

Article

Determination of the Advanced Mining Influence Range in Coal Mines Based on the Statistical Analysis of Mining-Induced Seismicity

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Abstract: Determining the advanced mining influence range of an underground working face is crucial for preventing dynamic disasters, such as coal bursts and gas outbursts. In this study, the occurrence of advanced seismicity before the working face as well as its correlation with the acoustic emission (AE) activity of coal and rocks under axial loading was analyzed. Based on the results, a novel statistical method to determine the advanced mining influence range based on advanced seismicity data was proposed and then validated with a case study. The results show that advanced seismicity is caused by the combined effects of static and dynamic stresses at the working face. This seismicity can be used to assess the mining influence degree of the working face on the advanced coal and rock mass, and determine the advanced mining influence range. Using the novel statistical method, the normalized curves for the total number and total energy of the advanced mining-induced seismicity can be plotted. Then, the advanced mining influence range can be determined using thresholds. The thresholds can be established based on the AE activities observed in coal and rock samples under axial static loading. In the case study in this research, the thresholds for the total seismic number and total seismic energy are 0.076 and 0.052, respectively. The corresponding advanced mining influence ranges are 275 m and 245 m, respectively. Field monitoring confirms an advanced mining influence range of 255 m, which validates the results obtained using the novel statistical method.

Keywords: underground coal mining; dynamic disasters; advanced mining influence range; statistical analysis; mining-induced seismicity



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1. Introduction

Coal bursts and gas outbursts are typical dynamic disasters in underground coal mines and have raised global concerns [1]. With the increasing depth of mining and the complex conditions at these depths, stress at the working face becomes severely deteriorated, resulting in dynamic disasters occurring more frequently [2,3]. These dynamic disasters are most observed in advanced roadways. For example, there were 1355 coal burst incidents between 1983 and 2023 in China, of which about 93.1% occurred in advanced roadways [4,5]. These dynamic disasters are typically caused by the combination of dynamic and static loads within the advanced mining influence zone of the working face [6]. This zone is affected by both the static load from the advanced abutment pressure and dynamic disturbances from the working face. Accurately determining the advanced mining influence range of the working face is crucial for ensuring safety, including bolting control, pressure-relief measures, and limiting the number of personnel, especially in areas at risk of coal bursts and gas outbursts [7,8].

At present, most studies have focused on the static load from the abutment pressure at the working face, using methods such as theoretical analysis, numerical calculation, lab testing, and field monitoring [9–13]. In theoretical analysis and numerical simulation, underground field conditions are often simplified, making them differ significantly from the actual complex conditions and mechanical properties found in the field. Stress gauges have been widely used to monitor stress in coal and rock masses. Distributed optical fibers have also been gradually introduced for stress monitoring in underground coal mines [14,15]. However, these field monitoring methods are often costly in terms of both time and money. They also sometimes fall short of expectations due to issues with equipment reliability and stability in the harsh underground environment. To monitor the dynamic disturbance at the working face, micro-seismic monitoring systems are widely used in underground coal mines prone to dynamic disasters [16]. These systems monitor and analyze mining-induced seismic activity, focusing on the spatial, temporal, and intensity characteristics of the mining-induced seismicity, as well as seismic wave attenuation, focal mechanisms, and seismic tomography [17–20]. However, these methods only monitor and analyze dynamic disturbances and do not integrate with the monitoring of the advanced static load. As a result, they fail to provide a comprehensive view of the overall mining influence at the working face.

Mining-induced seismicity in the advanced area of the working face is caused by the superposition of the advanced static load and dynamic disturbance [21,22]. Therefore, by analyzing the distribution characteristics of the mining-induced seismicity, the advanced mining influence range of the working face can be determined using specific methods. Based on the understanding of the mining-induced seismicity mechanism, a novel statistical method of mining-induced seismicity was proposed. This method includes a threshold and a procedure for determining the advanced mining influence range of the working face. A case study was conducted to validate the effectiveness of the novel method, and potential issues with its application are discussed in this paper. The aim of the study is to quantitatively determine the advanced mining influence range by statistical analysis of mining-induced seismicity. The results offer valuable insights for improving safety and preventing dynamic disasters in underground coal mines.

2. Occurrence Mechanism of Advanced Mining-Induced Seismicity

Mining-induced seismicity, in a narrow sense, refers to seismic activity that can be perceived by people. More broadly, it is the vibration caused by the rapid release of elastic energy in coal and rock masses due to mining disturbances. This seismic activity can be captured and recorded by monitoring equipment [23]. It has been verified that during longwall mining in underground coal mines, the overburden load of the roof strata above the goaf transfers to surrounding areas. Before the working face, there is an abutment stress that adds extra static stress on the advanced coal and rock masses. This stress typically increases first, reaches a peak at the juncture of the plastic and elastic areas, and then decreases as the distance from the working face increases. Additionally, the collapse of the roof strata after the working face can also exert dynamic stress disturbances on the coal and rock masses ahead of the working face. The amplitude of these dynamic stress disturbances is attenuated as a power function during propagation. Static stress and dynamic stresses become superposed before the working face, as shown in Figure 1a. Mining-induced seismicity can occur in areas after and before the working face. The former is caused by the breaking and collapse of the roof strata. The latter is caused by the instability of the coal and rock masses under the coupling load of static and dynamic stresses. Analyzing seismic activity before the working face can help to assess how mining affects the advanced coal and rock masses and determine the advanced mining influence range.

