A coal burst model based on roof vibration and coal slippage

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Abstract. Rock burst poses a serious threat to mining, and its mechanism still needs to be studied. Statistics show that more than 85% of rock bursts occur in mining roadways. The authors investigated the mechanism of rock burst in the roadways by creating a finite elastic long beam dynamic model in longwall mining based on the elastic foundation theory. In this study, the fracture failure of the basic roof and the related dynamic effects are analyzed. The results indicate that the occurrence of the free vibration of the basic roof is caused by fracturing during the first face advance. It is also found that the vibration frequency increases and the period decreases with the increase in roof thickness. Furthermore, the strength and elastic modulus increase with the increase in roof hardness. The effect of a thick, hard roof on the coal mass is mainly reflected in the vibration of the roof above the coal seam. During free vibration of the roof, the stress applied by the roof on the coal mass decreases. Under the action of horizontal stress, the coal mass slips along the interface between the roof and coal mass, which may result in rock burst. The mode of the basic roof vibration and the viscoelastic properties of the coal mass significantly influence the vibration–slippage impact. With the increase in the strength, thickness, and horizontal stress of the roof, the possibility of sliding between the coal seam and the roof also increases, which may potentially result in rock burst. This mechanism may explain the occurrence of rock burst in large-scale coal bodies that move out in the roadway, which could provide a reference for the prevention and control of such phenomena.

1. Introduction
Rock burst can cause sudden and considerable destruction, which can seriously threaten coal mining. Of the 2510 records of rock burst, 2178 occurred in the roadway in coalmines, which accounts for 86.8 % of the total [1]. In recent years, several serious accidents of rock burst in the roadways of coal mine have been reported in China, such as the “11 November” rock burst accident in No. 3 mine of Hongyang, the “9 July” accident in Longjiapu coal mine in 2019, the “2 August” accident in Tangshan coal mine in 2019, and the “22 February” accident in Longgu coal mine in 2020. Based on the analysis of rock burst phenomena in the roadways by other authors, it can be concluded that it has the following characteristics [2-8]: (1) it mostly occurs in the advance roadway during mining, generally 0-80 m ahead of the working face; (2) it generally occurs in the range of abutment pressure in front of the working face, under the influence of mining-induced stress; (3) the coal mass is destroyed and moves out as a whole after the occurrence of rock burst, but the roof damage is not severe; and (4) the basic roof is generally thick and hard.

A thick and hard roof is a typical geological condition for rock burst [9-15], and numerous scholars have studied the mechanism of rock burst under such condition. Based on the Mohr–Coulomb criterion, Lippmann et al. treated rock burst as a structural instability of the elastic–plastic limit and
revealed that it was a process of losing static equilibrium. They established a rock burst model that involves relative sliding between the coal seam, roof, and floor [16]. Brauner proposed the gripping theory, which states that coal mass is gripped between the roof and floor and that the strength condition is such that the boundary of the coal mass and surrounding rock (and the coal mass itself) reaches the limit equilibrium condition [9]. Pan thought that sudden roof cracking releases stored elastic energy in rock burst [1]. To further explain rock burst, Dou proposed a principle of dynamic and static loading. In this principle, the static loading includes the in situ stress and abutment pressure, whereas the dynamic loading includes stresses induced by the failure of coal pillars, roof fracturing, large-scale movement of overlying strata, and fault slip [17]. Mou subdivided the mechanisms of rock burst induced by roof strata into two types: “static-state mechanism of rock burst” of stable strata and “dynamic-state mechanism of rock burst” of dynamic strata. The former mechanism is related to the impact of coal mass caused by the sudden release of elastic energy that is stored in rock strata when the roof strata do not break or slip on a large scale. The latter refers to coal impact triggered by strong vibration due to large-scale fracturing or sliding collapse of the roof, as well as the release of impact energy and other dynamic loading [18]. Li et al. argued that the spatial region, where compression and rebound occurred after the hard roof fracture, was the source of rock burst [19]. Furthermore, they subdivided rock burst under the dominant action of a hard roof into two types: interlaminar stagger and coal wall instability [20]. According to Tan, the significant elastic potential energy and gravitational potential energy that are released during the fracture and hard roof instability can cause destruction, expansion, and movement of the coal mass, as well as the occurrence of rock burst [21]. Wang examined how large-scale fracturing of coal and rock masses in the stope generates high-energy dynamic stress waves and how the coupling between the stress waves and in situ stress can cause large-scale damage to the surrounding rocks, which results in rock burst [22]. In general, rock burst under the hard roof condition can be understood in two ways. First, the load formed by roof fracturing causes rock burst from the perspective of statics. Second, the dynamic disturbance of shock or elastic waves caused by roof fracturing causes rock burst. However, the current understanding cannot clearly elucidate the mechanism behind the occurrence of rock burst in mining and roadways due to the regular roof fracturing in longwall mining.

