Research on improved rock blasting damage constitutive model considering compression-shear damage

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Abstract. It is of great importance to study the proper rock blasting damage constitutive model for the design of rock blasting excavation parameters and the damage assessment of retained rock. Therefore, on the basis of the classic KUS rock damage constitutive model which only involved tensile damage, considering the compression-shear damage of rock near the explosion source caused by extensive blasting load, an improved rock blasting damage constitutive model is established. Meanwhile, the distribution of rock damage zone of a single blasthole is calculated by dynamic finite element software based on the improved model, and the results show that the ratio of crushing zone radius to cartridge radius is between 4.3 and 4.6 under different charging radius, while the ratio of fracture zone radius to cartridge radius is between 78.9 and 83.8, which is close to the existing research results. Thus, the accuracy of the established constitutive model of rock blasting damage is verified.

1. Introduction

With the development of geotechnical engineering construction technology, advanced excavation methods such as TBM (Tunnel Boring Machine) have been gradually applied to the rock excavation of underground engineering and tunnel engineering, but at present, the drilling and blasting method is still the main method of rock excavation, which has the characteristics of high efficiency, convenience and applicability. The drilling and blasting method can achieve the effect of rock breaking through a large amount of energy generated by explosive charges detonation, which inevitably causes damage to the rock mass around the excavation contour. Hence, it is of great significance to accurately determine the scope of the damage of the surrounding rock for the stability of the surrounding rock and the corresponding support scheme design of underground engineering.

The study of rock blasting damage constitutive model is a developing process, different researchers have established corresponding rock blasting damage constitutive model, among which GK model\textsuperscript{[1]}, TCK model\textsuperscript{[2]}, KUS model\textsuperscript{[3]}, Thorne model\textsuperscript{[4]} and Yang\textsuperscript{[5]} model are representative. However, the definition of damage in the above model is based on the microcrack propagation caused by the volume tensile strain of rock, namely rock blasting tensile damage. In the drilling and blasting construction, the rock around the blast hole will produce compression-shear damage under the great blasting impact load. Based on this, Wang\textsuperscript{[6]} established a statistical constitutive model of rock damage softening based on continuum damage mechanics, and calculated the compression shear damage of rock around the blast hole with spherical and cylindrical charge respectively. Hu\textsuperscript{[7]} compared and selected the
classical blasting damage constitutive model through numerical calculation, and coupled the RDA model which considered the compression-shear damage into the tensile damage constitutive KUS model, but the parameters involved in the RDA model are difficult to get values.

In conclusion, on the basis of the widely used tensile damage KUS model, considering the compression-shear damage of rock near the explosion source caused by strong blasting load, an improved blasting damage constitutive model of rock is established. Meanwhile, based on the improved model, the numerical calculation of damage area distribution of rock around a single blast hole under the initiation is carried out by LS-DYNA, and the range of compression-shear damage and tensile damage area around the blast hole under different cartridge diameters is quantitatively analyzed. Finally, the accuracy of the established damage constitutive model is verified by comparison with the existing research results.

2. Improved blasting damage constitutive model
The rock blasting damage constitutive model includes the evolution equation of blasting damage and the stress-strain relationship of rock under blasting impact load. The blasting damage of rock includes the tensile damage caused by the propagation of microcracks under the volume tensile stress, and the compression-shear damage caused by the extremely high blasting impact load near the blast hole.

2.1. Definition of tensile damage variable
According to Grady[1], the volume tensile strain of rock is caused by the blasting load, which leads to the propagation of microcracks inside the rock, and the activated microcracks density obeys the two parameter Weibull distribution as shown in equation (1).

\[ C_d = \gamma N a^3 \]  

(1)

Where, \( \gamma \) is a random distribution parameter, \( N \) is the number of cracks per unit volume, and \( a \) is the average radius of microcracks. The average radius of microcracks and the number of cracks per unit volume are determined by equation (2) and (3).

\[ a = \frac{1}{2} \left( \frac{\sqrt{20 K_{IC}}}{\rho c \dot{\varepsilon}_{\text{max}}} \right)^{2/3} \]  

(2)

\[ N = k \varepsilon_{IV}^m \]  

(3)

Where, \( k, m \) is the material parameter, \( \varepsilon_{IV} \) is the volume tensile strain, \( K_{IC} \) is the type I fracture toughness, \( \rho \) is the density, \( c \) is the longitudinal wave velocity of the rock, \( \dot{\varepsilon}_{\text{max}} \) is the maximum volume strain rate. Take equation (2) and (3) into equation (1) as followed equation (4).

\[ C_d = \frac{5}{2} k \left( \frac{K_{IC}}{\rho c \dot{\varepsilon}_{\text{max}}} \right) \varepsilon_{IV}^m \]  

(4)

Kuszmaul[3] considered the influence of rock damage during the propagation of microcracks, and obtained the expression of modified crack density as equation (5).

