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Research Article

Main Roof Breakage and Vibration Induced Coal Burst Occurring in Longwall Roadways

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Rock burst is one major threat to mining safety and economy. Rock burst occurring in the longwall mining roadway accounts for 85% of the total amount of burst events. This paper investigates the causality mechanism of rock burst in longwall roadways by establishing a finite elastic beam model in the working face based on the elastic foundation theory. The breakage process of the main roof and related dynamic effects are analysed. The result shows that the movement of the main roof shows free vibration under certain damping resistance. It is also found that the roof dominant vibration frequency increases with the increase in the thickness and elastic modulus of the roof. During roof vibration, the vertical stress applied on the coal mass is unloaded. The destressing of the roof-coal interface causes the coal mass in the roadway rib to slip into the roadway under the horizontal ground stress, resulting in rock burst. The possibility of rock burst increases with increase in the strength and thickness of the roof and horizontal ground stress within the coal mass. This mechanism explains the occurrence of rock burst in the mining roadway; it provides the fundamental theory for the prevention and controlling technologies of longwall roadway rock burst.

1. Introduction

Rock burst is a destructive and sudden geological dynamic disaster, which prompts a serious risk to coal mine production. According to the recorded 2510 times of data, more than 85% of rock burst occurs in the underground roadway [1]. Recently, several serious rock burst accidents occurred in the underground coal mining industry, such as the coal burst incident in Hongyang #3 Coal Mine, Longjiapu Coal Mine, and Tangshan Coal Mine. The phenomenon of rock burst mostly occurs in longwall roadway where is just advance of the working face; that is, it is closely related to the mining-induced dynamic stress. The roof of rock burst coal seam is usually thick and hard. After rock burst, it is often observed that the coal mass is moved into the roadway from the ribs as a whole and the roof has no obvious deformation nor serious damage.

The geological condition of hard roof is closely related to rock burst occurring in the longwall roadway [2–7]. The causality of coal burst under the condition of hard roof has been studied by many scholars [1, 3, 8–12]. Pan [1] believes that if the roof is hard rock and the stratum structure is whole, once the roof breaks violently, it rapidly releases a huge amount of elastic energy stored in the system, which may induce rock burst [1]. According to the theory of coal mass clamping developed by Brauner [13], the coal body is clamped by the roof and floor strata. One condition related to rock burst occurrence is that the coal-roof interface or the coal mass itself meets its critical equilibrium condition. Based on Mohr–Coulomb material criterion, Lippmann [14] considered rock burst as a structural instability of the surrounding rock; rock burst was thought as a procedure of a static in-equilibrium, and the slippage of coal seam with the roof and floor was considered in the developed rock burst model.

The mechanism of coal burst induced by hard roof can be classified into two categories: stable roof with static overloading mechanism and dynamic load mechanism induced by moving strata [15–22]. The steady-state mechanism refers to the coal burst induced by the rapid release of elastic potential energy accumulated within the roof, but the roof does not fracture or deform greatly. The dynamic mechanism is described as coal burst caused by dynamic loads such as strong vibration and impact energy that lead to roof breaking or collapse.

Dou et al. [23] proposed a principle for rock burst considering superposition of static and dynamic loads, in which the static load refers to the in situ ground stress and mining activity-induced stress and the dynamic load refers to the failure of coal pillar, roof caving, overlying strata movement, fault sliding, etc. However, under hard roof conditions, He et al. [24] classified the rock burst into two categories: interlayer dislocation or coal rib instability. Li et al. [25] believe that the location where the roof rebound occurs after roof fracturing was the seismic source in the rock burst event. Tan et al. [26] addressed that the elastic and gravity potential energy released during the fracture and instability of hard roof lead to the coal mass failure, forming rock burst. Wang et al. [27] addressed that fracture of coal and rock mass in the working panel generated a huge amount of energy and stress wave, and the coupling effect of the stress wave and ground stress led to further damage of the surrounding rock around the working panel, which finally induced rock burst. Due to the complicity of the roof fracture in the longwall mining procedure, the mechanism of rock burst in the roadway is not clear yet.

