Review of Chinese coal burst experience and analysis of microseismic data from Australian mines

CSIRO-UNSW AGREEMENT 2016020449

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CSIRO Report No. EP167887

December 2016
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1 Introduction

An ACARP project C25004 entitled “REVIEW OF AUSTRALIAN AND INTERNATIONAL COAL BURST EXPERIENCE AND CONTROL TECHNOLOGIES” has been granted in 2015. This project is led by Prof Ismet Canbulat of UNSW with participation from several organisations including CSIRO, Strata Control Technologies, Golder Associates, and University of Pittsburgh. The overall aim of this project is to develop preliminary coal burst control guidelines for Australian coal mines. This objective will be met by (i) conducting an international review of coal burst practices, (ii) reviewing Australian coal burst experience, (iii) reviewing the international and local established and/or experienced failure mechanisms, (iv) identification of recommended coal burst control technologies, and (v) evaluation of control technologies against the Australian experience, regulations, mine design and operational practices.

CSIRO’s tasks in this project are:

1. Comprehensive review of the experience in China on outburst research and practice
2. Analysis of CSIRO’s microseismic and geotechnical monitoring data for Australian coal mines.

This report describes the work done by CSIRO to address the two tasks listed above.

2 Review of the study on the mechanism, prediction and prevention technologies of coal burst in China

This chapter presents and summaries the key findings achieved in the past five years in China, including the characteristics and classification of coal burst, mechanisms of coal burst induced by the geological conditions, prediction and prevention technology of coal burst. It is revealed from these investigations that the characteristics of coal burst occurrence is a non-linear dynamic process of steady accumulation and rapid release of elastic strain energy. Based on site specific mine design, burst patterns and inducing factors, coal bursts can be classified into three categories: (1) coal burst induced by material failure, (2) coal burst induced by coal seam slippage along bedding planes (3) coal burst induced by tectonic structure instability. The microseismic and mining-induced pressure systems could be employed to capture the precursory information of coal burst occurrences. Energy absorption support equipment, new type of bolts with constant resistance and greater elongation, multi-stage and high strength support systems are used effectively to prevent and control coal bursts. Optimised mine design and roadway support also play a key role in coal burst prevention and risk control. These significant research efforts in China were systematically discussed for better understanding and controlling of coal burst and providing the essential foundation of deep mining research.

2.1 Background

Deep mining conducted under unfavourable stress redistribution and concentration could lead to a sudden and violent failure of a coal seam, release cumulated elastic energy and expel a large amount of coal and rock into the roadway or working face where workers and machinery are present (Jiang et al., 2012; 2015). The occurrence of this phenomena is recognized as coal burst which has been a major safety concern in underground coal mines around the world for more than fifty years. This phenomenon can cause fatalities,
injury and significant economic losses for the coal mining industry. Since the mining depths exceed 1000m, both the frequency and severity of coal bursts has increased rapidly in China. Coal bursts occurred in 32 coal mines in 1985 while more than 147 coal mines at the end of 2014 were experiencing coal bursts. Some serious cases including the Chengshan coal burst incident of Jixi mining district in 2008, the Yuejin coal burst incident of Yima mining district in 2010 and the Qianqiu coal burst incident of Yima mining district in 2011. All have resulted in significant economic losses and serious casualties.

Since the first coal burst incident occurred in UK in 1738, global experts started research work with the goal to analyze the mechanism and prevention techniques of coal bursts. In 1915, the South African coal burst research committee was established to study rock burst in both coal and metal mines. The Czechs started intensive research along with Poland since the first domestic coal burst in 1912. To date, researchers have proposed numerous theoretical models with respect to the mechanism of coal bursts, including the strength theory, stiffness theory, energy theory, and the bursting liability theory etc. These different theories can be generally divided into three categories: (1) based on the nonlinear fractal theory, mechanical properties coal and rock masses. The damage characteristics of coal seam and the development and occurrence of coal burst were investigated; (2) based on the study of tectonic characteristics around burst-prone zones, the relationship between fault and fold structure, geometry of the surrounding rock; (3) based on mining method, the relationship between engineering disturbance, mining activities and the occurrence of coal bursts.

In China, research into coal bursts was initially carried out in 1960s and great achievements were obtained in both forecast and prevention techniques of coal burst. In 2009, Ministry of Science and Technology of China launched a National Basic Research Program (973 Program) project, entitled "Fundamental research on mechanism and prevention of coal mine dynamic disasters at great depth". In the course of the project between 2010 and 2014, the following key scientific issues were highlighted; (1) geological conditions and quantitative methods to analyse coal bursts (2) properties and engineering behaviour of discontinuous rock masses under the dynamic loading (3) time-spatial distribution of mining-induced stresses and accumulated elastic strain energy (4) prevention and control technology of coal burst. These issues were systematically discussed to better understand and control coal bursts and to provide the essential foundation for deep mining research.

Based on the large amount of theoretical, experimental, numerical and field test studies, some of the achievements are summarized in this report to highlight the characteristics and classification of coal bursts, mechanism of coal burst induced by unfavourable tectonic structure, prediction and prevention technologies of coal bursts.

2.2 Characteristics and classification of coal burst

Large mining voids are formed when employing the longwall mining method, a widely employed mining method in coal mines in China. The surrounding rock mass experiences significant disturbance during the extraction of longwall panel, which leads to large deformation and stress redistribution. Furthermore, the dynamic engineering activities and rapid unloading could induce the sudden release of concentrated stress and accumulated elastic energy leading to the occurrence of a coal burst. Due to the requirement in the field of mining engineering and rock mechanics, many researchers began to generalize the characteristics and classification of coal burst since the 1930s. The following coal burst characteristics are identified:

Type 1: Suddenness. There are no obvious macro precursors. Coal burst can happen in a very short time;

Type 2: Complexity. It is difficult to determine the time, place and intensity before the occurrence of coal burst;
Type 3: Harmfulness. Coal burst will cause casualties, roadway failure and equipment damage in the underground opening;

Type 4: Inductivity. The other dynamic disasters including outburst and explosion of gas and roof or floor water inrush could be induced by the occurrence of coal burst.

