Characteristics and contributing factors of major coal bursts in longwall mines

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Abstract
Coal burst has become one of the most serious hazards in longwall coal mines of many countries, and extensive studies have been conducted on the mechanism, prediction, and prevention of coal bursts. However, most of these studies focus on qualitative descriptions of burst environments and specific case analyses. Few studies have been carried out to explore knowledge through a number of past coal bursts in longwall mines. The main objective is to quantitatively analyze the current burst-prone conditions in longwall coal mines of China and to summarize corresponding lessons. A database consisting of 54 major coal bursts was established. The characteristics and contributing factors of involved coal bursts were analyzed quantitatively, and high-risk areas that are common in coal mines were then identified. Finally, some suggestions and lessons were proposed. This study may help for identifying controlling factors and high-risk areas at a specific mine, and it might provide insights into the control of coal bursts in longwall coal mines.

Keywords
burst risk, coal burst, contributing factor, geologic structures, longwall mine

1 | INTRODUCTION

The longwall mining technique is a highly productive underground coal mining method, and it is widely used in many countries. Coal bursts (also known as coal bumps or rock bursts) refer to the violent failure of the coal seam, roof, or floor in underground coal mines, and they cause the rapid ejections of broken coal and the abrupt and large deformations of mining face and roadways.¹ The coal burst has become one of the most serious hazards in underground longwall coal mines of China, and it poses a serious threat to the safety of personnel in mines. Therefore, it is of importance to fully understand the conditions and characteristics of past coal bursts so as to prevent coal bursts.
elaststic strain energy in surrounding rock and coal will release, and seismic events generate. When seismic waves encounter the highly stressed coal and rock, the occurrence of coal bursts is possible. Therefore, all coal bursts are accompanied by seismic events, but only a few seismic events could lead to the occurrence of coal bursts. Control techniques of coal bursts can be divided into predictive, preventative, mitigating, protective, and administrative methods. Predictive controls mainly contain risk assessment and risk monitoring. The risk assessment is conducted based on the evaluation of contributing factors, and the overall risk level is then assigned to mining areas. Risk monitoring techniques that are widespread in China include stress monitoring, test drilling, microseismic monitoring, electromagnetic radiation, and seismic velocity tomography. Preventative controls can be implemented by optimizing mine layout and pillars, mining protective seam in multiple seam mining, avoiding gob corners, using yield pillars, and so forth. Mitigating controls are conducted by using dynamically related support systems and destressing techniques, such as destress drilling, water infusion, and roof fracturing. Protective measures, such as physical barriers, protective equipment, and remote-control equipment are used to protect miners from burst events. Previous studies are very helpful for revealing coal burst mechanisms and providing general solutions to coal burst controls. However, existing studies focused on qualitative descriptions of burst environments and the analysis of specific cases. Few studies have been carried out to explore knowledge through a number of past coal bursts in longwall mines. Therefore, it is necessary to quantitatively analyze the burst-prone conditions from a number of recent burst events so that valuable lessons can be learned and targeted preventive measures can be taken.

In this study, 54 major coal bursts that occurred in longwall mines of China over the past 16 years were collected. On the basis of the database, the characteristics of burst conditions were quantitatively analyzed. Subsequently, the controlling factors to these major coal bursts were identified and the high-risk areas were discovered. Finally, this paper presented some lessons from these events and suggestions for preventing such events in the future. The study might provide insights into the identification of potential burst hazards and help for the prevention of coal bursts in longwall coal mines.

2 CHARACTERISTICS OF MAJOR COAL BURSTS

China is one of the countries with the most severe coal bursts in coal mines. As of 2019, the number of burst-prone coal mines had reached 121. Thousands of coal bursts have occurred in these coal mines. Compared with minor coal bursts, major coal bursts attracted more attention, and the relevant information was comprehensive. Therefore, in this study, to quantitatively analyze the burst environments, 54 major coal bursts that caused serious consequences or casualties were constructed from various documents, including investigation reports, published papers, and relevant reports. These events occurred in 38 underground longwall coal mines of China over the past 16 years (from 2004 to 2020). A total of 362 fatalities and 240 injuries were identified, and the total length of destroyed roadways exceeded 8000 m. The database is summarized in Table 1.

2.1 Productive capacity and burst history of involved coal mines

In China, coal mines are categorized into large (>1.2 Mt/a), medium, and small (<0.3 Mt/a) according to the annual productive capacity. It can be seen from Figure 1 that most of the involved mines are large ones with productive capacities ranging from 1.2 to 4.0 Mt/a, and only three are medium mines. In addition, over half of these mines have productive capacities ranging from 0.9 to 2.4 Mt/a. The results indicate that coal bursts are likely to be related to the productive capacity of coal mines. Compared with small coal mines, the mining activities of the involved mines are more intensive. The intensive mining activities provide insufficient time for mined areas to stabilize and, as a result, increase the burst risk. Compared with mines with greater productive capacities (e.g., >4.0 Mt/a), the mining environments of the involved mines are generally more complex. The complex mining conditions are prone to cause stress concentrations and thus increase the burst risk remarkably.

For the involved 38 coal mines, most had undergone many minor or medium coal bursts before these major coal bursts occurred. Only four coal bursts (No. 8, No. 9, No. 12, No. 13) were considered to be the first coal burst in corresponding mines.

