UNIVERSIDAD
NACIONAL
DE COLOMBIA
S E D E B O G O T Á

FACULTAD DE CIENCIAS
DEPARTAMENTO DE GEOCIENCIAS
RESEARCH GROUP IN GEOPHYSICS

Diffraction Characteristics of Small Fault ahead of tunnel face in coal roadway

Bo Wang[1], Shengdong Liu[1]*, Fubao Zhou[2], Jun Zhang[1], Fangkun Zheng[1]

1 State Key Laboratory of Deep Geomechanics & Underground Engineering and School of Resource and Earth Science, China
University of Mining and Technology, Xuzhou 221116, China
2 School of Safety Engineering, China University of Mining and Technology, Xuzhou 221116, China
*Email of Corresponding Author: wbsyes@126.com

ABSTRACT

Small fault ahead of the tunnel face in coal roadway is the important hidden hazard factor of coal and gas outburst accidents. The study of small fault prediction has important practical significance, which is the urgent demand of coal mine safety production. The diffraction of breakpoint can be used to identify the fault. However, unlike surface seismic exploration, the diffraction is with approximately horizontal incidence when the advanced detection is carried out in the roadway. The common advanced detection system is mainly as the reference of traffic tunnel, without considering the influence of low-velocity coal seam. Considering the influence of an acoustic wave of the roadway cavity and channel wave of the coal seam, the advanced detection model of small fault ahead of tunnel face is established. Diffraction advanced observation system in which sources located in front of tunnel face is constructed, and the numerical calculation of the high-order staggered-grid finite difference is carried out. The simulation results show that: Compared with the data collected by reflection observation system, in seismic records acquired by diffraction observation system, the suppression effect of acoustic wave is appeared. The diffracted P-wave of the breakpoint of component X is clear with strong energy and short-wave group. Multiple diffractions of the breakpoint are not found, but the multiple diffraction of tunnel face endpoint is obvious. The difference between breakpoint diffraction and multiple diffractions of the endpoint is clear, and diffracted P-wave of the breakpoint is easy to identify. The multiple reflected channel wave between the fault and the tunnel face is very obvious, and the reflected channel wave of small fault is so hard to identify. Migration results show that the imaging resolution of diffracted P-wave of small fault is higher than the reflected channel wave, and breakpoint location of imaging is consistent with the actual model.

Características de difracción de falla pequeña en la calzada de carbón de un túnel

RESUMEN

La falla pequeña en la calzada de carbón de un túnel es un factor importante no visible en los accidentes por explosión en minas de gas y carbón. El estudio de la predicción de falla pequeña tiene un importante sentido práctico: la demanda urgente de seguridad en la producción carbonífera. El punto de quiebre de la difracción puede utilizarse para identificar la falla. Sin embargo, al contrario que la exploración sísmica superficial, la difracción se acerca a la prevalencia horizontal cuando se realiza la detección avanzada en la calzada. El sistema común de detección avanzada se usa principalmente para referenciar el tráfico del túnel, sin considerar la influencia de la baja velocidad en la veta de carbón. Al valorar la respuesta de la onda acústica en la cavidad de la calzada y la onda de canal de la veta de carbón se establece el modelo de detección avanzada de pequeña falla para la calzada del túnel. Se construyó el sistema de observación avanzada de difracción en el cual las fuentes se localizan en frente de la cara del túnel y se realizó el cálculo de diferencia finita en una red escalonada de orden alto. Los resultados del modelo muestran que a diferencia de la información recolectada con el sistema de observación de reflexión, en los registros sísmicos adquiridos con el sistema de observación de difracción se puede ver el efecto de supresión de la onda acústica. El punto de quiebre de la onda P difractada para el componente X es claro, con energía fuerte y en el grupo de onda corta. No se encontró el punto de quiebre para difracciones múltiples pero es evidente la difracción múltiple para el punto final de la cara del túnel. Es clara la diferencia entre el punto de ruptura de la difracción y las difracciones múltiples del punto final, mientras el punto de ruptura de la onda P difractada es fácil de identificar. Los resultados de migración muestran que la resolución de imágenes de la onda P difractada de falla pequeña es mayor que la onda de canal reflejada y la ubicación del punto de quiebre de la imagen es consistente con el modelo actual.