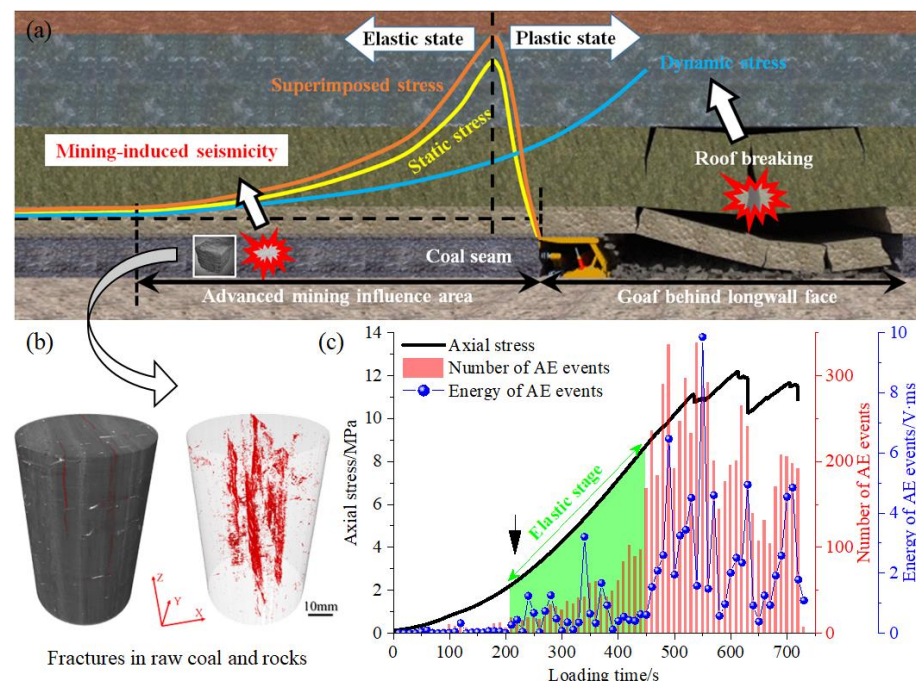


Figure 1. Mechanical response of the advanced coal and rock mass. (a) Mining-induced static and dynamic stress distribution, (b) fractures in raw coal and rocks, and (c) acoustic emission (AE) activity of the raw coal and rock samples under different axial stress.

As inhomogeneous and anisotropic materials, raw coal and rock strata contain structural defects, as shown in Figure 1b; these lead to abnormal mechanical behaviors under mining disturbance. Acoustic emission (AE) activities, including the number and energy of AE events, of a coal sample under axial load was tested and the results are shown in Figure 1c. Here, the number and the energy of the AE events were calculated every 10 s during the axial loading. It can be seen that the AE activities increase with the axial loading. It becomes strongest in the plastic phase or where the peak stress occurs. Especially, when it comes to the elastic stage, AE activity sooner or later clearly boosts with the increasing load. This is caused by the generation and expansion of cracks in the raw coal. Similar to axial loading tests in the laboratory, with the advancing of the working face, the advanced coal and rocks undergo elastic deformation and plastic deformation and eventually break. The advanced coal and rocks are also under a nonlinear increasing stress path, just like the stress curve in Figure 1c. Defects and cracks in raw coal and rock masses deform and release elastic energy when the mining-induced superposed stress exceeds the initial stress, resulting in seismic activity. Moreover, the development of cracks and seismic activity evolve similarly in concert with AE activities, as shown in Figure 1c. Briefly, the advanced coal and rock masses in the working face and the coal and rock samples in axial compression tests are under similar stress conditions, which will lead to similar mechanical behaviors. Therefore, the ratios of the number and energy of AE events at the active point in the elastic stage to the peak value can be used to estimate the ratios of seismic activity at the boundary of the advanced mining-induced area to those in the peak stress area. This approach allows for the determination of the advanced mining influence range based on statistical analysis.

3. Novel Statistical Method of Mining-Induced Seismicity to Determine the Advanced Mining Influence Range

A novel statistical method of advanced mining-induced seismicity was developed to quantitatively assess the advanced mining influence range. Figure 2 illustrates the framework of this statistical method for analyzing mining-induced seismicity.

