Numerical Simulation Research on Rockburst Prediction of Gaoloushan Deep Tunnel Based on Strength-stress Ratio Method

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Abstract. In view of the complex geological environment of deep buried tunnel, the great harm of rock burst, and the serious hidden danger to the underground engineering construction and the safety of the workers, it is necessary to adopt an effective method to reasonably predict the rock burst, so as to carry out the rock burst disaster warning. Based on the strength-stress ratio method, the possibility of rockburst in the deep-buried tunnel of Pingliang-Mianyang National Expressway is predicted in this paper. At the same time, the FLAC3D numerical simulation software was used to build a numerical model to simulate the excavation process of the deep buried tunnel, so as to analyze the stress state of the surrounding rock of the deep buried tunnel, and the ratio of the maximum principal stress \( \sigma_1 \) of the surrounding rock obtained from the simulation calculation to the uniaxial compressive strength \( R_c \) of the rock in the excavation process. According to the ratio, the possibility level of rockburst at different length sections along the deep buried tunnel is divided, analyzed and predicted, and compared with the actual situation of rockburst in the field, the results show that the location of rockburst and the rockburst level of the corresponding length are basically the same. This discriminant method can provide reference and relevant reference for rockburst prediction of similar engineering.

1 Introduction

Rockburst refers to a dynamic mechanical phenomenon in which the stored strain energy is released instantly in the deep underground excavation or in the area with high tectonic stress, resulting in a sharp and violent outburst or ejection of some rocks around the excavation space from the parent rock [1]. Rock burst is very harmful, which greatly threatens the construction of underground engineering and the safety of personnel and equipment. Moreover, the process of rock burst is very complex, and
there are many control and influence factors. The mechanical properties of rock mass, the in-situ stress state, the permeability characteristics of rock mass, the cross-section shape of underground cavern and the excavation method all become the influencing factors of rock burst. To sum up, there are two main factors: one is the nature of the rock; The second is the stress of surrounding rock. Among these two factors, lithology is generally considered to be the primary and the internal factor for the occurrence of rock burst, while surrounding rock stress is secondary, which belongs to the external factor for the occurrence of rock burst and is also the necessary condition for its occurrence [2].

At present, the prediction methods of rock burst are mainly divided into theoretical analysis, numerical simulation analysis and field measurement analysis [3].

The theoretical analysis method is mainly used to predict the occurrence of rock burst by studying the mechanism of rock burst and classifying the factors affecting the occurrence of rock burst, so as to achieve the prediction of rock burst. Foreign scholars Russense[4] proposed a criterion for comparing the maximum tangency stress of the tunnel wall with the uniaxial compressive strength of rock; Barton[5] proposed a criterion for comparing the uniaxial compressive strength of rock with the maximum principal stress of original rock; Turchaninov[6] proposed a criterion for comparing the maximum tangency stress of the tunnel wall. After analyzing the criterion of the relationship between the axial stress of the cave and the uniaxial compressive strength of rock, with the in-depth research of domestic scholars, Tao Zhenyu [7], Xu Linsheng and Wang Lansheng et al. [8] proposed the criterion based on the strength theory, and Hou Liang [9] and Peng Zhu [10] proposed the relevant criterion of the critical buried depth of rock burst. The energy-based criteria are as follows: Goodman[11] ‘s energy shock index, Kidybinski[12]’s elastic energy index, and Tang Lizhong [13]’s energy storage and consumption index, Gong Fengqiang [14]’s residual elastic energy index. With the comprehensive analysis of the impact on Rockburst disasters, Gu Mingcheng et al. [15] proposed the comprehensive criterion of Rockburst in Qinling Tunnel through the actual investigation on the situation of Rockburst. Qiu Shili [3] proposed the Rockburst tendency Index RVI (Rockburst Vulnerability Index). Zhang Chuanqing et al. [16] proposed the potential rockburst index.

With the development of technology, some scholars have applied numerical simulation to the prediction of rock burst. Feng Xiating [17] was the first to apply neural network intelligent method to rockburst risk estimation. Xu Jia et al. [18] established a neural network prediction model. Feng Xiating and Zhao Hongbo [19] established the prediction and early warning model of support vector machine rockburst earlier. Qiu Daohong et al. [20] and Wen Tingxin [21] also introduced quantum genetic algorithm and rough set theory to optimize the prediction model of support vector machine rockburst. The support vector machine method has made rapid development in the prediction of rock burst.

