speed is slightly lower.

## 4.4 Interpretation of results

The results of this in-seam wave reflection detection are shown in Fig. 9. There are 6 abnormal areas measured, of which YC1 ~ YC4 should be caused by the destruction of the mined-out area in the 23(4)09 working face; the YC5 location analysis is affected by the fault Affected, YC6 extends the boundary of the entire detection area, and it is inferred that it should be affected by the 23(4)11 headgate interface. It was verified by boring test that there is a large area of mined-out area in the 23(4)09 working face, and there is a fault at the YC5 anomaly. It can be seen that the in-seam wave exploration has a better response effect in this area.

## 5 Conclusion

Through this research on the in-seam wave response characteristics under different geological conditions in Shuangliu Coal Mine, it is calculated that the density of the coal seam in this area is about 1.36 compared with the density of the roof and floor rock (shale sandstone), so this area has the conditions for the formation of in-seam wave. The specific conclusions are as follows:

- (1) The formation of in-seam wave in this area is related to the direct roof and floor of the coal seam, and has little to do with the indirect roof and floor. The in-seam wave are formed when the coal thickness is 3 m, 5 m and 8 m;
- (2) Coal thickness has obvious influence on the characteristics of in-seam wave dispersion curve, but coal thickness basically has no influence on Airy phase velocity. When the difference between the top and bottom plate wave velocities is large, the dispersion response of Airy phase is better;
- (3) The speed of the Airy phase of the No.3 Coal Seam in-seam wave in Shuangliu Coal Mine is 1000 m/s and the dominant frequency is 140 Hz, which can provide a theoretical basis for in-seam wave detection in surrounding mines.
- (4) Reflected in-seam wave detection is carried out at the boundary of the mined-out area, and the obtained dispersion curve is messy, which is obviously different from the normal coal dispersion curve.

## Declarations

### Data Availability

The data used to support the findings of this research are included within the paper.

### Conflicts of Interest

The authors declare that there are no conflicts of interest.