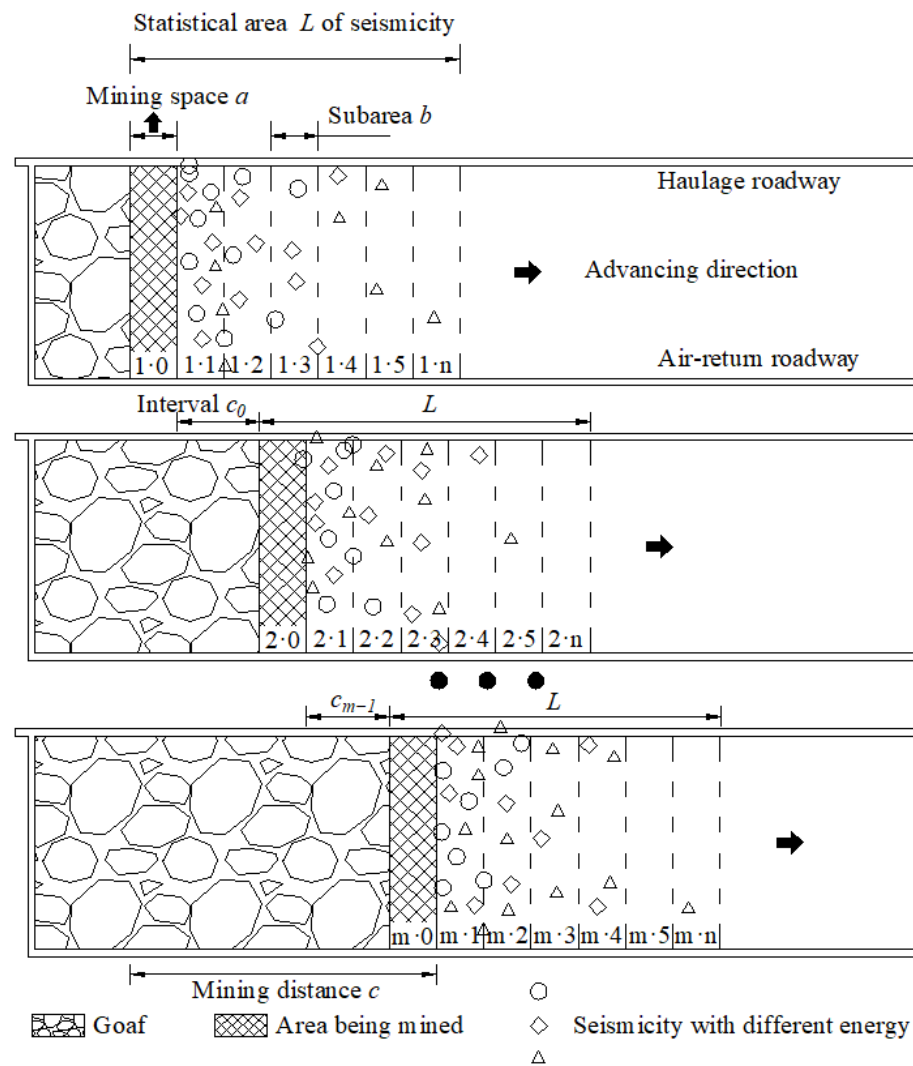


Figure 2. Framework of the statistical method of mining-induced seismicity.

The steps for using the statistical method to determine the advanced mining influence range are as follows:

Step 1: Mining-induced seismicity in the working face is monitored using the micro-seismic monitoring system. The source location and seismic energy are calculated. It is important to exclude seismic events caused by human activities, such as pre-splitting blasting and borehole drilling, from this analysis.

Step 2: A mining area with a distance c after the working face is selected. Then, m mining phases with a distance a are divided. The distances between the mining phases are $c_0, c_1, \dots$, and c_{m-1} . The maximum distances between the mining-induced seismicity and the mining phase are calculated. The largest of these distances is used as the statistical area L of mining-induced seismicity. It is recommended to set c between 100 and 300 m, ensuring similar geological and mining conditions, and a between 10 and 30 m to match periodic mining conditions. The number of the mining phases m should be more than three.

Step 3: The statistical area L is equally divided into n advanced subareas with a distance b . For all mining phases in step 2, the total seismic energy e_{in} and the seismic number q_{in} within the n advanced subareas are calculated and superimposed:

$$E_n = e_{1n} + e_{2n} + e_{3n} + \dots + e_{mn} = \sum_{i=0}^m e_{in} \quad (1)$$

$$Q_n = q_{1n} + q_{2n} + q_{3n} + \dots + q_{mn} = \sum_{i=0}^m q_{in} \quad (2)$$

where E_n and Q_n are the sums of the seismic energy and the seismic number in the advanced subareas, respectively; e_{in} and q_{in} are the total seismic energy and the total seismic number of a certain advanced subarea in all mining phases, respectively, and m is the number of the mining phases.

Step 4: The distances d_i between the midlines of the advanced subareas and the mining phases are calculated as Equations (3) and (4). These distances are used as the abscissas to plot curves of the total seismic number and the total seismic energy in the advanced areas. The ordinates represent the total seismic number and total seismic energy.

$$d_i = \frac{a-b}{2} + ib, i = 1, 2, \dots, n \quad (3)$$

$$d_0 = 0 \quad (4)$$

where d_i is the distance between the midlines of the advanced subareas and the mining phases, a is the mining length of the mining phase, and b is the length of the advanced subareas.

Step 5: The total seismic number and the total seismic energy curves in step 4 are then normalized and divided by the maximum ordinates, as Equations (5)–(8):

$$Q_{max} = \max(Q_i), i = 0, 1, 2, \dots, n \quad (5)$$

$$E_{max} = \max(E_i), i = 0, 1, 2, \dots, n \quad (6)$$

$$R(Q_i) = \frac{Q_i}{Q_{max}}, i = 0, 1, 2, \dots, n \quad (7)$$

$$R(E_i) = \frac{E_i}{E_{max}}, i = 0, 1, 2, \dots, n \quad (8)$$

where Q_{max} and E_{max} are the maximum total seismic number and the maximum total seismic energy in the advanced subareas, respectively. $R(Q_i)$ and $R(E_i)$ are the normalized total seismic number and the normalized total seismic energy in the advanced subareas, respectively.