Currently, the causality of coal burst under the condition of hard roof can be classified into two types: one focuses on the static load induced by the roof fracture and the other emphasizes the dynamic disruption of the shock wave or stress wave induced by the roof fracture. Consequently, the related mechanisms are different. For a static problem, elastic stability analysis, elastic-plastic analysis, or local deformation is often employed. For a dynamic problem, the propagation of shock wave or elastic wave in rock is often analysed.

From a viewpoint of structural dynamics, we establish a causality mechanical model of rock burst based on analysis of the movement of coal and rock strata induced by roof fracture to put forward the causality mechanism of roadway rock burst.

2. Main Roof Breakage

Underground excavation destroys the original equilibrium state of underground rock mass, and the overlying strata move towards the goaf in the working face. The structural state and deformational behaviour of the overlaying strata represent one important topic in mining engineering research. As the strength of coal seam is much lower than that of surrounding rock, the roof can be assumed to be elastic. Accordingly, an elastic beam model has been established to study the periodic weighting behaviour of the main roof based on the Winkler elastic model [28]. According to the elastic beam theory, the breaking point of the main roof is ahead of the working face, where the bending moment of the main roof is the maximum, as shown in Figure 1. The breaking line is often several meters in front of the working face, which causes stress redistribution in the surrounding rock.

Based on the study of the deflection changes before and after the main roof fracture, it was found that roof compression and rebound occur when the main roof gets fractured. The distribution of roof rebounding and compression areas is obtained by establishing a rock beam model [29–37]. Xie et al. [38] presented similar results based on elastic thin plate mechanics model under elastic boundary condition. Based on the elastic boundary assumption, it can also be found that the main roof breakage of the mining roadways also enters the coal mass.

When the main roof gets fractured, the distance between the fracture line and the working face (Lc) is normally several meters. The smaller the elastic coefficient of the boundary is, the larger the Lc will be and vice versa. In addition, the greater the thickness of the main roof or the greater the elastic modulus of the roof rock, the larger the Lc.

2.1. *Dynamic Analysis of Main Roof Breakage*

2.1.1. Dynamic Model. According to the relationships among the coal seam, immediate roof, and main roof, this paper develops a dynamic model to describe the deformational behaviour of the main roof in the breakage process based on the elastic beam theory and the finite elastic boundary assumptions, as shown in Figure 2.

In the model, the immediate roof and the coal seam are combined to be an elastic footing and the main roof is assumed to be an elastic beam. Based on Winkler's theory [39], the relationship of finite elastic beam is

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

where $w(x,t)$ is the beam displacement; $p\ (x,\ t)$ is the dynamic load; I is the moment of inertia of the beam's cross section; E is the beam elastic modulus; m is the beam mass per unit length; c is the oscillating coefficient of the footing; b is the beam; and k is the stiffness of the footing.

The initial condition of beam displacement $w(x,t)$ is

$$\begin{cases} w(x,t)|_{t=0} = f(x) \\ \dfrac{\partial w(x,t)}{\partial t}|_{t=0} = g(x) \end{cases}, \tag{2}$$

and the infinite distance condition of $w(x,t)$ is

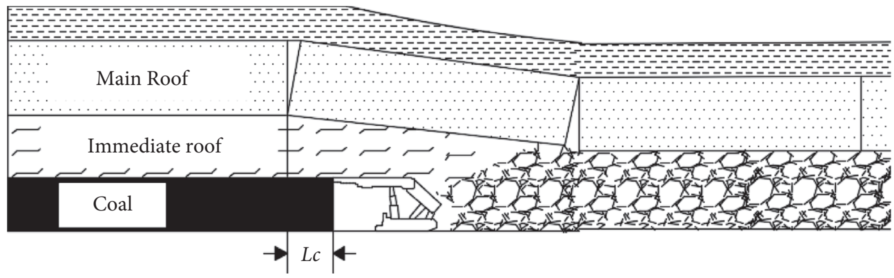

Figure 1: Main roof fracturing.

