Research Article

The Time-Space Joint Response Characteristics of AE-UT under Step Loading and Its Application

Xiaoran Wang,^{1,2} Xiaofei Liu ,^{1,2} Enyuan Wang ,^{1,2} Chong Zhang,^{1,2} Haishan Jia,^{1,2} and Dexing Li^{1,2}

¹Key Laboratory of Gas and Fire Control for Coal Mines, China University of Mining and Technology, Ministry of Education, Xuzhou 221116, China

²School of Safety Engineering, China University of Mining and Technology, Xuzhou 221116, China

Correspondence should be addressed to Xiaofei Liu; liuxiaofei@cumt.edu.cn and Enyuan Wang; weytop@cumt.edu.cn

Received 12 August 2017; Revised 24 November 2017; Accepted 5 December 2017; Published 18 January 2018

Academic Editor: Andrzej Katunin

Copyright © 2018 Xiaoran Wang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The acoustic emission (AE) and ultrasonic (UT) simultaneous monitoring program is designed using concrete samples under step loading. The time-varying response characteristics of AE-UT are studied and the cross-correlation analysis between AE-UT parameters is obtained. Moreover, the joint response of UT-AE spatial distribution field is analyzed, and an AE-UT joint monitoring method to detect early-warning signals of a rockburst disaster in a coal seam is proposed. The results show the following. (1) During the loading process, the AE pulses/energy and UT attenuation coefficient first slowly decrease and then increase steadily and finally rapidly increase, while the UT velocity shows a trend of first gradually increasing and then slowly decreasing and finally a sharp decline. (2) AE pulses and energy are significantly or highly correlated with the UT velocity and attenuation coefficient. The AE energy and UT attenuation coefficient can better characterize the damage evolution of concrete under step loading. (3) The UT field evolves ahead of the rupture on the surface, and the long/narrow strip distribution region of UT parameters is consistent with the future failure zone; meanwhile, the AE events can visually reflect the evolution path of internal damage as well as the dynamic migration mechanism of UT field.

1. Introduction

Concrete as a raw material is widely used in construction engineering such as buildings, roadways, bridges, and tunnels. It is very important for public safety to carry out damage analysis, stability monitoring, and remaining life estimation of those constructions using appropriate methods [1]. Various techniques such as surface topography, scanning electron microscopy (SEM), infrared thermal imaging, computerized tomography (CT), and electromagnetic radiation (EMR) have been used to observe the damage process in laboratory tests [2, 3]. In recent years, passive (acoustic emission, AE) and active (ultrasonic, UT) testing techniques have been gradually applied to the structural instability and safety monitoring [4, 5].

UT monitoring technique is a kind of active nondestructive testing method. Analyzing the response laws of the

received UT wave, we can retrieve the material's damage state, predict the material's intensity, and provide an early warning of structural instability disasters [6–9]. Many scholars have carried out a number of researches on the correlation between UT parameters and stress in the crack evolution process. Nur [10] studied the influence of microcracks on the wave velocity, and the quadratic function relationship between wave velocity and stress was concluded in the crack closure stage. Liu et al. [11] established polynomial regression between the UT parameters (velocity, amplitude, and frequency) and stress levels of coal under step loading and discussed the relationship between UT velocity, crack width, and damage variable. Molina and Wack [12] described the fracture field characteristics combining the surface crack images and UT attenuation, and they explained that UT attenuation had a high sensitivity to crack propagation. Sun and Zhu [13] reported the relationship between wave velocity

FIGURE 1: Diagram of the experimental system. (1) UT monitoring system. (2) ARB-1410 card. (3) Generated UT wave. (4) Received UT wave. (5) Preamplifier. (6) Generated UT probe. (7) Received UT probe. (8) UT test points. (9) AE sensor. (10) AE monitoring software. (11) AE monitoring system. (12) Loading system. (13) Shielded room.

and stress/strain under the failure process of brittle rocks and found the critical point of wave velocity to predict the geological hazards based on Weibull's distribution and renormalization group theory. All of these researches show that the UT parameters have a close relationship with the applied stress, and the closure, initiation, propagation, and coalescence processes of internal cracks are the basic reasons for the change of UT parameters.