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## Figures

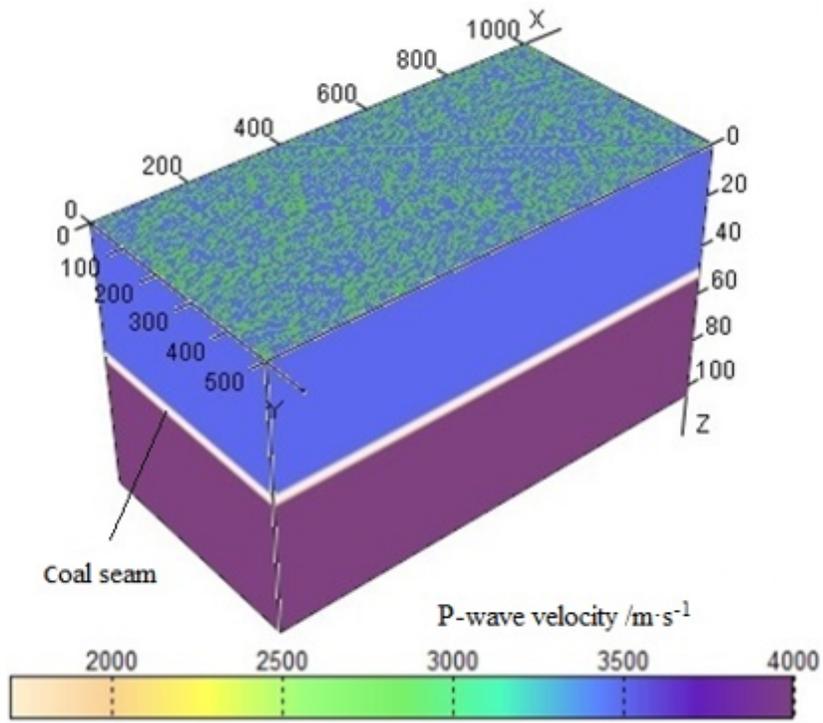
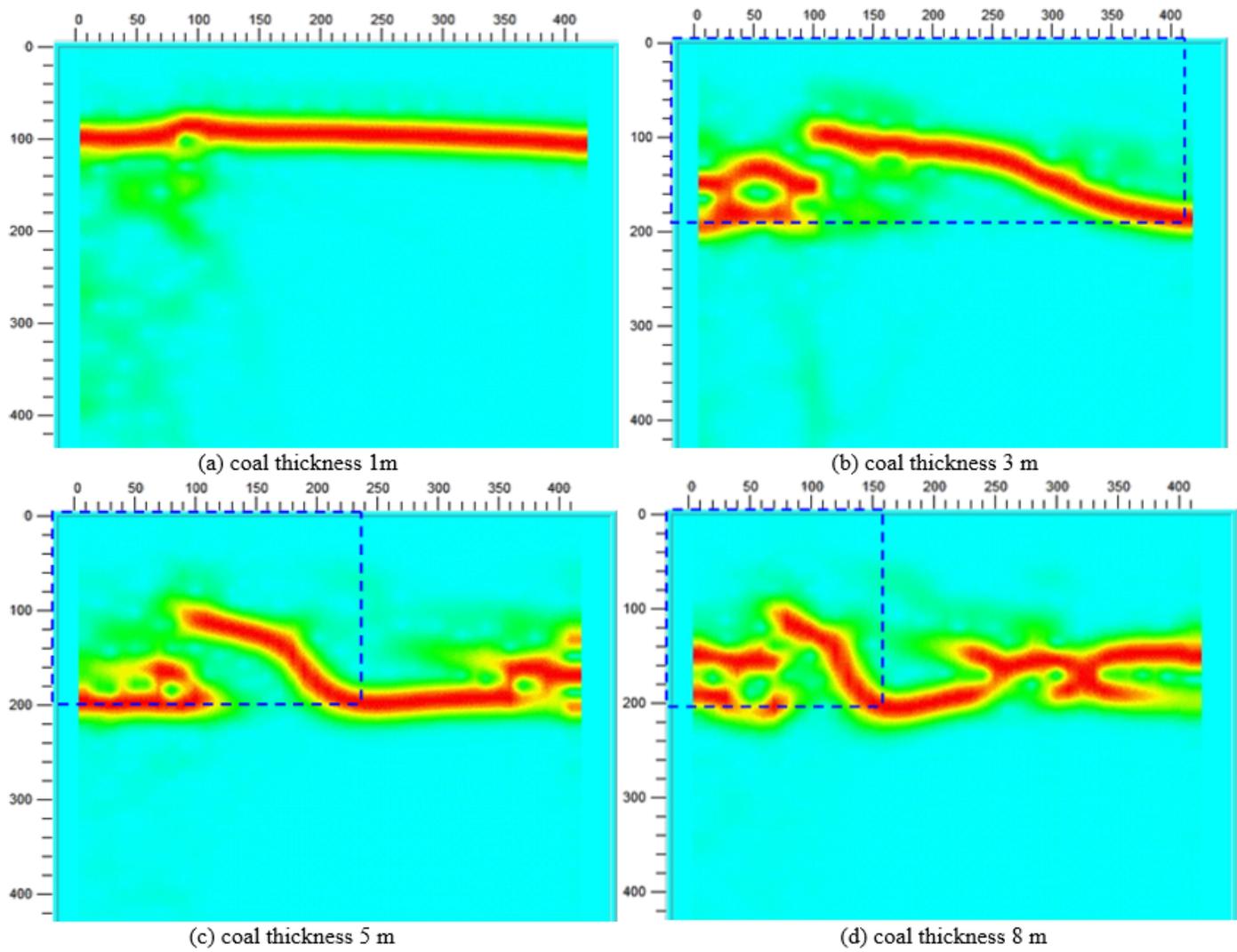


Figure 1

3D numerical stereo model



**Figure 2**

Dispersion diagram under different coal thickness conditions (Horizontal axis coordinate: frequency/Hz; vertical axis coordinate: speed/ $\text{m}\cdot\text{s}^{-1}$ )