2.2 Stage and locations of occurrence

As shown in Table 1, 35 (65%) coal bursts took place during panel extraction, and the roadway (or gate entry) development was associated with 19 bursts (35%). Moreover, the average length of destroyed roadways during panel extraction (189 m) was much larger than that (118 m) during entry development. For the events that occurred during panel extraction, 20 events (57%) affected the gob-side entries, 14 (40%) the solid-side...
| No. | Time      | Province | Coal mine | Period                              | Location                        | Mining depth/m | Destruction length/m | Fatalities/injuries |
|-----|-----------|----------|-----------|-------------------------------------|---------------------------------|----------------|----------------------|---------------------|
| 1   | 2015.5.24 | Shanxi   | Mengcun   | Roadway maintenance                 | Main roadways                   | 720            | 220                  | 0/6                 |
| 2   | 2015.2.22 | Xingjing | Shandong  | 3105 Panel extraction               | Gob-side entry                  | 1000           | 486                  | 10/0                |
| 3   | 2016.6.9  | Hebei    | Hebei     | Roadway development                | Two crossheadings near panel    | 800            | 160                  | 7/5                 |
| 4   | 2015.8.2  | Jilin    | Jilin     | 305 Panel extraction               | Solid-side entry                | 940            | 220                  | 9/12                |
| 5   | 2016.2.6  | Shandong | Shandong  | 1301 Panel extraction              | Protective pillar               | 1010           | 200                  | 21/4                |
| 6   | 2018.10.20| Longtun  | Longtun   | Roadway development                | Drainage roadway and No. 3      | 1050           | 200                  | 20/0                |
| 7   | 2017.2.1  | Shanxi   | Shanxi    | 103 Panel extraction               | Main roadways                   | 940            | 100                  | –                   |
| 8   | 2017.1.11 | Liaoning | Liaoning  | 702 Panel extraction               | Gob-side entry and face         | 1082           | 214                  | 10/1                |
| 9   | 2016.6.25 | Jilin    | Shandong  | 420 Panel extraction               | Main roadways                   | 1050           | 300                  | 7/0                 |
| 10  | 2016.7.25 | Jilin    | Shandong  | 3500 Panel extraction              | Longwall set-up room            | 987            | 300                  | 2/0                 |
| 11  | 2016.7.26 | Xingjing | Shandong  | 570 Panel extraction               | Longwall set-up room            | 680            | 120                  | 4/1                 |
| 12  | 2017.7.29 | Zhaotou  | Shandong  | 3302 Panel extraction              | Mining face and two entries     | 920            | 100                  | 0/2                 |
| 13  | 2015.5.12 | Liaoning | Shandong  | 1601 Panel extraction              | Adjacent set-up room            | 658            | 90                   | 9/0                 |
| 14  | 2015.5.26 | Xingjing | Shandong  | 1601 Panel extraction              | Main roadways                   | 900            | 100                  | 0/6                 |
| 15  | 2015.1.10 | Henan    | Neimenggu | Panel extraction                   | Solid-side entry                | 680            | 160                  | 2/0                 |
| 16  | 2015.1.10 | Henan    | Neimenggu | Panel extraction                   | Solid-side entry                | 586            | 586                  | –                   |
| 17  | 2015.3.24 | Shanxi   | Heilongjiang | Panel extraction | Panel extraction | 525 | 525 | 3/3 |
| 18  | 2015.3.21 | Shanxi   | Heilongjiang | Panel extraction | Panel extraction | 497 | 497 | 5/0 |
| 19  | 2015.3.27 | Shanxi   | Heilongjiang | Panel extraction | Panel extraction | 500 | 500 | 1/3 |
| 20  | 2015.8.2  | Shanxi   | Heilongjiang | Panel extraction | Panel extraction | 1260 | 1260 | 5/0 |
| 21  | 2015.8.5  | Shanxi   | Heilongjiang | Panel extraction | Panel extraction | 1320 | 1320 | 5/0 |