1 Introduction

In China, the deaths from 2012 to 2016 was 451 because of coal mine gas accidents (Liu et al., 2016), so coal mine gas prevention and control are very grim, and gas control is the most important work of coal mine safety production. Most accidents of coal and gas outburst in tunnel face of coal roadway occur near the geological structure (Shepherd et al., 1981; Lama et al., 1998), especially small fault (Gao et al., 2015). This paper focuses on the research of small fault ahead of the tunnel face, which is the important hidden factor of coal and gas outburst accident. It is of great practical significance to the prevention and control of gas accidents.

At present, there are a lot of advanced geophysical exploration methods adopted in the roadway, which can be divided into three classes: seismic class, electromagnetic class, and other class (Roslee et al., 2017). At present, the seismic wave method is less affected by the detection environment, which is most suitable for the prediction of geological structure (Lüth et al., 2006; Jetschny et al., 2011). The seismic wave method of advanced detection mainly includes the reflected wave method, surface wave method, scattered wave method, channel wave method, diffraction method and so on (Wang et al., 2016).

The advanced detection by using reflected wave method is started early in the field of traffic tunnel. According to the launching order, seismic advanced detection technology includes: HSP, TVSP, TSP, TRT, ISIS, TGP, TSD, USP, TSWD, etc. (Inazaki et al., 1999; Otto et al., 2002; Lüth, et al., 2005; Jetschny et al., 2010). Compared with the advanced tunnel prediction, the research on reflected wave in coal roadway is few, including RTSP, MSP, etc. (Wang et al., 2015).

In the aspect of advanced detection of surface wave and scattered wave in underground coal mine, the advanced detection technique of Rayleigh surface wave was carried out in Fangezhuang Mine (Cheng et al., 2014). Zhao et al. (2006) obtained higher image positioning accuracy based on inverse scattered imaging theory. Cheng et al. (2013) studied the seismic scattered wave imaging in coal roadway by using numerical simulation method.

In the aspect of reflected channel wave, Essen et al. (2007) analyzed the response characteristics of Rayleigh channel wave of split coal through numerical simulation; Yang et al. (2012) carried out numerical simulation research with seismic wave field of small structure, and then pointed out that the Rayleigh surface wave generated from the reflection of Rayleigh channel wave can be used as the characteristic wave of the advanced detection of small structure. Lu et al. (2013) obtained the reflected channel wave by using tunnel boring machine as the source to carry out the advanced detection survey with a vertical fault with fault throw of 8m.

In the aspect of the diffraction, Yang et al. (2010) analyzed the wavefield of the advanced detection model of the geological interface, and then pointed out that the diffraction was the powerful wave to identify the interface. Deng (2012) pointed out that the diffraction of breakpoint due to the large-scale fault was the effective wave to detect the position of the coal seam. However, the studies on advanced detection in the underground coal roadway do not include the study of diffraction characteristics of small fault; therefore, the characteristics of diffraction wavefield of small fault are studied in this paper through the numerical simulation, so as to solve the fine imaging of small fault ahead of tunnel face.

2. Principle

When a seismic wave meets coal seam breakpoints, these discontinuity points can be regarded as the new sources, which can produce a kind of new disturbance to propagate around the elastic medium (Lindang et al., 2017; Kamsani et al., 2017).

This wave of disturbance is called diffraction. In essence, the physical premise of diffraction generation is the wave impedance difference and minor geological structure. The diffraction follows a concept of full wavelength, and its propagation is in agreement with the "Huygens Fresnel" principle.

The relation between the incident wave and the diffracted wave is one-to-many, while the relation between the incident wave and the reflected wave is that one-to-one, as shown in Figure 1. The reflected wave is generated when the seismic wave encounters the medium of sudden change in the propagation process, which is the change of travel time and amplitude caused by large-scale heterogeneity Lai et al., (2017). Because the fault throw in coal roadway is less than 10m, it is hard to form the reflection of the fault. However, due to the small scale of the fault and the appear wave impedance difference between coal seam and surrounding rock (the average density and P-wave velocity of coal seam and surrounding rock are respectively as: $\rho1=1400Kg/m3$, $V1=2000m/s$; $\rho2=2800Kg/m3$, $V2=3500m/s$), the obvious diffraction could be formed in the process of seismic advanced detection in coal roadway, as shown in Figure 2.
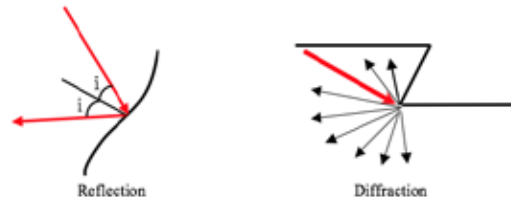

Figure 1. Diagram of reflection and diffraction.

