Quantitative analysis of rockburst for surrounding rocks and zonal disintegration mechanism in deep tunnels

Qihu Qian\textsuperscript{1*}, Xiaoping Zhou\textsuperscript{2}

\textsuperscript{1}Engineering Institute of Engineering Corps, PLA University of Science and Technology, Nanjing, 210007, China
\textsuperscript{2}School of Civil Engineering, Chongqing University, Chongqing, 400045, China

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Abstract: Rock masses without pre-existing macrocracks can usually be considered as granular materials with only microcracks. During the excavation of the tunnels, microcracks may nucleate, grow and propagate through the rock matrix; secondary microcracks may appear, and discontinuous and incompatible deformation of rock masses may occur. The classical continuum elastoplastic theory is not suitable for analyzing discontinuous and incompatible deformation of rock masses. Based on non-Euclidean model of the discontinuous and incompatible deformation of rock masses, the distribution of stresses in the surrounding rock masses in deep tunnels is fluctuant or wave-like. The stress concentration at the tips of microcracks located in vicinity of stress wave crest is comparatively large, which may lead to the unstable growth and coalescence of secondary microcracks, and consequently the occurrence of fractured zones. On the other hand, the stress concentration at the tips of microcracks located around stress wave trough is relatively small, which may lead to the arrest of microcracks, and thus the non-fractured zones. The alternate appearance of stress wave crest and trough thus may induce the alternate occurrence of fractured and non-fractured zones in deep rock masses. For brittle rocks, the dissipated energy of microcrack growth is small, but the elastic strain energy stored in rock masses may be larger than the dissipated energy growths of pre-existing microcracks and secondary microcracks. The sudden release of the residual elastic strain energy may lead to rockburst. Based on this understanding, the criteria of rockburst are established. Furthermore, the relationship between rockbursts and zonal disintegration in the surrounding rock masses around deep tunnels is studied. The influences of the in-situ stresses and the physico-mechanical parameters on the distribution of rockburst zones and the ejection velocity of rock fragments are investigated in detail.

Key words: underground tunnel; rockburst; zonal disintegration; non-Euclidean model

1 Introduction

With the development of underground rock engineering structures at great depth, rock mass failure becomes an increasingly challenging issue for underground engineers. Unlike shallow-buried rock masses, deep rock masses in complex geological condition with high in-situ stress, high earth temperature, high water pressure and engineering disturbance, are characterized by discontinuous, incompatible and large deformations. Rockbursts and zonal disintegration are typical failure modes of deep rock masses. During the excavation of a tunnel in the deep rock masses, the fractured and non-fractured zones occur alternately around tunnels, which was referred as the zonal disintegration phenomenon in some related publications [1–4] and was never reported in shallow rock engineering before. Rockburst is a rock failure phenomenon associated with ejection, acoustic emission or microseismic events induced by a sudden release of elastic strain energy stored in the rock masses.

Great efforts have been made to understand rockburst and zonal disintegration phenomena as two main types of failure modes of deep rock masses. Under the hypothesis of linear damage of rock after its peak stresses, rockburst around circular tunnels was analyzed by Pan and Xu [5]. Based on crack propagation in rock masses, the rockburst mechanism was studied and the concept of stress intensity isogram for surrounding rock masses was proposed by Wang et al. [6]. In-situ investigation on zonal disintegration in
surrounding rock masses around tunnels was carried out, and reliable evidences to prove the existence of zonal disintegration phenomenon were obtained by Shemyakin et al. [7]. Based on the incompatible deformation of rock masses, a non-Euclidean model of surrounding rock masses around circular tunnels under hydrostatic pressure condition was presented by Guzev et al. [8, 9]. Moreover, on the basis of the discontinuous and incompatible deformation of rock masses, a new non-Euclidean continuum model of the zonal disintegration of surrounding rock masses around a deep circular tunnel in a non-hydrostatic pressure state was established by Qian and Zhou [10]. In addition, the mechanism of zonal disintegration phenomenon of surrounding rock masses was analyzed by using energy criterion [11]. However, the efforts are mainly made to study rockburst and zonal disintegration separately. The studies on the relationship between rockburst and zonal disintegration are very limited.