The traditional classifications of coal burst are numerous. Pan et al. (2003) divided the coal burst into the rock compression type, roof fracture type and fault reactivation type. He et al. (2005) classified coal burst into single energy induced type and compound energy induced type in the mining space where the transformation and accumulation of elastic energy take place. Qian (2014) pointed out that the coal burst could be subdivided into the sliding mode coal burst resulting from fault-slip and strain mode coal burst resulting from the failure of the rock masses. These different classifications can be generally divided into three categories: (1) according to the position of the occurrence of coal burst, it can be divided into coal seam burst, roof burst and floor burst; (2) according to the sources of pressure, it can be divided into the gravity type, tectonic type and gravity-tectonic type. However, the characteristics of deformation and failure of the underground opening in coal industry, hard rock mining and civil engineering are different. The tunnels in civil should not experience large deformation or failure since the consideration of long-term service. In contrast, the roadways in coal mines, especially in the longwall panel, are temporary underground openings where relatively excessive deformation or even failure is permissible for the short-term service. Therefore, as shown in Figure 1, Jiang et al., (2014) pointed out that the characteristics of coal burst occurrence is a non-linear dynamic process of steady accumulation and rapid release of elastic strain energy. Based on site specific mine design, burst patterns and induced factors, coal bursts can be classified into three categories as listed below.

Type 1: Coal burst induced by material failure

Due to rapid propagation and penetration of material fractures, the occurrence of coal burst will take place when the concentrated stress reaches the strength of surrounding rock strata and coal seam, resulting from the excavation of a roadway or longwall panel.

Type 2: Coal burst induced by coal seam slipping

Slip dislocation induced coal burst means results from the influence of mining activities, since stiffness disparity exist between the roof strata and coal seam or between the floor strata and coal seam, the coal bursts will be induced by the coal seam slipping under the disturbance of mining activities.

Type 3: Coal burst induced by tectonic structure instability

Since elastic energy has accumulated in the tectonic structure over geological time, a sudden fault or fold instability could lead to the occurrence of coal burst when the roadways or longwall panels were excavated.

Figure 1 The scheme of classification of coal burst. (a) Coal burst induced by material failure; (b) Coal burst induced by coal seam slipping; (c) Coal burst induced by tectonic structure instability
It is revealed from coal mining practices that the degree of damage in underground constructions caused by the second and third type of coal burst are greater than that caused by the first type of coal burst. For instance, the coal burst incident in Qianqiu coal mine was induced by the F16 fault structure instability in Yima Mining District. Therefore, coal bursts induced by tectonic structure instability have been a major concern in deep underground coal mines where the surrounding rock strata and coal seam are under high in-situ stresses. These aspects will be discussed in detail in Section 3. In addition, due to the high-stress concentration, the second and third types of coal burst also occur more frequently during the extraction of island longwall panels, recoveries of coal or rock pillars, coal mining under the condition of hard roof.

### 2.3 Factors contributing to the occurrence of coal burst

As discussed above, the coal burst is associated with the tectonic structure, island longwall panels, coal or rock pillar recoveries, hard roof, and the increase of mining depth and mining intensity. Actually, the bursting liability of coal seams, which is an inherent material property, plays a significant role in the occurrence of coal bursts during the extraction of roadway or longwall panels. According to the statistics obtained from coal mines where coal bursts frequently occur (Jiang, 2014), 75% of the coal seams with bursting liability have experienced coal bursts, while 29% of these coal seams have high bursting liability. Based on theoretical, experimental, numerical and field test results, a review of the research achievements of coal burst induced by the geological conditions including the bursting liability, tectonic structure (mainly refers to faults), island longwall panel and hard roof are presented in this section.

#### 2.3.1 Relationship between the bursting liability and the coal burst

*Experimental study on the relationship between maceral components and bursting liability*

As shown in Figure 2, it was revealed from the current findings of scanning electron microscope (SEM) experimental study (Jiang and Zhao, 2009) that the occurrence of coal burst was influenced by not only the unstable propagation of cracks, but also by the macerals components in the coal. Generally, the microstructure features of coal specimen can be determined by the three parameters: $d_{002}$, the interval space of aromatic layer; $L_c$, the average thickness of microcrystalline laminas; and $L_a$, the diameter of aromatic layer. These three parameters are calculated by the formula (1):

![Figure 2](image-url)

*Figure 2 The microstructure features of coal specimen recovered from XinZhouyao coal mine after the occurrence of coal burst (Magnification: ×3000). (a) shear crack; (b) tensile crack*
\[
\begin{align*}
\xi &= \frac{\lambda}{2\sin\theta_{02}} \\
\xi &= \frac{0.94\lambda}{\beta_{02}\cos\theta_{02}} \\
\xi &= \frac{1.84\lambda}{\beta_{02}\cos\theta_{02}}
\end{align*}
\]  

(1)

where the \( \lambda \) is the wave length of X ray.

The formula \( \xi = (L_0 - L) / L_0 \) can be defined as the bursting liability indices of coal specimen to determine the magnitude of the burst proneness of a coal seam. And it was found (Jiang and Zhao, 2009) that a high degree of the occurrence of coal burst corresponds to a high \( \xi \) value.

Based on the experimental study of acoustic emission monitoring (AE), X-ray computerized tomography (CT) and scanning electron microscope (SEM) under uniaxial compression loading condition, Zhao and Jiang (2010) suggested the precursory information of coal burst in terms of the microstructure observed by employing the synchronized experiment system. The bursting liability indices including failure duration index (\( D_t \)) and strain energy storage index (\( W_{ET} \)) indicated that the coal seam is characterized as a dynamic brittle material with high coal burst proneness in hazardous conditions. As presented in Figure 3, although the SEM results show that there are some micro cracks in the coal specimen, the CT images indicate that no visible macro fractures are observed. Therefore, the coal seam with high burst proneness is a dense material and a relatively high value of 0.9 \( \sigma_c \) (\( \sigma_c \) is the uniaxial compressive strength) can be recognized as the stress precursors for the failure of burst-prone coal specimen under uniaxial compression, as shown in Fig.3. It is revealed that the prediction of coal burst is quite challenging due to its violent and sudden occurrence.