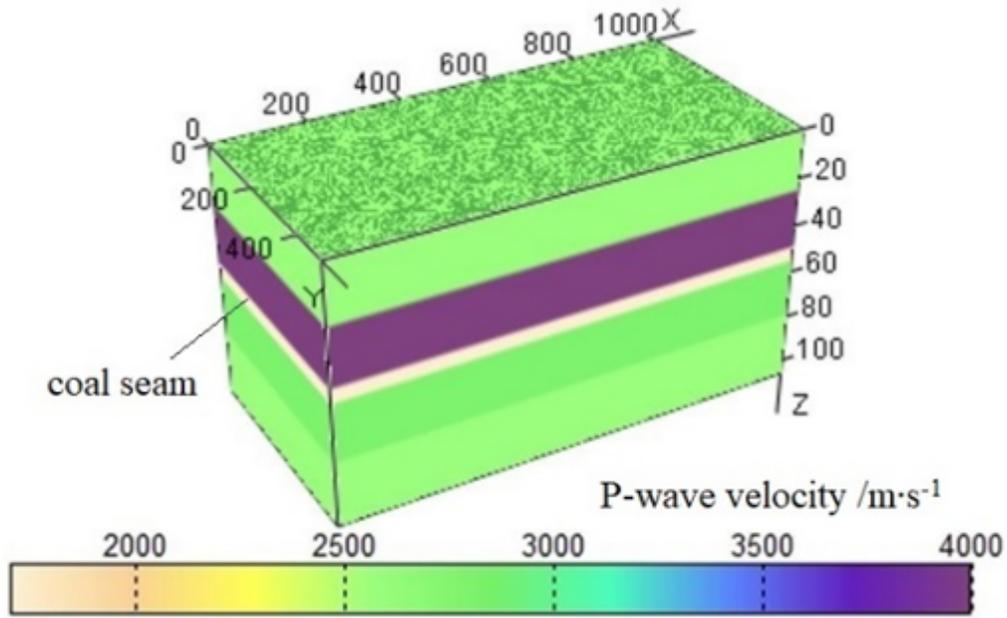


Figure 3

Numerical model of different roof and floor rock properties

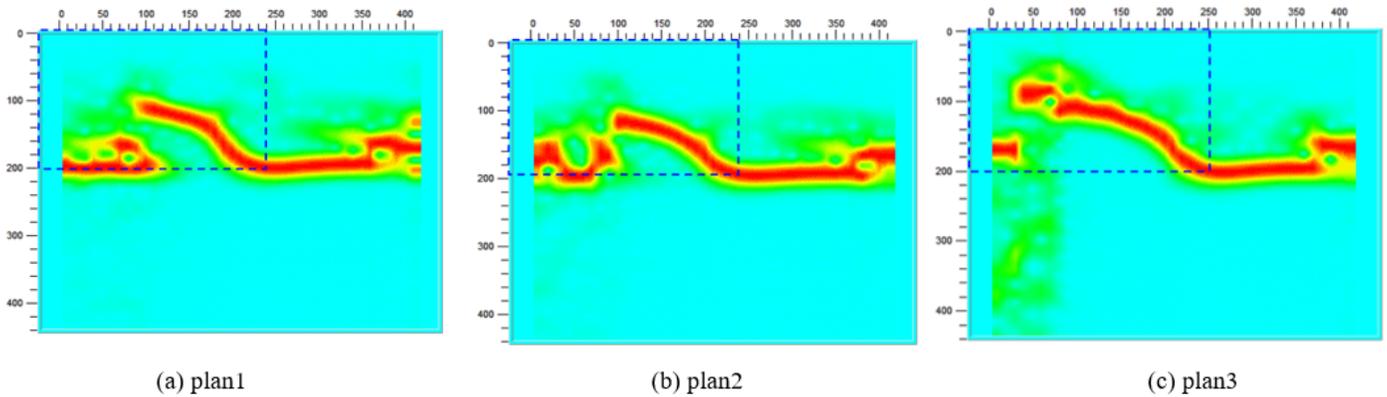


Figure 4

Dispersion curves of different roof and floor rock properties (Horizontal axis coordinate: frequency/Hz; vertical axis coordinate: speed/ $\text{m}\cdot\text{s}^{-1}$ )