Step 6: In the normalized total seismic number and total seismic energy curves, thresholds are respectively set to determine the advanced mining influence ranges. If the normalized values in a particular advanced subarea exceed the thresholds, that subarea is within the advanced mining influenced area. The maximum distance at which these values are exceeded represents the advanced mining influence range for the working face at that location. The thresholds can be established based on AE activities observed in laboratory tests of coal and rock samples under axial loading.

4. A Case Study

4.1. Site Overview

Working face 205 is located in the 2# panel of a 1000-m-deep coal mine in the Binchang mining area, Shaanxi Province, China. It is the fifth longwall face, with working faces 201–204 having already been mined. The widths of working face 205 in inclination and strike directions are 200 m and 1450 m, respectively. The layout of working face 205 is shown in Figure 3a. The average thickness and dip angle of the 4# main mineable coal seam are 9.7 m and 0° – 8° , respectively. The 4# coal seam has strong burst propensity [6]. In this working face, fully mechanized top-coal caving mining is adopted, and the coal mining height and caving height are 3.5 m and 5.5 m, respectively. In situ stress tests indicate that the three-dimensional stresses are 41.8 MPa, 22.5 MPa, and 17.5 MPa, and the 4# coal seam is severely stressed.

An “SOS” micro-seismic monitoring system with 23 geophones was installed in the coal mine to monitor the mining-induced seismicity during coal mining. The placement of the geophones was regularly optimized as the working face advanced to improve the locating accuracy of mining-induced seismicity [20]. A 940-m-deep borehole ZY-1 was constructed in working face 205 and a 930-m-long distributed optical fiber was installed

in the borehole to detect the overburden strata movement during coal mining, as shown in Figure 3b. The distributed optical fiber can capture the deformation of the strata under mining activity and is now widely promoted in coal mines [14]. When the deep borehole was put into operation on 6 December 2020, it was 292 m away from working face 205.

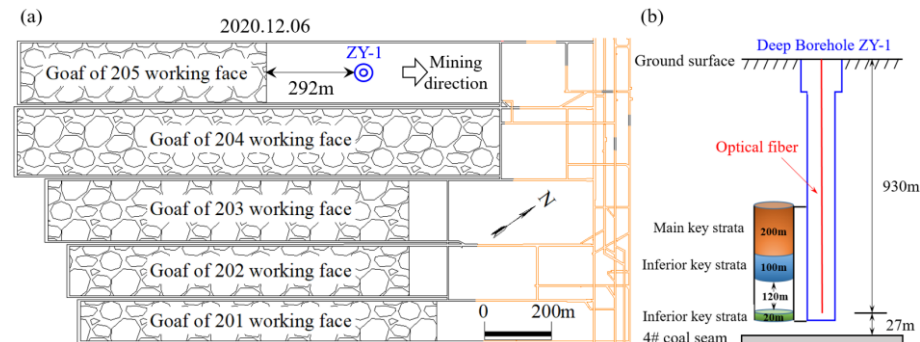


Figure 3. Layout of (a) working face 205 and (b) the deep borehole ZY1 with optical fiber for monitoring overburden strata strain.

4.2. Statistical Analysis of Mining-Induced Seismicity

To analyze the advanced mining influence range, mining-induced seismicity data from working face 205, covering 8 August 2020 to 4 January 2021, were selected. During the period, the mining distance c was 188.5 m. A continuous statistics method was adopted, setting the distances between the mining phases $c_0, c_1, \dots$, and c_{m-1} at 0 m. The periodic weighting distances at working face 205 from August 2020 to January 2021 ranged from 10.9 m to 23.1 m. Consequently, eight phases were defined based on the daily advance records, with the corresponding advancing distances a for each phase listed in Table 1.

Table 1. Advancing schedule of working face 205 from 8 August 2020 to 4 January 2021.

Phase No.	Duration	Advancing Distance/m
1	8 August 2020–13 August 2020	24.0
2	14 August 2020–22 August 2020	24.4
3	23 August 2020–15 September 2020	23.3
4	16 September 2020–28 September 2020	23.6
5	29 September 2020–19 October 2020	24.9
6	20 October 2020–3 November 2020	24.2
7	4 November 2020–27 December 2020	21.0
8	28 December 2020–4 January 2021	23.1
Total		188.5

Figure 4 shows the spatial distribution of mining-induced seismicity across the eight phases. It is evident that as the working face advances, the mining-induced seismicity also moves forward, with high-energy events primarily concentrated in the advanced area close to the working face. The maximum distance between the mining-induced seismicity and the working face is 500 m. Hence, the statistical area L was set to 500 m, and it was divided into 100 advanced subareas ($n = 100$), each with a distance b of 5 m.