Figure 2. Diffraction of advanced detection.

3. High-order Staggered-grid Finite Difference

In general, the structure of Coal seam is layered. Coal seam, layered roof, and floor can be regarded as horizontal isotropic media (Lai et al., 2017). The equation of the acoustic wave propagating in two-dimensional isotropic media is as follows:

$$\frac{1}{v^2}\frac{\partial^2 P}{\partial t^2} = \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial z^2} \qquad (1)$$

Where $P = P(x,z,t)$ represents acoustic wave field, $v = v(x,z,t)$ represents velocity field.

The difference scheme of time second-order and space $2N^{th}$-order difference accuracy is as follows:

$$P_{i,j}^{n+1} = 2P_{i,j}^{n} - P_{i,j}^{n-1} + L_x^2\left[\sum_{i=1}^{N} C_i\left(P_{i+1,j}^{n} + P_{i-1,j}^{n}\right) + C_0 P_{i,j}^{n}\right] +$$

$$L_z^2\left[\frac{4}{3}\left(P_{i,j+1}^{n} + P_{i,j-1}^{n}\right) - \frac{1}{12}\left(P_{i,j+2}^{n} + P_{i,j-2}^{n}\right) - \frac{5}{2}P_{i,j}^{n}\right] \qquad (2)$$

The source is the spike pulse, and Ricker wavelet is used as spike pulse source and time domain formula of Ricker wavelet is as follows:

$$w(t) = A\left[1 - 2\pi^2 f_0^2 \left(t - t_0\right)^2\right]\exp\left[-\pi^2 f_0^2 \left(t - t_0\right)^2\right] \qquad (3)$$

Where A is the amplitude, f_0 is the dominant frequency of wavelet, t_0 is the beginning time?

When the forward modeling of 2Nth-order difference accuracy in the condition of the regular grid is carried out, the stability condition is as follows:

$$\frac{v_{max}(x,z)\cdot\Delta t}{\Delta x} \leq \frac{1}{\sqrt{2\sum_{i=1}^{N_i} a_{2i-1}}} = c(l) \tag{4}$$

Taking into account the requirements of computational efficiency and simulation accuracy, time two-order and space tenth-order are adopted in this paper and $c(l)$ is 0.541. The PML absorbing boundary is adopted as a model boundary to reduce the boundary disturbance caused by the artificial boundary.

4. Wavefield Characteristics Analysis

Figure 3 shows the advanced detection model of small fault ahead of tunnel face with the fault throw of 10m. The dip angle of fault is 45 degrees, and the model size is 300 m × 300 m. The grid spacing is set as 0.25 m × 0.25 m, and sampling interval is Δt=0.1 ms. Taking into account the source features of field survey, the seismic frequency is set as 400 Hz. The coordinate range of the tunnel face is X=130 m and Z=149 ~ 152 m, while receivers are respectively located in the roadway roof and floor. The number of receivers is 40 in the roof and floor.
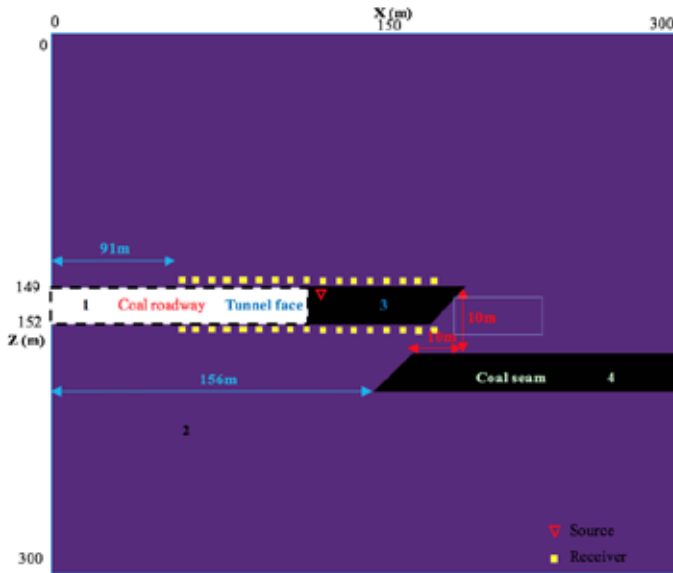

Figure 3. Model of advanced detection.

