Driving force of rockburst in deep tunnels with geological structures based on nonequilibrium evolution

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Abstract. Data from field tests show that rockburst often occurs during the excavation of deep tunnels with geological structures. In the prediction and avoidance of rockburst, the driving force and evolution of the broken rock zone are more important than the final failure state. Deformation reinforcement theory is based on the minimum plastic complementary energy principle and reflects the nonequilibrium evolution for continuous entities. The residual unbalanced force of elastoplastic iteration describes the distance between the balanced and unbalanced states if the equilibrium and yield conditions cannot be satisfied simultaneously. On the basis of the unbalanced stress distribution that cannot be transferred and eliminated in the elastoplastic iteration process, the unstable zone can be distinguished and employed to predict rockburst. The distribution and direction of the unbalanced force represent the possible failure location and mode of the unstable structure. The magnitude of the unbalanced force indicates the severity of the failure. The unbalanced force criterion is compared with the traditional stress criterion through numerical simulations. Numerical simulations show that the worst condition with different geological structures can be addressed with an unbalanced force distribution. An unbalanced force can be employed as the driving force and criterion of rockburst.

1. Introduction

1.1. Background

The excavation speed of a tunnel boring machine (TBM) is 4–10 times that of traditional drilling and blasting methods. Under a high excavation speed, low disturbance, and inadequate strain energy release from surrounding rocks, the TBM method often requires uniform tunneling conditions[1-3]. Rockburst frequently occurs in deeply buried tunnels composed of brittle and high-stiffness rock masses containing joints and faults[4]. When TBM excavation disturbs a balanced system, the potential deformation energy of rock masses is released fiercely, resulting in a unique dynamic destruction[5, 6] that leads to severe consequences and mass casualties.

In August and October 2016, a TBM was used to traverse the undesirable geological segments of the Duoxiongla traffic tunnel with jointed and fractured surrounding rock mass mainly consisting of granite (Figure 1). A number of segments were filled with developed geological faults and compression zones. Frequent rockburst-induced TBM jamming delayed the construction period for ten days to a month, thereby resulting in significant losses for the construction project at an elevation of nearly 3,000 m. Four instances of TBM jamming were recorded. Then, detailed investigations were conducted to determine the reason behind the jamming. The possible causes included faults or compressor-crushed zones around rockburst sections. Figure 2 shows that rock mass fragments from a
mucking system suffered from extreme crashing without flakes or bulks. The fourth instance of jamming was extremely severe because the whole TBM shield was buried, unlike that in the first three instances wherein only a part of the TBM shield was buried. According to the field investigation, a set of geological structural planes along the tunnel axis caused the local collapse. However, the geological structures were not the only cause of rockburst; a high stress–strength ratio was another important clue that led to the great convergence deformation. The deformation lasted for a long time even after lining.

To analyze the generation mechanism of rockburst or sudden rock failure, researchers have developed numerous theories and test methods on the basis of assumed rock strength, stiffness, energy, fracture, etc. Rockburst can be roughly divided into two types, namely, strainburst and impact-induced rockburst[7, 8]. The fourth jamming in the Duoxiongla tunnel was an impact-induced rockburst induced by the parallel joints and TBM excavation. The research on impact-induced rockburst is not as broad as that on strainburst. Hence, a relevant criterion should be established to predict rockburst tendency in TBM tunneling and predict the worst situations, especially in tunnels with geological structures such as the Duoxiongla tunnel.

1.2. Rockburst tendency criteria and research routine
A number of simple criteria have been developed on the basis of the data obtained from field and laboratory tests. The degree of stress intensity, which reflects the relationship between stress and surrounding rock strength, can be employed to predict rockburst. Russense’s criterion[9] is the ratio of the maximum tangential boundary stress to the laboratory unconfined compressive strength. The Turchaninov criterion[10] is the ratio of the sum of axial stress and maximum shear stress in the cross section to the uniaxial compressive strength. The energy release in the process of loading and unloading is another criterion and is referred to as the energy release rate (ERR)[11]. The elastic strain energy index[12] is the ratio of the elastic strain energy released by unloading to the elastic strain energy lost. The rock impact energy criterion[13] is the ratio of the energy before the peak strength to the energy required for failure after the peak. Other criteria are based on complicated mechanics. Liu et al.[14] explained the formation of rockburst and proposed the rockburst damage energy index on the basis of damage mechanics. Peng et al.[15] derived a formula for measuring the critical stress of rockburst during the excavation of an underground cavern on the basis of Griffith theory and fracture mechanics. Zhang et al.[16] summarized a five-factor comprehensive method based on fuzzy mathematics.

