Research Article

Generating Behaviors of Strong Tremors and Experimental Study of Rockburst-Triggering Criterion

Guifeng Wang ^{1,2}, Feng Jin ¹, Siyuan Gong ¹, Linming Dou ¹, Chaojun Fan ²,
Wu Cai ¹ and Xiaoyuan Yuan ¹

¹State Key Laboratory of Coal Resources and Safe Mining, School of Mines, China University of Mining and Technology, Xuzhou 221116, China

²Department of Energy and Mineral Engineering, G3 Center and Energy Institute, The Pennsylvania State University, University Park, State College, PA 16802, USA

Correspondence should be addressed to Feng Jin; ts18020014a31@cumt.edu.cn and Siyuan Gong; gsy_cumt@cumt.edu.cn

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Numerous tremors occur during excavation and mining periods in coal mines, and low-energy tremors often occur before strong tremors. In addition, it is found that not all strong tremors cause rockbursts. Therefore, generating behaviors of strong tremors and the triggering criterion for the occurrence of the rockburst must be investigated. In this study, generating behaviors of strong tremors were inferred by velocity tomograms and energy density clouds. An innovative facility capable of applying dynamic disturbance to roadway models was developed to study the triggering criterion for rockbursts. Velocity tomograms indicated that the stress concentration extended to the syncline region with the advance of the coalface. High-energy-density clouds expanded rapidly and regularly in some areas that were parts of the high-velocity region, indicating that the stress increased rapidly in these areas, until strong tremors took place nearby. AE activities suggested that the modelled roadway offered good resistance as the dynamic loading energy grew from 29.4 J to 117.6 J. Then, sharp AE activity at the dynamic loading energy of 147 J indicated the ultimate shock resistance of the roadway was almost reached. Finally, bursting failure of the modelled roadway was observed at a dynamic loading energy of 176.4 J.

1. Introduction

Rockbursts are the sudden and intense release of elastic energy accumulated in a coal-rock mass during tunnelling and mining. Rockbursts have become a common safety issue in underground coal mining in China. In recent years, more than 170 coal mines in China have suffered rockbursts. The rockburst on 1 March 2011 in the 25110 working face in Yuejin Coal Mine (Yima City, Henan Province, China) damaged a 300 m long section of the roadway (Figures 1(a) and 1(a1)). Fifty rockbursts occurred during the mining of the 250204 working face in Yanbei Coal Mine from April 2011 to May 2013. In five months in 2012, four rockbursts occurred in 11-2 working face in Xing'an Coal mine (Heilongjiang Province, China), while eight rockbursts had already occurred in the adjacent

working face (Figures 1(b) and 1(b1)). Ten rockbursts took place in Huating Coal Mine (Pingliang City, Gansu Province, China) located in a large fold structure zone from 1 March 2014 to 8 April 2014. On 15 March 2013, a rockburst in Junde Coal Mine, Hegang City (Heilongjiang Province, China), led to the closure of both the tailgate and headgate and trapped 25 miners (Figures 1(c) and 1(c1)). Another rockburst occurred on 15 September 2016, during the tunnelling of the open-off cut in Junde Coal Mine, killing five miners. Previous research demonstrates that rockbursts are likely to be induced in high-stress regions. Recently, with the application of microseismic (MS) monitoring, researchers and mining engineers have gradually reached a consensus whereby high-stress concentration and strong tremors both play an important role in the occurrence of rockbursts [1–3]; that is, when

FIGURE 1: Photos in Yuejin (a, a1), Xing'an (b, b1), and Junde (c, c1) coal mines before (upper row) and after (lower row) rockbursts.

roadways with high-stress concentration nearby are disturbed by strong tremors, rockbursts are prone to occur.

During tunnelling and mining periods, there are many mining-induced tremors of different energies and low-energy tremors often occur before strong tremors. In addition, it is found that not all strong tremors cause rockbursts [4, 5]. Kaiser and Cai [6] found that whether a rockburst was eventually observed or not was closely related to the shock resistance of roadways. Often, obvious shocks can be felt in the roadway at the moment of a strong tremor, but no rockburst ensues. Thus, a proper understanding of generating behaviors of a rockburst from low-energy tremors to the occurrence of strong tremors, and the rockburst-triggering criterion that determines the occurrence of rockbursts can provide useful insights into the evaluation of rockburst hazard as well as revealing their causes. However, diverse geological conditions, mining environments, and changing mining-induced stress make the evolution of microfractures in coal-rock masses extremely complex, bringing the difficulty in precisely identifying the complicated evolution of tremors [4–10]. As the tremor evolution corresponds to the occurrence and development process of microcracks in coal-rock masses, the spatial tremor distribution is extremely complex and evolved in a nonlinear manner over time. Effective means to get the stress and energy characteristics before strong tremors still remain in the exploration and development because of the complexity of the tremor-generating behaviors and the difficulty of precisely identifying the rockburst-triggering criterion in a complicated rock mass fabric. In addition, rockbursts triggered by strong tremors occur in an instant, and it is difficult to study the triggering criterion and failure characteristic of such rockbursts [11–13]. Thus, relevant studies are still in their exploratory or developmental stage.