\[ C_d = \frac{5}{2} k \left( \frac{K_{IC}}{\rho c \dot{\varepsilon}_{\text{max}}} \right) \varepsilon_{IV}^m (1 - D_t) \]  

(5)

Where, \( D_t \) is the rock tensile damage factor. Considering rock damage, the expression of effective Poisson’s ratio \( \overline{\nu} \) as shown in equation (6).
The definition of tensile damage variable $D_t$ in the volume tensile state of rock as shown in equation (7).

$$D_t = \frac{16(1 - \tilde{\mu}^2)}{9(1 - 2\tilde{\mu})} C_d$$

2.2. Definition of compression-shear damage variable
Referring to paper [8], the stress thresholds of microcracks initiation and propagation in rock under compression and shear were obtained through a large number of indoor and field experimental data, as shown in equation (8).

$$\begin{align*}
\sigma_1 - \sigma_3 &= A \sigma_{cd} \\
\sigma_1 - \sigma_3 &= B \sigma_{cd}
\end{align*}$$

Where, $\sigma_1$ and $\sigma_3$ are the first and third principal stresses respectively, which $\sigma_{cd}$ are the dynamic compressive strength of rock, $A$ and $B$ are the parameters, and the value ranges are 0.4-0.6 and 0.8-1.0 respectively. According to the theory of damage mechanics, the material begins to be damaged when the microcracks inside the material start to crack, and the macro shear band formed with the microcracks expansion and fusion indicates that the material has been damaged. Therefore, the parameter $F_{Dc}$ is introduced as followed equation (9).

$$F_{Dc} = \frac{\sigma_1 - \sigma_3}{\sigma_{cd}}$$

The damage of rock mass is a continuous process. In this paper, it is assumed that the development of compression-shear damage is a uniform evolution process. Therefore, the definition of compression-shear damage $D_c$ is shown in equation (10).

$$D_c = \begin{cases} 
0 & F_{Dc} < A \\
\frac{F_{Dc} - A}{B - A} & A \leq F_{Dc} \leq B \\
1 & F_{Dc} > B
\end{cases}$$

2.3. Isotropic hardening elastic-plastic constitutive model
Under the blasting load, the mechanical behavior of rock satisfies the elastic-plastic constitutive law of isotropic hardening, and the corresponding yield condition is shown in equation (11)~(15).

$$\begin{align*}
\bar{E} &= E(1 - D) ; \bar{K} = K(1 - D) ; \bar{G} = \frac{3(1 - 2\mu)}{2(1 + \mu)} \bar{K} \\
d\sigma_{ij} &= \bar{K}d\varepsilon_{ik}\delta_{ij} + 2\bar{G} d\varepsilon_{ij} \\
\phi &= \sigma_1^2 - \sigma_2^2
\end{align*}$$

\(3\)
\[ \sigma_i = \sqrt{\frac{3}{2} S_{ij} S_{ij}} \] (14)

\[ S_{ij} = \sigma_{ij} - \frac{1}{3} \sigma_{kk} \delta_{ij} \] (15)

Where, \( \sigma_i \) is stress intensity, and \( S_{ij} \) is stress deviation. The plastic strain in hardening stage and the hardened yield strength are as followed equation (16) and (17).

\[ \varepsilon_{eff}^p = \int_0^\sigma \sqrt{3} \tilde{\varepsilon}_{ij}^p \, dt \] (16)

\[ \sigma_y = \sigma_0 + \beta E_p \varepsilon_{eff}^p \] (17)

Where, \( \beta \) is hardening parameter, \( E_p \) is plastic strengthening modulus, and \( \tilde{\varepsilon}_{ij}^p \) is plastic strain rate.

3. Numerical verification of blasting damage constitutive model

3.1. Damage zone of rock around a single blast hole

After the detonation of a single blast hole, the damage zone of rock around the blast hole can be roughly divided into crushing zone and fracture zone. Many researchers had done a lot of theoretical and experimental research on the damage zone of rock around a single blast hole. Donzé[9] hold that the formation of the crushing zone of the rock around the blast hole is due to the explosion impact load far greater than the dynamic strength of the rock, and the radius of the crushing zone is about 5 times of the charging radius. Hagan[10] deduced the formation mechanism of the rock crushing zone through micromechanics, and obtained the ratio of the radius of the crushing zone to the charging radius in the range of 1-10 through the experimental data. The radius of crushing zone calculated by Gao[11] through the theory of rock strength is about the ratio of charging radius between 1 and 3, while the ratio of fracture zone radius to charging radius is between 70 and 100. Xia[12] calculated the range of rock mass crushing zone and fracture zone around the hole under single hole blasting with cylindrical charge by dynamic finite element numerical software, and obtained that the ratio with charge radius is 3 times and 73 times respectively.