AE is an elastic wave generated from the deformation and generation of microcracks, which is a powerful tool to investigate the evolution of internal damage in three-dimensional space [14–16]. As a passive monitoring method, AE technique has been widely used in many aspects of scientific research and field applications. Xiao et al. [17] studied the AE time-varying and frequency-spectrum response characteristics in different dynamic destruction scenarios based on the stress release rate. Wang et al. [18] established the intrinsic relationship between the AE and damage/stress/strain parameters, which could be used to dynamically evaluate damage and stress state of a specimen by AE parameters. Using the three-dimensional AE locating technique, Liu et al. [19] and Wang et al. [20] obtained the evolution path of microcracks initiation, propagation, coalescence, and nucleation visually and better understood the microscopic evolution mechanism for rock rupture. Liu et al. [21] established a microseismic system to monitor the concealed fault activation process in mining activities and obtained critical information of microseismic signals for early warning against rockburst disasters.

Through AE continuous monitoring, microcracks development can be analyzed quantitatively to characterize the damage state, which is the root cause for the UT parameters change in the loading process. Some scholars have carried out some beneficial explorations on the AE and UT simultaneous monitoring under loading conditions [22, 23], but there are still the following problems: (1) AE and UT have realized integrative monitoring, but the analysis is only from one aspect of the them and lacks joint response characteristics; AE and UT are both closely related to the damage state,

but it is not clear whether the AE and UT parameters are correlated. (2) UT monitoring can evaluate the damage state quantitatively, but it only can get the damage state at a certain stress rather than the dynamic migration path and its mechanism in real time. The AE locating technology can be used as a good tool to observe the real-time evolution of internal cracks. But the joint analysis of AE and UT spatial distribution characteristics is still a blank, while it is the key for better understanding the microscopic evolution mechanism and early warning against instability disasters.

Based on this, the AE and UT synchronous monitoring system of concrete under step loading is designed and the response characteristics of AE pulses/energy and UT velocity/attenuation coefficient are analyzed firstly. Then, the correlation between AE and UT parameters is studied using the correlation analysis. Besides, the joint response characteristics of UT and AE spatial distribution field are analyzed, combined with the surface rupture image. Finally, the AE-UT joint monitoring method is proposed for rockburst early warning in a coal seam. The research results can provide an important experimental basis for damage estimation, instability disasters early warning, and a better understanding of the damage evolution mechanism comprehensively.

2. Experimental System and Program

2.1. Scheme of Experiment System. The experimental system mainly consists of the loading system, AE monitoring system, and UT monitoring system (Figure 1). The experiments are conducted in a shielded room which can isolate most of the environmental noises and provide a relatively stable/quiet condition. The loading system is an electrohydraulic servo pressure testing machine controlled by a microcomputer (YAW4306), which can perform uniaxial, step, and cyclic loading compression tests.

The AE monitoring system is the Rock-Test for Express-8 with 24 channels. In order to achieve the 3D locating

TABLE 1: The positions of AE probes and UT test points (based on coordinate system in Figure 1).

Number	UT test points				AE sensors		
	x/mm Generating	y/mm receiving	y/mm	z/mm	x/mm	y/mm	z/mm
(1)	100	0	10	90	10	10	100
(2)	100	0	10	10	90	10	100
(3)	100	0	90	10	90	90	100
(4)	100	0	90	90	10	90	100
(5)	100	0	30	70	10	10	0
(6)	100	0	30	30	90	10	0
(7)	100	0	70	30	90	90	0
(8)	100	0	70	70	10	90	0
(9)	100	0	50	50	-	-	-

FIGURE 2: The generated UT wave and received UT first wave.

function, 8 AE sensors (NONA-30) are arranged at different coordinate positions (Figure 1 and Table 1). The AE locating algorithm is based on the time-difference locating method. The P-wave threshold crossing technique is used to determine the AE arrival time, and velocity is the average value of 9 points per stress level in Section 3.3. The AE sensors are attached and fixed to the sample's surface with a special coupling agent. Lead break amplitude should be above 90 dB to make sure that the coupling quality between AE sensors and the sample is good. The preamplifier value and AE threshold are both 40 dB, and the AE sampling rate is 1 MSPS.