TABLE 1 Summary of major coal bursts
| No. | Time     | Coal mine  | Province | Period                                      | Location                      | Mining depth/m | Destruction length/m | Fatalities/injuries |
|-----|----------|------------|----------|---------------------------------------------|-------------------------------|----------------|-----------------------|---------------------|
| 27  | 2013.1.12| Wulong     | Liaoning | Entry development of 3431B Panel            | Solid-side entry             | 825            | 50                    | 8/0                 |
| 28  | 2012.3.6 | Suncun     | Shandong | Roadway development                        | Roadway                      | 1060           | 30                    | 2/1                 |
| 29  | 2012.3.31| Liangbaosi | Shandong | Panel extraction                           | Main roadways                 | 950            | 130                   | 2/0                 |
| 30  | 2012.12.7| Nanshan    | Heilongjiang | Panel extraction                             | Two gob-side entries          | 500            | 51                    | 0/2                 |
| 31  | 2012.12.10| Zhangshuanglou | Jiangsu | 9421 Panel extraction                      | Main roadways                 | 800            | 60                    | –                   |
| 32  | 2012.11.17| Chaoyang   | Shandong | Entry development of 3112 Panel             | Gob-side entry                | 900            | 112                   | 6/2                 |
| 33  | 2012.10.17| Gushan     | Neimenggu | Panel extraction                            | Solid-side entry             | 350            | 70                    | 0/13                |
| 34  | 2011.4.1 | Chaoyang   | Shandong | 3110 Panel extraction                      | Gob-side entry                | 850            | –                     | 1/5                 |
| 35  | 2011.3.1 | Yuejin     | Henan    | Gushan 069 Panel extraction                 | Gob-side entry                | 1000           | 200                   | 0/3                 |
| 36  | 2011.11.3 | Qianqiu    | Henan    | Entry development of 21221 Panel            | Solid-side entry             | 800            | 380                   | 10/64               |
| 37  | 2010.8.29| Junde      | Heilongjiang | Panel extraction                            | Gob-side entry                | 500            | 85                    | –                   |
| 38  | 2010.8.11| Yuejin     | Henan    | 25110 Panel extraction                      | Solid-side entry             | 1000           | 360                   | 0/2                 |
| 39  | 2010.10.8| Kuangou    | Xingjiang | Panel extraction                            | Ming face and two entries     | 317            | 200                   | 4/1                 |
| 40  | 2009.2.28| Gucheng    | Shandong | Panel extraction                            | Tailgate entry                | 950            | 260                   | 1/5                 |
| 41  | 2008.7.16| Chengshan  | Heilongjiang | Panel extraction                            | Solid-side entry             | 580            | 33                    | –                   |
| 42  | 2008.6.5 | Qianqiu    | Henan    | Panel extraction                            | Solid-side entry             | 736            | 105                   | 13/11               |
| 43  | 2007.8.6 | Yuejin     | Henan    | Panel extraction                            | Entry near stop mining line  | 810            | 40                    | 1/2                 |
| 44  | 2007.6.19| Yuejin     | Henan    | Panel extraction                            | Gob-side entry                | 810            | 380                   | 0/2                 |
| 45  | 2007.5.15| Dongtan    | Shandong | Panel extraction                            | Solid-side entry             | 580            | 150                   | –                   |
| 46  | 2007.12.27| Nantun    | Shandong | Panel extraction                            | Crosscut in panel            | 685            | 50                    | 0/3                 |
| 47  | 2006.9.9 | Huafeng    | Shandong | Panel extraction                            | Gob-side entry                | 1000           | 71                    | 2/2                 |
| 48  | 2006.6.10| Huafeng    | Shandong | Panel extraction                            | Gob-side entry                | 1000           | 170                   | 0/7                 |
| 49  | 2005.2.14| Sunjawan   | Liaoning | Panel extraction                            | Gob-side entry                | 760            | 180                   | 214/30              |
| 50  | 2005.12.12| Nanshan   | Heilongjiang | Panel extraction                             | Ming face and two entries     | 560            | 200                   | –                   |
| 51  | 2005.1.3 | Dongtan    | Shandong | Longwall set-up room excavation of 405 Panel | Longwall set-up room          | 586            | 70                    | –                   |
| 52  | 2004.9.6 | Baodian    | Shandong | Crosscut excavation                        | Crosscut                      | 370            | 60                    | 2/6                 |
| 53  | 2004.6.27| Muchengjian | Beijing | Panel extraction                            | Ming face and two entries     | 720            | 330                   | 1/9                 |
| 54  | 2004.11.30| Jisan     | Shandong | Panel extraction                            | Gob-side entry                | 700            | 100                   | –                   |
entries, 7 (20%) affected the mining face, 5 (14%) the trunk or main roadways, and 3 (8.5%) the nearby crosscuts. For the events that took place during roadway development, 7 (37%) affected the gob-side entries, 5 (26%) the nongob side entries, 3 (16%) the nearby crosscuts, 3 (16%) the longwall setup rooms, and 1 (5%) the main roadways. The results indicate that two gate entries are more vulnerable to coal bursts than the longwall face, and the gob-side entry suffers more than the solid-side entry.

2.3 | Deformation of affected roadways

The deformation of affected roadways by coal bursts is closely related to the support system and the location of roadways. The main deformation forms of affected roadways were roof fall, floor heave, sidewall (rib) convergence, and even close. Because the roadway support was generally weak during development, the main deformation modes of roadways induced by coal bursts during development were roof fall and sidewall convergence. As the supports of gate entries ahead of the mining face were strengthened, the floor became the weakest part, and the main deformation modes of entries during panel extraction were floor heave and sidewall convergence.

For deep-buried roadways, two sidewalls bore large abutment loads, which could generate large shear stress in the floor. As a result, coal bursts (e.g., No. 1) commonly led to large floor heaves. For roadways where the coal was left on the floor, coal bursts (e.g., No. 1, No. 7, No. 26), could cause large floor heaves when coal bursts occurred. For gob-side entries, the barrier pillar carried large lateral abutment loads, consequently, large pillar offsets and sidewall convergences could be observed when coal bursts (e.g., No. 8) occurred. For solid-side entries, two sidewalls sustained large abutment loads, which generated large shear stress in the floor and, as a result, the floor failed and heaved.

3 | CONTRIBUTING FACTORS TO MAJOR COAL BURSTS

3.1 | Mining depth

The mining depth plays an important role in the occurrence and destructiveness of major coal bursts. As shown in Table 1, all major coal bursts in the database took place at depths greater than 300 m, 92% at depths greater than 400 m, and almost half at depths greater than 800 m. From Figure 2A, as the mining depth increased, the number of major coal bursts showed a remarkable increase. Because the mining activities at coal seams at depths larger than 1000 m were administratively limited in the burst-prone coal mines of China, the number of coal bursts decreased when the mining depth exceeded 1000 m. Moreover, as shown in Figure 2B, the average length of destroyed roadways also increased with the mining depth. The results mean that the severity of coal bursts increased with the mining depth as well. This can be explained that as the mining depth increases, the gravitational stress generally shows an increase, and much more strain energy is stored...
in the surrounding coal and rock. As a result, coal and rock have a higher tendency to fail violently. It can be predicted that when the mining depth exceeds a critical value (e.g., 1500 m), it may become the controlling factor for the occurrence of coal bursts.

