Analysis of rockburst driving mechanism based on unbalanced force

C Y Li1,2, F S Xie1, P X Qin1,2, Y Zhang1, Q Yang1, Y R Liu1, Z S Li1

1 State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China
2 Huaneng Tibet Yarlung Zangbo River Hydropower Development Investment Co., Ltd., Chengdu 610093, China

Corresponding author’s e-mail: yangq@tsinghua.edu.cn

Abstract. Rockburst is a sudden disaster that occurs during the underground excavation. It is still challenging to predict the rockburst quantitatively. In the underground excavation, the complex geological structures, the mechanical properties of rock mass, the shape of the excavation and the construction process have an important influence on the occurrence and extent of the rockburst. Nonlinear finite element analysis can model these influencing factors comprehensively and efficiently. However, it is very difficult to analyze the overall stability of the system based on the nonlinear finite element method, and the quantitative indicators for rockburst prediction based on the nonlinear finite element analysis are rare. According to the deformation reinforcement theory, the distribution of unbalanced force during the structural deformation indicates the potential damage zone and its distance from the unbalanced state to the equilibrium. It can also be considered as the driving force of the non-equilibrium evolution of rock mass. In this paper, the physical mechanism and prediction of rockburst are both explored based on the nonlinear finite element analysis using the concept of the unbalanced force. The distribution of unbalanced force during tunnel excavation is modeled considering the geological structures and in-situ stress field. The sensitivity analysis of case studies with changing ratio between horizontal and vertical in-situ stress, inner and outer layer stiffness, and fault dip angle is conducted. Unbalanced force distribution accords with the conclusion of strength theory and stiffness theory and can be used to explore strain rockburst and strain-structure slip rockburst. The unbalanced force can reflect the driving mechanism of rockburst and can be employed as the driving force of rockburst.

1. Introduction
Rockburst is a sudden disaster, which is caused by the excavation breaking the original mechanical balance and releasing the deformation energy of rock mass rapidly. Rockburst in deep buried long tunnel may cause serious consequences. For example, rockburst during the construction of Jinping II long tunnel caused serious damage to tunneling equipment and support system, with serious casualties, schedule delays, increased costs. Rockburst occurs mainly in the complete hard rock (strain burst). If the rock mass have scattered structural plane or bedding plane, these structural plane often control effect to the degree and scope of rockburst (strain-structure slip rockburst). The existence of large fault may cause rockburst with larger influence area and stronger destructivity (fracture sliding). The current theory of the rockburst mechanism includes the strength theory, stiffness theory, energy theory, tendency theory, etc.[1-5]. These theories all have their own mechanical models and evaluation indexes. This paper mainly explores how to establish a theory of rockburst mechanism and prediction based on nonlinear finite element analysis.

The strength theory[6-8] takes the strength-stress ratio as the rockburst criterion, which is simple and practical. Rockburst is also closely related to rock mechanical properties. The evaluation of rockburst proneness[4, 5] is reflected by propensity indexes, such as the index of rockburst proneness, impact energy index, energy release rate, improved brittleness index, dynamic time, strength brittleness Coefficients and so on. Strength theory and rockburst proneness theory mainly reflect the stress and
material properties of structural characteristic parts, and they are insufficient to reflect the overall stability of the structural system.

If the flexible press is used for uniaxial compression test, the rock specimen will be severely damaged. If the test is carried out with a rigid press, the failure process of the rock specimen is very smooth. Petukhov[9] and Cook[10] linked this phenomenon to the mechanism of rockburst, and pointed out that the reason for the severe failure of rock specimen (corresponding to rockburst) was that the stiffness of rock specimen was greater than that of the press (the loading system), which was the basic idea of "stiffness theory". Blake[11] further pointed out that the stiffness of mine structure (ore body) greater than that of mine load(surrounding rock) is a necessary condition for rockburst. Chinese scholars[12] have also carried out research in this field. Based on the stiffness theory, the energy theory is further developed[13, 14], reflecting the energy transformation of structural system. Stiffness theory and energy theory take the overall stability of structural system as the starting point, which is a big step forward compared with strength theory and tendency theory, but they simplify the practical problems greatly and belong to the conceptual model.