The UT monitoring system mainly includes the generated and received system of UT signals (ARB-1410 card), generated and received UT probes (NANO-30), and a preamplifier. The ARB-1410 card can generate various UT signals with different frequencies and amplitudes, and the detailed information of the generated UT signals is shown in Figure 2(a) and Table 2. To obtain the UT field, we employ 9 UT test points as shown in Figure 1 and Table 1. UT velocity and attenuation coefficient are the most basic UT parameters which correlate

strongly with applied stress. The calculations of UT velocity and attenuation coefficient are shown below [11, 24]:

$$v = \frac{L}{t_1 - t_0} \quad (1)$$

$$\alpha = 8.686 \frac{\ln A_0 - \ln A_1}{L}, \quad (2)$$

where v is the UT velocity (m/s); L is the distance traveled in samples (m); t_0 and t_1 are the modified arrival times of the generated and received UT first wave, respectively (s); α is the attenuation coefficient (dB/m); A_0 and A_1 are the amplitude of the generated and received UT first wave, respectively (dB).

The UT signals will be recorded in the voltage form by software. So, before formula (2) can be calculated, the voltage signals must be converted into wave signals by the following formula:

$$A = 20 (6 + \lg B) - \text{pre}, \quad (3)$$

TABLE 2: The detailed information of the generated UT signals.

Waveform	Dominant frequency	Firing interval	Threshold value	Sampling frequency	Amplitude	Preamplifier value
Sine wave	300 kHz	2 s	40 dB	10 MHz	8.5 V	40 dB

FIGURE 3: The step-loading path of concrete and experimental test program.

where A is the amplitude of the UT wave (dB); B is the voltage of the recorded UT wave (V); pre is the preamplifier value in Table 2.

The arrival time of the UT signal is determined using the first wave threshold crossing technique by the software automatically. But the arrival time determination is not accurate sometimes, so it is necessary to modify the arrival time of UT signals manually (as shown in Figure 2(b)) [11].

2.2. Sample Preparation. The concrete samples used in this paper are cube (100 mm × 100 mm × 100 mm) with a total number of 4. The materials of concrete samples mainly contain cement, sand, coarse aggregates, and water with a mass ratio of 1:1.6:0.5:0.58. Mix and stir these materials evenly and then pour the mixture into the mold and strongly vibrate it to reduce bubbles inside the samples. Then, we should put these concrete samples in a cool and ventilated place for 28 days before the experiments.

2.3. Experimental Test Program. We assume step loading in the experiments with 30 kN in each loading step (Figure 3). The applied loading rate is 300 N/s. In order to realize the AE and UT synchronous monitoring, we carry out AE monitoring in the stress increase (SI) stage, former 100 s of stress stable (FSS) stage, and latter 100 s of stress stable (LSS) stage. In the middle 400 s of the stress stable (MSS) stage, we test the UT signals. After finishing the above preparation, we should start the loading machine and AE monitoring system. When the applied load reaches the stress stable stage, we should suspend the AE monitoring system and meanwhile start the UT test system to collect UT signals. After finishing

the UT test of the 9 points, we should close the UT monitoring system and restart the AE monitoring system. This cycle is repeated until the samples reach complete failure. The cracks evolution process on the surface of concrete samples is recorded by a digital camera under the whole loading process.

2.4. Data Processing Method. In this paper, cross-correlation analysis (CCA) is used to analyze the correlation of these two signals. The discrete series of AE parameters (AE pulses and energy) is X , and the discrete series of UT parameters (velocity and attenuation coefficient) is Y . So, the degree of correlation between AE and UT signals can be represented by a correlation coefficient r_{xy} .

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (4)$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i,$$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i,$$

where i represents the i th step loading; n is the total number of load steps; x_i is the AE parameters in the i th step loading, which is the AE pulses and energy accumulative sum of the SI stage, the FSS stage in the i th step, and the FSS stage in the $(i-1)$ th step; y_i is the UT velocity and attenuation coefficient variation in the i th step loading; $\bar{x}$ and $\bar{y}$ are the average values of x_i and y_i , respectively; r_{xy} is the correlation coefficient of AE and UT signals, and its value range is $[-1, 1]$; when $|r_{xy}|$

FIGURE 4: Typical stress-strain curve and microcracks growth of concrete (from the literature [13]).

is closer to 1, the correlation is higher, and when $|r_{xy}|$ is closer to 0, the correlation of the two signals is low.