Relationship between zonal disintegration and rockburst is studied in the paper. The mechanism of the nucleation of secondary microcracks induced by microcracks, the mechanism of the transition of the secondary microcracks from stable to unstable propagation, and the mechanism of the coalescence of secondary microcracks and formation of macrocracks (which lead to rockbursts) are investigated. A new method to analyze stability of deep rock masses is also established.

2 Stress field obtained by non-Euclidean model

In the following discussions, the discontinuous and incompatible deformation of rock-like material was considered using an incompatible strain tensor in the kinematic equations. The internal space of rock-like material after deformation was treated as a non-Euclidean one [10]. Moreover, based on the evolution equation of incompatible tensor, a new non-Euclidean model suitable for non-hydrostatic stress condition was established, and the elastic stress field of surrounding rock mass around deep circular tunnels under unloading was obtained [10]. The expression can be written as follows:

\[
\sigma_r = \frac{\sigma_v + \sigma_h}{2} \left( 1 + \frac{r_0^2}{r^2} \right) + \frac{\sigma_v - \sigma_h}{2},
\]

\[
\eta_{\theta\theta} = \frac{\sigma_v - \sigma_h}{2} \left( 1 + \frac{r_0^2}{r^2} - 3 \frac{r_0^4}{r^4} \right) \sin(2\theta) +
\]

\[
\frac{E}{r(1-\nu)\gamma^2} \left[ A J_0(y^{1/2}) r + B N_0(y^{1/2}) r \right] \sin(2\theta) - \frac{3E}{r(1-\nu)\gamma^2} \left[ A J_0(y^{1/2}) r + B N_0(y^{1/2}) r \right] \sin(2\theta)
\]

where \( r_0 \) is the radius of tunnels; \((r, \theta)\) is the polar coordinates; \( \gamma^2 = E/[4q(1-\nu)] \), \( q \) is a non-Euclidean parameter that can be determined by experiments; \( E \) is the Young’s modulus; \( \nu \) is the Poisson’s ratio; \( \sigma_v \) is the vertical in-situ stress; \( \sigma_h \) is the horizontal in-situ stress; and \( C \) is determined by the function that coincides with the Wronskian of the linearly independent solutions \( J_0(y^{1/2}) \) and \( N_0(y^{1/2}) \), \( J_0, N_0 \) and \( K_0 \) are zero order Bessel, Neumann and Macdonald cylindrical functions, respectively. The parameters \( A, B, A_i \) and \( B_i \) can be written as follows:
According to Eqs. (1)–(3), the distribution of stresses is plotted in Fig. 1. It is obvious, from Fig. 1, that the distribution of stresses of surrounding rock masses is fluctuant. The following parameters are used in Figs. 1 and 2: $\sigma_\tau = 0.4$ MPa, $\sigma_b = 0.1$ MPa, $\nu = 0.2$, $q = 1.448$, $C_1 = 18,620 \text{ m}^{-2}$, $C_2 = 18,620 \text{ m}^{-2}$, $E = 450 \text{ MPa}$, $r_0 = 0.07 \text{ m}$, $\theta = 0^\circ$, $c_0 = 4 \text{ mm}$ (initial length of microcrack), $c_1 = 8 \text{ mm}$ (final length of microcrack after growth), $K'_{IC} = 0.03 \text{ MPa} \cdot \text{m}^{1/2}$ (fracture toughness of rock interface), $K_{IC} = 0.12 \text{ MPa} \cdot \text{m}^{1/2}$ (fracture toughness of rock). The distribution of fractured zones in surrounding rock masses around tunnel is shown in Fig. 2. Unlike that predicted by traditional continuum theory, the fractured and non-fractured zones shown in Fig. 2 alternately occur, and the width of fractured zones decreases with increasing distance away from tunnel wall.