In the current study, a new rockburst tendency criterion based on deformation reinforcement theory (DRT) [17] is proposed and verified through nonlinear numerical simulations under different geological conditions. Figure 3 shows the general scheme. Field test data, including those obtained from acoustic velocity tests and digital panoramic borehole imaging, are analyzed to obtain the thickness of the loosened zone, geostress, and rock strength parameters used for the numerical
simulations. The plastic zone in the nonlinear simulation is employed for comparison with the field data result. An outcome of the simulation is the unbalanced force vector field. Theoretical plastic analysis and the ratio of geostress and rock strength are considered to verify the simulation results. The unbalanced force vector field provides extensive information about the nonequilibrium evolution process. In addition to the estimated geostress and rock strength parameters in the deep tunnel, the influence of the geological structure, including the joint connectivity rate, joint density, and joint dip angle, is examined to establish the worst situation during the excavation of the Duoxiongla tunnel. The distribution and magnitude of the unbalanced force are adopted as the pivotal criterion and driving force of rockburst.

2. **Unbalanced force as the driving force and criterion of nonequilibrium evolution**

The new Austrian tunneling method principle (NATM)[18], the Pan Jiazheng extremum principle (PWP)[19], and DRT are proposed to explain the same principle in rock mechanics from different aspects. The NATMP is proposed for tunnel support, the PWP for landslide protection, and DRT for ideal elastoplastic continuum materials. DRT is summarized from a universal perspective and can be described in the following three aspects:

- When the external load is more massive than the structural resistance, the unbalanced force is the difference that cannot be eliminated between the load and the resistance and is thus indicative of structural instability;
- Under given loads, the direction of structural deformation is toward the asymptotically stable state, and the unbalanced force is minimized;
- At the asymptotically stable state, the unbalanced force distribution reflects the nonequilibrium evolution mechanism of the structure, including the failure position and pattern.

The unbalanced force is a corollary of DRT. It is a set of equivalent nodal forces of the difference between two stress fields; it is also referred to as the residual force in the finite element method (FEM) iteration or the residual value in the Newton–Raphson method[20]. It is written in Equation (1):

$$
\Delta F = \sum_B B^T (\sigma^{eq} - \sigma^{yc}) \, dV
$$

where $\Delta F$ is the total unbalanced force for the structure. $B^T$ is the displacement gradient matrix. $\sigma^{eq}$ is the trial elastic nodal stress field obtained under the assumed absence of plastic flow. $\sigma^{yc}$ is the
actual stress satisfying the yield criterion. The minimized distribution of the unbalanced force at the asymptotically steady state can be considered as the driving force of the subsequent failure behavior. To reach such a state, this work proposes the principle of minimum plastic complementary energy (PCE)[17]: under given external loads, the elastoplastic system tends to unleash maximum resistance, thereby minimizing the overall unbalanced force.

$$E(\sigma) = \sum \int \|\sigma^{eq} - \sigma^{yc}\| = \sum \int (\sigma^{eq} - \sigma^{yc}) : C : (\sigma^{eq} - \sigma^{yc}) \, dV$$

(2)

where $C$ is the flexibility tensor. The unbalanced force is a vector form of the total nodal residual stress while PCE is a scalar form based on the definition of Equations (1) and (2). We can intuitively associate the former with local failure and the latter with overall stability. However, rockburst is not equal to the overall minimum PCE but is indicative of local severe destruction around the tunnel. As the unbalanced force only donates force on nodes, a variable called plastic complementary energy density (PCED) is employed to evaluate the complementary energy in unit volume, as shown in Equation (3).

$$PCED_i = \frac{1}{V_i} \int \|\sigma^{eq} - \sigma^{yc}\| = \frac{1}{V_i} \int (\sigma^{eq} - \sigma^{yc}) : C : (\sigma^{eq} - \sigma^{yc}) \, dV$$

(3)

where $V_i$ denotes the volume of element i. The PCED of elements is a scalarization and the average of the unbalanced nodal force vector. Hence, the distribution of the unbalanced force vector represents the failure location and mode, and its magnitude, i.e., PCED, indicates the severity of the failure.