The mining-induced seismicity data from the eight phases were analyzed using the method described in Section 3. Figure 5 displays the curves of the total seismic number and the total seismic energy. Both curves generally follow the pattern of typical abutment stress before the working face, as shown in Figure 1. The seismic activity curves initially increase and then decrease as the distance from the working face grows. The peak seismic activities, including both the seismic number and the seismic energy, occur at a distance of 45–75 m ahead of the working face.

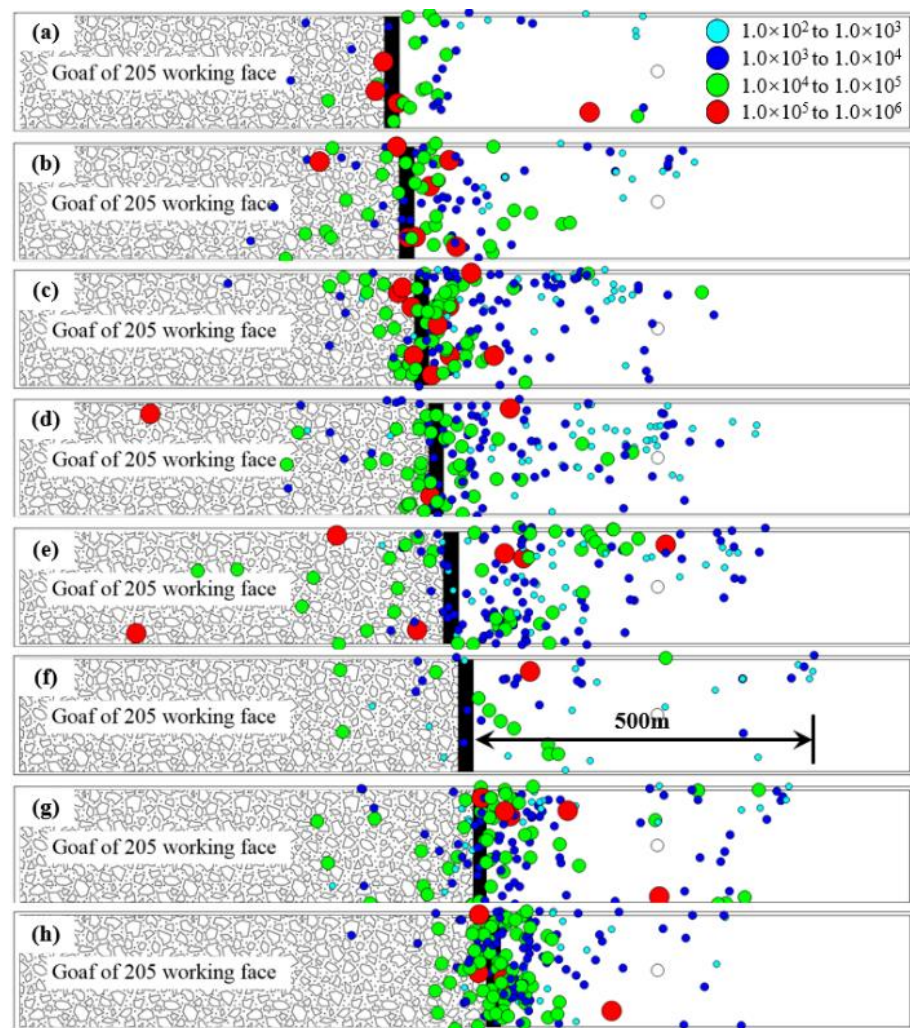


Figure 4. Spatial distribution of mining-induced seismicity at working face 205 during (a) Phase 1, (b) Phase 2, (c) Phase 3, (d) Phase 4, (e) Phase 5, (f) Phase 6, (g) Phase 7, (h) Phase 8.

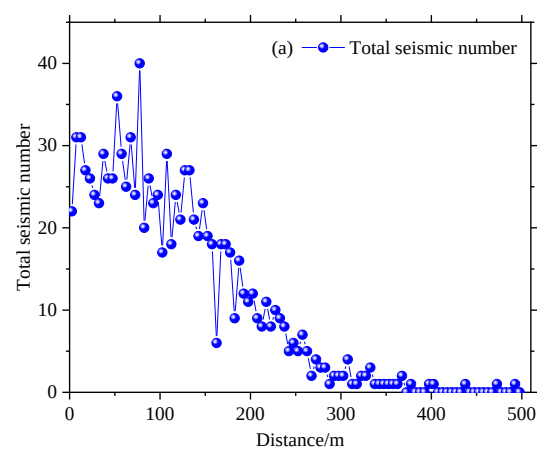


Figure 5. Cont.