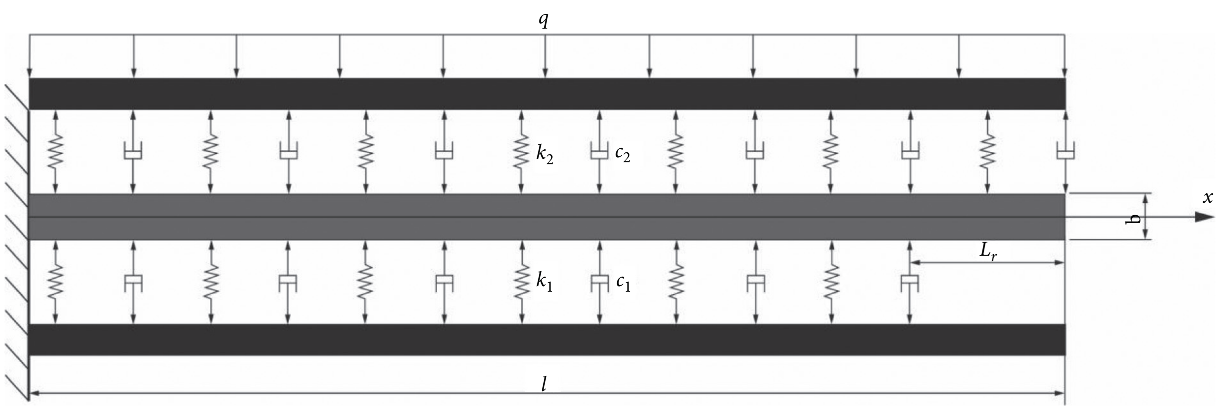

Figure 2: Elastic beam model of longwall main roof breakage.

$$w(x,t) = \exp(-at)\int_{-\infty}^{+\infty}\left\{f(r)\frac{\partial R(x-r,t)}{\partial t} + [af(r)+g(r)]R(x-r,t)\right\}\mathrm{d}r+,$$
$$\frac{1}{m}\exp(-at)\int_{-\infty}^{+\infty}\left[\int_0^t p(r,t)\exp(a\tau)R(x-r,t-\tau)\,\mathrm{d}\tau\right]\mathrm{d}r. \tag{3}$$

For a cantilever beam, where its one end is fixed and another end is free, the equation of the diagonal vibration of the beam is

$$w(0,t) = 0,$$
$$\mathrm{ES}\frac{\partial w(l,t)}{\partial x} = 0. \tag{4}$$

2.1.2. Initial Condition of Main Roof Vibration. The solution of the established dynamic model is relied on the boundary condition. The diagrams before and after the main roof breakage are shown in Figure 3. Figure 3(a) shows the roof just before breakage. Due to the suspended roof, the main roof ahead of the working face intends to move upward. Figure 3(b) shows that the main roof gets fractured in front of the working face. Figure 3(c) shows the state of the overlaying strata after the main roof breakage.

Field observations show that after the main roof is broken, the roof in front of the working face shifts upward [29, 40–44]. Tan and Yang [29] observed an upward displacement of several 100 mm at the 2126 working face of Baoyuan Coal Mine, the E708 working face of Zhangjiakou Coal Mine, the #5 seam working faces of Mentougou Coal Mine, and the 8320 working face of Dafeng Coal Mine.

2.1.3. Influencing Factors of Main Roof Vibration. The factors affecting the main roof movement are the magnitude difference of the bending moment in the procedure of roof breakage and the stiffness of the main roof and the coal seam. Field observations show that if the compressive coefficient of the coal seam is large and the main roof is relatively soft, the vertical rebounding displacement of the main roof is small. In case of hard roof and high elasticity coal seam, the magnitude of the main roof rebounding displacement is relatively large.

Due to the inelastic properties of the coal seam and the immediate roof, they are equivalent to damping resistance. That is, the movement of the main roof can be simplified as free vibration under certain damping resistance. One effect of the vibration of the main roof is the periodic change in the