The PCED is an algorithmic-independent index for evaluating structural stability. It implies whether a nonequilibrium system can evolve into a stable state. The unbalanced force transforms into the other zone so as to realize the ultimate bearing capacity for the structure during a nonlinear iteration. In the absence of an unbalanced force, i.e., $E(\sigma) = 0$, the system evolves into an equilibrium state; otherwise, $E(\sigma) > 0$. The PCED indicates how far the nonequilibrium system is from an equilibrium state. The location where the unbalanced force accumulates can imply possible crack formation and rockburst occurrence. Rockburst can be considered as a specific stage in surrounding rock evolution. Through numerical simulations, the unbalanced force can be regarded as the driving force. During the self-equilibrium evolution of rock mass structures, internal damage, and energy dissipation tend to accumulate. When the system receives enough damage, the minimum PCE gradually increases, thereby causing the system to deviate further from the equilibrium state. In this case, system stability cannot be maintained any longer, and extreme destruction such as rockburst occurs.

A three-dimensional finite element analysis program (TFine) is developed on the basis of DRT to study the nonequilibrium evolution of a rock mass structure. The FEM is a mature numerical simulation method while DRT is a step forward from the conventional FEM and proposes a new criterion for cracking failure, which is of great significance to nonequilibrium evolution and rockburst prediction. Deng et al.[21] found that the unbalanced force vector mainly exists in the connected area between salt deposit reserves. In their work, the plastic zone also extended to a relatively broad range. The phenomenon implied that a plastic zone connection is a necessary but an insufficient condition of failure; by contrast, the unbalanced force vector is sufficient and necessary.

3. Applicability of DRT in loosened zone analysis

3.1. Field data analysis
The field tests in the Duoxiongla tunnel include acoustic velocity tests and borehole image data from tunnel sections with good surrounding rock (Figure 1); however, data from the TBM jamming sections are lacking. The thickness of the loosened zone can be obtained through existing data. TFine can be employed to acquire the post-extraction yield zone and diagram of the plastic zone corresponding to the thickness of the loosened zone determined from the field data. The distribution of unbalanced force can also be obtained. The comparison between the test data and the simulation is carried out to verify the in-situ geostress in the Duoxiongla tunnel.
On the basis of the 117 spot data of acoustic velocity, the maximum, mean, and minimum velocities of all tested boreholes are summarized and illustrated in Figure 4. The average velocity of all the boreholes is between 4,613 and 5,417 m/s, which indicates the presence of only a few cracks in the rock and is regarded as a suitable condition for TBM tunneling in the tested sections. The negative skewness and kurtosis for the velocity data can also be obtained quickly; hence, Weibull distribution should be utilized in rock failure analysis[22, 23]. Although three types of spot velocity data are obtained, the most important one is the minimum velocity because it determines the weakest part of a borehole. Hence, the minimum velocity is analyzed on the basis of the Weibull probability distribution, as shown in Figure 5. In this figure, most of the dots lie near the reference line while about 10% of the dots are left below it. On the basis of this taxonomy, the test spots are divided into two categories, which are discussed in detail in the next section.

The testing spots with a minimum velocity above 4,630 m/s are considered to have no apparent damage to the rock mass; hence, they are employed to obtain the geostress without disturbance on the basis of Equation (4) proposed by Hughes et al.[24], that is,

\[ \rho V_p^2 = \lambda + 2 \mu - \frac{P}{3\lambda + 2\mu}(7\lambda + 10\mu + 6l + 4m) \]  

(4)

Here, \( \rho \) is the density, and \( V_p \) denotes the P-wave velocity. \( \lambda, \mu, l, \) and \( m \) are the elastic constants for the media. \( P \) denotes the hydrostatic pressure or confining pressure. The Duoxiongla tunnel, located at Mount Namcha Barwa, results from the Himalayan metamorphism process. The lithology is relatively simple and mainly consists of granite in the tunnel area. Liu[25] conducted experiments to determine the elastic constant for granite. As for the other simulation parameters, Yasar et al.[26] proposed Equation (5) to determine the density \( \rho \).

\[ V_p = 4.3183 \times \rho - 7.5071 \]  

(5)

The average density of these spots is 2.90 kg/m\(^3\). This value is substituted into Equation (4). The average geostress can be deduced as 23.3 MPa on the basis of the average wave velocity of all the undamaged boreholes, that is, 5,025 m/s. The average geostress is consistent with the field tests conducted by Feng[27] but is much larger than the geostatic stress for an average cover depth of 250 m as in the Duoxiongla tunnel. The geostress inversion result shows that high tectonic stress plays an important role in TBM jamming.
on the basis of the location of the borehole. As the distance between every two boreholes is 8.2 m, the two weak segments within the tested tunnel measure nearly 100 m (PM-004–PM-115 and PM-96–PM-110).