### 3 Characteristics of fractured zones and rockburst zones

Relationship between the evolution of microcracks and the evolution of damage of rock was established by Golshani et al. [12–15]. The stage before microcracks growth is the elastic phase of rocks. The stages of growth of microcracks and stable growth of secondary microcracks are the nonlinear hardening phases of rocks. The stage of unstable propagation of the secondary microcracks corresponds to the strain softening phase of rocks [13–15]. Based on the above studies, the developments of rockbursts in continuum surrounding rock mass are categorized into three stages, including microcrack growth, stable propagation of secondary microcracks, and unstable growth and coalescence of secondary microcracks to form macrocracks.

#### 3.1 Microcrack growth

It is assumed that the distribution of microcracks is homogeneous, and the initial length of microcracks is regarded as $c_0$, which can be determined by mesoscopic experiment. The final length of microcracks after growth is $c_1$ and the fracture toughness of the rock interface is $K'_{IC}$. After the excavation of tunnel in the deep rock masses, microcracks will grow along the rock interface. The mechanical behaviors of deep rock masses are characterized by discontinuous and incompatible deformation. The classical elastoplastic theory is not applicable anymore. The non-Euclidean model can be used to analyze the distribution of stresses of surrounding rock mass after the microcrack growth. Based on the non-Euclidean theory, the principal stresses can be written as
The tensile stresses on the surfaces of microcracks are obtained as

\[ \sigma'_1 = \sigma_s + \sigma_{\theta} + \frac{1}{2}\sqrt{(\sigma_s - \sigma_{\theta})^2 + 4\tau_{\theta}\theta} \]

\[ \sigma'_2 = \frac{\sigma_s + \sigma_{\theta} - \frac{1}{2}\sqrt{(\sigma_s - \sigma_{\theta})^2 + 4\tau_{\theta}\theta}}{2} \]  

(8)

The mode I stress intensity factor at the tips of microcracks is expressed as

\[ K_I = -[\sigma'_1 + f(c_0)S'_2]\sqrt{2d_i \tan \left( \frac{\pi c_0}{2d_i} \right)} \]  

where \( d_i \) is the spacing between microcracks that can be obtained by mesoscopic experiments.

The critical condition for the growth of microcracks along the rock interface is

\[ K_I = K_{IC} \]  

(12)

When the stress intensity factor at the tips of microcracks satisfies the critical condition (Eq.(12)), the microcracks will grow. The dissipated energy density of microcrack growth can be determined by the integral of energy release rate \( G \) along the length of microcracks \( c = c_1 - c_0 \):

\[ U_1 = \frac{N_i(\kappa + 1)(1 + \nu)}{2E}, \]

\[ \int_{c_0}^{c_1} \left( \frac{\pi c}{2d_i} \right)^2 \left( \sigma'_1 + f(c)S'_2 \right) \, dc \]  

(13)

where \( f(c) = d / c \), and \( N_i \) is the density of microcracks that can be obtained by mesoscopic experiment.

3.2 Stable propagation of secondary microcracks

It is observed from the experiments that microcracks will propagate through rock matrix under certain stress conditions, leading to the appearance of microcracks [15, 16]. Based on the length of microcracks and fracture toughness of rock, the critical condition for secondary microcrack nucleation can be written as

\[ \sigma'_2 + f(c_2)S'_2 = -\frac{K_{IC}}{\sqrt{2d_i \tan \left( \frac{\pi c_2}{2d_i} \right)}} \]  

(14)

where \( K_{IC} \) can be determined by experiments.

The stress intensity factor at the tips of the secondary microcracks can be expressed as

\[ K_I = -[\sigma'_2 + f(l)S'_2]\sqrt{2d_i \tan \left( \frac{\pi l}{2d_i} \right)} \]  

(15)

where \( f(l) = d / l \), \( l \) is the growth length of secondary microcracks.