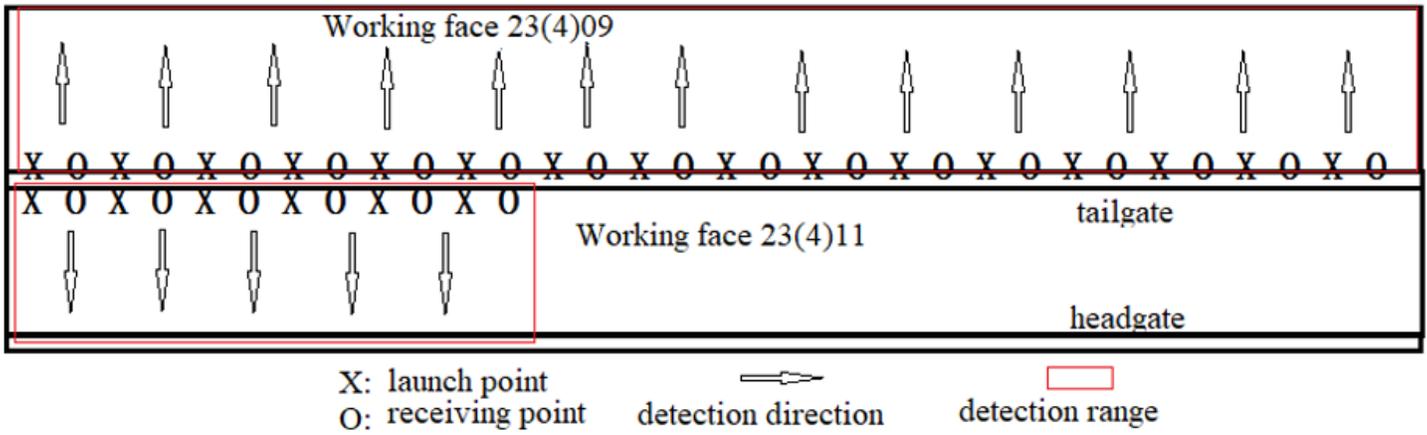


Figure 5

Layout of observation system

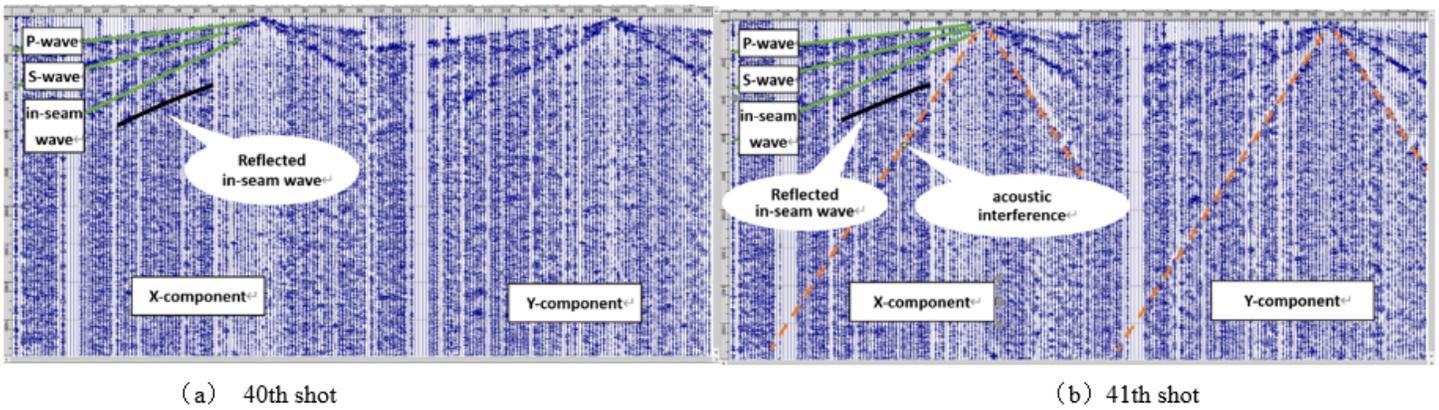
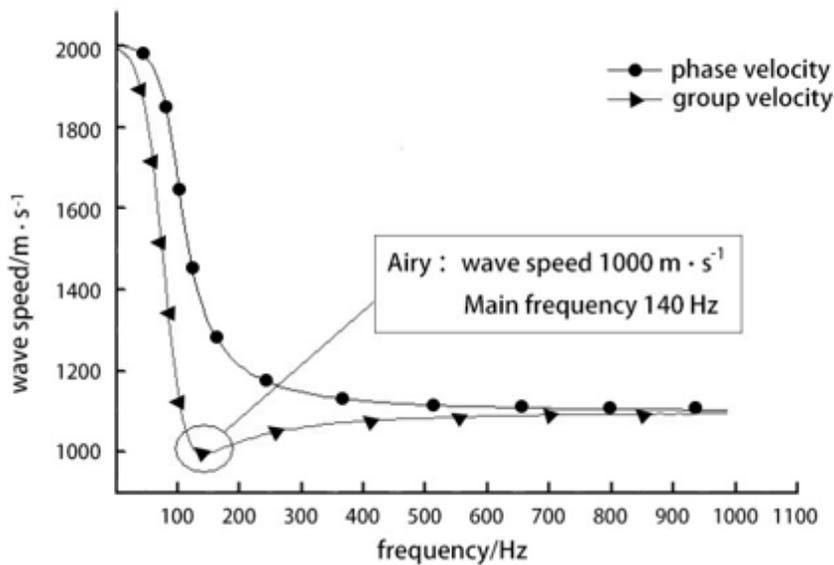


