Cause Analysis and Control Measures for Roadway Bursting Caused by Mining-induced Tremors of Hard Roof–A Case Study of the Inner Mongolia Coalfield, China

Zhigang Liu\textsuperscript{a,b,c}, Ruoxiang Zhang\textsuperscript{b}, Xikui Sun\textsuperscript{b}, Wenzheng Shang\textsuperscript{a}

\textsuperscript{a} Institute of Mining Engineering, Shandong University of Science and Technology, Tai’an 271019, China
\textsuperscript{b} Shandong Energy Group, Jinan 250013, China
\textsuperscript{c} A Key Laboratory of Deep Coal Resource Mining, School of Mines, Ministry of Education of China, China University of Mining and Technology, Xuzhou 221116, China

\texttt{15865721818@163.com}

Abstract. Rock burst caused by mining-induced tremors is a dynamic disaster in mines that can cause great damage. Based on the mining-induced tremor that occurred at the MKQ Coal Mine, Inner Mongolia Autonomous Region, China, on March 3, 2018, the present paper studies the mechanism of mining-induced tremor occurrence using theoretical analysis, numerical simulation, and focal mechanism. The study found four inferior strata and a primary key stratum in the overlying strata on LW3102, and discovered that upon breaking the key stratum movement releases a large amount of energy thereby causing the mining-induced tremor. When the internal stress of the coal pillar in the air-return way of LW3102 reaches 72.77 MPa, the static load stress concentration appears in the coal body near the air-return way, thereby facilitating easy coal body instability due to the overlay of the dynamic load, which in turn produces the rock burst. Based on the analysis of the moment tensor theory, this study finds the ratio of the moment tensor double couple part (MDC) of the strong mining-induced tremor focal to be 8.91%, indicating that the tensile fracture appears in overlying strata on LW3102, and a large amount of energy is released, thereby inducing the mining-induced tremor. The rock burst of the working face is controlled by applying control measures.

Keywords. mining-induced tremor; rock burst; key stratum; focal mechanism; roof blast; coal pressure-relief
1. Introduction

Mining-induced tremors are dynamic manifestations characterized by violent vibration and destruction, which is caused by the release of energy due to instantaneous instability in high-stress areas of the mine, such as unstable zones of coal, rock, and faults, under external disturbance (e.g., He, X.Q. et al., 2014, Pan et al., 2005). A mining-induced tremor, a natural disaster, is an earthquake induced by mining (e.g., Qi et al., 2014, Jiang et al., 2014, Mark, 2018). At present, rock-burst disasters triggered by mining-induced tremors in China are serious, and more than 177 mines have been affected in China's main coal-producing areas (e.g., Li, 1985, He et al., 2005, Dou et al., 2018, Zhang et al., 1998). Mining-induced tremors (e.g., He, J. et al., 2014, Lan et al., 2012, Cai et al., 2014, Yang et al., 2018) are usually caused by instability of the coal body, activation of faults, and roof breaking; moreover, roof breaking causes a higher rock-burst frequency, which in turn increases the severity of the disaster. Many scholars have researched and made progress in the mechanism and control technologies of mining-induced tremors caused by roof breaking. Overlying strata movement, tremor disturbance, and rock-burst control measures in top-coal caving mining were studied by Li (2018). Also, the energy release of overlying strata fracture and the criterion for interval of roof pre-splitting were considered. Dou (2015) theoretically studied rock-burst energy and stress conditions under dynamic and static combined loads; they hypothesized the theory of dynamic and static combined loads inducing rock bursts and analyzed the dynamic and static load characteristics of a coal mine. Cao (2010) found that the superposition of energies increases the aggregated energy of the coal-rock system, when the energy and stiffness conditions of the system are simultaneously satisfied under the combined dynamic and static load; under these conditions, a rock burst in a coal seam can occur. Jiang (2013) used the theory of the spatial structure of the overlying strata to study the movement regulation of the overlying rock of the fully-mechanized caving face of an asymmetric island and also examined the prediction and evaluation methods of the hard-rock-fracture mine earthquakes. To address the disadvantages of traditional forecasting theories and the nonlinear dynamic feature of mine quakes, Zhou (2002) developed a “cell-mapping-catastrophic forecasting model of mine quake”, based on the cell-mapping theory and catastrophic theory.