The correlation degree of the two signals can be divided into 4 grades according to the correlation coefficient: ① $0 < |r_{xy}| \leq 0.3$, weak or no correlation; ② $0.3 < |r_{xy}| \leq 0.5$, low correlation; ③ $0.5 < |r_{xy}| \leq 0.8$, significant correlation; ④ $0.8 < |r_{xy}| \leq 1.0$, high correlation.

3. AE-UT Temporal Response Characteristics of Concrete under Step Loading

3.1. Mechanics and Cracks Growth Characteristics of Concrete under Loading. According to the literature [13] and previous test results of concrete mechanical properties, the loading process of concrete can be divided into the following stages (as shown in Figure 4): (1) microcrack closure stage I (oa stage): the original microcracks inside concrete are compacted, and the stress-strain curve presents a concave type; (2) elastic stage II (ab stage): the stress-strain curve is approximately linear, in which a small amount of microcracks will begin to grow accompanied by the occurrence of cracks closure, and the cracks are randomly distributed; (3) microcrack initiation and stable growth stage III (bc stage): the microcracks expand steadily, the stress-strain curve exhibits nonlinear characteristics, and the specimen begins to exhibit damage; (4) accelerated microcrack growth stage IV (cd stage): the development of microcracks exhibits a qualitative change and the internal cracks propagation speed is accelerated. At this stage, a large number of internal cracks inside concrete samples gradually converge and nucleate to form the main rupture.

3.2. AE Time-Varying Response Characteristics. In the internal microcracks development process, there will be accompanying AE signals. The AE time-varying response characteristics of SI, FSS, and LSS stage under different loading steps are

shown in Figure 5. The AE pulses mainly reflect the frequencies of microruptures while AE energy represents the energy released during the fracture process of loading concrete.

At the initial stage of loading, the AE pulses and energy of the SI stage are large because of the internal microcracks compaction. With the applied load increasing, the original internal microcracks become fewer because the applied load does not reach the crack initiation stress to generate new cracks. Therefore, the AE signals gradually reduce. However, at FSS and LSS stage, the stress is small and the cumulative damage effect is relatively weak, so initial microcracks cannot close, and the AE pulses and energy both show low values but an increasing tendency. Compared with the LSS stage, the AE signals of the FSS stage are more active relatively. When the applied stress enters the linear-elastic and microcrack stable growth stage (12–27 MPa), the microcracks begin to generate inside the sample. These generated cracks are random and the number is relatively stable. So, in the SI, FSS, and LSS stages, AE pulses and energy show a steady increasing trend with a small amplitude. When the specimen enters the microcrack accelerated growth stage (27–36 MPa), irreversible deformation will occur, and the small cracks expand and coalesce to form larger cracks. The AE signals at SI, FSS, and LSS stages all show a rapid increasing trend. It is worth noting that the AE signals of the LSS stage begin to exceed the FSS stage, because the cracks will also develop with time although the stress is maintained. The specimen exhibits fatigue damage and shows a strong creep rheological property. When the specimen is approaching the failure stage (36–42 MPa), a large number of cracks are connected to form the macroscopic main failure. The AE signals of SI, FSS, and LSS stages reach the maximum value, and the total AE signals in the LSS stage exceed the SI stage when the specimen reaches complete failure in 9500 s.

3.3. UT Time-Series Response Characteristics. According to formulas (1)–(3), the UT velocity and attenuation coefficient

FIGURE 5: AE time-varying characteristics of concrete under step loading.

FIGURE 6: The evolution of UT parameters under different applied stresses.

under different stresses are calculated, respectively, and shown in Figure 6. Due to the irregular shape, size, and distribution of the cracks inside the concrete specimen, the stress field is inhomogeneous and the UT response characteristics are different in different test points albeit with a similar character of change generally. Therefore, this paper uses the average, maximum, minimum, and standard deviation value of the 9 UT test points to analyze the UT response characteristics at each stress level.

From Figure 6, we can see that the UT response goes through three stages on the whole. At the initial loading stage (0–9 MPa), the internal microcracks are compacted, and the

concrete sample presents an obvious loading strengthening characteristic. The UT velocity increases but the attenuation coefficient decreases gradually. With the applied stress increasing, the UT average velocity decreases slowly from 4836 m/s at 9 MPa to 3961 m/s at 30 MPa, while the attenuation coefficient increases from 2.36 dB/m to 17.72 dB/m and increases by 15.36 dB/m. In this stage, the applied stress exceeds the crack initiation stress, and the cracks begin to develop stably. After that, the specimen enters the accelerated microcrack growth stage, in which the specimen produces a large number of irreversible deformations and the small cracks grow to form large cracks. The UT velocity and

TABLE 3: Correlation coefficient between AE and UT parameters.