3.2. Numerical calculation of a single hole blasting

In order to verify the rationality of the blasting damage constitutive model proposed in this paper, the damage characteristics of rock around a single blast hole in semi-infinite space are studied. A two-dimensional numerical model is established for the plane area rock perpendicular to the blast hole axis, as shown in figure 1, and the length and width of the model are 8m, the blast hole radius is 38mm, and the charging radius is 25mm. According to the symmetry of loading and boundary conditions, only 1/4 model needs to be built, and normal constraints are imposed on the lower boundary and left boundary of the model, while the upper boundary and right boundary of the model are set as non-reflecting boundary, so as to eliminate the reflection of blasting stress wave on the boundary, which is more consistent with the actual engineering conditions.

According to Chapman-Jouguet theory of detonation wave, the triangular blast load is applied on the wall of the blast hole, and the peak load \( P_b \) in the simplified load curve after cylindrical charge detonation is shown in equation (18).

\[ P_b = \frac{P_0 V_d^2}{2(\gamma + 1)} \left( \frac{d_e}{d_h} \right)^{2\gamma} \left( \frac{l_e}{l_h} \right)^{\gamma} \] (18)
Figure 1. Schematic diagram of numerical model

Where: $\rho_0$ is the explosive density, $V_d$ is the explosive detonation speed, $d_c$ and $d_b$ are the charge and the blast hole radius, $l_c$ and $l_b$ are the total length of the charge and the length of the blast hole respectively, generally taken $l_c = l_b$ for shallow hole blasting, $\gamma$ is the load calculation parameter, which the value range is 2-3, $n$ is the load increasing coefficient, which value range is 9-11. In the numerical simulation, the No.2 rock emulsion explosive is adopted in the blast hole, so the values of $\gamma$ and $n$ are 3 and 10 respectively, explosive density $\rho_0$ is 1200kg/m$^3$ and explosive detonation velocity $V_d$ is 3600m/s. The calculated peak load $P_b$ in the simplified load curve applied on the blast hole wall is 1.57 GPa, the physical and mechanical parameters of the rock around the blast hole are shown in Table 1.

Table 1. Physical and mechanical parameters of the rock

| Density /($\text{g/cm}^3$) | Elastic modulus /GPa | Poisson's ratio | Uniaxial compressive strength/MPa | Bulk modulus /GPa | Shear modulus /GPa |
|---------------------------|-----------------------|----------------|---------------------------------|------------------|-------------------|
| 2.5                       | 20                    | 0.22           | 100                             | 12.1             | 6                 |

3.3. Analysis of numerical calculation results

The distribution diagram of tensile damage and compression-shear damage zone of surrounding rock around the blast hole is shown in figure 2, and it can be concluded that the radius of compression-shear damage value equal to 1 (crushing zone) is 0.115m, while the radius of tensile damage greater than 0 (fracture zone) is 1.973m. Therefore, it can be found that the ratio of the radius of crushing zone and fracture zone to the radius of cartridge is 4.6 and 78.9 respectively.

Keep the diameter of the blast hole unchanged, change the radius of the cartridge in the blasthole, which is 20 mm and 22 mm respectively, and calculate the corresponding radius of the crushing zone and the fracture zone, which are 0.087 m and 1.676 m, 0.095 m and 1.768 m respectively. The radius of crushing zone and fracture zone of the blast hole surrounding rock under different cartridge radius is shown in the table 2 below.
(a) tensile damage  (b) compression-shear damage

Figure 2. Distribution diagram of different types of damage range of rock around the blast hole

Table 2. Radius of rock crushing zone and fracture zone around the blast hole with different cartridge radius

| Cartridge radius /m | Crushing zone radius /m | Fracture zone radius /m | Ratio of crushing zone radius to cartridge radius | Ratio of fracture zone radius to cartridge radius |
|---------------------|-------------------------|-------------------------|-----------------------------------------------|-----------------------------------------------|
| 20                  | 0.087                   | 1.676                   | 4.4                                           | 83.8                                         |
| 22                  | 0.095                   | 1.768                   | 4.3                                           | 80.4                                         |
| 25                  | 0.115                   | 1.973                   | 4.6                                           | 78.9                                         |

It can be seen from the table 2 that the ratio of crushing zone radius to cartridge radius is between 4.3 and 4.6 under different charging radius, while the ratio of fracture zone radius to cartridge radius is between 78.9 and 83.8, which is close to results of the paper[11,12], so the rationality of the established blasting damage constitutive model established in this paper is verified.

4. Conclusion
In this paper, considering the compression-shear damage of rock caused by the strong blasting load around the blast hole, the classical KUS rock damage constitutive model is improved, and the rock blasting damage constitutive model considering compression-shear damage and tensile damage is established. At the same time, based on the improved model, the distribution of rock damage zone around a single blast hole is numerical calculated, the results show that the ratio of crushing zone radius to cartridge radius is between 4.3 and 4.6 under different charging radius, while the ratio of fracture zone radius to cartridge radius is between 78.9 and 83.8, which is close to the existing research results, and verifies the rationality and accuracy of the improved model in rock blasting engineering.

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