In essence, rockburst is the unsteady expansion of brittle fracture of rock, which is not related to the yield zone reflecting toughness, nor to the ultimate bearing capacity of structure. The cracking of rockburst is somewhat similar to the cracking of building caused by the uneven deformation of foundation, when the foundation load is far below the ultimate bearing capacity of foundation. The 3D cracking analysis of rock mass structure is difficult and requires a great amount of calculation, and the results are very unstable. Various advanced numerical methods, such as extended finite element[17], phase field model[18], and near-field dynamics[19], cannot solve this problem well. The high efficiency of finite element analysis is based on the continuity of the structure. Cracking destroys the continuity of the structure, which sharply reduces the efficiency and stability of the crack analysis based on the finite element method.

Before reaching the ultimate state of the structure, the deformation coordination condition may lead to the local stress concentration of the structure, and the structural cracking initiation actually weakens the local deformation coordination condition to reduce the stress concentration. In nonlinear finite element analysis, the mechanical effect of cracking is usually simulated by damage or softening material models. However, the complexity of such models makes the calculation unstable and the amount of calculation is too large. In this study, on the contrary, the material model without damage or softening is adopted. This simple material model is inevitably unable to adapt to the structural analysis with high stress concentration area, resulting in no solution in calculation and the presence of stable residual unbalanced force that cannot be eliminated. In fact, the residual unbalanced force is an indirect reflection of the structural cracking initiation: the area where the unbalanced force is concentrated is the possible cracking site, and the magnitude of the unbalanced force is the driving force of the unsteady expansion of the cracking.

In this paper, the driving mechanism and driving force of rockburst are discussed by the elastoplastic finite element analysis. Elastoplastic finite element analysis can fully reflect the influence of crack surface, in-situ stress and cavity shape, but its solutions are all equilibrium solutions, that is, the force (equivalent nodal force of external load) and the resistance (equivalent nodal force of stress field) must be balanced, so that the structure is balanced and stable, and there will be no rockburst. Deformation reinforcement theory[20,21] expands the conventional elastoplastic finite element analysis, allowing the force and resistance to be inconsistent, and the difference between them is the unbalanced force. Its basic idea is that the unbalanced force is the driving force of structural failure and the reinforcement force required by the structure to avoid damage. In this paper, a series of typical examples (varying in-situ stress, surrounding rock stiffness and crack plane) are used to illustrate the rationality of the unbalanced force as the driving force of rockburst.

Since the unbalanced force is only a distributed force vector on the nodes, it is not convenient to evaluate the possibility of rockburst of the whole structure. Therefore, the total unbalanced force (TF) is used to calculate the total amount of unbalanced force in the model, as a quantitative index for the evaluation of rockburst propensity,
\[ TF = \sqrt{\left(\frac{1}{2} \sum \Delta F_x \right)^2 + \left(\frac{1}{2} \sum \Delta F_y \right)^2 + \left(\frac{1}{2} \sum \Delta F_z \right)^2} \]  

Where \( \Delta F_x, \Delta F_y, \Delta F_z \) is the unbalanced force component of each node, and \( n \) is the number of model nodes.

2. Strain rockburst in homogeneous tunnel
In order to study the strain rockburst, a basic homogeneous tunnel model is first established. The external size of the established homogeneous tunnel finite element model is 50m\(\times\)50m\(\times\)50m. The diameter of the circular cavity is 10m without supporting. The total number of elements is 48 784, and the total number of nodes is 45 360. The physical and mechanical parameters of surrounding rock are listed in Table 1. Both the front and back (\(x=0m, x=50m\)) and the bottom (\(z=25m\)) are constrained. The uniform surface forces \( \sigma_x \) and \( \sigma_y \) were applied on the left and right sides (\(y=-25m, y=25m\)) and the top surface (\(z=-25m\)), as shown in Figure 1.

**Table 1. Physical and mechanical parameters of rock**

| Material | Density/10^3kg/m³ | Elasticity modulus/GPa | Poisson ratio | Friction coefficient | Cohesion/MPa |
|----------|-------------------|------------------------|---------------|---------------------|--------------|
| rock     | 2.6               | 22                     | 0.22          | 1.35                | 1.5          |

**Figure 1.** Schematic diagram of tunnel model

The calculation cases is divided into two groups. The first group keeps the same horizontal and vertical in-situ stress, that is, keep \( \sigma_x = \sigma_y \), and only adjust the magnitude of in-situ stress, making it vary in 10–80MPa. In the second group, the horizontal in-situ stress is different from the vertical in-situ stress. The vertical in-situ stress is kept constant at 40MPa, and the horizontal in-situ stress (\( \sigma_y \)) is varied in 10–80MPa.