					UT			
AE	UT velocity				$ r_{xy} $	UT attenuation coefficient		
	Test result		Average	Test result		Average		
AE pulses	0.7383	0.7524	0.7689	0.7532	0.8501	0.8106	0.8371	0.8326
AE energy	0.7744	0.8265	0.7693	0.7901	0.8706	0.8902	0.8446	0.8685

attenuation coefficient both reach the critical turning point corresponding to about 70% of the peak stress. Then, the UT velocity begins to decrease sharply and the average velocity reduces by nearly 40% at the peak stress which is only 2659 m/s. But the average attenuation coefficient shows a sharp increasing trend and reaches 59.58 dB/m at peak stress, which increases by over 7.5 times compared with the value under no applied loading. In the whole loading process, the maximum and minimum values of UT parameters (velocity, attenuation coefficient) at the 9 test points show the same trend as the average value. But the full range (difference between the maximum and minimum values) and the standard deviation of the 9 UT test points both decrease first and then increase. This phenomenon reveals that the concrete failure process is the combination of the identity and diversity change processes, in which the physical properties of concrete change from intrinsic heterogeneity to homogeneity and then to heterogeneity.

4. Discussion

4.1. Correlation Analysis between AE and UT Parameters. The rupture inoculation process of concrete samples is a continuous development process, including initial microcracks closure, initiation, propagation, and coalescence. These are the root causes of the UT parameters' changes. Therefore, there must be a certain correlation between UT and AE parameters. According to formula (4), the correlation coefficients between the AE and UT parameters are calculated, and the results are shown in Table 3.

From Table 3, the ranges of $|r_{xy}|$ between AE and UT parameters are 0.7383–0.7689, 0.8106–0.8501, 0.7693–0.8265, and 0.8446–0.8902, with average values of 0.7532, 0.8326, 0.7901, and 0.8685, respectively. In contrast, the correlations between AE energy and UT parameters are better than that of AE pulses, which indicates that the AE energy can better characterize the damage state of concrete samples. The values of $|r_{xy}|$ between UT attenuation coefficient and AE pulses and energy are both more than 0.8, showing a high degree of correlation, while the UT velocity is significantly correlated with AE parameters, which has a lower correlation compared with the attenuation coefficient. The essence of the fracture evolution process is the energy accumulation, transference, redistribution, and release. AE energy and UT attenuation coefficient both are the parameters coming from the energy point of view. They show obvious advantages on representing the damage state of the specimen and there is a high degree of correlation between them.

4.2. Joint Response Characteristics of AE and UT Spatial Distribution Field. The physical properties of concrete samples are inhomogeneous in space distribution. So, it is of great importance from the aspect of spatial field distribution to fully understand the damage process and its mechanical mechanism [25, 26]. The spatial distribution of damage and stress can be obtained at a certain time (stress) using UT monitoring, but it cannot get the dynamic migration path and its mechanism in real time. The development and evolution path of internal cracks can be observed visually in real time by AE locating technology, which can provide a tool for revealing the evolution process of the UT spatial field distribution.

In the initial loading stage (6 MPa, Figure 7(a)), the internal cracks close and the sample becomes homogeneous gradually. The ranges of the UT velocity and attenuation coefficient of 9 test points are 4621 m/s–5033 m/s and 4.09 dB/m–4.52 dB/m, respectively. And the top right area is the low velocity zone which is consistent with the large energy AE event concentration area. There is no obvious crack growth in the surface rupture image.

When the sample is in the linear-elastic stage (15 MPa, Figure 7(b)), a faintly visible fine crack appears on the right side of the sample surface, and its position is consistent with the large energy AE events concentration region. The distribution of UT velocity decreases while UT attenuation coefficient increases from the center to the boundary. The greater the density of AE events, the smaller the UT velocity and the greater the UT attenuation coefficient. Large energy AE events begin to appear and the damage begins to develop on the left area based on the AE locating results. All of those indicate that the right area of the sample is still in high stress, but the stress in the left side significantly increases and high stress begins to migrate to the left from the right area.

