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Causality mechanism of coal bump occurred in longwall roadways

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Abstract Coal bump occurring in longwall roadways accounts for more than 87% of total coal bump events. However, there is no practical mechanical model that can explain the causality and process of coal bump, resulting in that the prediction and prevention of rockburst heavily depend on engineering experience or lessons. Considering the mechanical characteristics of surrounding rock, the suspended roof behind working face and stress state of the rib coal, a seesaw structure model related to incentive of the coal bump and a mechanical model related to instability of rib coal block are established in this paper based on theoretical analysis and numerical calculation, which is capable to clarify the causality mechanism, process, key factors and critical state of coal bump. The hard suspended roof behind the working face produces periodic abutment pressure on the coal around the working face. The result of numerical calculation shows that, under the condition of high compressive stiffness of hard coal around the working face, the roof in front of the working face rebounds upward. The phenomena of roof rebound suggests that the overlying strata of the working face form a seesaw structure. In the area of roof rebound, the normal stress on the roof-coal interface is reduced. Stress analysis of a rib coal block has been conducted. Result shows that, the tectonic stress perpendicular to the rib can overcome the fractional resistance pushing the rib coal into the roadway once the normal stress on the roof-coal interface de-stresses to a certain level. Accordingly, a critical state equation of coal bump has been established. It can be concluded that, de-stressing of the roof-seam interface caused by roof rebound triggers coal bump. The tectonic stress is its force source, and the tensile strength of coal and the shear strength of the coal seam with roof and floor are bump resistances. This study clarifies the causality mechanism and process of coal bump occurred in longwall roadway that provides a theoretical basis for prediction and prevention technology.

Keywords Coal bump, burst mechanism, abutment pressure, roof rebound, roof-coal de-stress;, fractional slippage

1 Introduction

Coal bump, or coal burst, rock burst, is a type of violent geological disaster that is described by sudden and rapid destruction of coal mass around the roadway or a coal pillar, causing casualties and significant economic loss. The first reported coal bump event occurred in the South Stafford coalfield of England in 1738 (Zhang et al. 2017). In 1960, a coal bump occurred in Coalbrook North coal mine in South Africa, resulting in 437 deaths, which is the largest coal bump accident recorded. Along with deep underground mining, coal bump has become a major disaster for all leading coal producing countries. For example, as the biggest producer and consumer of coal in the world, China currently has 132 burst proneness coal mines with an average mining depth of 653 m, and coal bump accidents occurred on 20-10-2018, 9-6-2019 and 2-8-2019, resulting in 21, 9 and 7 miner deaths, respectively (Qi et al. 2019). According to statistics of 2510 reported destructive coal bump events, it is found that coal bumps occurring in the roadway account for 87% of all bump events (Pan 2018). Coal bumps in longwall roadways

cause destruction of rock bolt, steel shed support and other reinforcement structures. The reduction of cross-sectional area of the roadway can reach 50-70%. Among the most severe and disastrous coal bump disasters occurring in 2010-2015, 11 out of 14 bumps were in the longwall roadway (Pan 2018).

The location of most coal bumps occurring in roadways is in the range of 0-80 m in front of the working face, as shown in Fig. 1. Among them, the frequency and severity of bumps occurring in gob-side roadways are more than that of unmined panel-side roadways. The cause of this kind of coal bump is precisely the aim of this study, and the term “bump” excludes other kinds of bump events.

Fig. 1 Occurrence of coal bumps in longwall roadways.

Through statistical analyses and observations of numerous coal bump events, the following phenomena of bump events and geo-characteristics of the sites can be abstracted (Qi et al. 2019; Pan 2018; Qi et al. 1995; Qi

et al. 2003; Jiang et al. 2013; Dou et al. 2018; Jing et al. 2015). (1) The ground stress of bump collieries is often relatively high. (2) The strata of a bump panel are usually formed by hard main roof and hard coal seam; in addition, a thin, soft layer of powdery coal (0.1-0.2 m) can often be identified between them (Qi et al. 1995). (3) During bumps, there is usually massive movement of rib coal block into the roadway, but the roof generally does not have apparent deformation nor fracturing. In addition, sliding scratch and/or roof-coal strata separation can often be observed; the gap can be 0.1-0.15 m or more. (4) One puzzling phenomenon in bump events is that the floor may or may not heave. Once floor heave occurs in a bump event, it heaves heavily at the location where the coal is charged into the roadway fiercely. (5) Another noteworthy point is that the bump often occurs where the seam thickness changes sharply. (6) Field observation also suggests that coal bump may have a certain correlation with mining induced stress, including large or small dynamic interruption, such as roof caving, top coal caving, blasting, face shield moving or even hydraulic prop retracting.