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**Figure 3** Experimental results of uniaxial compression test, AE, CT and SEM on specimen recovered from Zhaogezhuang coal mine

**Mechanism of fracture propagation in coal specimen with bursting liability**

Zhao et al. (2013) pointed out that investigation of stress concentration of coal seams subjected to different loading conditions is important in understanding the mechanism of fracture propagation in coal specimen. In practice, the scanning electron microscope (SEM) investigations were conducted to present the fracture propagation of coal specimen recovered from Zhaogezhuang coal mine using the three-point beam bending tests under quasi-static and dynamic loading. It was found from the test results that the crack propagation calculated by the propagation velocity was a nonlinear variation process due to the heterogeneity of coal specimen. Moreover, Figure 4 presents the representative three-dimensional fracture surfaces of coal
specimen under quasi-static and dynamic loading conditions. It can be reflected from this figure that the specimen fracture surface roughness is higher under impact loading than that under quasi-static loading, which suggested greater energy release under impact loading.

![Image](image1)

**Figure 4** Representative three-dimensional fracture surfaces of coal specimen under quasi-static and dynamic loading conditions. (a) under quasi-static loading conditions; (b) under dynamic loading conditions

In order to further investigate the influence of the inherent bedding fracture properties in coal specimen on the mechanism of coal burst, dynamic indirect tensile test (Zhao et al., 2014) were conducted by using the Split Hopkinson Pressure Bar (SHPB) to impact the coal specimen recovered form Xinzhouyao coal mine. Numerical simulation, which is entitled as Distinct Lattice Spring Model (DLSM) method, was also incorporated in this study to better understand the influence of different bedding structures on the dynamic strength of coal. The numerical model was established by using the 3D reconstruction technology based on the detailed bedding structure data provided by X-ray micro CT experimental study. From the comparison between the experimental and numerical results, as shown in Figure 5, it can be seen that both the roughness and discontinuous condition of the bedding and the bedding direction are important in the analysis of the dynamic indirect tensile strength. Therefore, the occurrence of coal burst are strongly influenced by the bedding properties including the roughness, discontinuous and directional conditions of coal seam and surrounding rock strata during the construction of underground openings.

![Image](image2)

**Figure 5** The failure patterns of the coal specimens with different bedding angles predicted by the DLSM and the SHPB test. (a) Bedding plane model; (b) Rough bedding plane model; (c) Discontinuous rough bedding plane model; (d) SHPB test
2.3.2 Investigation on the mechanism of coal burst induced by fault structure

3D map technologies of the fault structure in deep coal mining

The detection of fault geometry and structure characteristics plays a significant role in the study on the fault reactivation which is the dominant factor inducing the occurrence of coal bursts. The 3D seismic integrated interpretation technique (Du et al., 2015; Peng et al., 2008; Li et al., 2015) e.g. the technologies of seismic detection, high-resolution seismic image, seismic data merging process, three-dimensional visualization and seismic inversion, is employed to investigate the distribution of primary fault structure in deep coal mining. Figure 6 presents the seismic interpretation results of a horizontal section of coal seam and vertical section of surrounding rock strata in Guqiao coal mine. It can be seen from these figures that the primary fault geometry is complex due to geological evolution. The coal seam and surrounding rock strata could be subdivided into normal area, influenced area near the fault and the primary fault area experiencing large deformation and severe damage.

![Figure 6](image)

**Figure 6** The seismic interpretation results of fault zone in Guqiao coal mine. (a) horizontal section of coal seam; (b) vertical section of surrounding rock strata

Relationship between the coal burst and fault reactivation

It is indicated from the previous studies (Jiang et al., 2014) that coal bursts occur frequently in the shaft region of syncline structure and the reverse fault area where the horizontal compressive stress is concentrated. For example, based on the study of geological data in Yima coal mine area (Lv, 2013), F16 fault structure was detected by using the 3D seismic integrated interpretation technique and reconstructed in three-dimensional numerical model, as seen in Figure 7.

![Figure 7](image)

**Figure 7** Tectonic structure and 3D-numerical reconstruction of F16 reverse fault in Yima coal mine. (a) Fault structure; (b) 3D-numerical reconstruction of F16 fault.

The frequent occurrence of coal burst in Yima mining area (e.g. the Qianqiu coal burst incident in 2011) could be explained as a phenomenon induced by integrated effect of the intensive mining-induced pressure and compressive stress arising from F16 reverse fault reactivation process during the coal mining, as shown
in Figure 8 (a). According to the monitoring results of electromagnetic radiation (EMR) and hydraulic support resistance (Lv et al., 2014), longwall support resistance and EMR always experience sharp increase and sudden decrease before the coal burst accidents occur (see Figure 8(b)). Therefore, the increase and decrease of EMR or support resistance could be identified as the precursory information of coal burst.

![Figure 8](image1.png)

**Figure 8** Schematic diagram of fault reactivation (a) fault reactivation process; (b) monitoring results of EMR or support resistance

To better understand tectonic stress distribution of F16 reverse fault, two-dimensional physical model was established to study the process of fault reactivation during the extraction of longwall panel (Wang et al., 2016). Figure 9 presents the distribution of the tectonic stress monitored at fault plane. It is indicated that the mining-induced pressure experiences a multi-stage variation during the coal seam mining, including slight increase, gradual increase, gradual decrease, sharp increase, succeeding stabilization, and sharp decrease. Since the fault slip is a nonlinear dynamic process of steady accumulation and unsteady release of stress or even elastic strain energy, the mining-induced pressure behaves violently in the fault-influenced zone, Therefore, the sharp increase and succeeding stabilization of stress could be identified as the precursory information of fault slip. This conclusion is consistent with the monitoring result of EMR and support resistance.