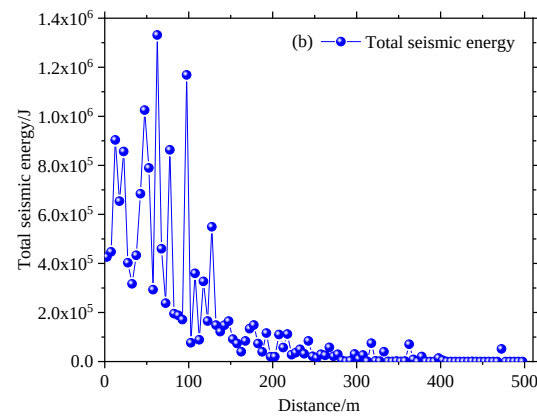
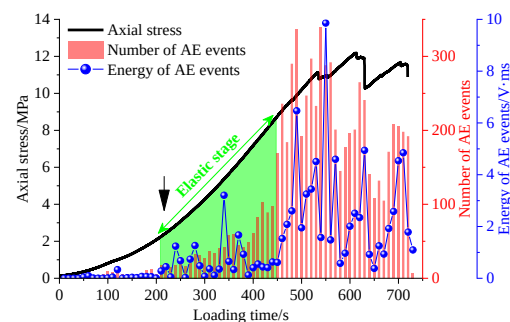


Figure 5. Statistical results of advancing mining-induced seismicity at working face 205. (a) Total seismic number, (b) Total seismic energy.

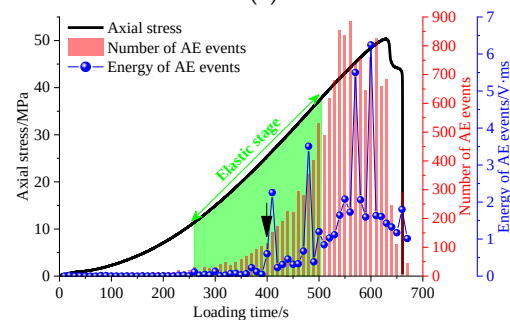
4.3. The Threshold from AE Activity of Coal and Rocks under Axial Loading

Uniaxial compression tests were performed on cylindrical samples to examine the fracture characteristics of coal and rock under mining-induced stresses. The samples included raw coal, coarse sandstone, and medium sandstone from the 4# coal seam and adjacent roof strata in the 2# panel. The tests used the MTS Landmark 375.50 system and a PCI-II AE system with eight sensors. The AE system had a sampling rate of 2 MHz and a threshold of 40 dB. Given the non-linear increase in abutment stress on the advanced coal and rocks, displacement control was used to apply axial load at a rate of 0.1 mm/min.

The AE activities of the coal and rocks under axial loading are shown in Figure 6. Notably, the number and energy of AE events are calculated every 10 s. It can be seen that the AE activities of the tested samples exhibit similar patterns. Specifically, the ratios of AE event numbers in the elastic stage to their peak value are 0.051, 0.084, and 0.094 for the coal, coarse sandstone, and medium sandstone samples, respectively, with a mean of 0.076. The ratios of the AE energy are 0.050, 0.040, and 0.066 of the peak value, respectively, with a mean of 0.052. These two mean ratios were used as thresholds to define the advanced mining influence ranges in terms of seismic number and total seismic energy.



(a)



(b)

Figure 6. Cont.

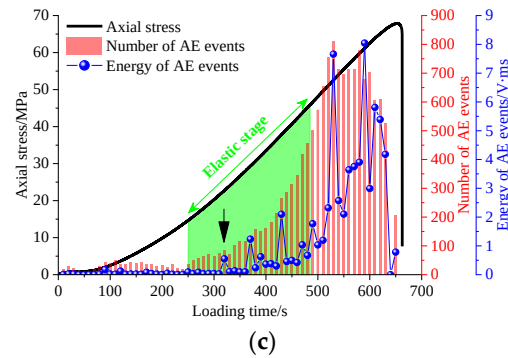


Figure 6. AE activity in coal and rock samples under axial loading. (a) Coal sample. (b) Coarse sandstone sample. (c) Medium sandstone sample.

4.4. Determination of the Advanced Mining Influence Range

The normalized total seismic number and total seismic energy curves from Figure 5 are shown in Figure 7. It is evident that the advanced mining influence ranges are 275 m for seismic number and 245 m for seismic energy. Therefore, the advanced mining influence range for working face 205 during the mining period from 8 August 2020 to 4 January 2021 is 275 m.

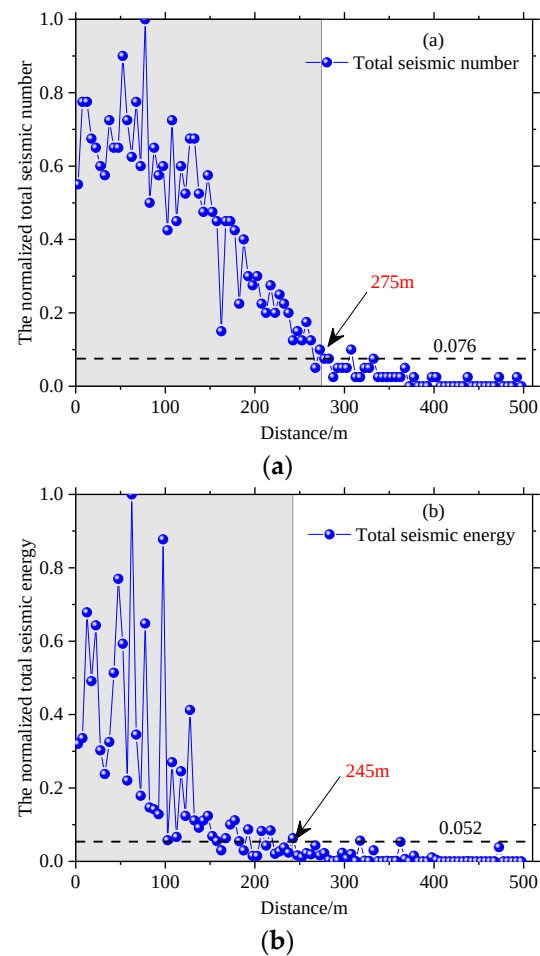


Figure 7. Determination of the advancing mining influence range at working face 205. (a) The normalized total seismic number curve. (b) The normalized total seismic energy curve.