The mechanism of coal bump is one major research task for the rock mechanics society. It is commonly accepted that coal bump is a type of sudden and violent energy release of the surrounding rock. The potential energy accumulated in the rock converts to kinetic energy, pushing the rib coal into the roadway accompanied by a sound noise and air waving. Although the theoretical research on coal bump has been conducted for more than 70 years, the mechanism of coal bump remains elusive. Consequently, the prediction and monitoring technology is lacking sound theoretical basis, and the prevention measures mainly rely on experience. Therefore, development of new theory and mechanical models is imperative. The research on the causal mechanism of coal bump is critical to understand the consequences of a coal bump event and to explain the observed phenomenon, which is also essential for prediction and prevention technologies.

2 State-of-the-art

In a recent paper (Qi et al. 2019), 10 major principles or mechanical models related to coal bump mechanism were reviewed. The first

3 principles just apply related fundamental theory of rock mechanics to coal bump, which are coal strength and stress principle, energy conservation and panel stiffness. Another two bump theories are a combination of several rock mechanics principles. Three mechanical models are worthwhile to mention as they were developed specifically for coal bump. Considering repeated loading of the coal mass, Zhang et al. (1987) named it static fatigue and developed a critical state equation to evaluate the instability of the coal body after softening. However, the related softening properties are not clearly defined to realise the proposed constitutive equation. In a following study, Pan and Zhang (1996) assumed that the roof was an elastic beam and established a mechanical model to evaluate the deformation of the roof and the stress state of the rib coal (Fig. 2). It was proposed that the ratio of the elastic modulus of the coal body to the gradient of its post-peak curve was an important parameter for bump prediction. With consideration of the observed phenomena of roof-coal strata sliding or separation after bump events, Qi et al. (1995) established a stick-slip

Fig. 2 Roof and coal deformation around roadway (Pan et al. 1995).

model to describe the interaction of the coal and the roof around the roadway, as shown in Fig. 3.

In a follow-up study (Qi et al. 2003), the stress state of the roof and floor were also analysed. In this model, the bump event was proposed as rib coal block charging into the roadway by overcoming static friction. However, the horizontal driving force was not clear, and the critical state of a bump event was not provided, as the studied object was point B. in Fig. 3.

Fig. 3 Stick-slip model developed in Qi et al. (1995).

Considering that bump events are often associated with mine tremors, Dou et al.(2015) and Gao et al.(2008) emphasized the effect of the dynamic load induced by mining activities and concluded that the

bump was caused by the superposition of the mining induced dynamic stress against static ground stress, as shown in Fig. 4.

Fig. 4 Superposition of dynamic stress against static stress (Dou et al. 2015).

Principles based on fundamental theory of rock mechanics provided direction for the follow-up theoretical developments. Three focalised mechanical models draw inspirations from viewpoints of ground stress, rib coal slippage and dynamic load. However, the causation of coal bump events is still unclear. Accordingly, keeping the geo-conditional features and characteristics of mechanical properties of a bump panel in mind, developing an occurrence model to understand the consequences of coal bump is the target of this paper. Moreover, a comparison of the newly developed model with the aforementioned big three is also provided in a later section of this paper.

3 Model development

Literature suggests that the cause of coal bumps occurring in longwall roadways is quite complicated. Coal bump is closely related to overburden induced stress as its frequency increases with mining depth. One common geo-characteristic of bump panels is that both its roof and coal seam are relatively hard. Post-bump observations suggest that slippage of the rib coal block by overcoming frictional resistance is the most likely failure mode of the rib coal mass. Based on these points, a causality model of bump can be developed with considerations of working face abutment pressure, high compressive stiffness of the face coal, de-stressing of the roof-coal interface in front of the working face due to roof rebounding, and rib coal mass slippage.

3.1 Working face abutment pressure

Due to overlying strata caving behind a longwall working face, vertical stress is concentrated on the coal body around the working face (Galvin 2016; Qian et al. 2010; Peng 2019; Song et al. 2017; Tang et al. 2017; Xue et al. 2018; Xue et al.