![Figure 9](image2.png)

**Figure 9** Distribution of the tectonic stress and schematic images of the fault reactivation simulated by the physical study
2.3.3 Investigation on the mechanism of coal burst induced by island longwall panel mining

Coal burst occurs more frequently in an island longwall panel, which is surrounded by previously mined panels, than in other longwall panels due to its high-stress concentration. Therefore, the study of coal burst in the island longwall panel is of significant importance in terms of coal mine safety and productivity. Wang et al. (2013) investigated the relationship between the distribution of mining-induced pressure of island longwall panel and the geological conditions including mining depth, mining height, material anisotropy and tectonic stress. In particular, numerical simulations were conducted to understand the distribution of abutment pressure in front of the mining face during the roof periodic weighting with advancement of the island longwall panel. It can be seen from the Figure 10 that the peak abutment stress occurs at the intersection of the mining face and roadway. The location of this peak stress region moves forward with the occurrence of each roof periodic weighting. Therefore, it is implied that coal burst was most likely to occur at the intersection of the mining face and roadway.

![Image: Plastic state and Vertical stress](image)

**Figure 10 The abutment stress of the island mining panel during periodic weighting**

The investigation on the influence of goaf symmetry on the abutment pressure is of significance to assess the coal burst risk of island longwall panel (Pang, 2013). Figure 11 shows the compared results abutment pressure distribution with respect to the different type of island longwall panel.

Coal or rock pillar instability is most likely to induce the coal burst since the stress concentration in the elastic core in the centre of pillar (Wang et al., 2011). Figure 12 presents a gradual decrease of the size of the pillar elastic core accompanied with the development of stress-strain curve during the gradually loading process. Because the coal pillar width is accordance with the size of the elastic core, the risk of coal burst in a coal pillar with a large width is greater than that of a coal pillar with a small width.
2.3.4 Investigation on the mechanism of coal burst induced by the failure of hard roof

Since the hard roof strata, especially the thick sandstone roof strata, is liable to sharply accumulate elastic strain energy due to the mining activities, coal burst could occur when the sudden failure of hard roof takes place in the deep coal mining field. Based on the dynamic theories, Zhu et al. (2014) proposed a mechanical model of hard roof which is considering the dynamic parameters including inertial force, inertial moment and roof rotational acceleration. Figure 13 presents the characteristics of roof deformation with the variation of rotational acceleration due to the gradual hard roof movement. It can be seen from the results that the roof deformation increases sharply when the rotational acceleration reaches a certain value. It is indicated that the sudden movement of roof strata could induce sharply release of elastic strain energy.
Figure 13 Characteristics of roof deformation with the variation of rotational acceleration

Similarly, Lu et al. (2010) stated that the sudden failure of hard sandstone roof is a significant factor contributing to the occurrence of coal burst. The characteristics of low frequency microseismic events can be identified as the precursory information of coal burst. Zhao et al. (2012) pointed out that the instantaneous release of accumulated energy in hard roof is the major factor inducing the coal burst.

2.4 Multi-parameter monitoring and prediction technologies of coal burst

Some significant achievements of prediction technologies of coal burst were obtained in China in the past ten years. To date, these prediction technologies have the components of traditional prediction method and geophysical prediction method, which will be discussed respectively in this section. The traditional prediction method, e.g. drilling cuttings method, borehole stress measurement and mining-induced pressure monitoring, is widely employed in most of coal mine in China because of their advantage of low-cost and operability. The geophysical prediction method consists of electromagnetic radiation, micro-seismic method, seismic CT technology and charge induction technology.

2.4.1 Traditional prediction technologies of coal burst

Although the drilling cuttings method is a traditional method of coal burst, the influence area of concentrated stress could be effectively determine by the change of drilling cuttings quantity and the dynamic phenomena in the borehole drilling process. According to the prediction and prevention criterion of coal burst in China (Ministry of Coal Industry, 1987), a larger quantity of drilling cuttings extracted from the borehole with the diameter of 41-50 mm is in accordance with a higher degree of stress state. Therefore, the assessment of coal burst risk could be conducted according to the degree of stress concentration. Figure 14 presents a representative variation of drilling cuttings obtained from Xinzhouyao coal mine (Lu, 2012).
2.4.2 Integrated prediction system of micro-seismic and mining-induced pressure

Based on the geophysical detection theories, Jiang et al. (2011) and Liu et al., (2014) developed the integrated prediction system which is a modern multi-parameter prediction technology to conduct the integrated detection of micro-seismic and mining-induced pressure with respect to coal burst. Considering the requirement of real time precursory information of time-spatial-strength in terms of coal burst, micro-seismic and mining-induced pressure should be detected in real-time to investigate the variation of storage energy and stress state of surrounding rock strata, as shown in Figure 15. By employing this system, the relationship of seismic energy and damage degree of surrounding rock strata is established. In addition, the real-time assessment of coal burst risk could be conducted from global zone to local zone in the mining area, as shown in Figure 16.

Figure 14 Representative variation of drilling cuttings obtained from Xinzhouyao coal mine (a) borehole drilling; (b) drilling cutting curve

Figure 15 Schematic diagram of the integrated detection of micro-seismic and mining-induced pressure
2.4.3 Distributed micro-seismic monitoring system of coal burst

The distributed micro-seismic monitoring system is another geophysical prediction method of coal burst, which is proposed by Dou et al. (2012; 2014) and Cai et al., (2014a; 2014b). Based on the establishment of this system, the multi-dimensional information identification, potential seismic sources determination and maximum and total equivalent stress detection could be conducted for the prediction of coal burst. Based on the distributed micro-seismic monitoring system, the factors of microseismic time, space and intensity could be comprehensively considered in the same monitoring area to assess the coal burst risk. In addition, the long-distance mining-induced microseismic of the whole coal mine could be automatically detected in real time by this monitoring system to determine the occurrence time and position of seismic events with energy of greater than 100 J.