Although the aforementioned work regarding the mechanism and prediction of mining-induced tremors and rock bursts has demonstrated considerable progress, mining-induced tremors also exhibit obvious individual characteristics; therefore, studying a particular case is necessary. In this study, a strong mining-induced tremor in the MKQ mine, China, is studied, the causes for the same are analyzed, and targeted control measures are presented.

2. Site characteristics
2.1. General Situation of Working Face

The MKQ Coal Mine, owned and operated by the China National Coal Group Corporation, lies in the southwestern part of the Inner Mongolia Autonomous Region, China. Being the second mining face of MKQ Coal Mine, LW3102 is arranged in the southern limb of the 3-1 coal seam in the No.11 Mining District. Recoverable region length is 5539.3 m and the width is 300 m. The east side of the working face is an unmined coal seam, the west side is the goaf of LW3101, and the width of the isolated coal pillar is 35 m; the south side is close to the mine field boundary, and the protective coal pillar width is 71.8~79.7 m; the north side is an auxiliary air-return way of 3-1 coal, at a distance of 151.2 m from the stop line. The buried depth of LW3102 is 677-707 m, the angle is 1°-4°, and the mining height is 3.85-5.45 m. The mining began on August 10, 2017 and by the end of March 18, 2018, the cumulative length of mining was 860 m and the residual length was 4679 m. The layout of LW3102 is shown in Figure 1.
2.2. Characteristics of Coal and Rock in LW3102

2.2.1. Bursting liability of coal. The results of various indices of coal seam bursting liability are shown in Table 1; The coal seam bursting liability were conducted by following the Chinese national recommended standard GB/T25217.1-2010, which is named “Methods of test, monitoring and prevention of rock burst - part 2: Classification and laboratory test method on bursting liability of coal”. In Table 1, this data indicates that No. 3-1’s coal seam bursting liability is high.

| Duration dynamic failure (DT/ms) | Bursting energy index (K_E) | Elastic strain energy index (W_ET) | Uniaxial compressive strength (Rc/Mpa) |
|----------------------------------|-----------------------------|-----------------------------------|---------------------------------------|
| 53.4                             | 4.33                        | 4.87                              | 53.56                                 |

2.2.2 Bursting liability of rock strata. The rock strata bursting liability were conducted by following the Chinese national recommended standard GB/T25217.1-2010, which is named “Methods of test, monitoring and prevention of rock burst - part 1: Classification and laboratory test method on bursting liability of roof strata.” The bending energy index of the rock roof is 115.2 kJ, which is in the critical range between weak bursting liability and strong bursting liability; our analysis indicates that the bursting liability risk of the rock seam is high.

3. Case study

3.1. Characteristics of Rock Burst
On March 3, 2018, when the length of mining of LW3102 was 810 m, a rock burst occurred in the air-return pathway. Through field investigation, it was found that there was no obvious change in the air-return way, which is 0-30 m ahead of the working face; a single pillar was bent and the timber stack was inclined (a few collapses) in the air-return way which was 120-180 m ahead of the working face, as shown in Figure 2. When the rock burst occurred, the workers felt abnormal air flow in the air-return way and the volumetric air flow rate was reduced from 2100 m³/min to 1820 m³/min.
Fig. 2 Roadway destroyed by strong tremor happened on March 3, 2018

3.2 Data acquisition

3.2.1 Micro-seismic monitoring system. The ARAMIS M/E micro-seismic monitoring system was installed at the MKQ Coal Mine in December 2017. The micro-seismic monitoring system includes two types of sensors: seismometers (numbers start with “S”, NSGA) and probes (numbers start with “T”, GVU). Four seismometer (NSGA) geophones and two probes (GVU) were arranged near LW3102; the layout is shown in Figure 3.
At 19:11:51 p.m. on March 3, 2018, the micro-seismic monitoring system monitored the mining-induced tremor and recorded energy of $1.0 \times 10^7$ J; the corresponding waveform is shown in Figure 4. The elevation of the focus is 701 m (93 m above the roof of the coal seam), the mining-induced tremor is located above the coal pillar of the air-return way of LW3102, and the focus of mining-induced tremor is about 60 m in front of LW3102.