### 3.2 Strong roof and floor

The strong rock refers to the rock with uniaxial compressive strength larger than 60 MPa. Strong roofs near coal seams played an important function in 34 major coal bursts (61%) in the database. These strong roofs mainly consisted of hard sandstone and conglomerate, and they could be classified into two types. The first type was generally located within 50 m above the coal seam, and its thickness ranged from 10 to 40 m. The second type was far away from the coal seam, but its thickness was usually over 100 m. A total of 21 events (e.g., No. 39, No. 40, No. 23) were closely related to the first type of strong roofs, and 13 events (e.g., No. 17, No. 22, No. 43) were the second type. A total of 22 of these 34 coal bursts occurred during panel extraction, and the remaining 12 events during roadway development. Moreover, the strong roofs were usually the secondary factor to coal bursts during roadway development. The results indicate that the strong roof contributes more to coal bursts during panel extraction than that during roadway development. Besides, the smaller the mining depth, the more remarkable the contribution of strong roof or floor to coal bursts.

Generally, the strong roof has two effects on the occurrence of coal bursts. First, the strong roof cannot readily cave but instead overhang a long distance over the gob, which results in high static stress in the adjacent coal seam. Second, when the strong roof bends, a large amount of strain energy can be accumulated in the bent strong roof. The sudden failure of the strong roof is commonly associated with a large seismic event, which could exert high dynamic stress in the adjacent coal seam.

### 3.3 Geologic structures

Geologic structures, such as faults and folds, have a remarkable influence on the coal bursts. Over half of coal bursts in the database were associated with faults, and at least four events were closely related to folds (anticlines and synclines). Most of the folds result from compressional stresses. The main contribution of folds on coal bursts is that folds could lead to stress concentrations in coal seams and result in coal bursts. Generally, faults have two main effects on the occurrence of coal bursts. First, faults cut coal seams into small blocks, which could lead to stress concentrations in coal seams and even structural instability. For example, the coal burst (No. 2) that occurred in the Xinjulong Coal Mine was closely related to two normal faults. As shown in Figure 3, the 2305S panel was cut by the normal FD6 fault (length: 400 m, throw: 0–10 m, dip angle: 70°) and the normal

![Figure 3](image-url)
FD8 fault (length: 720 m, throw: 10–15 m, dip angle: 70°). The distance between two faults at the 2305S panel was approximately 278 m. Because two normal faults had roughly the same strike, a wedge-shaped graben structure was formed between two faults. As the panel face advanced, two faults were reactivated. The graben structure gradually moved downward, which caused a significant increase in the stress of coal seam and resulted in the major coal burst. Second, the sudden movement of faults, especially large faults, could release a large amount of strain energy and generate seismic waves that exert dynamic stresses in surrounding coal and rock. When seismic waves encounter the highly stressed coal and rock, the occurrence of coal bursts is possible. For instance, a large reverse fault (F16) extends 45 km through the Qianqiu Mine, the Gengcun Mine, and the Yuejin Mine. Its throw ranges from 50 to 500 m, and the horizontal separation ranges from 120 to 1080 m. The F16 fault reactivation induced by mining activities has caused many great seismic events that triggered hundreds of coal bursts in the three coal mines. Generally, the reverse fault results from the compressive stresses that cause the footwall and hanging wall to move toward each other. For the normal fault, the footwall and hanging wall move apart from each other, leading to tension. Compared to the normal fault, the reverse fault may contribute more to coal bursts.

3.4 Change in coal seam thickness

It can be seen from Figure 4 that the seam thicknesses involved in these major coal bursts ranged from 1.5 to 15.0 m, and the number of coal bursts did not increase or decrease with the increase in the coal seam thickness. The results reveal that major coal bursts could occur in coal seams with any thickness, and the seam thickness does not seem to be a dominant factor in coal bursts. However, the sudden change in seam thickness usually accompanies stress concentrations where the burst risk may rise. For instance, as shown in Figure 5, the coal burst (No. 27) occurred when a solid-side entry was being developed in the Wulong Coal Mine. There were no big geological structures near the excavation heading, and the roof and floor were not strong. When the excavation face was approaching the bifurcation of the coal seam, the coal burst took place. The bifurcation of the coal seam was recognized as the controlling factor to this coal burst.

3.5 Island mining

According to the Rule for Prevention and Control of Coal Mine Bursts that was enacted by the National Mine Safety Administration of China, the island panel refers to a panel adjacent to gobs at two and more sides. Island mining refers to extracting an island panel or developing a roadway in areas adjacent to gobs at two and more sides. Since abutment loads transfer from surrounding gobs to the island area, the high-stress concentration is a universal feature of island mining, and small disturbances may result in coal bursts. The island mining contributed to 19 (35%) major coal bursts in the database. Eight events of them took place during entry development in island areas, and eleven events during panel
extraction in island areas. The mining depths for these events ranged from 350 to 920 m, which indicated that the island mining could increase the risk of coal bursts significantly for both shallow and deep mines. For contributing factors to coal bursts in shallow mines, the island mining was usually accompanied by other adverse factors, such as strong roofs and faults. For deep coal mines, the island mining might become the controlling factor to coal bursts.

Two typical events that were closely associated with island mining were analyzed here. The coal burst (No. 14) that occurred in the Zhaolou Coal Mine was mainly attributed to the island mining. As shown in Figure 6, the 1305 longwall panel was surrounded by two gobs of mined panels (1304 and 1306). When this panel was being extracted, its three faces were surrounded by gobs. Therefore, the 1305 panel was a typical island panel. The mining depth in the island panel was approximately 920 m. There were no significant geologic structures, and the roof and floor were not strong. When the coal burst took place, the advancing lengths in the two entries were just 7.2 and 1.6 m, respectively. The primary reason for this event was the high static stress in the coal seam induced by the island mining.