Figure 2(a)-(h) shows the distribution of unbalanced force and plastic zone near the tunnel with in-situ stress value of 10-80MPa under the same horizontal and vertical in-situ stress. Figure 3(a)-(h) shows the distribution of unbalanced force and plastic zone near the tunnel with a horizontal in-situ stress of 10-80MPa and a constant vertical in-situ stress of 40MPa. The red part in the figure represents the plastic zone, and the arrow represents the unbalanced force. It can be seen that with the increase of local stress, both the unbalanced force and the range of plastic zone increase. When the vertical ground pressure remains unchanged and the horizontal ground stress continues to increase, the unbalanced force concentration area and the plastic zone concentration area gradually concentrate from the side to the top, that is, under the homogeneous geological conditions and the same depth of tunnel, the smaller the lateral pressure is, the greater the possibility of rockburst occurs on both sides. The greater the lateral pressure, the greater the chance of rockburst at the top. This is consistent with the results
obtained from the rough estimation of the site of rock burst according to the stress concentration effect of orifice.

![Figure 2. The distribution of unbalanced force and plastic zone when horizontal and vertical geostress is the same](image)

![Figure 3. The distribution of unbalanced force and plastic zone when vertical geostress is constant](image)

### 3. Unbalanced force and stiffness theory of rockburst

Inspired by stiffness theory that differences in the different parts stiffness of surrounding rock have the influence of rockburst, the surrounding rock is considered to be stratified and the trend of rockburst was considered when the stiffness of different parts of surrounding rock was changed.

The surrounding rock of the model is divided into near-field surrounding rock and far-field surrounding rock, as shown in Figure 4. The size, boundary conditions and material parameter conditions of models are consistent with the homogeneous surrounding rock model in Chapter 2, with the vertical in-situ stress $\sigma_z = 40\text{MPa}$ and horizontal in-situ stress $\sigma_y = 30\text{MPa}$. The calculation conditions include: the elastic modulus of the near field surrounding rock is kept as 25GPa, and the elastic modulus of the far field surrounding rock is changed in the range of 5~50GPa; The elastic modulus of the far field surrounding rock is kept as 25GPa, and the elastic modulus of the near field surrounding rock is changed in the range of 5~50GPa.
Figure 4. Schematic diagram of surrounding rock stratification

Figure 5 shows the changes of plastic zone and unbalanced force when the near-field surrounding rock stiffness is maintained at 25GPa and the far-field surrounding rock stiffness is 5Gpa-50GPa. Figure 6 Changes of plastic zone and unbalanced force when the stiffness of far-field surrounding rock is maintained at 25GPa and the stiffness of near-field surrounding rock is 5Gpa-50GPa. When the elastic modulus of near field surrounding rock remains unchanged, and when the elastic modulus of far field surrounding rock increases gradually, the unbalanced force around the tunnel gradually decrease, and the plastic zone also decreases gradually, and the risk of rockburst decreases. Similarly, when the elastic modulus of far-field surrounding rock remains unchanged and the elastic modulus of near-field surrounding rock gradually increases, the unbalanced force gradually increases and the risk of rockburst increases. This is consistent with the understanding of the stiffness theory of rockburst.

Figure 5. The change of plastic zone and unbalanced force when the stiffness of near-field surrounding rock is invariable
However, the reduction of surrounding rock stiffness will inevitably lead to the reduction of strength, and the reduction of near field surrounding rock strength and stiffness can lead to a sharp increase in the unbalanced force. A possible measure to prevent and control rockburst in practical engineering is to set aside a certain depth and form part of the internal surrounding rock into artificial fracture zone, reduce its physical and mechanical parameters, so as to weaken the occurrence of rockburst. This method called the stress release method by blasting behind the work face[24]. The influence of this method on the unbalanced force of surrounding rock is discussed below.

The calculation model and the size of the tunnel are consistent with the homogeneous surrounding rock model in Chapter 2, and all models keep the same horizontal and vertical in-situ stress of 40MPa. A circle of artificial fracture zone is set, and the thickness of the fracture zone is kept at 1m, as shown in Figure 7.

![Figure 7. Schematic diagram of tunnel with fracture zone](image)

The fracture zone is simulated by the equivalent method of reducing the parameters. The physical and mechanical parameters of the surrounding rock is the same with the model above. Consider the influence of distance between the fracture zone and the tunnel, and physical and mechanical parameters of fracture zone.