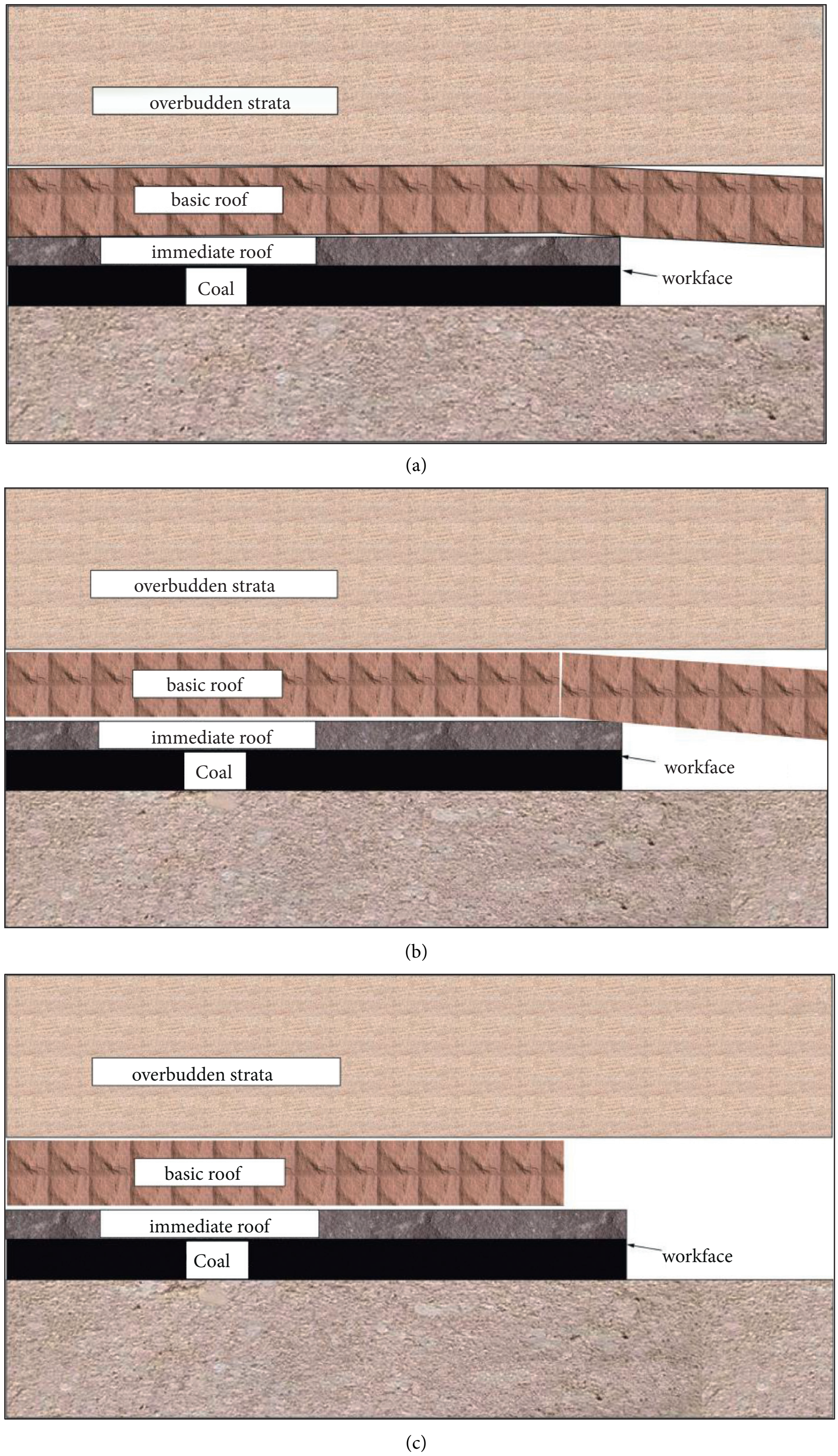

Figure 3: The procedure of main roof breakage: (a) before breakage, (b) at the point of main roof breakage, and (c) after main roof breakage.

vertical stress on the immediate roof and the coal seam, which weakens the confining effect of the main roof on the immediate roof and the coal seam at a certain moment.

Assuming that the density of the roof is 2.7×10^3 kg/m^3, the main roof dominant vibration frequency under different elastic modulus and thickness conditions is shown in

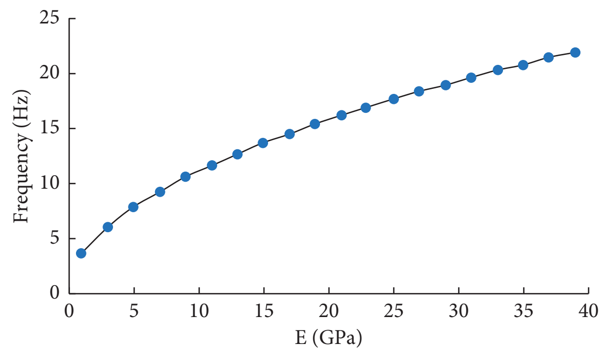

FIGURE 4: Dominant frequency of main roof vibration vs elastic modulus (10 m roof thickness).