The current research on rock burst mechanics can be roughly categorized into two: one deals with static stability problems, conducts purely elastic and elastoplastic analyses, or conducts analysis on deformation localization using the bifurcation theory; the other believes that shock wave or the dynamic disturbance of the elastic wave triggers the rock burst. From the perspective of structural dynamics, this paper creates a structural dynamic model after roof breakage, analyzes the dynamic response of coal and rock strata after roof breakage and its effect on coal seam destruction, and then proposes the mechanism of rock burst in the roadways.

2. Fracture and movement of the basic roof

Mining activities change the original equilibrium state of the underground rock mass. Moreover, they allow for the displacement of the overlying strata and the movement toward the goaf. Thus, one of the most important challenges in mining is the structure and movement law of the overlying strata. In general, large deformation occurs in coal seam due to its weak shear resistance. As a result, some scholars created the elastic foundation beam model based on the Winkler elastic foundation model [23,24]. They theoretically proved that the basic roof is broken in front of the coalface (Figure 1). Based on the comparison of the basic roof deflection before and after its breakage, it is obvious that the rebound and compression phenomenon occurs when the basic roof is breaking in advance of the coalface. Obtaining the distribution law of the interval of rebound and compression using the rock beam model is possible [25-27]. Xie et al. also obtained the same result based on the mechanical model of elastic foundation [28].
3. Structural dynamic analysis after roof breakage

3.1 Dynamic model of roof breakage

Using the relationship between the basic roof and the immediate roof, the coal seam, and the strata above it, the authors create a finite elastic long beam dynamic model. This model is based on Winkler’s elastic foundation in the mining process of a longwall working face, as presented in Figure 2. In the model, the coal seam and the immediate roof are an elastic foundation, and the basic roof is a finite elastic beam. The general dynamic equation of an infinite beam, based on Winkler’s foundation [29], is as follows:

$$EI \frac{\partial^4 w(x,t)}{\partial x^4} + m \frac{\partial^2 w(x,t)}{\partial t^2} + c \frac{\partial w(x,t)}{\partial t} + bkw(x,t) = p(x,t)$$ (1)

where \( w(x,t) \) denotes the displacement of the beam; \( p(x,t) \), the dynamic loading on the beam; \( E \), the elastic modulus of the beam; \( I \), the moment of inertia in cross section; \( m \), the mass per unit length of the beam; \( c \), the damping coefficient of the foundation; \( b \), the width of the beam; and \( k \), the stiffness coefficient of the foundation.

The initial condition of \( w(x,t) \) is as follows:

$$\begin{align*}
\left. w(x,t) \right|_{t=0} &= f(x) \\
\left. \frac{\partial w(x,t)}{\partial t} \right|_{t=0} &= g(x)
\end{align*}$$ (2)

and the infinite distance condition of \( w(x,t) \) is as follows:

$$\lim_{x \to \pm \infty} \frac{\partial^n w(x,t)}{\partial x^n} = 0, \quad n = 0, 1, 2, 3$$ (3)

Note that Eqs. (1–3) are the basic equations of the model, and the analytical solution thereof is as follows:

$$w(x,t) = \exp(-at) \left\{ \int_{-\infty}^{\infty} \left[ f(r) \frac{\partial R(x-r,t)}{\partial t} + [af(r) + g(r)]R(x-r,t) \right] dr \right. \right.$$

$$+ \frac{1}{m} \int_{-\infty}^{\infty} \left[ p(r,t)\exp(ar)R(x-r,t-t) \right] dr \left. \right\}$$ (4)