2020; Xue et al. 2018), as shown in Fig. 5. This is a well-recognised phenomenon in underground excavations, and the concentrated vertical load is named abutment pressure. The abutment pressure increases with greater mining depths as it is generated by the gravity of the overlaying strata.

Fig. 5 Abutment pressure act on a longwall working face.

In case of hard roof, the roof does not cave instantaneously with working face advancement. As a result, the main roof of a certain length is suspended behind the working face. The maximum length of the suspend roof is called periodic caving distance, and it increases with increased roof hardness. The suspend roof forms a cantilever beam behind the working face. Not only does the overburden of the cantilever beam induce great abutment pressure on

the face coal, it also generates a bending moment within the main roof.

In case of multiple hard roof strata, the abutment and bending moment may increase significantly. According to the Key Strata Theory (Qian et al. 2010), the key stratum is the bottom stratum of the fractural strata zone, and one or more sub-key strata may exist in caving zone, with each sub-key stratum forming a cantilever beam before caving, as shown in Fig. 6. In a recent hard roof caving article (Yu and Huo 2019), it was found that there were 2 sets of periodic weighting acting on the hydraulic shield, which were induced by the main roof caving and one sub-key stratum caving separately. Physical similarity modelling verified such caving behaviour. It can be concluded that, both main roof and sub-key strata generate abutment pressure on the working face coal and bending moment within the suspended roof.

Fig. 6 Un-caved strata generate abutment pressure on the face coal and bending moment within suspended main roof.

3.2 Main roof rebounding

Figure 7 illustrates the layout and vertical stress profile at a longwall working face. The gravity of overlying strata above the main roof produces a uniformly distributed vertical stress (blue arrows in Fig. 7); the un-caved overlying strata generate abutment pressure on the face coal via suspended roof, shown as black arrows in Fig. 7. In case of hard coal near the working face, the bend moment within the main roof can be transferred onto the roof in front of the working face (yellow arrow in Fig. 7) due to high compressive stiffness of the coal (elliptical section in Fig. 7). As a

result, the main roof in front of the working face tends to move upward. That is, in case of hard roof and hard coal near the working face, the overlaying strata form a seesaw-like structure using the face coal as a fulcrum. Once the roof in front of the working face turns upward, the normal stress of the roof-coal interface (red horizontal line in Fig. 7) decreases. The greater the roof rebounding, the sharper is the interface de-stressing. The red arrows in Fig. 7 show the sharply reduced normal stress along the roof-coal interface as most of the abutment pressure is borne by stiff face coal.

Fig. 7 Layout and vertical stress profile at a longwall working face.

Roof upward turning, or rebounding, is also a research topic relevant to face support shield protection. The hydraulic shield can be crushed by the periodic weighting, which correlates to the rebounding displacement of the roof in the roadway. In a recent study (Chen et al. 2019), the rebounding and compressive areas of the roof around a working face were studied through theoretical analysis, numerical calculation and field measurement. Results showed that according to the deformational states, the roof in front

of the working face could be divided into four zones: level I rebound zone, C-shaped compressive zone, level II rebound zone and far compressive zone, as shown in Fig. 8. In field studies, the longwall roof rebounding was measured as several tens of millimetres (Liu 1989; Tan and Yang 1996). The consequence of roof rebounding is destressing of the normal stress of the roof-coal interface, which may trigger rib coal bump.

Fig. 8 (a) Rebound areas and (b) bending moment around a longwall working face (Xue et al. 2020).

Roof-coal interface de-stressing is key to initiating a bump event. To further evaluate the de-stressing level, a numerical model was established based on the mechanical model illustrated in Fig. 7. The model and the calculated results are shown in Fig. 9. In the model, the roof and the coal seam are simulated as one long plate and one short plate, respectively; and the roof-coal interface is indicated by a black horizontal line. The overlying strata are replaced by a 16MPa vertical stress (equivalent to buried depth of 640 m) evenly distributed on the

roof. To simplify the calculation, the abutment pressure is not applied and neither is the interface element. The model is simple and highly repeatable.