The average deformation modulus and the mechanical parameters for the numerical simulation can be obtained according to the acoustic velocity tests. Barton[28] proposed the relationship between the deformation module and the Q value, as shown in Equations (6) and (7).

\[ E_m = 10Q_c^{1/3} \]  

\[ V_p = 4.7 + 0.6 \times \log Q_c \]  

where \( E_m \) is the deformation modulus of the surrounding rock. \( Q_c \) denotes the comprehensive index considering the influence of rock quality property, geological structure properties, and hydrogeological environment; it is normalized by \( \sigma_c/100 \), where \( \sigma_c \) is the uniaxial compression strength. \( V_p \) is the P-wave seismic velocity, which is also the wave velocity employed in the current study. For tunnels with an average cover depth of 250 m, such as the Duoxiongla tunnel, Equation (8) was not proposed directly by Barton[28]. Nevertheless, one could easily deduce the equation from one of his diagrams. Equation (8) can be obtained by substituting Equation (7) into (8), that is,

\[ V_p = 2.9 + 1.8 \times \log E_m \]  

Hence, the average deformation modulus for the tunnel with damage is 9.6 GPa, which is quite different from that of an undamaged tunnel. Yasar et al.[26] also proposed Equation (9) to determine the uniaxial compression strength \( \sigma_c \).

\[ V_p = 0.0317 \times \sigma_c + 2.0195 \]  

The average uniaxial compression strength is 83.6 MPa. All the rock strength parameters are used in the numerical simulation to verify the applicability of DRT to the study of the driving force of rockburst.

| Section | Borehole number | Statistical interval | Interval width | Percentage of length (%) | Thickness (m) | Average thickness (m) |
|---------|----------------|----------------------|----------------|--------------------------|---------------|-----------------------|
|         |                |                      |                | Below 4,630 ms\(^{-1}\) | Above 4,630 ms\(^{-1}\) |                  |
| 1       | PM-004         | 2.0–2.8              | 0.8            | 27.86                    | 72.14         | 0.22                  |
|         | PM-009         | 0.6–2.8              | 2.2            | 10.62                    | 89.38         | 0.23                  |
|         | PM-011         | 1.4–3.6              | 2.2            | 9.46                     | 90.54         | 0.21                  |
|         | PM-015         | 0.8–3.0              | 2.2            | 9.10                     | 90.90         | 0.20                  |
| 2       | PM-096         | 0.6–3.0              | 2.4            | 11.90                    | 88.10         | 0.28                  |
|         | PM-097         | 0.6–3.2              | 2.6            | 15.82                    | 84.18         | 0.41                  |
|         | PM-098         | 0.6–3.2              | 2.6            | 15.68                    | 84.32         | 0.41                  |
|         | PM-110         | 0.6–5.2              | 4.6            | 7.86                     | 92.14         | 0.36                  |

3.2. Determination of simulation parameters based on loosened zone analysis
The loosened rock zone evolution is a perspective for evaluating geostress and rock mass strength. Y Koizumi[32] once conjectured the relationship between TBM jamming and the range of loosened zones through theoretical analysis and seismic investigations. His research reveals the workability of measuring the P-wave velocity of different tunnel cross sections and obtaining the functional correlations between the velocity and the elastic module of surrounding rocks. In a numerical analysis, the loosened zone can be determined according to the plastic zone, but it does not indicate that failure or rockburst is bound to occur.

To acquire the rock mass strength parameters on the basis of field conditions, this study develops a simple model with a size of 80 m × 100 m × 80 m and sets a length of 100 m along the tunneling direction. A hole, the excavation zone with a diameter of 9.13 m, is set at the center of the x-z plane. No TBM segment is set so as to detect the loosened zone evolution shortly after excavation and before
lining. The confining pressure of 23.3 MPa is applied to the model as the geostress field. Then, the excavation algorithm is implemented to obtain the relationship between the plastic zone and the unbalanced force distribution after excavation disturbance.