The field monitoring method is mainly based on the field monitoring of rock parameters such as stress and deformation to predict the rock burst grade and the possibility of its occurrence. These parameters are closely related to the response of rock excavation, the deterioration of the physical properties of surrounding rock, the concentration or transfer of in-situ stress and the change of hydrogeological conditions. At present, the field monitoring methods mainly include microseismic monitoring, acoustic emission detection, microgravity monitoring and infrared thermal imaging [22].

In this paper, based on the strength-stress ratio method, numerical simulation is used to predict and analyze the rock burst in the surrounding rock of Gaoguoshan tunnel based on the engineering background of Gaoguoshan deep buried tunnel in Wujiu section of Pingliang-Mianyang National Expressway.

2 Project Overview
The project is located in Wenxian County, Longnan City, Gansu Province, through Fangma Mountain, the starting point is located in Jianshan Village, Jianshan Township, Wenxian County, the elevation is 1083.5m, the exit is located in Fanchang Village, Wenxian County, the elevation is 914.45m, the entrance pile number is YK46+350 (ZK46+260), exit pile number YK58+510 (ZK58+532), tunnel
length right line 12180m, left line 12272m, the maximum buried depth is about 1680m, is the upstream and downstream double hole deep buried extra long stone mountain crossing tunnel.

Figure 1. Geographical location of tunnel

According to the results of the engineering geological annotation of geophysical exploration and drilling strata outcropped in the tunnel site area is mainly quaternary unconsolidated accumulation and devonian system in bikou group (D21s4), lower palaeozoic era (Pz1bk) clastic rock fracture structure is complex, in the area of regional fracture with regional tectonic line direction changes, the overall protruding southward curved, concentrated development in the central area. The whole working area is affected by fold development, which has complex shape and variable formation occurrence. The secondary fold and interlayer fold development tunnel passes through the lithology of slate metamorphic sandstone and metamorphic conglomerate, in which the slate is soft rock and the metamorphic sandstone and metamorphic conglomerate are hard rock.

Gaogaoshan deep buried tunnel is located in the south mountainous area of West Qinling Mountains. It is an area of intense neotectonic movement, with frequent seismic activity, complex geological structure, exposed rock, large undulating surface, and developed gullies. The geological conditions of the tunnel are complex. With high ground stress (the maximum principal stress in 27-51MPa), high seismic intensity (VIII earthquake zone), high ground temperature (the highest ground temperature may be super high 30°C), the "three high", burial depth (the maximum burial depth of 1680m, The "big three", the length of the inclined shaft (the longest 2.28km) and the long ventilation distance of the construction excavation, are 9km long and 500m deep, large water flow (the maximum water inflow is 0.38m³/s), large temperature difference (the temperature difference between the mountains and the mountains is 10°C). The fault is characterized by more broken zones (there are fault zones at both the inlet and outlet) and more bad geology (fracture, water inrush, rock burst in high in-situ stress area, etc.). The tunnel site is a mountain canyon landform with complex geological structure, and the buried depth of the tunnel is more than 1000m, accounting for about 30% of the total length.

3. Principle and method of strength stress ratio method

Intensive-stress ratio method is to judge the possibility of rock burst and classify the grade of rock burst according to the strength-stress ratio. In recent years, many scholars have summarized a large number of typical cases and data of rock burst at home and abroad, analyzed the mechanism of rock burst, and put forward different assumptions and judgment bases for the occurrence of rock burst according to the distribution characteristics of radial stress or circumscribed stress in the surrounding rock of the cave. However, most of these methods need to carry out complex conversion of the results obtained from numerical simulation calculation before numerical solution can be carried out finally,
and the occurrence of rock burst can be predicted and the classification of rock burst grade can be made. The analysis process is very complex and does not have good practicability. Later, Professor Tao Zhenyu et al. [23] proposed a method to judge rock burst according to the maximum principal stress. Zhang Jingjian et al. [6] further improved Tao Zhenyu criterion and Gu Mingcheng criterion [15], and obtained a modified strength-to-stress ratio method, namely the modified valley. To predict the possibility of rock burst in tunnel surrounding rock by this criterion has better practicability and more accurate prediction results, and the specific form is shown in the following formula.