The second example was associated with mining in an island area in the Tangshan Coal Mine. As shown in Figure 7, when the 3654E roadway was being excavated, the major coal burst (No. 3) occurred in two crosscuts near the F5009 panel that had been just extracted. Although two crosscuts were not surrounded by gobs, they were in a protective pillar. The mining depth exceeded 800 m, and most of the area around the protective pillar had been mined out. The stress in the protective coal pillar was highly concentrated.

3.6 Critical pillars

According to previous studies, pillars can be categorized as yield pillars, abutment pillars, and critical pillars. Yield pillars with small widths could yield readily and fail nonviolently. Abutment pillars with large widths are designed to support abutment loads from adjacent gobs, and they can reduce abutment loads on the active panel. Therefore, they can reduce the burst risk. Critical pillars are defined as pillars that are too large to yield nonviolently but too small to resist high levels of abutment loads.

In the database, 14 (26%) coal bursts were attributed to the inappropriate pillar design. Over half of them occurred at depth greater than 800 m, which indicates that unappropriated pillars are more dangerous in deep mines than that in shallow mines. The width-to-height ratios of these bursting pillars ranged from 3.5 to 20.0. Eleven of the fourteen bursting pillars had width-to-height ratios ranging from 3.5 to 10, and only three (No. 11, No. 8, No. 5) had width-to-height ratios larger than 10.0. The three large pillars were designed as abutment pillars.

FIGURE 6 Coal burst in an island panel in the Zhaolou Coal Mine

FIGURE 7 Coal burst in an island pillar in the Tangshan Coal Mine
The mining depths of the three pillars were 987, 1082, and 1010 m, causing high levels of abutment loads. Although width-to-height ratios are larger than 10.0, the three pillars still cannot resist the high levels of abutment loads and they burst. Generally, two types of pillar bursts could be found within these major coal bursts. The first one was related to the barrier pillar between two adjacent panels. For example, as shown in Figure 8, the major coal burst (No. 8) took place at the gob-side entry during the 702-panel extraction in the Hongyang3 Coal Mine. The coal burst killed 10 miners, and the length of destroyed roadways was over 214 m. The mining depth was up to 1082 m, and the pillar was highly stressed owing to abutment loads from the mining face and the lateral gob. The width of gob-side pillar ranged from 31 to 45 m, and the width-to-height ratio was 10–14. The pillar was too large to yield nonviolently, which resulted in the major coal burst. Similarly, the coal burst (No. 5) that occurred in the Longyun Coal Mine was attributed to a critical pillar that was too small to support the abutment loads from gobs.31

The second type of pillar bursts (No. 11, No. 29, No. 31) was associated with pillars between main roadways or pillars between the stop-mining line of panel and main roadways. As shown in Figure 9, the coal burst (No. 11) occurred in three main roadways in the Liangbaosi Coal Mine when the 35001 panel was being extracted. Three roadways were developed in a coal seam. The pillar width ranged 40–50 m, and the corresponding width-to-height ratios ranged from 10 to 15. Since the mining depth in the burst area was nearly 990 m, the pillars were highly stressed after roadways were developed. The controlling factor to this event is the insufficient widths of pillars between roadways. The major coal burst (No. 29) took place at three main roadways when an adjacent panel advanced near the stop-mining line. The insufficient pillar width between the stop-mining line of the active panel and main roadways contributed to this pillar burst. It should be noted that large deformations of pillars between roadways are not allowed. Therefore, pillars between roadways should be designed as abutment pillars rather than yield pillars.

3.7 Mining activities interaction

The interaction between different mining activities accounted for the occurrences of 10 (19%) major coal bursts in the database. For these coal bursts, different mining activities in the same area were conducted simultaneously or in a short time interval. Several common cases are as follows: a gate entry ahead of the mining face was maintained during panel extraction, such as the events (No. 9, No. 8); nearby roadways were excavated during panel extraction, such as the events (No. 40, No. 16); a panel and a nearby panel were extracted simultaneously, such as the events (No. 2, No. 9, No. 4); mining activities in adjacent coal mines could also influence each other, such as the event (No. 34).

As shown in Figure 10, the coal burst (No. 9) took place in the Danshuigou coal mine when two panels in different coal seams (the upper 4203 panel and the under 9202...
panel) were being extracted simultaneously. The vertical distance between two coal seams was approximately 51 m. The 4202 panel beside the 4203 panel had been mined out. The major coal burst occurred in the tailgate (gob-side) entry 60 m ahead of the 4203 panel face where the tailgate was being maintained. The superposition of abutment loads from the under 9202 panel, the upper 4203 panel, and the 4202 gob and the disturbance induced by the entry maintenance resulted in this coal burst. Another example is that a roadway was being excavated while a nearby panel was being extracted. As shown in Figure 11, a gate entry was developed while the 2103 panel was being extracted in the Gucheng Coal Mine. The excavated face and the panel face advanced toward each other. The major coal burst (No. 40) took place when the entry face was 190 m away from the panel face. This event killed two miners and destroyed 200 m long roadways. The interaction between the 2103 panel extraction and the entry development was a primary factor in this coal burst.