In the microcrack stable growth stage (21 MPa, Figure 7(c)), the ranges of UT velocity and attenuation coefficient are 3856 m/s–4682 m/s and 14.44 dB/m–17.04 dB/m, respectively. The dispersions of UT parameters increase obviously. The high energy AE events further increase in the left area, which indicates that the high stress zone continues to migrate to the left. Some visible fine cracks begin to appear on the left side corresponding to the low UT velocity, and the cracks on the right side further extend to the bottom of the specimen corresponding to the dense area of AE events.

While the sample enters the microcrack accelerated growth stage (30 MPa, Figure 7(d)), the cracks on the right side connect with each other to form a macroscopic crack. And there also forms an obvious fine crack on the left side

FIGURE 7: The spatial joint response characteristics of UT-AE.

of the sample. The UT velocity severely attenuates due to the existence of the macroscopic crack on the right side. The left side is a high stress concentration area corresponding to the low velocity (high attenuation coefficient) zone. The UT field presents a long and narrow strip distribution characteristic. The large energy AE events are also distributed in a long strip shape, which are concentrated in the left and right sides of the specimen. This long and narrow strip distribution region is the future macro failure zone.

When the specimen is near failure (39 MPa, Figure 7(e)), the cracks on both the left and the right sides continue to grow and merge to form a macroscopic main failure. The failure mode is similar to the “X” conjugate wedge splitting type. Due to the existence of macroscopic cracks, the UT parameters severely attenuate (the velocity decreases and attenuation coefficient increases) sharply. So, both the left and the right sides are low velocity (high attenuation coefficient) zones. According to the AE event field and the surface rupture image, there are little cracks in the middle upper part of the sample, so it corresponds to the high velocity region (low attenuation coefficient). In the middle lower area of the sample, there are a large number of high energy AE events and serious cracks development corresponding to the low velocity region. The velocity and attenuation coefficient distribution ranges of the 9 test points are 2589 m/s~3682 m/s and 36.36 dB/m~50.27 dB/m, respectively. The dispersions of UT parameters reach their maximum values.

5. Field Application Prospects and the Significance of AE-UT Joint Monitoring

Rockburst disaster is a serious geological dynamic disaster in coal mines which can cause a large number of casualties. Particularly, with the increase of the mining depth, underground engineering faces special severe geographical environments such as high crustal stress, high geotemperature, high seepage pressure, and strong disturbance. In such geographical regions, the occurrence frequencies and intensity of rockburst disaster are gradually increasing. During the mining process, in front of the longwall face, a high stress concentration zone will occur. Besides, the mining activities will generate strong disturbance stress. Under the comprehensive effect of high static stress and strong disturbance stress, the zones in front of the working face are more likely to exhibit rockburst disasters where we should pay much attention.

According to the experiments and analysis in Sections 3 and 4, the AE-UT joint monitoring has the potential to be an effective tool of the rockburst early warning. So, we propose using the AE-UT joint monitoring method to forecast the rockburst disasters in the longwall working face. The detailed AE-UT joint monitoring prospect in the coal seam is shown in Figure 8. The AE-UT monitoring area is within 200 m in front of the working face. There are five measuring groups on both the upper roadway and the lower roadway. Each group has four UT test points and two AE monitoring sensors as shown in Figure 8(b), and the distance between the UT and AE sensors in each group is 5 m. The first group is located at 20 m ahead of the working face,

and the distance between each group is 40 m. The real-time monitoring data of each AE-UT sensor are sent and stored in the substations underground. Then, the monitoring data will be transferred to the ground host computer through the communication port. Then, we can analyze the AE-UT time-space response characteristics to provide an early warning against rockburst disasters. The AE-UT monitoring method in the longwall working face has a guiding significance for rockburst monitoring mainly in the following two aspects.

(1) It can help determine the critical precursor characteristics of rockburst disasters more comprehensively and evaluate the danger degree more accurately. The AE parameters begin to rise sharply and UT parameters reach the critical turning point. The UT field distribution begins to present long and narrow strip distribution characteristics, and the large energy AE events fields are gathered together. When the above cases appear, we can indicate that the coal seam has entered the damage accelerated development stage. And the computer will issue the early-warning alert about when and where the rockburst disasters will occur. Then, mining workers will take some measures to prevent the occurrence or reduce the consequences of disasters.