In this work, roles of strong tremor disturbance and high-stress concentration in the generation of rockbursts were analysed. Two case studies involving strong tremors

that triggered the rockburst and did not were studied. Generating behaviors of strong tremors were inferred by energy density clouds and velocity tomograms. Then, an innovative Pendulum Impact Test Facility capable of applying dynamic disturbance to roadway models was developed to study the occurrence of rockbursts to reveal why rockbursts occur. Damage evolution in rock masses surrounding the modelled roadway was monitored by an acoustic emission (AE) system. Acceleration signals and failure processes of the modelled roadway were also recorded. Relevant studies remain both rare and limited. This work involving both studies of generating behaviors of strong tremors and the triggering criterion for rockbursts may provide a new approach to future research on rockburst mechanisms.

2. Roles of Strong Tremor Disturbance and High-Stress Concentration in Rockbursts

A rockburst is caused by the abrupt release of elastic energy stored in coal-rock masses. Once a rockburst occurs, coal-rock masses surrounding the roadway are immediately driven by the released energy, thus damaging supporting structures and causing casualties (Figure 1). If a significant amount of elastic energy is accumulated in coal-rock masses and then abruptly released, a rockburst will occur. Therefore, an accumulation of sufficient energy is the premise for the occurrence of rockbursts. The energy accumulation is induced by stress concentration. So, when the stress concentration is higher and the stress peak away from excavated boundaries is closer, rockbursts are more likely to occur. Meanwhile, the occurrence of many rockbursts also requires adequate dynamic disturbance that triggers the abrupt release of energy stored in the coal-rock mass. Numerous rockbursts in coal mines are a result of high-stress concentrations combined with dynamic disturbances; that is, a rockburst may occur when the total stress and energy (due to

the superposition of static stress and dynamic disturbance) within the coal-rock mass reach a certain critical level. The combined effect of static and dynamic stresses was expressed as follows [3, 5, 14]:

$$\begin{cases} \sigma_s + \sigma_i - \sigma_c > 0, \\ E_s + E_i - E_d = E_e > 0, \quad E_d = \gamma S_R, \end{cases} \quad (1)$$

where σ_s and σ_i refer to the static stress within the coal-rock masses and the dynamic stress induced by seismic waves, respectively (MPa), σ_c is the critical stress required for a rockburst, E_s is the elastic energy stored in coal-rock masses and induced by the static stress, E_i is the dynamic disturbance energy, E_d is the dissipated energy due to sliding on existing cracks or joints and plastic deformation, γ is the dissipated energy required in the unit area, and E_e is the kinetic energy for coal-rock masses moving and flying to roadway. E_d can be defined as $E_d = \gamma S_R$, where S_R is the total failure area.

The dynamic stress generated by the seismic waves can be expressed as follows [15, 16]:

$$\begin{cases} \sigma_{iP} = \rho C_P v_{PP}, \\ \sigma_{iS} = \rho C_S v_{PS}, \end{cases} \quad (2)$$

where σ_{iP} and σ_{iS} are the normal stress and shear stress induced by the dynamic disturbance, respectively (MPa), ρ is the density of the coal-rock masses (kg/m^3), C_P and C_S are the propagation velocities of the P- and S-waves, respectively (m/s), and v_{PP} and v_{PS} are the particle vibration velocities of the P- and S-waves, respectively (m/s).

This is why numerous strong tremors, which will induce dynamic disturbance, happen during mining, while not all strong tremors can trigger rockbursts. For example, as shown in Figure 2(d), a strong rockburst took place in the 11-2 working face in Xing'an Coal Mine (Hegang City, Heilongjiang Province, China) on 15 October 2012 which damaged a roadway section over a length of 104 m. Figure 2 also shows tremors with different energies during mining from 19 September to 15 October 2012. In this period, numerous tremors occurred around the working face, while only one of them triggered a rockburst. Research has shown that the dynamic disturbance caused by seismic waves can be very high, and its influence is usually limited to a certain distance from the source, but the greater the seismic energy, the greater the dynamic stress and further the distance of influence [17, 18]. As shown in equation (1), the greater the energy released in a tremor, the higher the possibility of a sudden release of energy from a coal-rock mass, leading to the occurrence of rockbursts: thus, it is difficult to study rockburst failures that happen in a sudden, violent manner. Thus, how to study rockburst failures and verify the theory above has attracted much research attention [1, 3].