3.2.2 Mine-pressure monitoring system. Hydraulic support in LW3102 is installed with a KJ435 type mine-pressure monitoring system; the installation plan is shown in Figure 5.

On March 3, 2018 from 19:10–19:17 p.m., the mine-pressure monitoring system indicated that the pressure of the hydraulic supports increased significantly from the 64# hydraulic support to 176# hydraulic support and that their stress states increased gradually toward the air-return way. The influence distance was 197.75 m, within the range of hydraulic supports; the data is listed in Table 2.
Table 2 Pressure changes of the hydraulic supports

| Hydraulic support's number | Time       | Pressure before the rock burst /MPa | Pressure after the rock burst /MPa | Change value /MPa |
|---------------------------|------------|-------------------------------------|------------------------------------|-------------------|
| 64#                       | 19:12-19:14| 30.6                                | 33.6                               | 3                 |
| 70#                       | 19:13-19:17| 33.5                                | 35.0                               | 1.5               |
| 76#                       | 19:10-19:17| 33.4                                | 35.4                               | 2.0               |
| 82#                       | 19:10-19:17| 29.6                                | 31.3                               | 1.7               |
| 87#                       | 19:16-19:17| 30.0                                | 32.0                               | 2.0               |
| 94#                       | 19:11-19:17| 34.8                                | 37.0                               | 2.2               |
| 100#                      | 19:12-19:17| 30.6                                | 33.9                               | 3.3               |
| 106#                      | 19:08-19:17| 27.1                                | 29.6                               | 2.5               |
| 112#                      | 19:08-19:17| 27.8                                | 30.1                               | 2.3               |
| 118#                      | 19:16-19:17| 27.2                                | 30.5                               | 3.3               |
| 124#                      | 19:14-19:17| 29.4                                | 33.4                               | 4.0               |
| 130#                      | 19:11-19:17| 29.9                                | 34.7                               | 4.8               |
| 142#                      | 19:11-19:17| 30.5                                | 36.5                               | 6.0               |
| 148#                      | 19:12-19:17| 32.6                                | 40.7                               | 8.1               |
| 154#                      | 19:14-19:17| 38.3                                | 45.1                               | 6.8               |
| 158#                      | 19:10-19:17| 35.1                                | 42.4                               | 7.3               |
| 160#                      | 19:16-19:17| 30.5                                | 34.8                               | 4.3               |
| 164#                      | 19:07-19:17| 29.9                                | 41.1                               | 11.2              |
| 166#                      | 19:08-19:17| 26.8                                | 34.3                               | 7.5               |
| 168#                      | 19:12-19:17| 29.5                                | 42.6                               | 13.1              |
| 169#                      | 19:09-19:17| 29.5                                | 43.8                               | 14.3              |
| 172#                      | 19:13-19:17| 29.7                                | 40.1                               | 10.4              |

4. Cause analysis of the roadway bursting

4.1. Analysis of Overlying Rock Structure in LW3102

The position of the overlying strata key stratum of LW3102 is analyzed based on H033 borehole data (e.g., Cao et al., 2015, Zhu et al., 2017, Zhao et al., 2017), as shown in Figure 6.
(1) The stiffness condition of the key stratum indicates that there are five strata of thick and hard rock in the overlying strata of No. 3-1 coal seam: a) combined hard rock (17.68 m medium sandstone), b) hard rock (18.95 m medium sandstone), c) hard rock (25.00 m siltstone), d) hard rock (45.70 m fine sandstone), and e) hard rock (316.90 m fine sandstone).