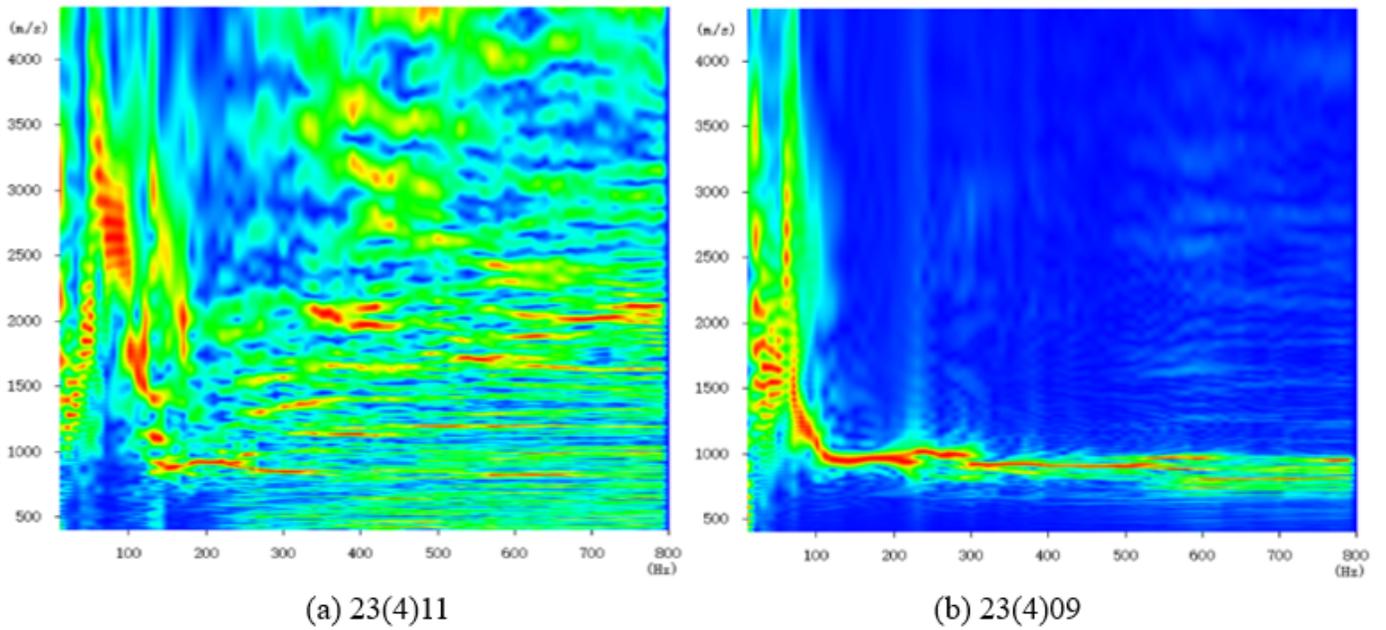
Figure 6

Original single shot record



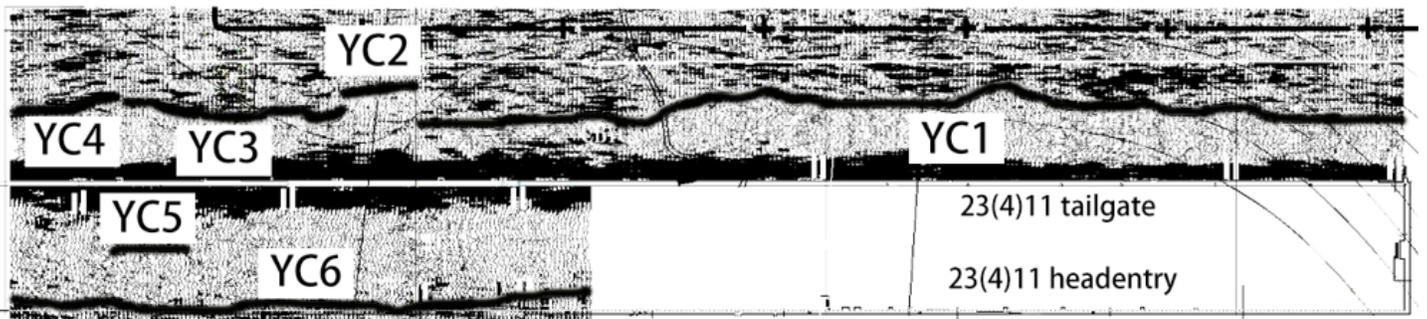
**Figure 7**

Theoretical dispersion curve



**Figure 8**

Dispersion curve of in-seam wave (Horizontal axis coordinate: frequency/Hz; vertical axis coordinate: speed/m·s<sup>-1</sup>)



**Figure 9**

Detection results