The critical condition for stable growth of secondary microcracks is

\[ K_I = K_{IC} \]  

(16)

When the growth length of secondary microcracks \( l \) reaches \( c_2 \), the load capacity of the rock reaches its maximum potential and the rock is fractured.

The critical condition for the rock fracture can be defined as

\[ \sigma'_2 + f(c_2)S'_2 = -\frac{K_{IC}}{\sqrt{2d_i \tan \left( \frac{\pi c_2}{2d_i} \right)}} \]  

(17)

Replacing \( c_0 \) with \( c_2 \) in Eq.(9), the uniaxial tensile strength of rock \( \sigma'_{\max} = \sigma'_2 + f(c_2)S'_2 \) and the stable growth length of secondary microcrack \( c_2 \) can be determined by iteratively using Eqs.(9) and (17).

The dissipated energy density of stable growth of the secondary microcracks can be determined by integration of the energy release rate \( G \) along the growth length of secondary microcracks \( l = c_2 - c_1 \):

\[ U_2 = \frac{N_2(\kappa + 1)(1 + \nu)}{2E} \int_{c_0}^{c_2} \left( \sqrt{2d_i \tan \left( \frac{\pi l}{2d_i} \right)} \right)^2 \left( \sigma'_2 + f(l)S'_2 \right) \, dl \]  

(18)

where \( N_2 \) is the density of secondary microcracks of stable growth, which can be obtained by the numerical simulation.

3.3 Unstable propagation, coalescence of secondary microcracks and formation of macrocracks

When the length of secondary microcracks is larger than \( c_2 \), the secondary microcracks will grow unstably and the load capacity of rock decreases, leading to the damage localization of rocks. The critical condition for damage localization is expressed as Eq.(17). Unstable growth of secondary microcracks will lead to the coalescence of secondary microcracks, and further the appearance of macrocracks and the failure of rock masses.

Growth length from nucleation to coalescence of secondary microcracks is
The growth length from unstable propagation to coalescence of secondary microcracks can be written as:

\[ l = d_i - c_1 \]  

(19)

It is assumed that the post-peak deformation modulus of rock is \( E_i \), and the dissipated energy density of unstable growth of secondary microcracks can be determined as:

\[ U_3 = \frac{N_3(\kappa + 1)(1 + \nu)}{2E_i} K_{IC}'(d_i - c_1) \]  

(21)

where \( N_3 \) is the density of secondary microcracks of unstable propagation, and it can be determined by the numerical computation; and \( E_i \) can be determined by the methods suggested in Ref.[15].

### 3.4 Criteria of rockburst based on energy analysis

The strain energy stored in rock masses can be defined as:

\[ U_e = \frac{1}{2} \sigma_{ij} e_{ij} \]  

(22)

For brittle rock, the elastic strain energy stored in the rock masses can be approximately replaced by the strain energy density. Substituting Hooke’s law into Eq.(22), the strain energy density stored in rock masses is:

\[ U_e = \frac{1 - \nu^2}{2E} (\sigma_r^2 + \sigma_\theta^2) - \frac{\nu(1 + \nu)}{E} \sigma_r \sigma_\theta + \frac{1 + \nu}{E} \tau_r^2 \]  

(23)

Neglecting thermal dissipation density during the growth of microcracks and secondary microcracks, the total dissipated energy density can be written as:

\[ U = U_1 + U_3 + U_3 \]  

(24)

The occurrence of rockburst should satisfy the following two conditions: (1) the coalescence of secondary microcracks and occurrence of macrocracks; and (2) the total dissipated energy density should be smaller than the elastic strain energy density:

\[ l = d_i - c_1 \]

\[ U < U_e \]  

(25)

If surrounding rock masses around tunnels satisfy the conditions (Eq.(25), rockburst tends to occur. If the location of rockburst is close to the tunnel wall, rockburst will more likely occur. If the first condition in Eq.(25) is satisfied, only fractured zones will occur.