Consider changing the Elasticity modulus of fracture zone and distance between the fracture zone and the tunnel, and the results are shown in Table 2. The unbalanced force decreases with the decrease of elasticity modulus and increase of distance. The change of elasticity modulus has a stronger influence than that of distance.

**Table 2. Unbalanced force(ton) with different distance and elasticity modulus**

| Distance | 2GPa  | 1GPa  | 0.5GPa | 0.2GPa |
|----------|-------|-------|--------|--------|
| 2m       | 218.44| 133.77| 53.09  | 4.44   |
Considering the influence of the strength change of fracture zone, the friction coefficient and cohesion is reduced in the same proportion. Keep the distance at 5m, elasticity modulus 2GPa. Results are shown in table 3. The strength of fracture zone has little influence to the unbalanced force. The reason is the reduction of stiffness will lead to the reduction of stress in fracture zone. Even if the strength parameter is reduced, if it is not close to yield, the strength parameter has almost no effect on the simulation results.

Table 3. Unbalanced force with different friction coefficient and cohesion

| Friction coefficient | Cohesion/MPa | Unbalanced force/t |
|----------------------|--------------|--------------------|
| 1.35                 | 1.35         | 183.60             |
| 1.215                | 1.20         | 183.60             |
| 1.08                 | 1.05         | 183.60             |
| 0.945                | 0.90         | 183.60             |
| 0.54                 | 0.60         | 183.60             |
| 0.27                 | 0.30         | 161.65             |

Considering the physical and mechanical properties of actual rock mass, the parameters fracture zone are taken as Table 4

Table 4. Physical and mechanical parameters of the fracture zone

| Material          | Density/10³kg·m⁻³ | Elasticity modulus/GPa | Poisson ratio | Friction coefficient | Cohesion/MPa |
|-------------------|--------------------|------------------------|---------------|----------------------|--------------|
| fracture zone     | 2.6                | 2                      | 0.35          | 0.50                 | 0.2          |

Change the distance between the fracture zone and the tunnel to 0.5-15m, and the results of unbalanced force are shown in Figure 8. With the increase of the distance, the unbalanced force decreases first and then increases. The unbalanced force of the 2m to 15m cases is less than that of the case without fracture zone(254.92t), and the unbalanced force is the least at 5m.

4. Unbalanced force and strain-structure slip rockburst

Zhou Hui et al.[22, 23] analyzed the control mechanism of structure facing rockburst through the study of deep buried tunnel of Jinping II Hydropower Station. Feng Xiating et al.[24] considering the
influence of hard structure on the grade and mechanism of rockburst, proposed to add the category of strain-structure slip rockburst in addition to the usual strain type and fracture type rock burst. The surrounding rocks of the tunnel discussed in chapter 2 and 3 are all intact, and the rockburst occurred also belongs to strain rockburst. The influence of structural plane is considered in this chapter, and the law of strain-structure slip rockburst is analyzed.

Based on the original homogeneous model, a 30m long and 0.26m wide fault structural plane was added through the center of the tunnel. This fault is regarded as a weak interlayer and solid element is adopted. Physical and mechanical parameters of the fault are listed in Table 5. Finite element models with fault dip angles of 0°, 30°, 45°, 60° and 90° were established, in which the dip angle refers to the angle between the fault plane and the horizontal direction. The vertical in-situ stress of each model is maintained at 40MPa and the horizontal in-situ stress is varied between 10-80MPa. Figure 9 is the schematic diagram of fault model.

**Table 5. Physical and mechanical parameters of fault**

| Material | Density/10^3 kg/m³ | Elasticity modulus/GPa | Poisson ratio | Friction coefficient | Cohesion/MPa |
|----------|---------------------|------------------------|---------------|----------------------|--------------|
| Fault    | 2.6                 | 2                      | 0.35          | 0.50                 | 0.2          |

![Figure 9. Schematic diagram of fault model](image)

Figure 10 shows the unbalanced force and plastic zone of the fault model with different horizontal in-situ stresses and different dip angles. For each case, the unbalanced force is concentrated near the fault of the tunnel wall, indicating that the rock burst mainly occurs near the fault, and the unbalanced force is greater than that of the homogeneous model without fault, indicating that the fault through the tunnel will greatly increase the risk of rockburst. Compared with the homogeneous model without faults, the distribution of plastic zones is no longer uniformly and symmetrically distributed around the tunnel, but the plastic zone near the fault is larger and the plastic zone near the tunnel wall far away from the fault is smaller. The concentrated distribution of unbalanced force and plastic zone near the fault also reflects the control effect of the structural face on strain-structure slip rockburst.