3. MS Monitoring

The 11-2 working face in Xing'an Coal Mine had a mining depth of about 600–680 m, with an inclined length of 137 m and a mining height of 2.6 m. It is located in a large fold structure, and the directions of the two roadways were

adjusted twice. Seismic velocity tomography had been used in the detection of stress changes during mining. Mining-induced tremors located by an MS monitoring system offered an easy way in which to conduct seismic velocity tomography. Time-related parameters pertaining to tremors were calculated to generate velocity tomograms using the simultaneous iterative reconstructive technique (SIRT) algorithm [19–22]. Research findings reveal that high-velocity regions are consistent with areas of high-stress concentration, and the locations where strong tremors occur in later mining. Layout of seismic geophones and schematic maps of SOS MS system and seismic velocity tomography were shown in Figure 3. Figure 4 shows the results of seismic velocity tomography at different face-advancing distances. Velocity tomogram (Figure 4(a)) indicates that region A had a high-stress concentration because multiple crossing roadways were located therein. Then, it can be seen from Figures 4(b)–4(d) that the area and strength of the high-velocity region increased with the advance of the coalface, which indicated that the stress concentration gradually became wider and higher and extended to the syncline region.

Before the rockburst on 15 October, a strong tremor of $1.15 \times 10^5 \text{ J}$ had already happened in the vicinity of the working face on 26 September, 2012; however, the tremor did not trigger a rockburst. Figure 5(a) shows the spatial distributions of tremors from 19 to 26 September 2012. It can be seen that these tremors gradually showed a relatively concentrated distribution; however, due to the extremely complex spatial characteristics of tremors, it is impossible to intuit the evolutionary law governing tremor activity over time, thus, generating behaviors of the strong tremor could not be inferred from these spatial distribution maps. Thus, a new spatial analysis method with an energy density index for MS monitoring was developed by our research team. The locations, energy, and distances of tremors and time parameter were taken together to describe the evolution of tremors and their spatial distribution. The energy density index of ρ_{pj} can be expressed as follows [4, 7, 23, 24]:

$$\rho_{pj} = \lg \left(\frac{\sum_{t_i \in P} \sqrt{E_{t_i}}}{S_j} \right), \quad (3)$$

where ρ_{pj} refers to the index of energy density ($\lg(\sqrt{\text{J/m}^2})$), E_{t_i} represents the energy of tremors in the statistical grid cell (J), P denotes the statistical time (d), and S_j represents the area of the statistical region (m^2).

Figure 5(b) shows energy density clouds of tremors obtained by using the calculation method with the index of energy density shown in equation (3): energy density clouds began to appear in local region B of the working face on 19 September 2012. Then, region B became the core for the expansion of the energy density clouds. From 20 to 25 September 2012, the expansion of the energy density clouds surrounding region B accelerated, leading to increases in the area and strength of the high-energy-density regions. Energy density clouds were located in the syncline region with high-stress concentration as inferred by velocity tomograms

FIGURE 2: Tremors with different energies occurring during mining from 19 September to 15 October 2012.

FIGURE 3: Continued.

FIGURE 3: Layout of seismic geophones (a) and schematic maps of SOS MS system (b) and seismic velocity tomography (c).

FIGURE 4: Seismic velocity tomography results at different advancing distances during mining.

(Figure 3(c)). On 26 September 2012, a strong tremor of 1.15×10^5 J took place in the vicinity of the energy density clouds, while only obvious shocks were felt in the roadways and no rockburst occurred.

After the occurrence of the strong tremor on 26 September 2012, a quiescent period ensued, as shown in Figure 6, and then nuclei of energy density clouds appeared in region C of the working face on 8 October 2012. From 9

FIGURE 5: Evolution of spatial tremors (a) and energy density clouds (b) before a strong tremor (19–26 September 2012).

to 13 October 2012, the energy density clouds expanded rapidly around region C, with growing strength. On 14 October 2012, a large area of high-strength energy density cloud formed at the syncline structure. As displayed in Figure 6(h), a strong tremor of 1.29×10^5 J occurred in region C at first, while it did not trigger a rockburst. Then, it was followed by another strong tremor of 3.02×10^5 J, which induced a strong rockburst. In comparison with Figure 6, the strength of the energy density clouds increased greatly before the occurrence of the rockburst, which indicated that region C might be subject to a higher stress concentration, and the second strong tremor released more energy than the first; therefore, equation (1) was satisfied with the superposition of static stress and dynamic disturbance. Thus, a rockburst occurred.