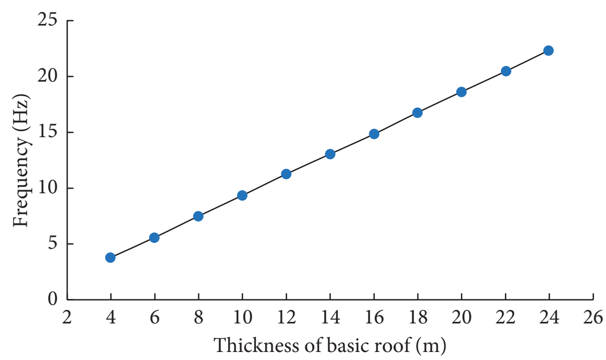

FIGURE 5: Dominant frequency of main roof vibration vs thickness ($E = 20$ GPa).

Figures 4 and 5. The frequency of the main roof vibration is within 30 Hz. Li et al. [45] also addressed that the frequency domain of main roof breakage was 0–50 Hz through microseismic monitoring.

2.1.4. Causality of Rock Burst in the Mining Roadway. A coal block with a width of l in the mining roadway rib is studied, as shown in Figure 6. Coal block B is connected to block A, but it is moved to the left side in the figure to facilitate drawing and description. Suppose the height of the mining roadway and the thickness of the coal seam are h and N is the normal force of the roof-coal interface. For the coal mass per unit length along the roadway, according to the horizontal direction (hereafter defined as the x direction) equilibrium, we have

$$\sigma_x h = f_1 + f_2 + \sigma_T h, \tag{5}$$

where σ_x is the horizontal stress by coal block B within the coal mass; f_1 and f_2 are the frictions from the roof and floor, respectively; and σ_T is the tensile strength between coal blocks A and B.

The movement of the main roof weakens the confining pressure at the roof-coal interface. In the severe condition, where the roof is separated from the coal seam (Figure 7), the fractional force of $f1 = 0$. At this moment, according to

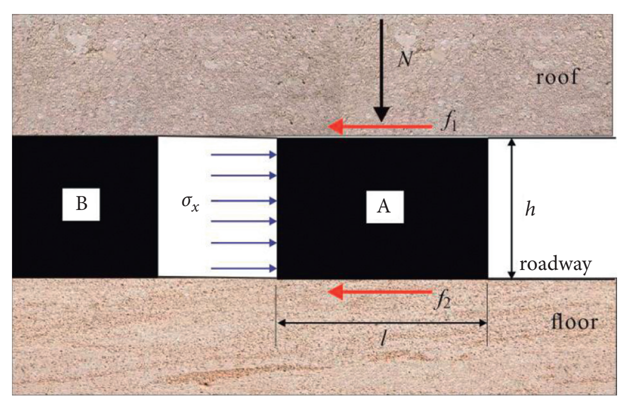

FIGURE 6: Stress analysis of coal block A in a mining roadway rib.

equation (5), the critical state equation of rock burst of block A is

$$\sigma_x h = (c_{c-r} + \rho g h \tan \phi_{c-r}) l + \sigma_T h, \tag{6}$$

where c_{c-r} and $t\phi_{c-r}$ are the Mohr–Coulomb properties of the coal-floor interface and ρ is the density of the coal.