By comparing the results of different dip angles and different in-situ stress conditions, when the horizontal in-situ stress is less than the vertical in-situ stress, the smaller the dip angle is, the higher the maximum unbalanced force is. When the dip angle is 0°, the possibility of local rockburst is the highest and the overall stability is the lowest. When the horizontal in-situ stress is equal to the vertical in-situ stress, the maximum unbalanced force and the overall stability of the tunnel change little with the fault angle, indicating that the local rockburst and the overall stability of the tunnel change little with the fault dip angle under uniform confining pressure. When the horizontal in-situ stress is greater
than the vertical in-situ stress, the greater the inclination is, the higher the maximum unbalanced force is.

Figure 10. Change of plastic zone and unbalanced force in fault model

Figure 11 shows the variation of the model's unbalanced force with horizontal in-situ stress when the fault dip is 45°. The unbalance force of the uniform model is 250 tons under the uniform in-situ stress of 40MPa, while the unbalance force of the 45° inclination fault model is 32 000 tons under the same in-situ stress, which is two orders of magnitude higher than that of the uniform model. With the increase of horizontal stress, the unbalanced force increases significantly. This indicates that the fault through the tunnel and high in-situ stress will greatly increase the risk of rockburst.

Figure 11. Variation of unbalanced force of 45° dip fault model with different horizontal in-situ stress

For the fault model with a 90° dip Angle, keep the in-situ stress as 40MPa and change the number of iterations for the calculation of unbalanced force. The results of plastic zone and unbalanced force with different iterations are shown in Figure 12(a)-(f). For the homogeneous model, the unbalanced
force decreases uniformly with the increase of the number of iterations. The unbalanced force near the fault decreases more slowly with the increase of iteration times than the unbalanced force at other positions. After iteration, the unbalanced force gradually concentrates near the fault, which reflects the control effect of the structure on rockburst.

![Figures](image)

**Figure 12. Unbalanced force and plastic zone distribution in fault model with different iteration steps**

5. Summary
In this paper, a tunnel model with uniform geological conditions and stiffness stratification, structural plane and other conditions is established, and the influence of these geological conditions on rockburst is analyzed through unbalanced force. The main conclusions are as follows:

(1) Compared with homogeneous geological conditions and uniform in-situ stress, with the increase of horizontal in-situ stress, the area of unbalanced force concentration changes from two sides to the top and bottom; The position of the maximum unbalanced force and the maximum tangential stress coincide basically, which accords with the strength theory of rockburst.

(2) Compared with homogeneous geological conditions, the variation of surrounding rock stiffness has a significant effect on the distribution of unbalanced force in the tunnel. The greater the stiffness of the near field surrounding rock, the greater the unbalanced force; The greater the stiffness of the far field surrounding rock, the smaller the unbalanced force. This is consistent with the understanding of rockburst stiffness theory. The stress release method by blasting behind the work face can reduce the unbalanced force.

(3) Once the structural plane is added into the homogeneous tunnel, the unbalanced forces are concentrated on the structural plane, and mainly concentrated on the intersection of the structural plane and the tunnel, which explains the main characteristics of strain-structure slip rockburst. The distribution regularity of unbalanced force obtained in this paper is consistent with the understanding of strength theory and stiffness theory of rockburst, and also agrees with the general understanding of strain rockburst and strain-structure slip rockburst. This shows that the unbalanced force can quantitatively explain the driving mechanism of rockburst to a certain extent, and the unbalanced force analysis can be applied to more complex rockburst analysis. The analysis of unbalanced force can also be used to guide rockburst support because the unbalanced force is reinforcement force.

Acknowledgments
This work has been supported by the science and technology project of China Huaneng Group Co., Ltd 'HMKJ18-27 Study on rockburst evolution law and key technology of control mechanism in extremely high geostress tunnel' (PM2019/P05), the National Key R&D Program of China (2018YFC0407005) and National Natural Science Foundation of China under projects 51739006 and 41961134032.