As shown in Figure 4, velocity tomograms showed that there was a large-scale region with high-stress concentration in front of the coalface. High-energy-density clouds expanded rapidly and regularly in some local areas that were parts of the high-velocity region, indicating further stress increases in these areas, until strong tremors occurred nearby. The evolution of energy density clouds was the response to the rising stress (static stress) in some local areas before the rockburst. With the increase of the static stress, numerous tremors with small energy appeared first, and then strong tremors occurred. Thus, the nucleation and strengthening of energy density clouds could be used as the precursor of strong tremors. When a strong tremor occurred, it generated strong seismic waves and dynamic stress. The rockburst occurred once the stress and energy

FIGURE 6: Evolution of spatial tremors (a) and energy density clouds (b) before a rockburst (8–15 October 2012).

generated by the combination of static and dynamic stresses exceeded the limits in some local areas. Energy density clouds and seismic velocity tomographs can indicate the stress and energy concentration and provide a new approach to assess the static stress during the generating process of a rockburst. Meanwhile, as shown in the equation (2), the higher the released energy of tremors, the higher the dynamic stress will be induced, then the higher the probability that the rockburst occurs. In order to reveal the effect of dynamic stress before a rockburst, laboratory tests had been done with dynamic disturbance applying to roadway models in Section 4.

Note that a rockburst is more likely to occur in areas with high-stress concentration. Conversely, they do not occur

readily in areas of low stress concentration because strong tremors with high seismic energies are needed in such circumstances and such events are rare; for examples, in some areas at a working face where there are folds and coal pillars, coal-rock masses are likely to store significant elastic energy after the mining-induced stress is superimposed on the tectonic stress or the stress imposed by coal pillars [22, 25, 26]. When the coalface is advanced to these regions that had high-stress concentrations, rockbursts are prone to occur therein. As shown in Figures 4–6, the high-stress feature in seismic velocity tomographs appeared earlier than the emergence of energy density clouds, which indicated the occurrence of tremors was the response to the further rising stress concentration.

FIGURE 7: Test facility (a); pendulum device (b); test photograph (c); test schematic diagram (d).

4. Model Testing

4.1. Methods. From the above analysis, it can be seen that when static stress and dynamic disturbance are superimposed, the total stress and energy can readily surpass their critical values, whereupon a rockburst may occur. The critical stress and energy required for a rockburst may vary with various factors including the coal-rock properties, stress state, loading rate, and supporting schemes. However, it is difficult to measure such parameters in the field. Laboratory tests or numerical simulation are effective means with which to study the occurrence of rockbursts and are conducive to revealing causes of rockburst. A novel Pendulum Impact Test Facility was developed to study the occurrence of rockbursts triggered by dynamic disturbance (Figure 7). A sleeve containing a sliding bar was buried in the model. By releasing the pendulum to strike this bar, a dynamic energy input was generated to simulate the abrupt energy release of a point seismic source in coal-rock masses near a roadway. Above the model, a hydraulic cylinder was set up to apply vertical stress, while horizontal stress on the two sides of the model was applied by oil packets. The similarity ratios of geometry, density, force, and energy are $C_l = 17.39$, $C_p = 1.47$, $C = 25.57$, and $C_E = 1.34 \times 10^5$,

respectively, according to similarity theory [17, 27, 28]. The modelled roadway, with an axial length of 400 mm, simulated an arched underground cavern with a bottom width of 4.0 m and a centreline height of 3.0 m. The physical and mechanical properties of the real and modelled rocks are listed in Table 1. According to field survey data and the requisite force scale, a vertical stress of 0.59 MPa and a horizontal stress of 0.86 MPa were applied to the model before excavation. After the tunnel was excavated, the vertical stress was increased to 1.18 MPa to simulate the influence of mining stress.