For a cantilever beam, in which the left end is fixed and the right end is free, the modal function of beam transverse vibration is as follows:

$$w(0,t) = 0, \quad ES \frac{\partial w(f,t)}{\partial x} = 0$$ (5)
3.2 Initial conditions and influencing factors of roof strata free vibration
To determine the specific solution in the above model, it is important to determine its initial conditions. The morphology of the basic roof, before and after fracturing, demonstrates that the bending of the roof above the goaf before fracturing (Figure 3a) leads to an upward displacement on the side of the coal mass. Then, the basic roof breaks in front of the workface (Figure 3b), which leads to a dynamic state in the basic roof above the coal face after fracturing (Figure 3c). A large amount of field data reveal that after the fracturing of the basic roof, the roof appears to be displaced upwards at a few degrees. Indeed, Tan has observed an upward displacement of $n \times 10^2$ mm in the roof of the Longwall 2126 (Baoyuan coal mine), Longwall 708 (Zhangxiaolou coal mine), and Longwall 8320 (Dafeng coal mine) [25].

The main factors that affect the basic roof movement are the variation in cross-sectional bending moment caused by roof fracturing, the rigidity of the basic roof, and the rigidity coefficient of the coal mass. At the same time, the observation results indicate that the stiffness coefficient of the coal mass is large, and the basic roof is soft. At this time, the upward displacement of the basic roof is negligible, and the displacement amplitude is large for a hard roof with good integrity and a coal seam with good elasticity. The immediate roof and coal seam exhibit inelastic mechanical properties, which create a damping effect. This means that the basic roof is free to vibrate under certain damping conditions.

As a result of this free vibration, the initial process is the periodic change in the loading stress of the basic roof relative to the immediate roof and coal seam. This causes the compressive stress to weaken or disappear in the basic roof relative to the immediate roof and coal seam. The second process is the periodic effect of the basic roof on the immediate roof and coal seam.
Figure 3. The process of basic roof fracturing demonstrating (a) the model before fracturing, (b) the model at the time of basic roof fracturing, and (c) the model after basic roof fracturing

It is assumed that the roof strata density is 2700 kg/m$^3$ and the periodic fracture step is 18 m. Figures 4 and 5 present the frequency (main frequency) of the basic roof vibration for different roof strata elastic modulus and thickness conditions. From these figures, it can be seen that the vibration frequency of the basic roof is within 30 Hz. The literature [18] also shows that based on microseismic monitoring, the main frequency distribution of basic roof fracturing is in the range of 0–50 Hz.

Figure 4. Graph demonstrating the relationship between the elastic modulus of the basic roof and vibration frequency (the basic roof thickness is 10 m)

Figure 5. Graph demonstrating the relationship between the thickness of the basic roof and vibration frequency (the elastic modulus is 700 GPa)

4. Mechanism of rock burst by sliding instability in mining roadways

The coal mass with width $l$ which is adjacent to the roadway is chosen as the research object (Figure 6). From Figure 6, it can be seen that coal block A and coal block B are connected. However, for the sake of clarity, coal block B is moved to the left. The height of the roadway and coal seam is denoted by $h$, whereas the normal stress at the interface between the roof and coal mass is denoted by $N$. For the coal mass along the unit length section of the roadway axis, the stress balance along the horizontal direction (herein referred to as the x direction) is defined as follows:

$$\sigma_x l = f_1 + f_2 + \sigma_T l$$

(6)

where $\sigma_x$ denotes the in situ stress component from block B in the coal mass; $f_1$ and $f_2$, the frictional forces between the top and bottom plates of block A, respectively; and $\sigma_T$, the tensile strength between block A and block B.
The vibration of the roof causes the positive pressure at the interface to weaken. In the extreme case, where the positive pressure reaches the separation of the roof and coal mass (Figure 7), the value of $f_1 = 0$. At this time, according to Eq. (6), the critical state of coal block A bursting into the roadway is determined as follows:

$$\sigma_x h = (c_{c-r} + \rho gh \tan \phi_{c-r}) l + \sigma_T h$$

where $c_{c-r}$ and $\phi_{c-r}$ denote the cohesion and internal friction angle of the coal–rock interface, respectively, and $\rho$ denotes the coal density. Therefore, the formula is used to discriminate the occurrence of rock burst after the separation of the roof and coal seam.