The present model is suitable for continuum surrounding rock masses that only contain microcracks. Because the discontinuous and incompatible deformation of rock masses is taken into account, the present results are precise.

According to the energy conservation law, the kinetic energy density can be expressed as:

\[ W = U_e - U \geq 0 \]  

(26)

The ejection velocity of rock fragments is:

\[ V = \sqrt{2W/\rho} \]  

(27)

where \( \rho \) is the density of rock masses.

The location of fractured zones and rockburst zones, the ejection velocity of rock fragments and the kinetic energy density can all be determined by the above equations.

### 4 Numerical simulations

Fractured zones and rockburst zones in surrounding rock masses around circular tunnels are analyzed. In the simulations, the following material parameters are used: \( r_0 = 7 \text{ m}, \nu = 0.15, q = 1.460, C = 4.599 \times 10^5 \text{ m}^{-2}, C_1 = 4.599 \times 10^5 \text{ m}^{-2}, K_{IC} = 0.3 \text{ MPa·m}^{1/2}, N_1 = 1650, N_2 = 1650, N_3 = 200, d_i = 7.5 \text{ mm}, c_0 = 0.4 \text{ mm}, c_1 = 0.8 \text{ mm}, \rho = 2200 \text{ kg/m}^3. \)

The distribution of fractured zones and rockburst zones in surrounding rock masses under different stress conditions is plotted in Fig.3. For brittle rock, the value of Young’s modulus is smaller than that of post-peak modulus. The following parameters are used in the simulation: \( d = 8 \text{ mm}, E = 28 \text{ GPa}, E_1 = 280 \text{ GPa}, K_{IC} = 1 \text{ MPa·m}^{1/2}. \) It can be observed from Fig.3 that the distribution of fractured zones and rockburst zones is
sensitive to the difference between the horizontal and vertical stresses. When the difference between the horizontal and vertical stresses is large enough, rockburst will occur in places far from the tunnel wall.

The dependence of area of rockburst zones in surrounding rock masses on the lateral pressure coefficient is plotted in Fig.4. It can be found from Fig.4(a) that the area of rockburst zones increases with the increasing lateral pressure coefficient when it is larger than 1. It can also be found from Fig.4(b) that the area of rockburst zones decreases with the increasing lateral pressure coefficient when it is smaller than 1.

Fig.4 Area of rockburst zones under different stress conditions.

The dependence of average ejection velocity of rockburst in surrounding rock masses on the lateral pressure coefficient is shown in Fig.5. It is observed from Fig.5(a) that the average ejection velocity of rockburst decreases with the increasing lateral pressure coefficient when it is larger than 1. It is seen from Fig.5(b) that the average ejection velocity of rockburst roughly increases with the increasing lateral pressure coefficient when it is smaller than 1.

The dependence of rockburst zones in surrounding rock mass on fracture toughness is plotted in Fig.6. In the simulations, the following parameters are used: \( \sigma_h = 30 \text{ MPa}, \sigma_v = 10 \text{ MPa}, E = 28 \text{ GPa}, E_1 = 280 \text{ GPa}, d = 8 \text{ mm}. \) It is found from Fig.6 that the distribution of rockburst zones is sensitive to the fracture toughness.

Fig.6 Distribution of fractured zones and rockburst zones under different fracture toughnesses.

The dependence of area of rockburst zones on fracture toughness is shown in Fig.7. It can be seen from Fig.7 that the area of rockburst zones decreases as the fracture toughness increases.

The dependence of average ejection velocity of rockburst zones on fracture toughness is plotted in Fig.8. It is observed from Fig.8 that the average...
The dependence of fractured zones and rockburst zones in surrounding rock mass on the post-peak modulus of rock is plotted in Fig.9. In the simulations, the following parameters are used: $\sigma_0 = 30$ MPa, $\sigma_y = 10$ MPa, $E = 28$ GPa, $d = 8$ mm. It is found from Fig.9 that the distribution of both fractured zones and rockburst zones is sensitive to the post-peak modulus of rock.