The receivers are located in the scope of X=91 ~ 169 m with trace intervals of 2 m. The depth of the receivers is 2 m in roof and floor. The two components X and Z are used for geophone receiving, and X direction denotes the tunneling direction, and Z direction denotes the direction being perpendicular to the floor (Roslee et al., 2017). The coordinate of the source is (134, 149), and specific medium parameters of the model are shown in Table 2.
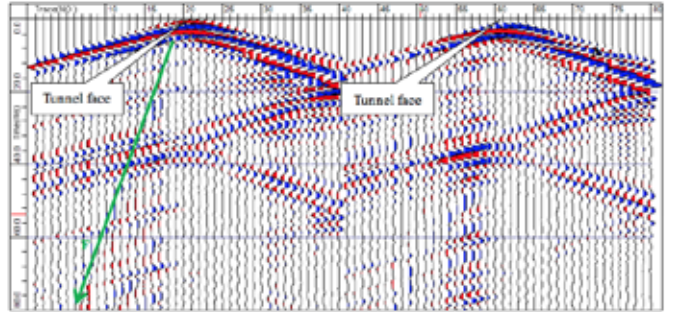
Table 1. Model parameter.

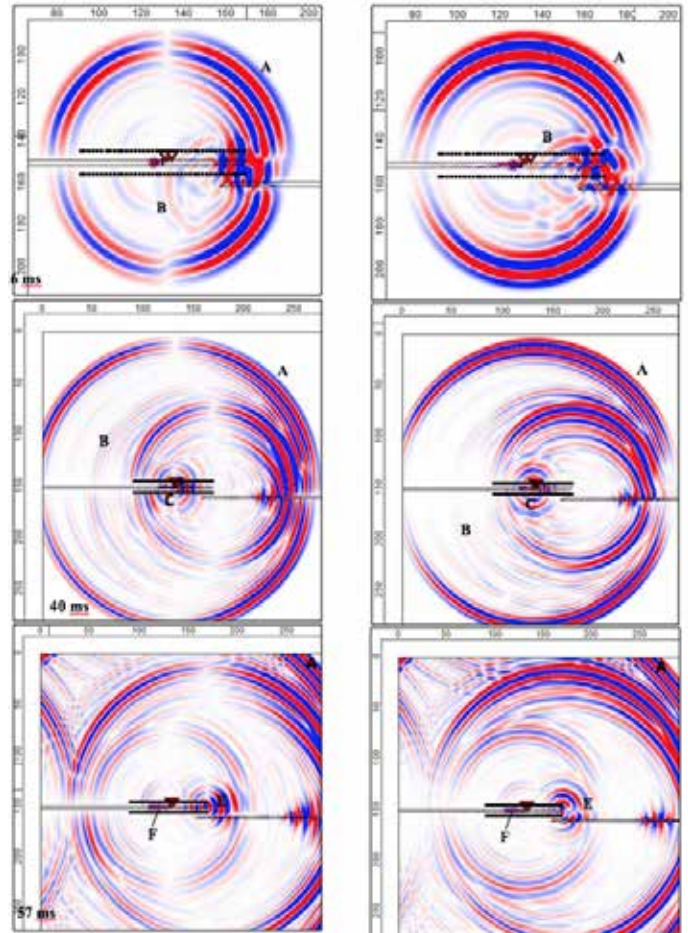| NO.	Name	V_s (m/s)	Density (kg/m³)	Other
1	Coal roadway	340	100	Height 3m
2	Surrounding rock	3500	2800	/
3	Upper coal seam	2000	1400	Thickness 3 m
3	Lower coal seam	2000	1400	Thickness 3 m
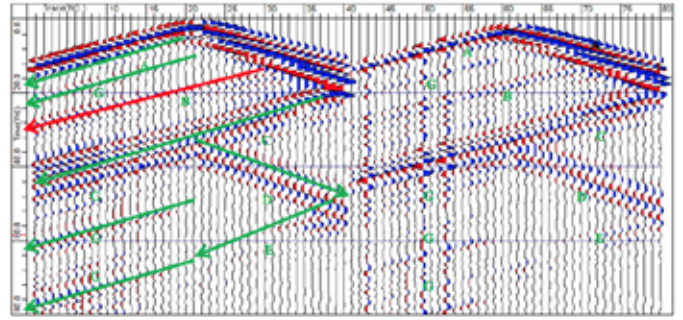
(a) X-component receiver in roof   (b) X-component receiver in floor