The cohesion c_{c-r} at the coal-floor interface can be considered as 0 if there exists rib convergence after roadway development. Though the rib convergence may be not great,

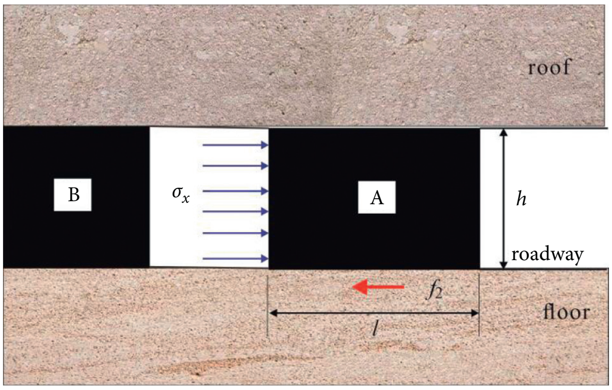

FIGURE 7: Stress state of block A after roof-coal separation.

the cohesion of the coal-floor interface near the rib will reduce to 0. In this case, equation (6) can be expressed as

$$\sigma_x - \sigma_T = \rho ghl \tan \phi_{c-r}. \quad (7)$$

3. Conclusion

The mechanism of coal burst occurring in longwall roadways is investigated by establishing the elastic beam model. The breakage process of the main roof and its effect are analysed. The following conclusion can be drawn:

(1) The movement of the main roof shows free vibration under certain damping resistance. The roof vibration frequency increases with increase in roof elastic modulus and strata thickness.

(2) Due to roof vibration, the vertical stress applied on the coal mass decreases. There exists a vertical stress unloading zone in front of the working face. In this situation, the roof in the front of the working face intends to move upwards, resulting in roof rebound or even roof-coal separation. It builds the conditions for the rock burst.

(3) Through the equilibrium analysis of the rib coal block of the roadway, once the vertical stress of the roof-coal interface is reduced or even the roof and the coal seam are separated, the ground stress in the coal body along the normal direction of the roadway rib pushes the rib coal block into the roadway generating a coal burst event.

(4) As the strength and thickness of the roof and horizontal ground stress within the coal mass increase, the probability of slippage between the roof and the coal seam increases and the probability of rock burst also increases. The ground stress is the force source of coal burst occurred in the longwall roadway.

This study explains the causality of rib coal mass bursting into the roadway, and it provides a theoretical guideline for the prevention and controlling measures of coal burst in the roadway.

Data Availability

All data of this article have been included within this manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] Y. Pan, *Rockburst in the Mining*, p. 135, Science Press, Beijing, China, 2018.

[2] A. T. Iannacchione and J. Zelanko, “Occurrence and remediation of coal mine bumps: a historical review,” in *Proceedings of the National Institute for Occupational Safety and Health*, pp. 27–68, Norton, VA, USA, May 1995.

[3] J. F. T. Agapito and R. R. Goodrich, “Five stress factors conducive to bursts in Utah, USA, coal mines,” in *Proceedings of the 19th international conference on ground control in mining*, p. 93, West Virginia University, Morgantown, WV, August 2000.

[4] R. Baltz and A. Hucke, “Rockburst prevention in the German coal industry,” in *Proceedings of the 27th international conference on ground control in mining*, p. 46, West Virginia University, Morgantown, WV, July 2008.

[5] H. Maleki, “An analysis of violent failure in U.S. coal mines-case study,” in *Proceedings of the Mechanics and Mitigation of Violet Failure in Coal and Hard-Rock Mines*, p. 5, U.S. Department of the Interior, Bureau of Mines, PA, May 1995.

[6] D. Xue, J. Zhou, Y. Liu, and L. Gao, “On the excavation-induced stress drop in damaged coal considering a coupled yield and failure criterion,” *International Journal of Coal Science & Technology*, vol. 7, no. 5, pp. 58–67, 2020.

[7] B. Chen, “Stress-induced trend: the clustering feature of coal mine disasters and earthquakes in China,” *International Journal of Coal Science & Technology*, vol. 7, no. 4, pp. 676–692, 2020.

[8] L. Zhang, S. Chen, C. Zhang, X. Fang, and S. Li, “The characterization of bituminous coal microstructure and permeability by liquid nitrogen fracturing based on μCT technology,” *Fuel*, vol. 262, Article ID 116635, 2020.

[9] L. Zhang, J. Li, J. Xue, C. Zhang, and X. Fang, “Experimental studies on the changing characteristics of the gas flow capacity on bituminous coal in CO2-ECBM and N2-ECBM,” *Fuel*, vol. 291, Article ID 120115, 2021.