4.5. Validation of the Statistical Results by Field Monitoring

Figure 8 shows the monitoring results from the distributed optical fiber in the deep borehole. The strain curves on 29 December 2020 are virtually identical to those on 6 December 2020 with no significant changes, as illustrated in Figure 8a. During this period, the deep borehole was 292 m–265 m away from working face 205 and it remained unaffected by the mining disturbances of the working face. On 4 January 2021, the strain curve of the optical fiber began to differ from the curve recorded on 6 December 2020, as shown in Figure 8b. At this time, the deep borehole was 255 m away from working face 205. Subsequently, as the distance between the borehole and the working face decreased, the divergence in the strain curves became more pronounced, as illustrated in Figure 8c–d.

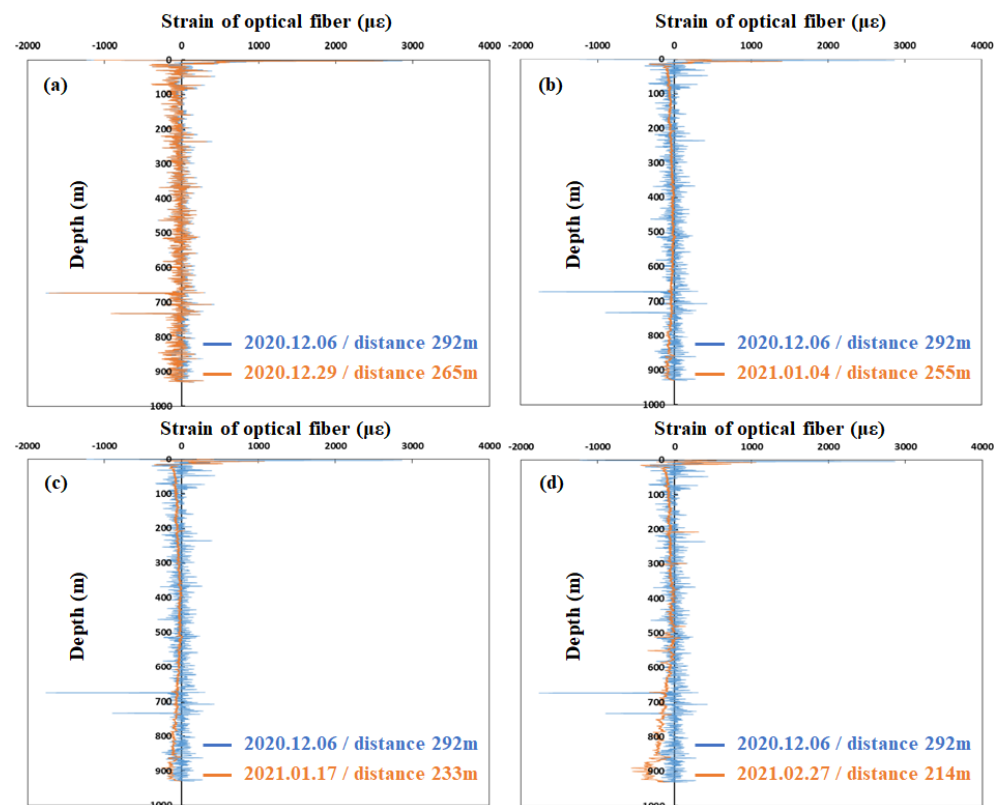


Figure 8. Strain curves of optical fiber in ZY-1 during the mining of working face 205. (a) on 29 December 2020, (b) on 4 January 2021, (c) on 17 January 2021, (d) on 27 February 2021.

The results inferred above indicate that when the working face is within 255 m of the borehole, compression deformation starts to occur in the overburden strata. This distance of 255 m is identified as the advanced mining influence range for working face 205 during this mining period. This finding matches the statistical analysis results of mining-induced seismicity and confirms the effectiveness of the method described in Section 3.

5. Discussion

The novel method proposed in this study was validated with a case study. Comparing to traditional methods, there is no need for additional work in the field and the method has economic benefits. The method is easy to understand and implement. More importantly, both the static stress and the dynamic disturbance caused by mining at the working face are involved in the method. This method also realizes regional and quantitative assessment of mining influence without any damage to the underground structures. In fact, the method is a reprocessing method of mining-induced seismic data. It is not applicable in coal mines without a micro-seismic monitoring system. As of 2023, China has over 150 coal mines at risk of coal bursts, and this number is rising as mining depths increase [24]. Furthermore,

mining-induced seismicity has been recorded in many countries with underground coal mines, such as Poland, Australia, Czechia, Slovakia, America, Canada, South Africa, etc. Micro-seismic monitoring systems are installed in nearly all coal mines with coal burst risks, and these can monitor mining-induced seismicity in real time. Consequently, the novel method for determining the advanced mining influence range is anticipated to be globally applicable.