Therefore, the stress source type of coal burst could be accurately located and assessment of coal burst risk could be reasonably evaluated through the distributed micro-seismic monitoring system. Figure 17 presents the schematic diagram of this system.
2.4.4 Electromagnetic radiation (EMR)

The electromagnetic radiation system is another method widely used in coal mine to assess the coal burst risk. As numerous investigations have shown (He et al., 2007), there is a relationship between the dynamic failure of rock and coal and the EMR intensity and impulse measured during the specified time. According to this prediction method, the coal burst could be classified into three levels including no, weak and high degree by which the prevention methods can be selected.

2.5 Prevention technologies of coal burst

Based on the understanding of mechanisms of coal burst, some significant prevention technologies and equipment of coal burst were effectively developed to prevent fatality, injury and machinery damage for the coal mining industry through the persistent efforts of numerous scientists in China over the last decade. These technologies and equipment are summarized as the follow sections.

2.5.1 Prevention of coal burst based on the mining design optimization

According to the coal mining practices, a reasonable mining design in the early age of coal mine could effectively avoid the occurrence of coal burst (Jiang et al., 2015). However, as discussed in the previous section, due to the high-stress concentration, coal burst occur more frequently during the extraction of island longwall panel, recoveries of coal or rock pillar, coal mining under the condition of hard roof. The existence of these unfavourable conditions is inevitable in some coal mine since their complicated geological conditions and limited mining technologies. Therefore, the mining design optimization, e.g. protective seam mining design, non-pillar mining design, development layout, roadway design with large width and pre-excavation of the pressure-relief roadway, is of significance for the prevention of coal burst.

2.5.2 Prevention of coal burst based on the pressure release theories

Since coal burst occur more frequently in the zones with high stress concentration, stress release could effectively eliminate the burst risk before the advancement of longwall mining face. Some effective pressure release technologies, e.g. pre-drilling boreholes, borehole blasting, coal seam water infusion, stress release slot and forced roof caving, were widely used in coal mine (Jiang et al., 2012). Figure 18 shows the schematic diagram of borehole stress release process and the relevant equipment employed in Xinzhouyao coal mine. The effect of borehole spacing on stress relief is presented in Figure 19. The numerical results suggested that the abutment stress could be released by boreholes of various lengths and spacing. The modelling results predicted that the effectiveness of stress relief increased with borehole length. The results also show that the stress will decrease with an increase in borehole spacing.
2.5.3 Prevention of coal burst based on the energy absorption supporting theories

Pan et al. (2014; 2013) developed a series of energy absorption support equipment, e.g. energy absorption components, energy absorption bolts, energy absorption hydraulic frame and the foam alloy material, to enhance the support resistance of surrounding rock masses. The major idea of energy absorption support equipment is to improve the supporting stiffness and provide the large deformation space in short time by the means of increasing the damping coefficient, which could realize the absorption of elastic strain energy in the process of the deformation of surrounding rock masses. Figure 20 presents the schematic diagram of energy absorption hydraulic frame.
2.5.4 **Prevention of coal burst by using the bolts with constant resistance and large elongation**

The traditional bolts could not be subjected to the deformation of larger than 200 mm and the impact loading arising from coal burst. To overcome this disadvantage, innovative research was conducted by He et al. (2014a; 2014b; 2014c) to develop a new type of bolt which could provide constant high resistance of 115 KN and extraordinarily large elongation of 1000 mm. This type of bolt has a key component of cone-like piston installed in an elastically-deformable sleeve pipe, as shown in Figure 21, which could generate constant frictional resistance when the cone body slides relative to the internal surface of the sleeve pipe. Therefore, this bolt has been wildly employed under complicated geological conditions with high in situ stress or even the soft rock properties. The working principle and the performance comparison between new type bolt and other bolt employed in China and abroad are presented in Figure 22.

**Figure 20** Schematic diagram of the energy absorption support equipment (a) energy absorption hydraulic frame; (b) deformed energy absorption components

**Figure 21** Schematic diagram of the bolts with constant resistance and large elongation
Figure 22 Schematic diagram of the working principle and the performance of the new type bolt (a) the working principle; (b) performance comparison between new type bolt and other bolts

2.5.5 Prevention of coal burst by employing multi-stage and high strength support system

Yima mining district have suffered severe coal bursts in the past decade since the increasing mining depth and unfavourable tectonic conditions. The multi-stage and high strength support system have been proved to be an effective method for the maintaining of stability of surrounding rock masses by the large amount of coal burst prevention experience. The multi-stage support system consists of three support stage with progressive enhanced support strength (Zhang, 2015), including the first stage under bolts support, the second stage under bolts incorporated with U36 steel arch support and the third stage under bolts combined with O-shaped steel arch and rectangle-shaped hydraulic support. Figure 23 shows the design layout and field application of the multi-stage and high strength support system in Yima mining district.

Figure 23 The design layout and filed application of the multi-stage and high strength support system in Yima mining district

2.5.6 Prevention of coal burst based on the strict management system

The strict operation procedure of mining and roadway support plays a significant role not only in maintaining coal mining production, but also in improving safety. Therefore, the safety precautions in the operational procedure should be strictly conformed to, e.g. working in the protective clothing, installation of impact absorber in roadway and reasonable mining sequence of longwall panels. Figure 24 shows the schematic images of impact absorber installed in roadway and men working in the protective clothing.
Figure 24 Schematic images of (a) impact absorber installed in roadway; and (b) men working in the protective clothing

2.6 Conclusions

Based on the large amount of theoretical, experimental, numerical and field test studies financially supported by the National Basic Research Program, the characteristics and classification of coal burst, mechanism of coal burst induced by the unfavourable tectonic structure, and prediction and prevention technologies of coal burst are discussed in this section. The main conclusions drawn from the investigations are summarized below.

(1) The characteristics of coal burst occurrence are a non-linear dynamic process of steady accumulation and rapid release of elastic strain energy. Based on site specific mine design, burst patterns and induced factors, coal bursts can be classified into three categories: as coal burst induced by material failure, coal burst induced by coal seams slipping and coal burst induced by tectonic structure instability.

(2) The coal burst is induced frequently by the coal type (with violent bursting liability), unfavorable tectonic structure, extraction of island longwall panel, recovery of coal or rock pillars, hard roof, the increase of mining depth and mining intensity. The mechanisms of coal burst induced by these factors was discussed.