(2) It is beneficial to further understand the damage evolution process and the mechanism of rockburst disasters. During the development of the rockburst disaster, small fractures converge to form large fractures and the large fractures coalesce to form the main failure. The evolution of UT field can reflect the migration of stress field, while the location of AE events can well represent the development of microcracks and explain the dynamic migration path of the UT field distribution.

6. Conclusion

(1) In the compaction stage, AE pulses/energy showed a decreasing trend, and the UT velocity showed an increasing trend, while the attenuation coefficient decreases gradually. During the crack stable growth stage, the AE pulses/energy showed a trend of steady increase with a small amplitude, the UT velocity slowly declined, and the attenuation coefficient slowly increased. In the microcrack accelerated growth stage, AE pulses/energy and UT attenuation coefficient present a rapid growing trend and reach the maximum value, while the velocity greatly reduces to the lowest value.

(2) AE pulses and energy are significantly correlated with UT velocity, while UT attenuation coefficient variation is highly correlated with AE pulses and energy. From the energy point of view, AE energy and UT attenuation coefficient can carry more abundant information of the damage state, which shows obvious advantages on representing the continuous damage evolution process.

(3) The failure process of concrete is the combination of the identity and diversity changes, in which the physical properties of loaded concrete change from intrinsic heterogeneity to homogeneity and then to heterogeneity. The dispersions of the UT parameters decrease firstly and then increase. In this process, the small cracks converge to form large cracks

FIGURE 8: The AE-UT joint monitoring prospect in the coal seam.

and the large cracks coalesce to form the main failure; the evolution of the UT field can reflect the migration of the stress field, while the location of AE events can well represent the development of microcracks and explain the dynamic migration path of the UT field distribution. The UT and AE field distributions evolve ahead of the surface failure. The long/narrow strip distribution region of UT parameters and the large energy AE event concentrated area are consistent with the future failure zone.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work is supported by the Fundamental Research Funds for the Central Universities (2017BSCXB13).