3.8 | Remnant pillars in multiple-seam mining

The multiple-seam mining is common in many coal mines of China. Even for shallow mines, overlying isolated pillars in a previously mined seam could cause high-stress concentrations in the under coal seam. Therefore, some remnant pillars left in overlying seams may become a contributing factor to the occurrence of coal bursts. In the database, five (9%) coal bursts (Nos.: 10, 19, 21, 26, 41) were associated with remnant pillars left in overlying coal seams.

For instance, there were 23 coal seams that could be mined in the Junde Coal Mine. The total thickness of these coal seams was approximately 51 m. Many coal bursts have occurred in this mine owing to the multiple-seam mining. The coal burst (No. 26) occurred when a panel face in the 17# seam approached three overlying remnant pillars in the 9# seam. The space between the 9# seam and the 17# seam was approximately 213 m. The 9# seam had been extracted and three pillars were left in this seam. Although the mining depth was only 584 m, a high level of stress concentration was generated in the underlying 17# seam close to these three pillars. Three overlying remnant pillars in the 9# coal seam were recognized as the controlling factor to this coal burst.

3.9 | Bottom coal left in roadways

The bottom coal refers to the coal left on the floor of the roadway, and it is common in thick seams or areas near geologic structures. In the database, nine (17%) coal bursts were associated with the bottom coal. The average depth of sites where these coal bursts occurred exceeded 840 m. In these events, the bottom coal was not the controlling factor. However, it caused large floor heaves, which aggravated the damage degree of coal bursts. The contributions of the bottom coal to coal bursts are as follows. The floor is generally unsupported. Therefore, it becomes the weakest part of the roadway. In addition, since the strength of coal is smaller than that of rock, the bottom coal is more likely to fail violently than rock on the floor under abutment loads in deep mines. As a
result, the bottom coal becomes a contributing factor to coal bursts.

3.10 Other factors

In addition to the factors mentioned above, other factors such as seismic events, crosscuts in panels, and intensive roadways near panels contribute to coal bursts as well. At least 14 (26%) coal bursts in the database were closely associated with seismic events. Seismic events are generally induced by the rupture of a strong roof, the fault slip, and blasting. For example, the coal bursts (No. 2, No. 36) were attributed to dynamic loads induced by fault slips, the coal bursts (No. 18, No. 13) the rupture of the strong roof, and the coal burst (No. 53) the blasting. Besides, 11 major coal bursts in the database were associated with crosscuts in panels or intensive roadways near panels. For instance, two events (No. 2, No. 13) took place when mining faces approached crosscuts in panels.

4 HIGH-RISK AREAS AND LESSONS FROM THE DATABASE

4.1 High-risk areas

According to the quantitative analysis of 54 major coal bursts, the following high-risk areas were identified.

1. The burst history is a significant indicator for identifying high-risk areas and predicting future bursts. (a) If coal bursts have occurred in a coal mine, the adjacent mines with similar mining conditions may suffer from similar bursts. (b) If a coal mine has undergone a type of coal burst, the risk of similar coal bursts in this mine will be very high. (c) For a panel, if a coal burst takes place during entry development, the probability of coal bursts during panel extraction will increase greatly.

2. If there is either a strong roof with a thickness greater than 10 m in the first 50 m above the mining seam, or a strong roof with a thickness greater than 100 m in the first 200 m above the mining seam, the risk of coal bursts will be significant during panel extraction.

3. Multiple faults cutting through panels and large reverse faults close to panels may become the controlling factor to major coal bursts. The high-stress concentration generally occurs in the hinge zone of the fold where the burst risk is high.

4. Island mining is usually the controlling factor to major coal bursts in deep mines.

5. Pillar bursts commonly occur in deep mines when the width-to-height ratio of pillars ranges from 3.5 to 20.0. These pillars include barrier pillars between two panels, pillars between main roadways, and protective pillars between the stop-mining line of a panel and adjacent roadways.

6. When a roadway is about to break through, the area near the pillar between two driving faces has a high burst risk. Five coal bursts (Nos.: 6, 10, 28, 47, 51) occurred when involved roadways were about to break. For these events, the pillars between two driving faces were 3, 22, 40, 18, and 2 m, respectively.

7. The bottom coal left in roadways could increase the burst risk significantly in deep mines.

8. Two gate entries are more vulnerable to coal bursts than the longwall face, and the gob-side entry suffers more than the solid-side entry.

9. Erosional channels or intrusive rocks could change the thickness and properties of the coal seam, causing stress concentrations. Besides, the sudden change in coal seam thickness and the bifurcation of coal seam are generally accompanied by a sharp change in stress. The burst risk may rise significantly in areas where erosional channels, intrusive rocks, and bifurcations of coal seam appear.

10. The position where the shape of panel changes, the vicinity of crosscut in the panel, and the vicinity of remnant pillars are high-risk areas in coal mines.

4.2 Lessons and suggestions

1. Mine layout

   - The burst history is a significant indicator for future coal bursts. The detailed analysis of past coal bursts could help identify high-risk areas, optimize the mine layout and then avoid future coal bursts.
   - When predominant burst-prone conditions exist, the effect of destressing measures on mitigating coal bursts may be very limited. The best way to mitigate the coal burst risk is to avoid mining in these areas.
   - In addition to avoiding island mining, critical pillars, mining activities interaction, remnant pillars in gobs, and bottom coal left in roadways, measures need to be taken to fracture the strong roof timely in shallow mines and to limit the mining intensity in deep mines.
   - Main roadways are generally used for many years, so they should be preferentially arranged in the rock rather than the coal seam.