(a) Z-component receiver in roof   (b) Z-component receiver in floor
Figure 4. Seismic data of diffraction advanced observation system.
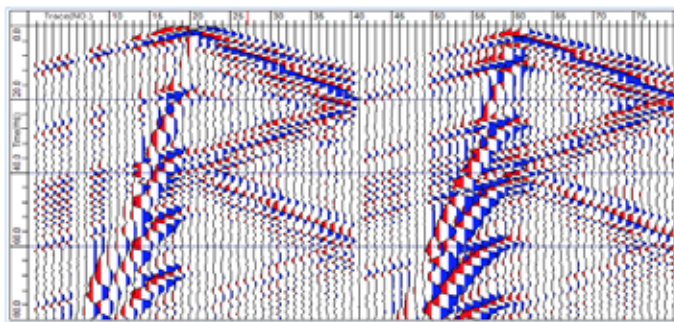

(a) X-component   (b) Z-component
Figure 5. Seismic wavefield snapshots.

Figure 4 shows the seismic data of component X and component Z with 0~80 ms, while Figure 5 shows the wavefield snapshots of components X and Z with 16 ms, 40 ms, and 57 ms. According to the seismic records and the wavefield snapshots of the model, with reference to kinematics and dynamics characteristics of various types of seismic wave, all kinds of waves can be recognized from the complex seismic wavefield, and they are as follows: *A* direct P-wave, this direct P-wave is with circular propagation from the source to the surrounding rock. *B* Diffracted P-wave, is formed by the diffraction of the direct P-wave when propagating to breakpoint of the fault. *C* 1# Reflected channel wave, is formed by the reflection of the direct channel wave when encountering fault. *D* 2# Reflected channel wave, is formed by reflection of 1# reflection channel wave when encountering the tunnel face; *E* 3# reflected channel wave, is formed by the reflection of 2# reflection channel wave when encountering fault; *F* the roadway acoustic wave, is formed by the direct P-wave when propagating into the cavity of the roadway; *G* the diffracted P-waves at the endpoint of the tunnel face are the multiple diffractions when direct P-wave encounters the endpoint (Kamsani et al., 2017).

The fundamental difference *B* between *G* diffracted P-wave and diffracted P-wave is as follows: *B* diffracted P-wave can also be observed from the receivers ahead of tunnel face and behind tunnel face, while *G* diffraction can only be observed from the receivers behind tunnel face. The diffraction *B* can be clearly identified based on the above difference.

It can be seen from Figure 4 that the resolution of breakpoint diffraction *B* is highest in seismic data of component X, and the diffraction is recorded by the receivers in the floor. The waveform of the diffraction *B* is clear with strong energy and short-wave group. In the figure, the reflected channel wave of the fault is also obvious, but the wave group of the channel wave is wider than diffraction, which causes the low resolution when using the channel wave.

Due to the existence of the channel wave in the coal roadway and the roadway axial being parallel with the horizontal coal seam, the common observation system of the tunnel reflected wave should be with poor applicability when detecting an advanced fault. Concerning to reflection observation system commonly used in traffic tunnel (Liu et al., 2016), the sources are arranged in the rear of tunnel face, which results in Figure 6 (Kamsani et al., 2017) . From the figure, it is found that the acoustic wave in seismic data is specially developed and the diffraction of the breakpoint is not identified.


(a) X-component receiver in roof   (b) X-component receiver in floor
**Figure 6.** Seismic data of reflection observation system.