\[
\begin{align*}
\frac{\sigma_1}{R_c} < 0.15 & \text{ (No rockburst occurred)} \\
0.15 \leq \frac{\sigma_1}{R_c} \leq 0.20 & \text{ (Weak rockburst activity)} \\
0.20 < \frac{\sigma_1}{R_c} \leq 0.40 & \text{ (Moderate rockburst activity)} \\
0.40 \leq \frac{\sigma_1}{R_c} & \text{ (Advanced rockburst activity)}
\end{align*}
\]

Where: \( \sigma_1 \) represents the maximum principal stress of tunnel surrounding rock; \( R_c \) represents the uniaxial compressive strength of rock sample.

4. Stress field simulation of tunnel excavation in Gaoloushan

4.1 Model establishment
The Gaoloushan Tunnel starts from KZ45+800 to KZ59+028. The longitudinal section diagram of the tunnel is shown in Figure 2. The main rock mechanics parameters are shown in Table 1. Taking the tunnel axis as the center, 80m(x) \( \cdot \) 80m(z) was selected as the calculation range on the vertical axis plane, and 80m was extended along the tunnel direction as the Y axis. In the FLAC3D modeling process, Mohr-Coulomb constitutive model was adopted, and the tunnel size was set according to the construction design drawing. There are a total of 126,597 nodes and 186,100 units in the model. The three-dimensional model of tunnel excavation and mesh division in FLAC3D software are shown in Figure 3. The simulation of the excavation process is realized by defining the group where the tunnel is located as null.
Table 1. Rock mechanical parameters within the simulation range

| Lithology            | Density /kg/m³ | Bulk modulus /MPa | Shear modulus /MPa | Frictional angle/° | Cohesion /MPa | Tension /MPa |
|----------------------|----------------|-------------------|--------------------|-------------------|---------------|--------------|
| Limestone            | 2670           | 129.38            | 89.08              | 30.56             | 19.35         | 12.5         |
| Schist               | 2690           | 54.24             | 42.39              | 32.60             | 25.39         | 5.5          |
| Bituminous slate     | 2680           | 27.03             | 44.57              | 31.10             | 22.70         | 11.5         |
| Metasandstone        | 2680           | 38.34             | 32.44              | 36.85             | 23.51         | 14.5         |
| Schist               | 2680           | 48.63             | 39.93              | 34.73             | 21.47         | 5.5          |
| Metasandstone        | 2650           | 36.83             | 29.97              | 35.20             | 22.71         | 14.5         |

Table 2. Simulation range

| The section interval | Interval | Buried depth |
|----------------------|----------|--------------|
| KZ47+640~KZ48+060    | 2×210m   | 645m         |
| KZ48+060~KZ49+700    | 8×205m   | 765m         |
| KZ49+700~KZ51+400    | 8×212.5m | 1445m        |
| KZ51+400~KZ53+400    | 10×200m  | 1215m        |
| KZ53+400~KZ55+370    | 9×218.89m| 865m         |
| KZ55+370~KZ56+690    | 6×220m   | 735m         |

Figure 3. 3D model of tunnel excavation and grid division

Boundary conditions are determined as follows: a horizontal displacement constraint is imposed on the left boundary of the model (X=0m) in front of the model (Y=0m), and a vertical displacement constraint is imposed on the lower surface of the model (Z=0m) in the back boundary of the model (Y=80m). The stress boundary conditions are applied at the right boundary (X=80m) and the top boundary (Z=80m), and the stress is applied perpendicular to the boundary surface.