References
[1] Qian Q H 2014 Definition, mechanism, classification and quantitative forecast model for rockburst and pressure bump Rock and Soil Mechanics 35(1) 1-6
[2] Feng X T, Xiao Y X and Feng G L 2019 Study on the development process of rockbursts Chinese Journal of Rock Mechanics and Engineering 38(04) 649-673
[3] Li C L 2019 Rockburst conditions and rockburst support Chinese Journal of Rock Mechanics and Engineering 38(04) 674-682
[4] Zhang C Q, Lu J J and Chen J 2017 Discussion on rock burst proneness indexes and their
relation *Rock and Soil Mechanics* 38(5) 1397-1404

[5] Singh S P 1986 Assessment of the rockburst proneness in hard rock mines *Pro. 5th Conf. on Gro. Contr. in Min.* 242-248

[6] Barton N, LIEN R and LUNDE J 1974 Engineering classification of rock masses for the design of tunnel support *Rock Mechanics Felsmechanik Mecanique Des Roches* 6(4) 189-236

[7] Hoek E, Martin C D 2014 Fracture initiation and propagation in intact rock - A review *Journal of Rock Mechanics and Geotechnical Engineering* 6(4) 287-300

[8] Turchaninov I A, Markov G A and Lovchikov A V 1981 Conditions of changing of extra-hard rock into weak rock under the influence of tectonic stresses of massifs *Proceedings of the International Symposium on Weak Rock* 555-559

[9] Petukhov I M 1957 Rockbursts in Kizel Coalfield Mines *Perm:Perm. Publ*

[10] Cook N G W 1965 A note on rockbursts considered as a problem of stability *Journal of the Southern African Institute of Mining and Metallurgy* 65(8) 437-446

[11] Blake W 1972 Rock-burst Mechanics *Quarterly of the Colorado school of mines* 67(1) 1-64

[12] Cheng C 2013 Study on rock mass Stiffness Effect of strain rock burst *China University of Mining and Technology (Beijing)*

[13] Jaeger J C, Cook N G W, Zimmerman R W 2007 Fundamentals of Rock Mechanics *Malden: Blackwell Publishing Ltd*

[14] Salamon M D G 1983 Rockburst hazard and the fight for its alleviation in South African gold mines *Rockbursts Prediction and Control* 11-35

[15] Zhuo J S, Zhang Q 2000 Interface element method of discontinuous media mechanics *Beijing:Science Press*

[16] Yin Y Q 2007 The basis of nonlinear finite element method *Beijing:Peking University Press*

[17] Belytschko T, Black T 1999 Elastic crack growth in finite elements with minimal remeshing *International Journal for Numerical Methods in Engineering* 45(5) 601-620

[18] Cazes F, Moes N 2015 Comparison of a phase-field model and of a thick level set model for brittle and quasi-brittle fracture *International Journal for Numerical Methods in Engineering* 103(1) 114-143

[19] Silling S A 2000 Reformulation of elasticity theory for discontinuities and long-range forces *Journal of the Mechanics and Physics of Solids* 48(1) 175-209

[20] Yang Q, LIU Y R and Chen Y R 2008 Deformation reinforcement theory and global stability and reinforcement of high arch dams *Chinese Journal of Rock Mechanics and Engineering* 27(6) 1121-1136

[21] Yang Q, Wang S G and Li C Y 2020 Internal driving force of deformation and failure of rock mass structure-unbalanced force *Journal of Engineering Geology* 28(2) 202-210

[22] Zhou H, Meng F Z and Zhang C Q 2015 Characteristics of shear failure of structural plane and slip rockburst *Chinese Journal of Rock Mechanics and Engineering* 34(9) 1729-1738

[23] Zhou H, Meng F Z and Zhang C Q 2015 Analysis of rockburst mechanisms induced by structural planes in deep tunnels *Bulletin of Engineering Geology and the Environment* 74(4) 1435-1451

[24] Xu X D 2008 Preliminarily Exploration on the Function Mechanism of Prevention and Treatment of Rockburst for Tunnel *Journal of Railway Engineering Society* 10 36-39

[25] Feng X T, Chen B R and Zhang C Q 2013 Mechanism, warning and dynamic control of rockburst development processes *Beijing: Science Press*

[26] Yang Q, Zhang Y and Y R Liu 2020 Driving force of rockburst in deep tunnel with geological structure based on non-equilibrium evolution *IOP Conference Series: Earth and Environmental Science* 570(5) 052053