2. Monitoring

   - The situ stress is an important factor that should be considered for the mine layout, and more in situ
(initial) stresses tests are needed in burst-prone coal mines.

- In addition to the stress monitoring in the coal seam, the online monitoring of three-dimensional stresses in the roof is suggested to monitor the stresses and the cantilever of the strong roof. Once the roof overhangs for a large distance, some fracturing controls can be taken to fracture the roof in time.

- Effective monitoring measures are needed to determine the influential scope and level of mining activities. In this way, the minimum distance between two activities sites and the minimum time interval between two activities in the same area can be determined to avoid the mining activities interaction.

- Many coal bursts had precursors, such as abnormal variation of seismic events (No. 11), dynamic phenomena during drilling holes (No. 3), and large deformations of entries (No. 9, No. 16). Unfortunately, these precursors did not attract special attention. Therefore, abnormal monitoring data and field phenomena should be valued in high-risk areas.

3. Destressing technique

In the past few years, presplitting blasting, roof cutting blasting, and hydraulic fracturing have been increasingly used in China. However, mine operators are still unclear about how to determine key parameters, such as the diameter, length, and space of blasting holes and the amount of explosive. Therefore, effectiveness evaluation methods with respect to these de-stressing measures are necessary to optimize the distressing time and key parameters.

4. Roadway support

Bolts and cables were broken owing to excessive tensile stress during many coal bursts in the database, which indicates the support resistance is weak. In contrast, during some coal bursts, the bolts and cables did not break but fell together with the roof, which means that the lengths of bolts and cables are insufficient. Therefore, the support of roadways should be strengthened in areas with high burst risk.

Field investigations of coal bursts showed that a nonclosed support system commonly led to a large floor heave and a rigid support structure might cause roadways or entries to be completely closed. Therefore, the roadway support should be enclosed and flexible in high burst risk areas, especially the areas where the bottom coal is left on the floor.

The main roadways are generally used for many years. The surrounding mining activities could increase the loads acting on the support, and the resistance of the support structure decreases with time. Therefore, the roadway support should be regularly reinforced to ensure the safety of the main roadways.

5 | CONCLUSIONS

1. More major coal bursts (65%) occurred during panel extraction than that (35%) during roadway development. Moreover, coal bursts during panel extraction were more destructive. By contrast, two gate entries were more vulnerable to coal bursts than the longwall face, and the gob-side entry suffered more than the solid-side entry.

2. The mining depth seems to be a controlling factor that influences the number and severity of major coal bursts in longwall mines. In addition, 61% of major coal bursts in the database were associated with the strong roof, 55% the fault, 35% the island mining, 26% the critical pillar, 19% the mining activities interaction, 17% the bottom coal left in roadways, and 9% the overlying remnant pillars in multiple-seam mining. Besides, the coal seam thickness does not appear to be a controlling factor in major coal bursts.

3. The burst history in a coal mine is a significant indicator for future bursts in the coal mine and adjacent coal mines. In addition, if a coal burst took place during entry development, the probability of coal bursts during panel extraction will increase greatly.

4. The following areas with high burst risk were identified: coal seams close to a strong and massive roof, areas that are cut by multiple faults or near large faults, deep island regions, areas beneath overlying remnant pillars, pillars with a width-to-height ratio of 3.5–20 in deep mines, roadways that are affected by multiple mining activities, deep roadways with bottom coal and unclosed support system, and a narrow pillar between two driving faces.

5. Detailed analyses of past coal bursts are suggested. Methods for evaluating the effectiveness of destressing techniques are needed. In addition, the enclosed, strong, and flexible support system should be used in high-risk areas, especially areas where the bottom coal exists.

The built database could act as a reference for relevant research. This study might help fully understand the burst-prone environment and optimize the mine layout. This paper only analyzed 54 major coal bursts in longwall mines of China. Further studies are still necessary to build and analyze a larger database containing a number of minor coal bursts.
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CONFLICT OF INTERESTS
The authors declare that there are no conflict of interests.