(3) The precursory information of the coal burst occurrence could be captured using the traditional prediction technologies, integrated prediction system of microseismic and mining-induced pressure and the distributed micro-seismic monitoring system.

(4) Coal burst could be effectively prevented by the innovation equipment development in China, e.g. the energy absorption support equipment, the new type of bolts with constant resistance and large elongation and the multi-stage and high strength support system. However, mining design optimization, strict operational procedures and roadway support will not only help maintain coal mining production but also ensuring mining safety.
3 Coal burst monitoring using microseismicity

3.1 Burst mechanisms and microseismicity

It is widely accepted that high stress is the primary factor to create burst-prone conditions. The stress can come from many sources. The overburden loading above the seam being mined plays a key role for the overall level of stress when deeper coal is mined. The horizontal tectonic stress is another factor to influence the stress regime. Underground excavation removes confinement stress to the roadway coal/rock mass. The induced abutment stress near the excavations stacks on the static stresses and increases the stress level. The migration of stress due to mining progress and a sudden breakage of roof or floor rock mass will also change the stress regime near the excavation.

It is known that rock/coal formation near the excavation deforms and fractures associated with the stress development, before an explosive-like coal burst actually occurs. These dynamic processes must be accompanied by seismic finger prints that should be observed using modern microseismic monitoring techniques.

The previous researches were mostly based on back analysis of data from coal burst events that had already occurred. Knowledge about coal/rock weakening processes leading to the final failure is still very limited, due to lack of monitoring data collected nearby a burst and before its occurrence.

Microseismicity manifests the change of rock condition under stresses, and it has been recognised as a potential tool to capture precursory events leading to a burst. Underground miners experienced rock talking and bumping during roadway development and coal mining, and they have used the sounds to assess the safety of their working environment. These sounds are generated by stress release and cracking inside the coal/rock mass that radiate seismic energy (Obert and Duvall, 1957; Hardy 1971).

Attempts to measure microseismicity for delineating and predicting rockbursts can be traced back to 1938 (Obert and Duvall, 1957; Antsyferov, 1966). In 1961, a three-dimensional array of seismometers was used underground in South Africa to study the seismicity of a mine working face at a depth of about 2.5 km (Cook 1963).

The microseismic information used for coal burst investigation can be summarised into following categories:

- **Seismicity** – The number of seismic events against a specific time interval. A sudden increase or decrease in seismicity indicates a significant change in the stress regime.
- **Event origin time and location** – The event distribution and its development may reveal stress condition changes. They are obtained from seismic arrival times.
- **Energy** – The seismic energy reveals energy release at a seismic source. It is obtained from waveform amplitude.
- **Fracture mechanisms** – It tells whether the source is associated with tensile, shear or both failures.

These seismic parameters have been used at many mines around the world for coal/rock burst monitoring. Although many microseismic projects have provided useful results about coal/rock fracturing characteristics, their correlation to a coal burst is still inconclusive.

3.2 CSIRO microseismic research – understanding ground responses to mining

CSIRO pioneered microseismic monitoring for longwall coal mining. Since its first microseismic monitoring project at Gordonstone Mine in Central Queensland, CSIRO has carried out microseismic research at more than 30 coal mines in Australia and overseas, for mining risk management and production control. Although the microseismic projects conducted by CSIRO did not aim at the coal burst issues, the results from these studies have significantly revealed microseismic signatures associated with different types of rock fractures.
and patterns associated with underground coal mining. These findings and experience are very valuable for coal burst study.

### 3.2.1 General microseismicity vs LW mining

Strata fracturing patterns and their development produced by longwall coal mining are of interest to mining engineers to understand longwall caving processes. The strata weakening information can be used to infer stress condition and distribution near the working face for risk management and production control.

Before microseismic monitoring was introduced into longwall coal mining by CSIRO in 1994, stress information associated with the mining was estimated using numerical modelling. Extensometers and stress meters were also used to address this issue but they could only provide data at individual locations. Microseismic monitoring uses geophones deployed around a longwall panel to remotely capture seismic waveforms that are radiated from a fracture source. Inversion of the waveforms allows the fracture location and mechanisms to be obtained. It becomes a unique tool to obtain ground truth associated with mining over a large area. Microseismic understanding of stress concentration and strata fracture development is very useful for estimation of coal burst prone areas and prediction of an impending burst event.

### 3.2.2 Case study – microseismic patterns at Gordonstone Mine

In 1994, a microseismic monitoring experiment comprising 27 triaxial geophones was carried out at Gordonstone Mine located in central Queensland (Hatherly et al. 1997). The objective of the project was to evaluate the efficiency of microseismic monitoring techniques for mapping longwall fracture patterns induced by the coal mining. At this mine the German Creek Seam of 3 m in thickness was being mined about 240m below the ground surface. The microseismic results have shown that in planview, with exception of few events nearly all of the events occurred within the longwall panel being actively mined and there is a symmetrical concentration of events on the tailgate side and maingate side with a noticeable decrease in the central part (Figure 25). On the vertical cross section (Figure 26), approximately 80% of the events are located above the seam and concentrated near the two gateroads.

Gordenstone Mine was not a coal burst prone mine and the microseismic results obtained at the mine has presented the general fracture patterns and stress conditions for such a longwall mine condition.

![Figure 25 Locations of three geophone boreholes (A, B and C) and distributions of 629 seismic events in planview of longwall panel 103 at Gordonstone Mine.](image-url)
3.2.3 Microseismicity and roof weighting:

**Case 1 – Prediction of initial caving at Southern Colliery LW703**

The correlation between microseismicity and longwall initial roof caving was studied at Southern Colliery in 1998 (Kelly et al. 1999). One of the project objectives was to investigate whether microseisms can provide certain precursory information about the first longwall caving. The microseismic monitoring system comprised 15 triaxial geophones deployed in two deep boreholes and on the ground surface. An extensometer consisting of 20 measurement anchor points was also installed in a borehole located in the centre of the panel and 25 m from the start line to observe the process of roof collapse during the first 50 m of mining.