5. Advanced Imaging of Small Fault

Based on the above analysis, the diffracted P-wave and the reflected channel wave are both the effective waves of advanced detection of a small fault in coal roadway. Based on the principle of prestack diffraction migration, the contrastive study is carried out with diffraction of the breakpoint and the channel wave (Roslee et al., 2017; Lindang et al., 2017; Kamsani et al., 2017; Lai et al., 2017) . Figure 7 shows the imaging results of *B* diffracted P-wave and *C* 1# reflected channel wave of component X which is received on the floor. The starting position of X-axis is 91m.

It can be seen from Figure 7, the lateral variation range of the fault location of reflected channel wave is about 20 m, and the distribution range of the channel wave migration imaging is large, and it is difficult to determine the position of small fault. The lateral variation range of breakpoint of diffraction is about 2 m, and the wave group of diffraction is short and high resolution, and imaging position of breakpoint of small fault is in accordance with the actual model, and the direction of breakpoint in full space is easily computed by polarization migration (Wang et al., 2016).
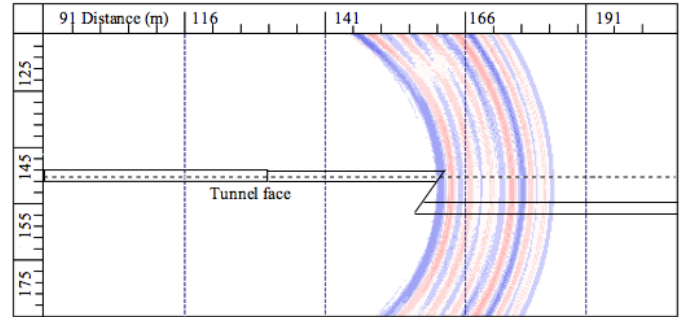
(a) Reflected channel wave
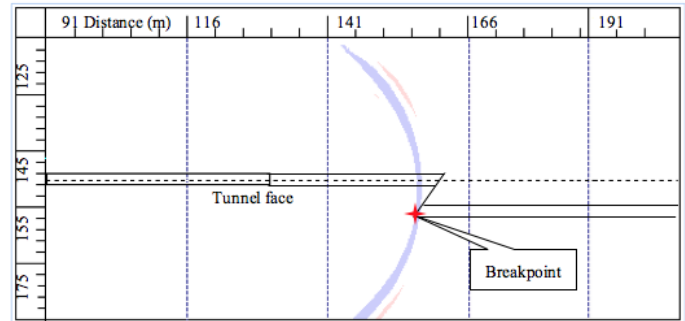
(b) Diffracted P-wave
Figure 7. Migration profile.

6. Conclusion

In this paper, considering the influence of the roadway cavity and coal seam with low velocity, the advanced detection model of small fault in front of heading face is established. The numerical simulation calculation is carried out by diffraction advanced observation system. The Through comparative analysis between the diffraction and reflection observation system, and there are not acoustic wave and obvious diffracted P-wave with short wave group by diffraction observation system in seismic data of component X. Compared with multiple diffractions of the endpoint, the diffracted P-wave is clear and easy to recognize and extract, and the reason is that: Diffraction of small fault can also be observed from the receivers ahead of tunnel face, but diffraction of the breakpoint should not be observed from the receivers ahead of tunnel face. The reflected channel wave of small fault is difficult to identify because there are multiple reflected channel waves between the fault and the tunnel face. Therefore, the diffraction of coal seam breakpoint is the naturalwave of small fault, and the results of the migration show that the imaging resolution of diffraction is high and breakpoint location of imaging is consistent with the actual model.

References

Cheng, J. L., Li, F., Peng, S. P., Sun, X. Y., "Research progress and development direction on advanced detection in mine roadway working face using geophysical methods." Journal of China Coal Society, 39 (2014): 1742-1750.

Cheng, J. L., Song, Y. L., Li, J. F., Gao, F., Xie, C., Chen, Q., "Numerical simulation of scattered wave imaging of advanced detection in the roadway." Proceedings of the Twenty-ninth Annual Meeting of the Chinese Geophysical Society (2013).

Deng, S. Q., Study on numerical simulation of whole-space elastic wave and reverse time migration imaging method, (Xuzhou: China University of Mining and Technology, 2012).

Essen, K., Bohlen, T., Friederich, W., Meier, T., "Modelling of Rayleigh-type seam waves in disturbed coal seams and around a coal mine roadway." Geophysical Journal International, 170 (2007): 511-526.