In general, the cohesion $c_{c-r}$ at the interface is considered to be 0, due to the convergence of the two sides after the roadway excavation. Even if the total convergence is small, the cohesion at the interface between the coal mass and the roof and floor near the roadway can be lost. In this case, Eq. (7) can be simplified to the following:

$$\sigma_x - \sigma_T = \rho gh l \tan \phi_{c-r}$$

In Eq. (8), the value of $\sigma_x$ can be determined via in situ stress measurement and is generally equal to (0.8–1.2)$\rho gh$. Direct measurement of the tensile strength $\sigma_T$ of the coal is difficult, and the reliability of indirect measurement is questionable. Engineering experience suggests that $\sigma_T$ is about 0.1–0.2 of the uniaxial compressive strength, and the higher estimate is in the 1–2 MPa range for coal. If the in situ stress along the roadway is high, or if a large disturbance occurs in the early stages, plate crack and buckling deformation may occur, as reported in the literature [9]. In this case, the value of $\sigma_T$ should be 0.

It can be seen that after the excavation of the roadway ($c_{c-r} = 0–1$ MPa) and under the conditions of losing roof clamping ($N = 0$), the tensile strength ($\sigma_T = 0–2$ MPa) and floor friction (0.01–0.2 MPa) of the coal mass cannot resist the horizontal stress of the coal mass, which then rushes into the roadway in the form of a rock burst.

Only the sliding frictional resistance ($\rho gh l \tan \phi_{c-r}$) in Eq. (7) is related to the coal wall impact section depth ($l$) of the roadway. However, the coal mass at any depth can contribute to the occurrence of rock burst due to the significant difference between the impedance and $\sigma_x$. The remaining terms in Eq. (7) are calculated according to the unit length along the axial direction of the roadway, which is independent of the impact section length in the roadway. Overall, it can be understood that regardless of the depth of the coal wall and the coal mass along the axial length of the roadway, it will contribute to the occurrence of rock burst, as long as separation occurs between the roof and coal mass interface.

5. Discussion

It can be broadly considered that rock burst in the roadway occurs in front of the working face. Furthermore, the roadway and roof structure experience a wide range of large roof displacement rebound due to the abutment pressure in the goafs of the working face and the adjacent working face.
Once the geological conditions change, or sudden loading or unloading occurs, the coal mass, which is highly rigid at its boundaries, has no time to compress and deform. The events of loading or unloading include static load accumulation, high-level rock breakage, collapse, mining-induced seismicity, and artificial vibration. Such sudden loading allows a large part of the torque transmitted by the highly rigid roof to enter the roof, forming a pressure relief rebound area, which leads to the increase in roof rebound displacement and connection of the rebound area. At the place where the rebound amount of the roof reaches or approaches the separation of the roof and coal mass, the in situ stress in the horizontal direction of the coal mass is spontaneously released. This provides a direct source of force for the rock burst event, which occurs as the two sides of the coal mass in the roadway are pushed into the roadway.

Roof fracturing causes coal mass vibration at a frequency of ~10 Hz, which constantly decreases. At this time, an ultra-low friction effect is generated, i.e., between the roof and the coal seam [30][31]. The coal seam also generates a vibration, but there is a difference between the two processes: the friction between the coal seam and the roof is greatly reduced or even dissipates, and the coal mass bursts under the action of horizontal stress.

The common point of the two processes is that the stress state of the coal mass has changed, given that in the former, a change occurs under static load and in the latter, a change occurs under dynamic load.

6 Conclusions
(1) A large positive pressure unloading event occurs at the interface between the roof and coal mass in front of the workface. This occurs due to the large interval of the periodic weighting step for a hard roof and high supporting pressure in the stope. This is based on the rebound theory of the stope roof.
(2) The bending moment formed by the supporting pressure is transmitted to the roof in front of the working face due to the large compression rigidity and bending rigidity of the coal mass near the working face. Under these specific conditions, the far end of the roof may be warped upward due to the action of the bending moment. Moreover, it can result in a rapid decline in the normal stress at the interface between the roof and coal mass. As such, a new interface forms, which can create conditions conducive to the occurrence of rock burst.
(3) The stress analysis of the roadway shows that the stress in the coal mass spontaneously unloads if the normal stress at the interface between the roof and coal mass is sufficiently low.

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