(2) The strength condition of the key stratum indicates that the fifth hard-rock stratum (316.90 m fine sandstone) is the primary key stratum, but the other four are all inferior key strata.

(3) Combined with the breaking sequence of adjacent hard-rock strata and primary and secondary key strata, the breaking order is reflected by the list of the five strata, which is in chronological order.

One side of LW3102 is the unmined solid coal seam, and on the other side is the goaf; therefore, the overlying strata show an "F" type spatial structure, as shown in Figure 7 and numerical simulation (Liu et al., 2017) results show that there are hard, unbroken strata above LW3102.
Fig. 7 Numerical simulation result of overlying strata above LW3102

4.2. Stress Analysis of LW3102

Figure 8 is the SZZ-stress distribution cloud map for LW3102 mining to 930 m. Figure 9 is the SZZ-stress curve along the propensity of LW3102 mining to 810 m. The original rock stress of the model was 18 MPa; from the figure, the stress of the coal pillar near the air-return way of LW3102 is observed to rise to 72.77 MPa and the stress concentration coefficient is observed to be 4.04, indicating a high risk for rock burst.

Fig. 8 SZZ-Stress distribution cloud map for LW3102 mining to 810 m: (a) plane stress; (b) profile stress
Figure 10 shows the lead abutment pressure distribution curve of LW3102, with a peak value of 60.01 MPa at about 10 m in front of the coal wall; the stress concentration coefficient of 3.33 is also indicated. The lead abutment pressure is restored to the original rock stress area, about 150 m in front of the coal wall, which is the expected distance of the influence of the lead abutment pressure.

4.3. Analysis of the Focal Mechanism

The location of the tremor’s focus is shown in Figure 11 and six moments S1, S2, S3, S4, T8, and T9 were used to conduct the moment tensor inversion (e.g., Liu et al., 2014, Tape et al., 2012, Riedesel et al., 1989). Further analysis based on the moment tensor theory (e.g., Zhu et al., 2016, Behzad et al., 2008, Jing et al., 2017), ratio of the moment tensor double couple part (MDC) of the strong
Mining-induced tremor is 8.91%, which can be judged that the destruction of rock seam where the focus is mainly tensile fracture and the focus parameters are shown in Table 3.

![Diagram](image1)

(a) The focus plane position

![Diagram](image2)

(b) The focus profile position

**Fig. 11** The distribution curve of the lead abutment pressure

**Table 3** Focus parameters

| ISO    | DC     | CLVD   | Trend   | Dip     | Focus rupture type |
|--------|--------|--------|---------|---------|--------------------|
| 30.67% | 8.91%  | 60.42% | 15.49°  | 180.05° | tensile fracture   |

According to the focus parameters, the direction of the fracture surface is almost perpendicular to the advancing direction of the working face, and the strike slip of the fault has not occurred, as shown in Figure 12.
Fig. 12 Formation of roof failure surface at the site of strong mining-induced tremor. According to the borehole histogram, there exist multilayer thick and hard strata above LW3102; with the continuous advance of LW3102, the area of the joint goaf formed by the goafs of LW3101 and LW3102 is increasing, resulting in the gradual increase of the beam bending degree of the overlying hard rock. When the beam bending of hard rock reaches a certain degree, due to the tensile stress state at the bottom of the overlying rock beam and the simultaneous tensile stress at the highest level in the middle part of the rock beam, the overall stress degree of LW3102 is relatively high, a tensile failure appears on the overlying hard-rock beam; thereby producing strong mine seismic with a large amount of energy.