References

- [1] T. Wen, H. M. Tang, Y. R. Liu, Z. X. Zou, K. Wang, and C. Y. Lin, "Newly modified damage statistical constitutive model of rock based on impact factor," *Journal of Chinese University of Mining & Technology*, vol. 45, no. 1, pp. 141–149, 2016.
- [2] B. Kong, E. Wang, Z. Li et al., "Electromagnetic radiation characteristics and mechanical properties of deformed and fractured sandstone after high temperature treatment," *Engineering Geology*, vol. 209, pp. 82–92, 2016.
- [3] G. H. Ge, C. Wang, and L. Li, "Acoustic wave propagation characteristics of the soft sandstone under loading," *Science Technology and Engineering*, vol. 15, no. 18, pp. 85–90, 2015.
- [4] H. Li, C. Yang, B. Li, and X. Yin, "Damage evolution and characteristics of ultrasonic velocity and acoustic emission for salt rock under triaxial multilevel loading test," *Yanshilixue Yu Gongcheng Xuebao/Chinese Journal of Rock Mechanics and Engineering*, vol. 35, no. 4, pp. 682–691, 2016.
- [5] J. Zhu and Y. Song, "Research on fatigue damage of concrete under biaxial compressive loading using ultrasonic velocity method," *Journal of Rock Mechanics and Engineering*, vol. 23, no. 13, pp. 2230–2234, 2004.
- [6] J. Chen, Z. Xu, Y. Yu, and Y. Yao, "Experimental characterization of granite damage using nonlinear ultrasonic techniques," *NDT & E International*, vol. 67, pp. 10–16, 2014.
- [7] H.-L. Wang and Y.-P. Song, "Ultrasonic pulses behavior in various-size concrete specimens under compression," *Journal of Dalian University of Technology*, vol. 47, no. 1, pp. 90–94, 2007.
- [8] L. Peyras, P. Rivard, P. Breul, A. Millet, and G. Ballivy, "Characterization of rock discontinuity openings using acoustic wave amplitude-application to a metamorphic rock mass," *Engineering Geology*, vol. 193, pp. 402–411, 2015.
- [9] N. Li, J. Sun, J. Jiao, B. Wu, and C. He, "Quantitative evaluation of micro-cracks using nonlinear ultrasonic modulation method," *NDT & E International*, vol. 79, pp. 63–72, 2016.
- [10] A. Nur, "Effects of stress on velocity anisotropy in rocks with cracks," *Journal of Geophysical Research*, vol. 76, no. 8, pp. 2022–2034, 1971.
- [11] X. Liu, X. Wang, E. Wang, Z. Liu, and X. Xu, "Study on ultrasonic response to mechanical structure of coal under loading and unloading condition," *Shock and Vibration*, vol. 2017, Article ID 7643451, 12 pages, 2017.
- [12] J.-P. Molina and B. Wack, "Crack field characterization by ultrasonic attenuation-preliminary study on rocks," *International Journal of Rock Mechanics and Mining Sciences*, vol. 19, no. 6, pp. 267–278, 1982.
- [13] Q. Sun and S. Zhu, "Wave velocity and stress/strain in rock brittle failure," *Environmental Earth Sciences*, vol. 72, no. 3, pp. 861–866, 2014.
- [14] A. Behnia, H. K. Chai, and T. Shiotani, "Advanced structural health monitoring of concrete structures with the aid of acoustic emission," *Construction and Building Materials*, vol. 65, pp. 282–302, 2014.
- [15] P. Hou, F. Gao, Z. Zhang, Y. Yang, and T. Teng, "Evaluation method of rock brittleness based on acoustic emission and energy evolution," *Journal of China University of Mining and Technology*, vol. 45, no. 4, pp. 702–708, 2016.
- [16] S. De Santis and A. K. Tomor, "Laboratory and field studies on the use of acoustic emission for masonry bridges," *NDT & E International*, vol. 55, pp. 64–74, 2013.
- [17] F. Xiao, G. Liu, Z. Zhang, Z. Shen, F. Zhang, and Y. Wang, "Acoustic emission characteristics and stress release rate of coal samples in different dynamic destruction time," *International Journal of Mining Science and Technology*, vol. 26, no. 6, pp. 981–988, 2016.
- [18] X. Wang, X. Liu, E. Wang et al., "Experimental research of the AE responses and fracture evolution characteristics for sand-paraffin similar material," *Construction and Building Materials*, vol. 132, pp. 446–456, 2017.
- [19] Q. S. Liu, J. Xu, X. W. Liu, J. Jiang, and B. Liu, "The role of flaws on crack growth in rock-like material assessed by AE technique," *International Journal of Fracture*, vol. 193, no. 2, pp. 99–115, 2015.
- [20] X. R. Wang, E. Y. Wang, X. F. Liu, H. Wang, X. L. Li, and D. X. Li, "Experimental study on the static loading rate effects of sandstone specimen containing pre-existing echelon cracks," *Journal of China Coal Societ*, vol. 42, no. 10, pp. 2582–2591.
- [21] C. Liu, S. Li, C. Cheng, and J. Xue, "Activation characteristics analysis on concealed fault in the excavating coal roadway based on microseismic monitoring technique," *International Journal of Mining Science and Technology*, vol. 27, no. 5, pp. 883–887, 2017.
- [22] T. C. Liang, H. K. Ge, Z. W. Guo, L. L. Song, and J. W. Zhang, "Evaluation of rock damage state with acoustic emission and velocity variation," in *Earthquake Research in China*, vol. 28, pp. 154–166, Earthquake research in China, 2012.
- [23] H.-R. Li, C.-H. Yang, F. Chen, H.-L. Ma, and S.-W. Wu, "Development and application of an integrative testing device for acoustic waves and acoustic emission of rock," *Yantu Lixue/Rock and Soil Mechanics*, vol. 37, no. 1, pp. 287–296, 2016.
- [24] M. Auberger and J. S. Rinehart, "Ultrasonic velocity and attenuation of longitudinal waves in rocks," *Journal of Geophysical Research: Atmospheres*, vol. 66, no. 1, pp. 191–199, 1961.
- [25] Y. Chen, X. W. Yang, and B. Han, "Spatial velocity variations of P waves during rock deformations," *Acta Geophysica Sinica*, vol. 12, no. 1, pp. 54–62, 1990.
- [26] K. Luxbacher, E. Westman, P. Swanson, and M. Karfakis, "Three-dimensional time-lapse velocity tomography of an underground longwall panel," *International Journal of Rock Mechanics and Mining Sciences*, vol. 45, no. 4, pp. 478–485, 2008.