Gao, K., Liu, Z. G., Liu, J., "Effect of geostress on coal and gas outburst in the uncovering tectonic soft coal by cross-cut," Chinese Journal of Rock Mechanics and Engineering, 34 (2015): 305-312.

Inazaki, T., Isahai, H., "Stepwise application of horizontal seismic profiling for tunnel prediction ahead of the face." Leading Edge, 18 (1999): 1429-1431.

Jetschny, S., Bohlen, T., Denise, D. N., "On the propagation characteristics of tunnel surface-waves for seismic prediction." Geophysical Prospecting, 58 (2010): 245-256.

Jetschny, S., Bohlen, T., Kurzmann, A., "Seismic prediction of geological structures ahead of the tunnel using tunnel surface waves." Geophysical Prospecting, 59 (2011): 934-946.

Kamsani S.R., Ibrahim N., Ishak N.A., "Psychological debriefing intervention: From the lens of disaster volunteers." Malaysian Journal of Geoscience, 1 (2017): 32-33.

Lai G.T., Razib A.M.M., Mazlan N.A., Rafek A.G., Serasa A.S., Simon N., Surip N., Ern L.K., Rusli T., Mohamed., "Rock slope stability assessment of limestone hills in Northern Kinta Valley, Ipoh, Perak, Malaysia." Geological Behavior, 1 (2017): 16-18.

Lama, R. D., Bodziony, J., "Management of outburst in underground coal mines." International Journal of Coal Geology, 35 (1998): 83-115.

Lindang H.U., Tarmudi Z.H., Jawan A., "Assessing water quality index in river basin: Fuzzy inference system approach." Malaysian Journal of Geoscience, 1 (2017): 27-31.

Liu, S. D., Wang, B., Zhang, J., Mine seismic method and technology, (Xuzhou: China University of Mining and Technology press, 2016).

Lu, B., "Advanced detection of coal mine fault taking tunneling machine as the source" (Proceedings of the Twenty-ninth Annual Meeting of the Chinese Geophysical Society, 2013).

Luth, S., Buske, S., Giese, R., Goertz, A., "Fresnel volume migration of multicomponent data." Geophysics, 70 (2005): 121-129.

Lüth, S., Giese, R., Otto, P., Krüger, K., Mielitz S., Bohlen, T., Dickmann, T., "Seismic investigation of the Piora Basin using S-wave conversions at the tunnel face of the piora adit(Gotthard Base Tunnel)." International Journal of Mining Sciences, 45 (2008): 86-93.

Otto, R., Button, E., Bretterebner, H., Schwab, P., "The application of TRT at the Unterwald tunnel." Felsbau, 20 (2002): 51-56.

Roslee R., Bidin K., Musta B., Tahir S., Tongkul F., Norhisham M.N., "GIS application for comprehensive spatial soil erosion analysis with MUSLE model in Sandakan town area, Sabah, Malaysia" Geological Behavior, 1 (2017): 01-05.

Shepherd, J., Rixon, L. K., Griffith, L., "Outbursts and geological structures in coal mines: A review." International Journal of Rock Mechanics and Mining Sciences, 18 (1981): 267-283.

Wang, B., Liu, S. D., Lu, T., Sun, H. L., "Coal seam thickness detection in mine roadway by using advanced prediction method." Electronic Journal of Geotechnical Engineering, 21 (2014): 4753-4762.

Wang, B., Liu, S. D., Zhou, F. B., Lu, T., Huang, L. Y., Gao, Y. J., "Polarization Migration of Three-component Reflected Waves under Small Migration Aperture Condition." Acta Geodynamica Et Geomaterialia, 13 (2016): 47-58.

Yang, S. T., Cheng, J. L., "Numerical simulation of fore detecting with seismic in coal roadway and study of wave field characteristics." Journal of China Coal Society, 35 (2010): 1633-1637.

Yang, S. T., Cheng, J. L., "The method of small structure prediction ahead with Rayleigh channel wave in coal roadway and seismic wave field numerical simulation," Chinese Journal of Geophysics, 55 (2012): 655-662.

Zhao, Y. G., Jiang, H., Zhao, X. P., "Tunnel seismic tomography method for geological prediction and its application." Applied Geophysics, 3 (2006): 69-74.