The normal stress on the roof-coal interface was studied. A blue dotted line is added showing the intact vertical stress (16 MPa) as a base line. The blue solid line is the calculated normal stress. It shows that the normal stress sharply declines to negative values (-0.2 MPa, mean tensile stress) after peak value if the

Fig. 9 Numerical model and normal stress distribution along the coal-rock interface.

face coal is in elastic deformation. In reality, the bearing capacity of the coal mass is limited, and the face coal deforms in accordance with roof bending, generating a stress concentrated zone just behind the working face. Hence, the normal

stress distribution is proposed to be the profile of the red dashed line in Fig. 9 (not to scale), which is also the classic textbook description of the abutment pressure effect in rock mechanics. However, coal bump is abnormal. If the coal mass around

the working face is capable to bear sufficient amount of vertical load, the normal stress of the interface just adjacent to the stress concentration zone de-stresses to a level below its intact ground stress, or even to zero. Therefore, based on the numerical model and roof rebounding practice, in case of a coal bump event, the normal stress distribution of the interface should be the profile of the solid red line in Fig. 9; this is one key point of the proposed occurrence theory in this study.

3.3 Rib coal slipping (coal bump)

This section analyses the relationship between roof-coal interface de-stressing and rib coal slipping, or simply, coal bump. A coal block with a width of l adjacent to the roadway is analysed, as shown in Fig. 10. Block B is the coal mass just adjacent to block A. The roadway height is assumed to be the same as the coal seam, indicated by h ; and N is the normal force of the roof-coal interface. According to static equilibrium in the horizontal direction (hereafter direction x), the reaction force of block A per unit length along the roadway is:

$$\sigma_x h = f_1 + f_2 + \sigma_T h \quad (1)$$

Where:

σ_x is coal mass ground stress along direction x ;

f_1 and f_2 are frictions generated by the roof and the floor;

σ_T is tensile strength between block A and B.

Fig. 10 Stress state of the rib coal block.

Assume the coal mass and two interfaces follow Mohr-Coulomb failure criterion, the critical state equation of block A slippage satisfies:

$$f_1 = (c_{rc} + \sigma_n \tan \phi_{rc}) l \quad (2)$$

$$f_2 = (c_{fc} + (\sigma_n + \rho g h) \tan \phi_{fc}) l \quad (3)$$

Where:

c and ϕ are Mohr-Coulomb properties of roof-coal and floor-coal interfaces, subscripts rc and fc stands for roof-coal and floor-coal respectively;

ρ is density of coal; and g is specific gravity.

Substituting Eqs. (2) and (3) into (1), and re-arranging:

$$\sigma_x = \frac{l}{h}(c_{rc} + c_{fc}) + \frac{l}{h} \cdot \sigma_n \cdot (\tan\phi_{rc} + \tan\phi_{fc}) + \sigma_r + \rho g l \tan\phi_{fc} \quad (4)$$

This is the critical state equation for a coal bump event. In Eq (4), the ground stress σ_x equals to 0 at the rib face and gradually increases to its intact ground stress magnitude with increasing rib depth. Extensive field measurements of intact ground stress in coal seam has not been conducted yet. In fact, within authors' knowledge, only one field work reported that the measured major principal stress in a coal seam reached 27.5 MPa (Cao 2019). For intact ground stress estimation, two methods are often employed. One of them is vertical stress times a coefficient factor that is determined from statistical data; however, due to lack of measured data, this method is not applicable currently. Another method is an analogy according to measured ground stress of surrounding rock, i.e., measure the intact ground stress of the main roof and then calculate the intact ground stress of the coal seam based on their elastic properties (Nemcik et al. 2006). Nevertheless, in both cases, for hard coal seams with buried depths of more than 600 m, it can be

commonly accepted that the intact ground stress of the coal seam is 10-20 MPa. Hence, the left-hand side of Eq. (4) would be at least 10 MPa beyond the rock bolt reinforced area. On the other hand, the last item in Eq. (4) is less than 100 kPa, which is negligible compared to the left-hand side. The mechanical parameters of c_{rc}, c_{fc} and σ_T are often in the order of 0.1-1 MPa. The tensile strength of the coal mass is often estimated as 1/10-1/20 of its uniaxial compressive strength.

Overall, we assume $c_{rc}=c_{fc}=\sigma_T=1$ MPa, $l=h=3$ m, $\tan\phi_{rc}+\tan\phi_{fc}=1.2$, $\sigma_x=10$ MPa at 3 m rib depth, and neglect the $\rho g l \tan\phi_{fc}$ item. It can be found that once the interface normal stress, σ_n , de-stresses from 16 MPa to 6 MPa, Eq. (4) can be satisfied, and the ground stress would push block A into the roadway leading to a coal bump event.