[10] J. Lin, T. Ren, Y. Cheng, J. Nemcik, and G. Wang, “Cyclic N2 injection for enhanced coal seam gas recovery: a laboratory study,” *Energy*, vol. 188, Article ID 116115, 2019.

[11] J. Lin, T. Ren, G. Wang, P. Booth, and J. Nemcik, “Experimental investigation of N2 injection to enhance gas drainage in CO2-rich low permeable seam,” *Fuel*, vol. 215, pp. 665–674, 2018.

[12] D. Xue, L. Lu, J. Zhou, L. Lu, and L. Liu, “Cluster modeling of the short-range correlation of acoustically emitted scattering signals,” *International Journal of Coal Science & Technology*, vol. 8, no. 22, pp. 1–15, 2020.

[13] G. Brauner, *Rockbursts in Coal Mines and Their Prevention*, A A Balkema, Rotterdam Netherlands, 1994.

[14] H. Lippmann, "Mechanics of "bumps" in coal mines: a discussion of violent deformations in the sides of roadways in coal seams," *Applied Mechanics Reviews*, vol. 40, no. 8, pp. 1033–1043, 1987.

[15] Z. Mu, *Study of the Burst-Energy Principle of Rock Burst Induced by Roof Stratum and its Application*, China University of Mining & Technology Press, Xuzhou, China, 2009.

[16] C. Mark, "Coal bursts in the deep longwall mines of the United States," *International Journal of Coal Science & Technology*, vol. 3, no. 1, pp. 1–9, 2016.

[17] J. Han, S. Wang, Y. Chen, and C. Cao, "Analytical derivation of rib bearing angle of reinforcing bar subject to axial loading," *Magazine of Concrete Research*, vol. 71, no. 4, pp. 175–183, 2019.

[18] D. J. Xue, Y. T. Liu, H. W. Zhou, J. Q. Wang, J. F. Liu, and J. Zhou, "Fractal characterization on anisotropy and fractal reconstruction of rough surface of granite under orthogonal shear," *Rock Mechanics and Rock Engineering*, vol. 53, no. 3, pp. 1225–1242, 2020.

[19] J. Wang, J. Yang, F. Wu, T. Hu, and S. A. Faisal, "Analysis of fracture mechanism for surrounding rock hole based on water-filled blasting," *International Journal of Coal Science & Technology*, vol. 7, no. 4, pp. 704–713, 2020.

[20] D. Cao, A. Wang, S. Ning et al., "Coalfield structure and structural controls on coal in China," *International Journal of Coal Science & Technology*, vol. 7, no. 2, pp. 220–239, 2020.

[21] S. Mao, "Development of coal geological information technologies in China," *International Journal of Coal Science & Technology*, vol. 7, no. 2, pp. 320–328, 2020.

[22] P. Małkowski, Z. Niedbalski, and T. Balarabe, "A statistical analysis of geomechanical data and its effect on rock mass numerical modeling: a case study," *International Journal of Coal Science & Technology*, vol. 8, pp. 312–323, 2021.

[23] L. Dou, J. He, A. Cao, S. Gong, and W. Cai, "Rock burst prevention methods based on theory of dynamic and static combined load induced in coal mine," *Journal of China Coal Society*, vol. 40, pp. 1469–1476, 2015.

[24] J. He, L. Dou, S. Wang, and C. Shan, "Study on mechanism and types of hard roof inducing rock burst," *Journal of Mining & Safety Engineering*, vol. 34, pp. 1122–1127, 2017.

[25] X. Li, N. Ma, Y. Zhong, and Q. Gao, "Storage and release regular of elastic energy distribution in tight roof fracturing," *Chinese Journal of Rock Mechanics and Engineering*, vol. 26, pp. 2786–2793, 2007.

[26] Y. Tan, M. Zhang, Q. Xu, W. Guo, F. Yu, and S. Gu, "Study on occurrence mechanism and monitoring and early warning of rock burst caused by hard roof," *Coal Science and Technology*, vol. 47, pp. 166–172, 2019.

[27] E. Wang, J. Feng, Q. Zhang, X. Kong, and X. Liu, "Mechanism of rock burst under stress wave in mining space," *Journal of China Coal Society*, vol. 45, pp. 100–110, 2020.