Figure 27 shows the relationship between the microseismicities and the displacements of the extensometer anchors in the first week mining. The first period of microseismicity occurred when the face was about 10m from the extensometers (Kelly et al. 1998). There was no movement indicated by the extensometers at this time. However, the seismic event locations indicated that the majority of the events occurred in front of the face. The second period of seismicity was associated with the time when the face advanced under the extensometers. The anchor closest to the coal seam started to move. Seismicity during other periods was associated with significant roof movement as indicated by the extensometers.

It appears that the first period of seismicity was the precursor of the first roof displacement and the second seismicity was the precursor of the significant roof caving occurred about 16 hours later.

**Figure 26** Projection of all events on vertical cross sections looking northeast. A failure zone is confined using dashed lines. GC denotes the German Creek Seam being mined.
Case 2 – Prediction of roof weighting at Southern Colliery LW704

A microseismic investigation of the process of heavy roof reaction to the progress of the longwall mining was conducted at longwall panel 704 (LW704) at Southern Colliery (Luo et al. 2000). The German Creek Seam was mined some 140m below the ground surface. The immediate roof strata of the mine are composed of massive sandstones that had resulted in heavy weighting at the longwall face and damaged the longwall face supports at longwall 702.

The microseismic system used in this project comprised 20 triaxial geophones with five deployed in each of four deep boreholes (Figure 28). Unfortunately, the chock-pressure monitoring system installed by the mine was not functioning, so the only information about weight on the chocks was from the deputy’s reports.

During the monitoring period, there were 15 roof weightings recorded in the Deputy’s Reports. However, the weightings were all reported within a working shift without detailed information on when the weighting was actually observed. Figure 28 shows the positions of the weighting events, each one drawn as a line at the end-of-shift face position.

Figure 28 Planview of seismic locations (black dots) and roof weighting events (color lines in the panel) at LW704 Southern Colliery.

Seven weightings (47% of the total recorded weights) were found to be associated with a similar microseismic pattern. In general, the microseismicity associated with roof weighting can be characterised by three periods. In the first period, the number of microseismic events increased sharply within about 2 hours. The peak seismicity could reach up to 2 times above the normal microseismic level. This was followed by the second period, with a significant drop in number of seismic events occurring over about 3–4 hours. In the third period the seismicity returns to background seismic level (Figure 29).

As the precise time when the roof weighting was observed is unknown in the Deputy’s Reports, it is not clear to which section of the seismic curve a roof weight should correspond. However, the peak seismicity occurs always at the start period of a shift. It is assumed therefore that the roof weightings observed at LW704 should occur after the peak of seismicity. If this is the case, the big change in microseismicity can be recognized to be a precursor before a roof weighting.
Case 3 – Prediction of roof weighting at Austar Mine

Cyclic weighting can result in production delays and this has happened in many deep mines with strong roof strata. In 2011, an investigation was undertaken at Austar Mine using integrated microseismic and stress monitoring systems to understand strata units contributing to the loading cycles and precursory information for the weighting events (Shen et al. 2013). Austar Mine mined the Greta Seam of 6 m thickness at a depth of approximately 520 m using the Longwall Top Coal Caving mining method.

The microseismic monitoring network includes a ground surface array and an underground array, comprising seven triaxial geophones. The stressmeter system also consists of a ground surface array and an underground array with six stressmeters in total.

The monitoring results have demonstrated that a correlation between the integrated microseismic and stress meter data and roof weighting events. A ‘Combined Trigger Index’ was developed based on microseismic and stress data to predict the weighting events (Figure 30). It has been found that for all the weighting events observed, a rate of successful warning of up to 83% was achieved (Shen et al. 2013).

3.2.4 Microseismicity for partially confined condition

Case study – roadway stability at a NSW mine

The process of roof rock deformation and breakage prior to and during a roof failure in a roadway was investigated using an integrated monitoring system consisting of displacement, stress and microseismic monitoring (Shen et al. 2008).
The microseismic system was an HMSi integrated seismic monitoring system manufactured by ESG (Canada). It was modified to allow both microseismic (sampling at 40kHz) and acoustic emission (sampling at 40MHz) signals to be recorded.

The monitoring results have shown that roof displacements started when the approaching longwall face was more than 30m away from the monitored location. The displacement continues to increase as the longwall face approached and crossed over the sensor location. As the longwall face passed the location by more than 20m, the roof finally collapses.

The roof weakening processes were manifested by microseismic results obtained in the roadway area, although most of the seismic events detected actually occurred in the longwall panel, and are not directly related to the roof failure mechanisms. Figure 31 shows the microseismicity and a typical seismic resonance frequency change recorded by this experiment. The results showed that the seismicity increase significantly before the roof collapse. The seismic resonance frequency presented a decreasing characteristics prior to the roof fall.

![Resonant frequencies decreasing](image)

Figure 31 Microseismicity and seismic resonance frequency obtained in the roadway area where the experiment was carried out. In the figure the measured roof displacement and stress results are also shown (red solid line—horizontal stress; other solid lines—roof displacement).

**Characteristics of seismic signals**

As different types of rock failure mechanisms generate different seismic waveforms, recorded seismic waveforms can be used to infer the types of source where the seismic energy is generated. Figure 32 shows an implosive event in the middle of the panel obtained at LW704 at Southern Colliery. All of the first particle motions of the geophones deployed around this event point towards the source direction. A conceptual interpretation of this implosive event is shown in Figure 33.
Figure 32 Planview of an implosive source (red sphere) recorded at LW704 at Southern Colliery. A, B, C and D are borehole locations. In each of the holes 7 triaxial geophones were installed. The red arrows indicate the first particle motion directions obtained the geophone locations.

Seismic waveform themselves can also tell the story about the source. Figure 34 shows the waveforms associated with a brittle fracture while the waveforms shown in Figure 35 are related with a slow fracturing event. Seismic waveforms associated with gas or steam injection into an open fracture can be seen in harmonic characteristics (Figure 36). Seismic events leading to a coal burst may have their own waveform characteristics. Unfortunately, there has been no seismic events occurring adjacent and prior to a coal burst were documented.
Figure 34 A high frequency event associated with brittle rock fracturing.