In the test, the pendulum (mass, 20 kg) was elevated from 150 mm to 900 mm in increments of 150 mm: the corresponding dynamic loading energies were 29.4 J, 58.8 J, 88.2 J, 117.6 J, 147 J, and 176.4 J, respectively. In this way, the successively growing tremor energy was simulated. The tremor energy measured in coal mines was basically 0.26% to 3.6% of the total energy released in the rupture of the coal-rock masses [17, 18]. The absorption efficiency of the dynamic energy input generated by the pendulum was assumed to be 85% [29]. Based on this, it was calculated that the simulated maximum tremor energy was 0.52×10^5 J to 7.23×10^5 J [17, 27], which was equivalent to the energy magnitude of strong tremors recorded in the field. An

TABLE 1: Mechanical and material properties of rocks.

Lithology	Natural rock properties			Model materials and ratios		Modelled rock properties		
	Unit weight (kN/m ³)	Compressive strength (MPa)	Young's modulus (GPa)	Ratio of sand and binder	Ratio of cement and gypsum	Unit weight (kN/m ³)	Compressive strength (MPa)	Young's modulus (GPa)
Coarse sandstone	25.2	81.67	31.39	4:1	7:3	20.629	2.945	0.72
Fine sandstone	24.8	59.75	26.51	5:1	7:3	18.2182	2.398	0.45
Coal seam	13.2	17.92	9.80	8:1	5:5	17.1794	0.821	0.29
Medium sandstone	24.5	71.28	29.88	4:1	5:5	18.3946	2.783	0.61

FIGURE 8: AE activity and acceleration signals at different input energies: (a, a1) 29.4 J; (b, b1) 58.8 J; (c, c1) 88.2 J; (d, d1) 117.6 J; (e, e1) 147 J; (f, f1) 176.4 J.

FIGURE 9: Cumulative AE counts and acceleration peaks at different input energies.

FIGURE 10: Rockburst failure of the modelled roadway recorded by a high-speed camera.

acoustic emission (AE) system was adopted to monitor the internal damage in rocks surrounding the roadway after each dynamic energy input. An ultradynamic signal testing system (DH5960) with an acquisition rate of 50 kHz was used to measure acceleration signals in the modelled roadway. A high-speed camera was used to track the instantaneous failure process.

4.2. Results of Laboratory Tests and Their Analysis. Figure 8 shows the characteristics of AE activity and acceleration signals when the input energy was increased.

As shown in Figure 9, AE activities did not exhibit significant changes as the input energy was increased from 29.4 J to 117.6 J. This suggested that the roadway retained good resistance to dynamic loading at that time. Meanwhile, acceleration peaks gradually increased with increased input energy. When the input energy increased to 147 J, the roadway remained stable, but the AC count increased, which indicated that significant damage had been sustained within the rocks surrounding the roadway, and in that case, the roadway almost reached its ultimate shock resistance. As the input energy increased to 176.4 J, the roadway underwent a rockburst, the instantaneous

failure process of which is demonstrated in Figure 10. The results revealed that the sudden energy release from rocks surrounding the roadway can only be triggered when the tremor energy reached a certain value, thus a rockburst occurred.

Under certain geological and stress conditions, the limiting tremor energy of a roadway structure is fixed, while roadway structures under different geological and stress conditions could bear different intensities of tremor [30, 31]. For example, in 492 rockbursts in Yima Coalfield (Yima City, Henan Province, China), most roadways underwent rockbursts when the tremor energy reached 1×10^5 J. Few roadways could bear a higher magnitude tremor. While, in 83 rockbursts in Huating Coalfield (Pingliang City, Gansu Province, China), most roadways suffered rockbursts when the tremor energy reached 1×10^6 J. The frequency and energy of tremors both significantly increase with increasing mining depth [2, 3, 32, 33]. This has resulted in numerous rockbursts being triggered in recent years. For example, before 1950, only two coal mines in China were reported to have suffered rockbursts, and the number increased to 8, 14, and 30 in the 1950s, 1960s, and 1970s, respectively, while there are now more than 170 coal mines in China suffering rockbursts.

5. Conclusions

The research involved both generating behaviors of strong tremors and the triggering criterion for the rockburst. The following conclusions were obtained:

- (1) The high-stress feature in seismic velocity tomographs appeared earlier than the emergence of energy density clouds. Energy density clouds exhibited obvious nucleation characteristics and expanded rapidly and regularly in some local areas that were parts of the high-velocity region, until strong tremors occurred nearby.
- (2) AE activities suggested that the modelled roadway still had significant shock resistance before the dynamic load reaches a certain value. After that, a jump in the AE count at an applied dynamic loading energy indicated the ultimate shock resistance of the roadway was almost reached. The sudden energy release from rocks surrounding the roadway can only be triggered when the tremor energy reached a certain value.

Data Availability

The calculation data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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