5. Control measures of roadway bursting

5.1. Roof treatment measures

The roof of the air-return trough is treated via the pre-splitting blasting method with emulsion explosive (e.g., Guo et al., 2016, Liu et al., 2018), the design of the boreholes are shown in Figure 13, and the construction parameters of the blasting boreholes for the emulsion explosive are shown in Table 4.
Table 4 Construction parameters of the blasting boreholes for emulsion explosive

| Name          | Borehole parameter of the working face side (Spacing of each group is 20 m) | Borehole parameter of the pillar side (Spacing of each group is 10 m) |
|--------------|---------------------------------------------------------------------------|---------------------------------------------------------------------|
| Depth of borehole /m | 50 45 50 | 42 30 |
| Angle of borehole /°  | 75 60 35 45 35 35 35 | 24 35 35 35 35 35 35 |
| Length of charge /m   | 32 30 27 24 24 24 24 24 | 18 18 18 18 18 18 18 |
| Sealing length /m     | 18 15 23 18 18 18 18 18 | 12 12 12 12 12 12 12 12 |
| Charge /kg          | 65 60 55 48 24 24 24 24 | 24 24 24 24 24 24 24 24 |

The fracture development of the borehole after blasting is observed via the borehole peeping method and the cracks in the borehole are obviously increased after blasting (Figure 14), which indicates that blasting can easily produce cracking effect in the hard roof.
5.2. Coal body treatment measures

Big-diameter borehole parameters of the coal body: the spacing between big-diameter boreholes is 0.75 m, the borehole’s depth is 20 m, and the borehole diameters are 150 mm. The boreholes are all perpendicular to the coal seam and are 1-1.8 m from the bottom of the roadway. Assuming that the coal quality is hard and accounting for the large-diameter borehole of the coal body, the pressure-relief effect is ensured by blasting the coal body at 6 m intervals, while avoiding big-diameter boreholes. The length of the pressure-relief boreholes for coal blasting is 15 m, the diameter of boreholes is 75 mm, and the charge is 5 kg. The layout of the scheme is shown in Figure 15.

Fig.15 Coal body large-diameter boreholes and blasting stress relief plane diagram (Black represents big-diameter pressure-relief boreholes of the coal body, red represents big-diameter boreholes of blasting)

Using the above pressure-relief technique, the integrity and intensity of coal mass were destroyed and static stress was reduced. Moreover, an artificial “loose and weak structure” (Cao et al., 2015) was formed in the coal seam, which can effectively absorb and scatter seismic energies radiated by strong tremors from high-level key strata.

6. Conclusions

(1) The mining-induced tremor caused support failure of the roadway of about 120-180 m in the advance working face of the air-return way, and the pressure within the 197.75 m scope of the working face increased significantly. The micro-seismic monitoring system measured an energy value of $1.0 \times 10^7$ J, indicating that the influence of the mining-induced tremor is large, which is typically caused by fracturing of the overlying rock.

(2) There exist four inferior key strata and one primary key stratum in the overlying rock of LW3102. Numerical simulation shows that in the process of mining, there exists a large area of suspended state in the key stratum and once the key stratum is broken, a large amount of energy is be released thereby causing the mining-induced tremor.

(3) The stress of the coal pillar of the air-return way in LW3102 reached 72.77 MPa, the stress
concentration coefficient was 4.04, the pressure peak value of LW3102 was 60.01 MPa, and the stress concentration coefficient was 3.33. The stress superposition causes the stress concentration to appear in the coal body of the working face and after accounting for the overlay of the mine dynamic load, the coal body easily loses stability, rupture, and thus causes the rock burst.

(4) Moment tensor theory was used to analyze the tremor and we found that the ratio of MDC of the strong mining-induced tremor focal was 8.91%, which indicates that the tensile fracture appeared in the overlying strata on LW3102 and released a large amount of energy, inducing the mining-induced tremor.

(5) After using control measures such as pre-splitting blasting of roof, big-diameter boreholes of the coal seam, and pressure-relief blasting of the coal seam, the rock burst of working face was effectively controlled.

**Acknowledgement**

This work was supported by “the Fundamental Research Funds for the Central Universities” (2018BSCXC29), and Postgraduate Research & Practice Innovation Program of Jiangsu Province.

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