As shown in Table 2, the plastic zone depths are 0.22 m in case 1 and 0.37 m in case 2. These values are consistent with the loosened zone depths in the two weak segments from the field tests. Two sets of friction coefficients and cohesion parameters are established accordingly. On the basis of the Drucker–Prager yield criterion, Hou et al.[33] derived formulas to determine the relationship between the strength parameters and the yield zone thickness of an axisymmetric circular tunnel in a perfect elastoplastic medium; these formulas can be employed to verify the inversion analysis results in Table 2.

| Section/Case | Plastic zone thickness (m) | Friction coefficient | Cohesion (MPa) | PCED (10,000 Nm⁻³) |
|--------------|---------------------------|---------------------|---------------|------------------|
| 1            | 0.22                      | 0.60                | 7.00          | 84.97            |
| 2            | 0.37                      | 0.57                | 6.00          | 210.67           |

Figure 6 shows the distribution of the unbalanced force under two conditions. In the figure, the two circles represent the tunnel while the black area is the plastic zone. The unbalanced force in the tunnel radial direction from the excavation surface can then be plotted. The arrows imply the distribution of the unbalanced force field. As the model is an entirely symmetrical structure, the unbalanced force is uniformly distributed around the tunnel. The arrows point to the tunnel center and indicate that the cracks on the excavation surface and the rock deformation are directed toward the tunnel center. The unbalanced force near the tunnel surface is relatively large and implies great damage to the rock mass. Furthermore, the damage weakens the strength parameters, friction coefficients, and cohesion in the numerical simulation.

Figure 6. Unbalanced force around the tunnel.

Hence, DRT can be applied to the nonequilibrium evolution analysis. Even though unbalanced force is detected from the tunnel excavation under homogeneous geological conditions, rockburst risk is still low because the PCED is not enough and can only result in cracks in the rock mass and loosened zone. This conclusion can be verified roughly through Barton’s rockburst criterion[34]. The ratio of the uniaxial compressive strength (83.6 MPa) to the geostress (23.3 MPa) is 3.59, which indicates low-risk interval for rockburst because of simple lithology and good rock mass quality.

4. Influence of geological structures on rockburst tendency

According to the field investigation of the Duoxiongla tunnel, the joints and fissures along the tunnel axis in the rock mass are the key factors that caused the TBM jamming in addition to the high geostress of 23.3 MPa. Specifically, during the fourth TBM jamming, the whole shield was buried. DRT is employed herein to detect the influence of the weak plane parallel to the tunnel axis on the
rockburst tendency. The influence of the connectivity rate, density, and dip angle of randomly distributed joints on the distribution of the unbalanced force and PCE is studied.

4.1. Joint connectivity rate
The connectivity rate of joints is defined on the basis of geometric projection[35]. In a rock band with a certain width, all structural surfaces in the band are projected to the measured baseline. The lengths of all projected lines on the baseline are summed up. The ratio of this sum to the baseline length is the connectivity rate of structural surfaces. A number of weak uniform joints that are parallel to one another and have widths equal to 0.05 m are set in the FEM model. The baselines are considered as the lines parallel to the tendency of the joints. The joint connectivity rates are set as 0.3, 0.4, 0.5, 0.6, and 0.7 in the five models. As the weak planes are parallel to the excavation direction of the tunnel, the plane model is employed. The rock mass strength parameters come from tunnel Section 2 in Table 2. The geostress of 23.3MPa is applied to the top of each model.

Figure 10 shows the PCED and yield ratio under different joint connectivity rates. The yield ratio denotes the plastic zone proportion of the whole model and is positively correlated with the joint connectivity rate. The PCED shows the same tendency as the yield ratio and thus implies the most severe damage zone.

Figure 7 shows the unbalanced force distribution and plastic zone, which can be employed to determine the location of rockburst. The black zone represents the plastic zone while the arrows denote the distribution of unbalanced force. The unbalanced force accumulates, and the plastic zone connects at both flanks of the tunnel under all conditions. With increasing joint connectivity rate, the unbalanced force becomes extensive, and the plastic zone extends to a deep area to influence other joints. The unbalanced force does not appear at the tunnel roof until the joint connectivity rate reaches 0.6 even though the plastic zone exists at the tunnel roof at low joint connectivity rates.

![Figure 7. Unbalanced force distribution and plastic zone under different joint connectivity rates.](image)
4.2. Joint density
The joint density, that is, the joint number in unit volume, is another important parameter of geological structures. The problem is simplified by embedding 30, 40, 50, 60, and 70 parallel weak joints into five models. The joint distribution is not as uniform as that described in Section 4.1. Several parameters need to be determined to simulate the distribution of cracks in the FEM model. The trace and width of the weak joints in each group obey a number of random distributions, as shown in Table 3. A random joint generating program is developed to generate all the random geological structures. The FEM models with randomly distributed and parallel joints are shown in Figure 8.