The locating accuracy of mining-induced seismicity using a micro-seismic monitoring system is crucial for determining the advanced mining influence range. In our method, x and y coordinates are used, and in general, the system generally provides better accuracy for horizontal (plane) coordinates than for vertical coordinates. To enhance locating accuracy, the network of geophones should be regularly adjusted according to the mining schedule to cover the mining area effectively [25]. This optimization will improve the locating accuracy of seismic events and, consequently, the reliability of the statistical results.

In the case study in this research, only mining-induced seismic events with energies over 100 J were analyzed due to technical limitations of the micro-seismic monitoring system. Omitting seismic events with energies below 100 J may lead to deviations in the total number of advanced mining-induced seismicity. However, this omission has minimal impact on the statistical results for the total energy of advanced mining-induced seismicity, because the total seismic energy depends mainly on the high energy events. Therefore, the advanced mining influence range determined by the threshold of the total seismic energy is considered more reliable.

The thresholds for determining advanced mining influence ranges were established based on AE activities of coal and rock samples under uniaxial loading. The differences of geological and mining factors, as well as the mineral compositions in coal and rocks in different mines, have a significant influence on the AE activities [26]. When the method is being used in a new working face or a new coal mine, the tests on the AE activities of coal and rock samples should be conducted once again. As the working face advances, the abutment stress in the advanced coal and rock masses increases non-linearly [27]. Therefore, the tests were conducted using displacement control mode. Aiming to minimize the influence of heterogeneity and anisotropy of the coal and rock masses on the results, adequate coal and rock samples should be used to test the thresholds in the laboratory. The loading rate significantly affects the mechanical behaviors of coal and rocks, impacting peak strength, elastic modulus, strain, AE activity, etc. As the loading rate increases, the number of detected AE events decreases according to a power function, while the absolute energy of these events increases significantly [28,29]. However, the ratios of AE event number or energy at the active point in the elastic phase to those at peak strength are largely unaffected. Therefore, the thresholds for determining advanced mining influence ranges can be effectively tested and established using uniaxial static loading.

Dynamic disasters in underground coal mines mostly occur in the roadway within the advanced influence range. When the working face advances, the advanced influence range should be re-determined regularly considering differences in the geological or mining conditions. Moreover, risk monitoring, support, and pressure-relief measures in the roadway within the advanced influence range should be strengthened for personnel safety and dynamic disaster control.

6. Conclusions

The occurrence of advanced seismicity and its correlation with the AE activity of coal and rocks under axial loading were analyzed. Building on this analysis, a new statistical method of advanced seismicity for determining the advanced mining influence range was proposed and validated. The main conclusions of this study are as follows.

1. Mining-induced seismicity before the working face is triggered by the instability of coal and rocks under the combined effects of static and dynamic stresses. This seismicity can be used to assess the degree of mining influence on the advanced coal and rock masses and to determine the advanced mining influence range. The stress

paths of the advanced coal and rock during coal mining are similar to those of coal and rock samples under axial loading in the lab. The ratios of the AE event number and energy at the active point in the elastic stage to their peak values in lab tests can be used to estimate the ratios of seismic activity at the boundary of the advanced mining influence area to those in the peak stress area.

2. A novel statistical method of the advanced mining-induced seismicity has been proposed to quantitatively assess the advanced mining influence range. First, multiple mining phases within a mining area are selected, and the advanced areas in front of each phase are divided into subareas. The total number and energy of seismic events in each subarea are then calculated and used to plot the total seismic number and total seismic energy curves, with the distances between the midlines of the subareas and the mining phases as the abscissas. Next, the curves from all phases are superimposed and normalized by their respective maximum values. The advanced mining influence range is then determined using thresholds derived from the AE activities of coal and rock samples under axial loading.
3. A case study was conducted using the mining-induced seismicity data from a 1000-m-deep working face in China. Using the novel statistical method, the total seismic event number and total seismic energy curves were plotted and normalized. Thresholds for determining the advanced mining influence ranges were established at 0.076 for the total seismic number and 0.052 for the total seismic energy. The advanced mining influence ranges based on seismic activity were determined to be 275 m for seismic number and 245 m for seismic energy. Additionally, monitoring results from distributed optical fibers in the deep borehole showed an advanced mining influence range of 255 m, which supports the accuracy of the novel statistical method.
4. The novel method is based on the reprocessing of mining-induced seismic data and it is easy to understand and implement. To improve the reliability of the statistical results, the geophone network in the micro-seismic monitoring system should be regularly optimized according to the mining schedule to fully encompass the mining area. Since the seismic number in the working face is more susceptible to variation, it is also acceptable to determine the advanced mining influence range using only the total seismic energy threshold.

In the future, based on the findings in this study, the division method and criterion of different dynamic risk areas before the working face will be further studied. A software platform incorporating this method will be developed to process seismic data and display the distribution the advanced dynamic risk areas in real time. This will effectively help to manage and control strong mine pressure and dynamic disasters.

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