Eq. (4) is the critical state equation for a coal bump event. Increasing the l to h ratio will work against the occurrence of a bump; hence the boundary of blocks A and B is most likely just beyond the rib bolting area, in practice often 2-3 m. Systematic joints commonly exist in coal mass, which can weaken its tensile strength greatly. The cohesion

of two interfaces may be reduced due to weakened interlayer and rib convergence after excavation. It suggests that the field condition may be worse than that calculated in advance. Nonetheless, accurate measurement and real-time monitoring of the ground stress and mechanical properties of surrounding rock are essential for coal bump prediction.

To summarize, the un-caved overburden generates abutment pressure on the face coal and bending moment in the suspended roof. In case of hard roof and hard face coal, a seesaw-like structure is formed around panel using face coal as the pivot point. Then, the main

roof in front of the working face tends to turn upward, causing reduction of normal stress of the roof-coal interface. Once the de-stressing of the interface reaches a threshold value, the rib coal block loses its gripping forces from the roof and the floor, and the ground stress perpendicular to the rib surface pushes the rib coal into the tunnel, leading to a coal bump event in the roadway.

3.4 Comparison with related bump models

A brief comparison of the developed causality model in this study with the aforementioned big 3 models is presented in Table 1.

Table. 1 Comparison of the developed model with the big 3 models in the literature.

	Ref.	Common grounds	Differences
1	Pan and Zhang 1996	Coal bump is induced by stress concentration, such as abutment pressure.	Pan and Zhang (1996) addressed rib coal softening as leading the bump; this model suggests high rigidity coal at the working face forming a pivot point that leads main roof rebounding in front of the working face.
2	Qi et al. 1995	Bump is frictional slipping of the rib coal into the roadway.	Qi et al. (1995) studied the movement of point B; this model studies the coal block movement in opposite directions, i.e., the spring represents the compressive coal mass and the block is bumping coal under roof confinement pressure.
3	Dou et al. 2015	Coal bump is related to mine tremor, or dynamic stress.	Dou et al. (2015) suggested that coal bump is triggered by the superposition of static and dynamic stresses; this model suggests that the potential energy of the compressive coal mass is sufficient to cause a bump event, and the dynamic energy is negligible.

4 Discussion

Based on the developed causality model of coal bump occurring in longwall roadways, the observed bump phenomena could be explained. Firstly, the gob of last panel also generates abutment pressure that forms another roof rebounding area in the working panel, as shown in Fig. 12. Due to superposition of rebounding areas, the frequency and everity of bumps occurring on gob-side roadways are greater than that on unmined panel-side roadways (Fig 2).

Phenomena (1) and (2) are favourable for coal bump; phenomenon (3) is caused by the rib coal block being

Fig. 11 Superposition of two rebounding areas along gob-side roadways.

pushed into the tunnel as a whole in bump events. For phenomenon (5), rapid change of coal seam thickness may affect the compressive stiffness of the coal mass. For phenomenon (4), why the floor may or may not heave in bump events? Floor heave

is due to the friction between the coal and the floor. The failure mode of the floor in a bump event is proposed to be buckling of the stratum. Therefore, if the shear strength of the coal-floor interface is greater than the critical stress of floor buckling, then the floor heaves; otherwise, only the coal block moves into the roadway.

5 Conclusions

Considering the geo-conditional features and characteristics and mechanical properties of a bump panel, this paper develops a causality model of coal bump occurring in longwall roadways to facilitate understanding of the consequences of a coal bump event and to explain the observed phenomenon. The following conclusions can be drawn:

- (1) The un-caved overburden generates abutment pressure on the face coal and bending moment in the suspended roof. In case of hard roof and hard face coal, a seesaw-like structure is formed around the panel using face coal as the pivot point (Figs. 7 and 8), which leads the main roof in front of the working face turning upward.

- (2) Based on numerical studies and roof rebounding practice, the normal stress of the roof-coal interface decreases sharply ahead of the working face as the face coal bears most of the abutment pressure.
- (3) Along with de-stressing of the interface, the rib coal block loses its gripping forces from the roof and the floor, and the ground stress perpendicular to the rib surface pushes the rib coal into the tunnel, leading to a coal bump event in the roadway. A critical state equation has been developed to justify the occurrence of a coal bump event; and key parameters related to coal bump are identified.
- (4) The bump phenomenon is explained using the newly developed causality model, and a comparison of the model is made against previous important models in the literature.

Ethical Statements

This work does not involve live subjects (human or animal).

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