The dependence of area of rockburst zones on post-peak modulus of rock is shown in Fig.10. It can be seen from Fig.10 that the area of rockburst zones increases as the post-peak modulus of rock increases.

The dependence of the average ejection velocity of rock fragments on post-peak modulus of rock is shown in Fig.11. It can be seen from Fig.11 that the average ejection velocity of rock fragments increases as the post-peak modulus of rock increases.

5 Discussions and conclusions

Rockburst and zonal disintegration possibly occur in rock masses with high in-situ stresses. They are of two different types of failure modes for deep rock masses. The mechanisms of zonal disintegration and rockburst in surrounding rock mass around circular tunnel are analyzed above and discussed below.

The physical process of zonal disintegration can be summarised as follows. During the excavation of tunnels in deep rock masses, the microcracks propagate through the rock matrix, secondary microcracks then appear, and the discontinuous and incompatible deformation of rock masses occurs. Based on non-Euclidean model of the discontinuous
and incompatible deformation of deep rock masses, the distribution of stresses of surrounding rock masses is fluctuant. As a result, the stress concentration at the tips of microcracks located around stress wave crest is comparatively large, which leads to the arrest of microcracks, and the occurrence of macroracks and fractured zones. However, the stress concentration at the tips of microcracks located nearby stress wave trough is relatively small, which leads to the stop of growth of microcracks, and the occurrence of non-fractured zones. The alternate appearance of stress wave crests and troughs induces the alternate occurrence of fractured and formation of non-fractured zones in deep surrounding rock masses. The deep rock masses don’t obey the rule of successive condition of fractured zones and non-fractured zones interpreted by classical continuum theory. Meanwhile, the classical continuum theory that is suitable for the shallow rock masses is not valid for the deep rock masses.

The mechanism of rockburst can be summarised as follows. When a rockburst occurs during the excavation of tunnels, it experiences three stages: (1) microcrack growth; (2) stable growth of secondary microcracks; and (3) unstable growth and coalescence of secondary microcracks to form macroracks. If the dissipated energy to grow microcracks and secondary microcracks is smaller than the elastic strain energy stored in rock masses, the residual strain energy will be released suddenly in the form of the kinetic energy of rock fragments, resulting in rockburst.

It can be concluded from the mechanisms of rockburst and zonal disintegration that both of them are induced by the unstable growth and coalescence of secondary microcracks to form macroracks. The elastic strain energy stored in rock masses can be either smaller or larger than the dissipated energy to grow microcracks and secondary microcracks. If the elastic strain energy stored in rock masses is larger than the dissipated energy to grow microcracks and secondary microcracks, the residual elastic strain energy will transform into the kinetic energy of rock fragments, leading to the occurrence of rockburst. Otherwise, zonal disintegration will occur.

A prediction model for rockburst, taking into account the zonal disintegration under non-hydrostatic stress condition, has been established. The numerical analysis is made based on the prediction model. The main conclusions from the numerical results are drawn as follows:

1. Rockburst occurs not only at the tunnel wall but also at the location far from the tunnel wall. The probability of occurrence of rockburst at the location far from the tunnel wall increases as the difference between horizontal and vertical stresses increases.

2. When the lateral pressure coefficient is smaller than 1, the area of rockburst zones decreases, while the average ejection velocity of rockburst zones increases as the lateral pressure coefficient increases. When the lateral pressure coefficient is larger than 1, the area of rockburst zones increases, while the average ejection velocity of rockburst zones decreases as the lateral pressure coefficient increases.

3. The area of rockburst zones decreases as the fracture toughness and the post-peak modulus of rock increase. However, the average ejection velocity of rock fragment increases as the fracture toughness increases.

4. The distribution of fractured zones and rockburst zones depends on the post-peak modulus of rock. The area of rockburst zones and the average ejection velocity of rock fragments increase as the post-peak modulus of rock increases.

References