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REFERENCES
1. Brauner G. Rockbursts in Coal Mines and their Prevention. A.A. Balkema; 1994.
2. Iannacchione AT, Zelanko JC. Occurrence and remediation of coal mine bursts, a historical review. US Department of the Interior, U.S. Bureau of Mines, January 1995:27-68.
3. Mark C, Gauna M. Evaluating the risk of coal bursts in underground coal mines. Int J Min Sci Technol. 2016;26:47-52. doi:10.1016/j.ijmst.2015.11.009
4. Lannacchione A, Tadolini SC. Coalburst Causes and Mechanisms: Proceedings of the Coal Operator's Conference, Wollongong, Australia, 10-12 February; 2016.
5. Calleja J, Nemcik J. Coalburst Causes and Mechanisms: Proceedings of the Coal Operator's Conference, Wollongong, Australia, 10-12 February; 2016.
6. Zhang M, Jiang F. Rock burst criteria and control based on an abutment-stress-transfer model in deep coal roadways. Energy Sci Eng. 2020;8:2966-2975. doi:10.1002/esce.201900215
7. Yan Y, Wei S, Li K. Inverse analysis of dynamic failure characteristics of roadway surrounding rock under rock burst. Energy Sci Eng. 2021;9:2298-2310. doi:10.1002/esce.201900215
8. Iannacchione A, Tadolini SC. Coal Mine Burst Prevention Controls: Proceedings 27th International Conference on Ground Control in Mining; 2008:20-28.
9. Jiang Y, Zhao Y, Wang H, Zhu J. A review of mechanism and prevention technologies of coal bumps in China. J Rock Mech Geotech. 2017;9:180-194. doi:10.1016/j.jrmge.2016.05.008
10. Mark C. Coalbursts that occur during development, a rock mechanics enigma. Int J Min Sci Technol. 2018;28:35-42. doi:10.1016/j.ijmst.2017.11.014
11. Wang P, Jiang L, Zheng P, Qin G, Zhang C. Inducing mode analysis of rock burst in fault affected zone with a hard-thick stratum occurrence. Environ Earth Sci. 2019;78:467. doi:10.1007/s12665-019-8448-0
12. Zhang C, Canbulat I, Hebblewhite B, Ward CR. Assessing coal burst phenomena in mining and insights into directions for future research. Int J Coal Geol. 2017;179:28-44. doi:10.1016/j.coal.2017.05.011
13. Mark C. Coal bursts in the deep longwall mines of the United States. Int J Coal Sci Technol. 2016;1:1-9. doi:10.1007/s40789-016-0102-9
14. Li T, Cai M, Cai M. A review of mining-induced seismicity in China. Int J Coal Mech Min. 2007;44:1149-1171. doi:10.1016/j.ijrmms.2007.06.002
15. Jiang L, Kong P, Zhang P, et al. Dynamic analysis of the rock burst potential of a longwall panel intersecting with a fault. Rock Mech Rock Eng. 2020;53(4):1737-1754. doi:10.1007/s00603-019-02004-2
16. Wei C, Zhang C, Canbulat I, Cao A, Dou L. Evaluation of current coal burst control techniques and development of a coal burst management framework. Tunn Undergr Space Technol. 2018;81:129-143. doi:10.1016/j.tust.2018.07.008
17. Zhang Q, Wang E, Feng X, Wang C, Qiu L, Wang H. Assessment of rockburst risk in deep mining, an improved comprehensive index method. Nat Resour Res. 2021;30(2):1817-1834. doi:10.1007/s11053-020-09795-0
18. Wang S, Hao S, Chen Y, Bai J, Wang X, Xu Y. Numerical investigation of coal pillar failure under simultaneous static and dynamic loading. Int J Rock Mech Min Sci. 2016;84:59-68. doi:10.1016/j.ijrmms.2016.01.017
19. Cai W, Dou L, Gong S, Li Z, Yuan S. Quantitative analysis of seismic velocity tomography in rock burst hazard assessment. Nat Hazards. 2015;75:2453-2465. doi:10.1007/s11069-014-1443-6
20. Pan Y, Xiao Y, Li Z, Wang K. Study of tunnel support theory of rockburst in coal mine and its application. J China Coal Soc. 2014;39(2):222-228.
21. Kaiser PK, Ca M. Design of rock support system under rockburst condition. J Rock Mech Geotech Eng. 2012;4:215-227. doi:10.3724/SP.J.1235.2012.00215
22. Koniecz P, Soucek K, Stas L, Singh R. Long-hole destress blasting for rockburst control during deep underground coal mining. Int J Rock Mech Min. 2013;61:141-153. doi:10.1016/j.ijrmms.2013.02.001
23. Fan J, Dou L, He H, et al. Directional hydraulic fracturing to control hard-roof rockburst in coal mines. Int J Min Sci Technol. 2012;22(2):177-181. doi:10.1016/j.ijmst.2011.08.007
24. Guo W, Zhao T, Tan Y, Yu F, Hu S, Yang F. Progressive mitigation method of rock bursts under complicated geological conditions. Int J Rock Mech Min. 2017;96:11-22. doi:10.1016/j.ijrmms.2017.04.011
25. Qi Q, Li Y, Zhao S, et al. Seventy years development of coal mine rockburst in China, establishment and consideration of theory and technology system. Coal Sci Technol. 2019;47(9):1-40.
26. Hu S, Tan Y, Ning J, Guo W, Liu X. Multiparameter monitoring and prevention of fault-slip rock burst. Shock Vib. 2017;229:7580109-7580160. doi:10.1155/2017/7580109
27. Pan J. Mechanism of Burst Start-Up of Rock Burst and its Application. Dissertation. China Coal Research Institute; 2015.
28. Lu C, Yang L, Zhan N, Zhao T, Wang H. In-situ and experimental investigations of rockburst precursor and prevention induced by fault slip. Int J Rock Mech Min. 2018;108:86-95. doi:10.1016/j.ijrmms.2018.06.002
29. Liu G, Mu Z, Karakus M. Coal burst induced by rock wedge parting slip, a case study in Zhaolou coal mine. Int J Min Reclam Envr. 2017;32:1-15. doi:10.1080/17480930.2017.1280745
30. Zhu S, Yu F, Jiang F, Liu J. Mechanism and risk assessment of overall-instability-induced rockbursts in deep island longwall panels. Int J Rock Mech Min. 2018;106:342-349. doi:10.1016/j.ijrmms.2018.02.005
31. Li D, Zhang J, Sun Y, Li G. Evaluation of rockburst hazard in deep coalmines with large protective island coal pillars. Nat Resource Res. 2021;30(2):1835-1847. doi:10.1007/s11053-020-09755-8
32. Alber M, Fritschen R, Bichoff M, Meier T. Rock mechanical investigations of seismic events in a deep longwall coal mine. *Int J Rock Mech Min*. 2008;46(2):408-420. doi:10.1016/j.ijrmms.2008.07.014

33. Koehle JR, DeMarco MJ, Wuest WJ. Critical pillar concept in yield-pillar-based longwall gate-road design. *Min Eng*. 1996;48:73-78.

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