Figure 35 A low frequency event associated with 'slow rock fracturing'.

Figure 36 Seismic waveforms associated with gas injection into an open fracture.

3.3 Discussions and suggestions

3.3.1 Seismic location and seismicity

Microseismic monitoring is used in coal mining to monitor the response of the coal/rock system to the development of roadway that may lead to coal burst. Event location is seen as a key parameter in understanding whether events are located at the working face or distant from the face along burst prone
zones. Microseismicity provides useful information about ground stability near a burst prone area, in particular whether there is an increase in ground failure events in certain locations around a burst prone zone.

In previous studies, a sudden increase in microseismicity has been found to have a certain relationship with a roof fall or weighting event. This relationship should also be applied to coal burst processes.

However, there has been no successful case that was reported in open literature about microseismic prediction of a coal burst and the reasons have not been investigated. After review of the microseismic data obtained from CSIRO and reports from open publications, several reasons are proposed in the following:

- **Different seismic characteristics**

  Longwall mining creates enormous rock fractures along roadways and across the longwall panel. Microseismic events associated with longwall caving process may have accounted for more than 90% of the recorded events. Although the total seismicity of the caving events provides information about the change of stress regime and damage scale of coal/rock mass of the whole longwall panel, they may not accurately reflect local coal/rock condition that may form a coal burst prone zone. The normal caving events and those with coal burst development may have different seismic characteristics.

Therefore, it is recommended to characterise different types of microseismic events associated with the different seismic groups. Study of seismicities of non-normal caving events may help with coal burst related seismicity analysis.

- **Monitoring strategy**

  A microseismic system used for a coal mine monitoring normally consists of a geophone network with a number of geophones installed in the ground, spacing at 50-100m. In order to obtain the 4D pattern of seismicity, the seismic signals must be recorded by four or more geophone stations. The system used is commonly operated in a trigger mode, based on short-time averages (STA) and long-time averages (LTA) algorithm. When at least four stations experienced a STA/LTA ratio greater than the set threshold, the system is triggered and the event recorded. This approach was developed for underground mines where there has been a focus on larger events leading to hazard identification.

  However, near excavations, the unconfined environment can generate a seismic event with smaller energy than fully confined condition. In addition, the coal/rock mass can be highly fractured because of blasting, mining, destressing and weathering. Fracturing mechanisms near the excavations may significantly attenuate the seismic signals that travel through it over a distance and a small seismic event may not be strong enough to trigger 4 geophones.

  A study conducted by CSIRO has shown the value of continuous data in order to detect weak events that were recorded by 1-2 nearby geophones and have a better comprehension of the rock mass damage close to the sensor locations near unconfined rock surface at an open pit (Figure 37). The strong events recorded by 4 or more geophones on that day are sparsely distributed in the pit. However, the weak events recorded at individual geophone sites clearly show extensive fracturing occurred at S10 and S13 that cannot be seen from strong seismicity.

  It is suggested that the weak seismic events can be as important as the strong seismic events for rock stability assessment and they should not be ignored in a microseismic monitoring project. The design of a microseismic network for coal burst monitoring should consider capturing both the strong and weak events, using both triggered and continuous recording modes.
3.3.2 Seismic energy and intensity

It has been established that seismic events induced by mining radiate seismic energy from as little as $10^6$ J for microseismic events to as much as $10^9$ J for large rockbursts and bumps (Cook, 1963; Blake et al., 1974) corresponding to seismic magnitudes of -6 to 5 (Gutenberg and Richter, 1956).

Seismic energy is normally obtained from calculation of seismic waveform amplitudes, after correction of seismic attenuation over the transmission distance. The energy of one event or accumulative energy of a group of events can be used for estimation of energy release in the coal/rock mass at the event location. This parameter of seismic energy has been used in earthquake study for inferring the scale of stored energy. The seismic intensity reveals the density of induced fractures within a specific volume of coal/rock mass. It is used to infer rock mass deteriorate processes. Both the energy and intensity have been used for coal/rock burst study. When these two parameters are used for coal burst investigation, attention must be paid on the uncertainty of their determinations.

First of all, the seismic energy is only a portion of the total energy released from a rock fracture. The percentage of the total energy that is converted to the seismic energy is very difficult to obtain because of limited knowledge about source mechanisms and geology details. Secondly, the energy calculation is based on the selection of waveform sections. Tensile, shear or both failures generate very different types of waveforms. Seismic anisotropy due to laminated strata and principal stress orientation can cause the S-waves to split. These changes make it difficult to find an algorithm that can handle these differences. The third challenge is the inconsistence of seismic responses of used geophones. Unlike seismometers used in earthquake study that can be calibrated routinely, geophones cannot be easily calibrated and its seismic responses may vary from each other. This response inconsistence leads to certain errors in the energy determination.

Although seismic energy and intensity cannot be determined accurately, they still provide useful information about the source and the condition of its surrounding coal/rock mass. It is advised to use these parameters in conjunction with other monitoring information for coal burst monitoring and prediction.
3.3.3 Seismic source mechanisms leading to coal burst

Different types of seismic waveforms associate with different rock failure mechanisms. It is not clear about what seismicity characteristics are possibly associated with coal burst, and what seismic characteristics are detectable that can be used as precursor for coal burst. It is necessary to study coal/rock failure mechanisms contributing to coal bursts and investigate the dynamic processes and their possibly associated microseismicity.

This research may need a collaboration of researchers in rock mechanics, numerical modelling and geophysics. It is important to understand the characteristics of coal burst related microseismicity, such as seismic intensity, energy, frequency range and possible waveform patterns that are crucial for design of a microseismic monitoring system for capturing precursory coal burst events more efficiently.

Acknowledgements

Prof Hongwei Wang from China University of Mining Technology (Beijing) has provided significant information on the literature review of Chinese experience. His assistance is very much appreciated.

References