| Joint parameters     | Description              | Setting                        |
|----------------------|--------------------------|--------------------------------|
| Location             | Coordinate of the joint center | Uniform distribution          |
| Width                | Average width of every weak joint | Normal distribution          |
| Trace                | Length of every weak joint | Negative exponential distribution |
| Dip angle            | Angle with the horizontal plane | Keep the same as 0°           |
| Joint density        | Fragmentation degree of rock mass | 30, 40, 50, 60, and 70, respectively |

Figure 11 shows the PCED and yield ratio under different joint numbers. In general, the yield ratio and PCED increase with an increase in the number of joints. However, the model with 50 joints is a particular case. Its PCED is the smallest one while its yield ratio is the biggest one among all the five models. The yield ratio is determined by the joint distribution and represents the overall yield degree but not the local damage around the tunnel of the model. Meanwhile, the PCED is determined by the most dangerous part of the surrounding rock. To some extent, a high overall yield ratio indicates a high strain energy absorbed by the rock mass and a low strain energy for rockburst. Hence, a high overall yield degree does not mean a high PCED. When the assembly among joints falls into an appropriate range as the 50-joint model, the yield zone connects, and the strain energy dissipates during the transaction of an unbalanced force, resulting in the smallest PCED.

Figure 8 shows the unbalanced force distribution and plastic zone under different joint numbers. Most of the unbalanced force accumulates, and the plastic zone connects at both flanks of the tunnel in all conditions. Some of the unbalanced force also appears at the roof or bottom of the tunnel if the joint number is adequate. As the joint location obeys a uniform distribution, the distance between the excavation zone and the nearest joints varies for each model. If the distance falls into an appropriate range, then the unbalanced force can accumulate at the roof or bottom. With an increasing joint number, the possibility for a joint to meet this requirement increases. Hence, the risk for roof or button rockburst increases with the joint number.

(a) Number = 30  (b) Number = 40  (c) Number = 50
4.3. Joint dip angle
The influence of the joint dip angle on rockburst tendency is also analyzed. A group of 50 parallel weak joints with dip angles of 0°, 30°, 45°, 60°, and 90° are embedded in the five models. The random joint generating program is employed again to generate all the random geological structures. All the other model settings are the same as those described in the last section.

Figure 12 shows the PCED and yield ratio under different joint angles. The yield ratio is the lowest when the dip angle reaches 45° and highest when the dip angle stays 0°. The PCED shows the opposite tendency. The reason has been described in the last section. A high yield ratio implies a wide yield zone and a large amount of strain energy dissipating in the nonequilibrium evolution, but it does not indicate a high rockburst tendency. Hence, the PCED at a dip angle of 45° indicates the highest rockburst risk.

Figure 9 shows the unbalanced force distribution and plastic zone under different dip angles. The unbalanced force accumulates at the location where the weak joints are tangent to the tunnel for all the models. Furthermore, the unbalanced force at the tangent plane varies with different dip angles and reaches the most significant value when the dip angle is 45°. The unbalanced force also accumulates at the location where the weak joints are orthogonal to the tunnel only when the dip angle is smaller than 45°. As the dip angle increases, the unbalanced force arrow at the orthogonal point becomes small. Hence, the unbalanced force transforms from the tangent plane to the orthogonal plane with an increasing dip angle.

Figure 8. Unbalanced force distribution and plastic zone under different joint numbers.
5. Summary
In this work, the feasibility of DRT in tunnel excavation is verified on the basis of field data and nonlinear numerical simulations. The work and conclusions are summarized as follows.

- The distribution of the unbalanced force during structural deformation indicates the degree and location of rock damage. It can also be considered as the driving force of the nonequilibrium evolution of rock mass.
- According to the field test, the geological structure is not the only cause of the TBM jamming in the Duoxiongla tunnel. The high average geostress of 23.3 MPa is another important clue.
- Through numerical simulations, the PCED, yield ratio, distribution of unbalanced force, and plastic zone can be obtained. A high yield ratio indicates a large damage area while a high PCED
means a high local rockburst tendency. The two variables have an internal relationship, but they are not equal. The unbalanced force vector can be considered as a semiquantitative indicator of rockburst tendency.

- The sensitivity analysis of the influence of parallel geological structures indicates that a high joint connectivity rate, high joint density, and dip angle of 45° correspond to the highest rockburst tendency under tectonic stress in the Duoxiongla tunnel. The rockburst tendency is also influenced by the relative distance between the excavation tunnel and the nearest joints. When the rock mass is broken enough (i.e., the joints are sufficient), the tangent and orthogonal planes of the joints and excavation zone should attract enough attention.

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