4.2 Simulation results

After the excavation simulation of sections KZ47+640~KZ56+690 was completed, the maximum principal stress of corresponding mileage was recorded, and the maximum principal stress of tunnel excavation and secondary stress distribution in the section was fitted. The distribution curve of the maximum principal stress of surrounding rock at different mileage along the tunnel was shown in Figure. 4(a)~(f). Typical sections are shown in Figure. (a)~(f). It can be seen from (f) that after tunnel excavation, compressive stress concentration is easy to occur at the left and right arch feet and the value of compressive stress is large. As can be seen from Figure (c) and (d), compressive stress concentration is only generated at the left and right arch feet and the value of compressive stress is
large. As a whole, the tunnel along the width and the surrounding rock under more stress state, with the tunnel buried depth and horizontal tectonic stress changes in the environment, surrounding rock stress distribution showed a larger difference, in the deep buried section, tunnel wall and vault area also has a higher compressive stress tunnel after excavation, the tunnel along the maximum principal stress value of up to 100.89 MPa.

![Image](image_url)

**Figure 4.** Cloud map of maximum principal stress distribution after typical cross-sectional tunnel excavation

4.3 The prediction results of rockburst are compared with the actual situation in the field

In the process of tunnel excavation simulation, the $\sigma_i/R$ values at the corresponding mileage are calculated, and the variation characteristics of the $\sigma_i/R$ values at different sections along the tunnel axis are obtained after fitting. This is shown in Figure 5. On this basis, the possibility of rock burst and the activity level of rock burst in different sections in the construction process of Gaoloushan tunnel excavation are predicted by combining the revised criterion of valley and pottery rock burst, namely the strength stress method, as shown in Figure 6.
Figure 5. Variation rule of maximum principal stress after secondary distribution of surrounding rock stress along tunnel axis

Figure 6. $\sigma_1/R_c$ values at different positions along the tunnel

According to the fitting $\sigma_1/R_c$ values at different sections of Gaogaoshan Tunnel, it can be seen that the tunnel is predicted to be divided into three different grades of rockburst areas, which are: high rock burst activity zone; Medium rock burst activity area and weak rock burst activity area, in which, mileage KZ48+265~ mileage KZ52+400 and mileage KZ53+619~ mileage KZ55+590 are in high rock burst activity area; In the middle area of rockburst activity, the ranges are KZ47+640~ KZ48+265...
and KZ55+590~ KZ56+690. Meanwhile, the ranges of KZ52+400~ KZ53+619 are at the boundary between the high and medium area of rockburst activity.

According to the actual situation in the field, high rockburst activity occurs at the position from the right waist of the arch to the top of the arch of the length KZ48+500, with large rock blocks caving. The right side of the excavation platform is broken down by falling blocks, and the rockburst debris is mostly in sheet or plate shape, as shown in FIG. 7 (a). Strong rock burst occurred at the position from the left waist of the arch to the top of the arch in section KZ49+227.2~+230.2, with continuous sound of rock burst, accompanied by rock spaling. The pit was in shallow pit type, close to the disturbance source, and the edge was controlled by the structural plane, belonging to the area of high rock burst activity, as shown in FIG. 7 (b). Due to the environmental and construction conditions of the site, we cannot get more information about the site temporarily. The results show that the distance of the two sites is basically consistent with the simulated prediction. The location where rock burst occurs is thus simulated reliably and can be used for effective guidance to the subsequent construction process.

5 Conclusion
(1) Based on the method of strength stress ratio, the rock burst of high-rise mountain tunnel is reasonably predicted and the rock burst grade is divided. The high rock burst activity area is KZ48+265~ KZ52+400, KZ53+619~ KZ55+590; In the middle rock burst activity area, the mileage is KZ47+640~ KZ48+265, and the mileage is KZ55+590~ KZ56+690, which is consistent with the site situation.
(2) The simulation of tunnel excavation process, can get the result calculated by numerical simulation software, simulation and site condition, the tunnel in the region around the arch foot and vault areas prone to stress concentration, and the compressive stress is large, the whole, tunnel along the width and the surrounding rock mass in compressive stress state, the more With the change of the tunnel depth and the horizontal tectonic stress environment, the stress distribution of the surrounding rock shows great difference. In the deep buried section, the tunnel side wall and the vault also have high compressive stress.
(3) According to this article predicts the level of different rock burst damage and the spot, should according to the corresponding area with reasonable support of the surrounding rock tunnel, large parts of tunnel surrounding rock with compressive stress value at the same time also should take
corresponding support measures, in order to prevent the tunnel rock burst occurs, as to avoid the delay of project as well as personnel and construction equipment damage.

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