[28] M. Qian and G. Zhao, "Mine pressure changes before and after Laoding fracture," *Journal of China University of Mining and Technology*, vol. 14, 1986.

[29] Y. Tan and Y. Yang, "The mechanism and engineering significance of rebound," *Mechanics and Practice*, vol. 21, 1996.

[30] J. Jiang, Y. Tan, and Y. Song, "Dynamic law of bearing pressure appearance and prediction method of intrusion pressure," *Journal of Engineering Geology*, vol. 72, 1994.

[31] X. Zhong, "The fracture position of the old roof and the rebound of the roof," *Journal of Xiangtan Mining Institute*, vol. 8, p. 47, 1993.

[32] J. Han, H. Liang, C. Cao, Z. Bi, and Z. Zhu, "A mechanical model for sheared joints based on Mohr-Coulomb material properties," *Géotechnique Letters*, vol. 8, no. 2, pp. 1–14, 2018.

[33] C. Cao, T. Ren, and C. Cook, "Calculation of the effect of Poisson's ratio in laboratory push and pull testing of resin-encapsulated bolts," *International Journal of Rock Mechanics and Mining Sciences*, vol. 64, pp. 175–180, 2013.

[34] D. Xue, J. Wang, Y. Zhao, and H. Zhou, "Quantitative determination of mining-induced discontinuous stress drop in coal," *International Journal of Rock Mechanics and Mining Sciences*, vol. 111, pp. 1–11, 2018.

[35] D. Xue, H. Zhou, Y. Zhao, L. Zhang, L. Deng, and X. Wang, "Real-time SEM observation of mesoscale failures under thermal-mechanical coupling sequences in granite," *International Journal of Rock Mechanics and Mining Sciences*, vol. 112, pp. 35–46, 2018.

[36] X. Wu, Y. Peng, J. Xu, Q. Yan, W. Nie, and T. Zhang, "Experimental study on evolution law for particle breakage during coal and gas outburst," *International Journal of Coal Science & Technology*, vol. 7, no. 1, pp. 97–106, 2020.

[37] L. Li, F. Li, Y. Zhang, D. Yang, and X. Liu, "Formation mechanism and height calculation of the caved zone and water-conducting fracture zone in solid backfill mining," *International Journal of Coal Science & Technology*, vol. 7, no. 1, pp. 208–215, 2020.

[38] S. Xie, D. Chen, J. Zeng, Q. Zhang, S. Yue, and X. Wu, "Space-time relationship between the first fracture of main roof structure and whole regional rebound," *Journal of China Coal Society*, vol. 44, pp. 2650–2663, 2019.

[39] Y. Huang and F. He, *Beams, Plates, and Shells on Elastic Foundations*, Science Press, Beijing, China, 2005.

[40] L. Dou, K. Yang, and X. Chi, "Fracture behavior and acoustic emission characteristics of sandstone samples with inclined precracks," *International Journal of Coal Science & Technology*, vol. 8, no. 1, pp. 77–87, 2021.

[41] D. J. Xue, H. W. Zhou, Y. T. Liu, L. S. Deng, and L. Zhang, "Study of drainage and percolation of nitrogen-water flooding in tight coal by NMR imaging," *Rock Mechanics and Rock Engineering*, vol. 51, no. 11, pp. 3421–3437, 2018.

[42] J. Wang, W. Wei, and J. Zhang, "Theoretical description of drawing body shape in an inclined seam with longwall top coal caving mining," *International Journal of Coal Science & Technology*, vol. 7, no. 1, pp. 182–195, 2020.

[43] X. Lian, H. Hu, T. Li, and D. Hu, "Main geological and mining factors affecting ground cracks induced by underground coal mining in Shanxi Province, China," *International Journal of Coal Science & Technology*, vol. 7, no. 2, pp. 362–370, 2020.

[44] J. Wang, S. Song, and P. Li, "An experimental research of dynamic characteristics for long wall shearer cutting unit gearbox in oblique cutting," *International Journal of Coal Science & Technology*, vol. 7, no. 2, pp. 388–396, 2020.

[45] L. Li, W. Li, and Y. Pan, "Influence of impact disturbance on anomalously low friction rock bursts," *Chinese Journal of Rock Mechanics and Engineering*, vol. 38, pp. 111–120, 2019.