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Blasting Damage Model of Rock with Initial Damages and Its Application

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Rock is a material subject to initial damage. Rock blasting-induced damage model is the most commonly used constitutive model for numerical simulation of rock blasting. At present, however, most models neglect the effects of initial damage on blasting. To this end, this paper explored the merits and demerits of typical blasting-induced damage models. Then, a rock blasting-induced damage model was proposed by modifying the typical blasting-induced damage models, with the effects of initial damage on damage evolution taken into account. Numbers of parameter in the proposed model are low and all the parameters can be obtained easily from laboratory tests under uniaxial dynamic and static loading. The criterion to determine the fracture state of rock is also given, which is related to initial damage and used for confirming the blasting-induced fracture zone.

1. Introduction

At present, the most commonly used constitutive models for blasting are based on damage mechanics. Grady and Kipp (1980) presented a blasting model (GK model) suggesting that tension plays a decisive role in dynamic fracture of rock. Taylor et al., (1985, 1986) established an elastic-damage model (TCK model), regarding as damage evolution is caused only by volume-tensile strain. Kuszmaul (1987) revised the formula in TCK model for activated cracks to establish a blasting model (KUS model) considering effects of crack density on damage evolution. Parameters in GK, TCK or KUS model must be obtained by high-strain-rate tensile tests which are difficult to be conducted. Therefore, Liu and Katsabanisj (1997) proposed a simple damage evolution equation and established the volume-tensile damage model (LK model) featuring easily obtained parameters. Yang et al., (1996) recognizing that rock strength are different in compression and tension, established an equivalent tensile damage model (YBK model) with simple damage evolution relation. In this model, parameters can be obtained through uniaxial compression test at high strain rate. Overall, blasting-induced damage models have been constantly improved.

The typical blasting-induced damage models suppose that damage is the evolution of internal defects, however, in these models, damage evolution equations fail to reflect the influence of initial damage on damage calculation. Yang et al., (1999) indicated that initial damage plays an important role in mechanical properties of rock. Gao et al., (2000) also argued that rocks are a material subject to initial damage that acts as a key factor for rock blasting. For large-scale projects, such as mine, hydropower station and long-distance mountain tunnel, the types of rock mass are basically the same, but maybe there are differences in initial damage of rock mass. In this case, initial damage is critical to designing blasting parameters as well as analyzing the security and stability of surrounding rock (Chen et al., 2016). For example, granite and basalt are major rock mass in three Gorges and Xiluodu hydropower stations respectively, both of which are large-scale underground excavation projects in China. For the two large-scale projects, Initial damage or integrity is considered as the main factor influencing blasting excavation.

In order to provide references for blasting excavation considering the influence of initial damage of rock, the author proposed a blasting-induced damage model through analysis of features of typical blasting-induced models, in which damage evolution relation can consider the influence of initial damage on damage evolution.

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2. Features and analysis of typical blasting damage models

2.1 Damage evolution law

In typical blasting-induced damage models, modes of rock failure mainly include fracture by damage accumulation and plastic-flow fracture. Damage accumulation is induced by crack-density development. If rocks are isotropic material, then damage variable can be formulated as:

$$D = f(C_{\mathrm{d}}) \tag{1}$$

where, D is a scalar for the damage variable of rock unit, representing the mechanical deterioration degree relative to the initial state; C_{d} is the crack density under the dynamic loading, generally relying on tensile strain; and f is an expression using crack density as the variable.
For typical blasting damage models, damage variables can be calculated according to Table 1. In this paper, suppose tension equals positive and compression equals negative.

Table 1: Calculating variables for rock blasting-induced damage

Damage model	Damage evolution equation	Calculation of crack density
TCK	$D=\dfrac{16(1-\mu)}{9(1-2\mu)}C_{\mathrm{d}}$	$C_{\mathrm{d}}=\dfrac{5kK_{\mathrm{IC}}^2\varepsilon_{\mathrm{v}}^m}{2(\bar{\rho}_{\mathrm{r}}\bar{c}\dot{\varepsilon}_{\mathrm{vmax}})^2}$
KUS	$D=\dfrac{16(1-\mu)}{9(1-2\mu)}C_{\mathrm{d}}$	$\dot{C}_{\mathrm{d}}=\dfrac{5kmK_{\mathrm{IC}}^2\varepsilon_{\mathrm{v}}^{m-1}\dot{\varepsilon}_{\mathrm{v}}(1-D)}{2(\bar{\rho}_{\mathrm{r}}\bar{c}\dot{\varepsilon}_{\mathrm{vmax}})^2}$
LK	$D=1-\exp(-V_0C_{\mathrm{d}})$	$C_{\mathrm{d}}=A_{\mathrm{L}}(\varepsilon_{\mathrm{v}}-\varepsilon_{\mathrm{vcr}})^{B_{\mathrm{L}}}\cdot t$
YBK	$D=1-\exp(-C_{\mathrm{d}}^2)$	$\dot{C}_{\mathrm{d}}=A_{\mathrm{Y}}(\theta-\theta_{\mathrm{cr}})^{B_{\mathrm{Y}}}$

Notes: As shown in Table 1, μ is the Poisson's ratio of damage, K_{IC} is the fracture toughness of rock mass, $\dot{\varepsilon}_{vmaz}$ is tensile strain rate at limit volume, $\dot{C}_d$ is the growth rate of crack density, $\bar{\rho}_r$ and $\bar{c}$ are density and longitudinal wave velocity of undamaged rocks respectively, k,m,A_L,B_L,A_Y and B_Y are material parameters, V_0 is the volume of rock unit, ε_v is volumetric strain, θ is equivalent tensile deformation (generally $\varepsilon_v \geq \theta$), ε_{vcr} is the threshold value of volumetric strain, θ_{cr} is the threshold value of equivalent tension strain and t is time. When $\varepsilon_v > \theta$, TCK and KUS models can be established. When $\varepsilon_v > \varepsilon_{vcr} > 0$ and $\theta > \theta_{cr} > 0$, LK and YBK models can be built.

In Table 1, TCK, KUS, and LK models are tensile damage models under volumetric tensile stress. Unlike TCK and KUS models, damage evolution in LK and YHB models is simply formulated and easy to calculate. If damage, in TCK and KUS models, occurs from the beginning of loading, then in LK and YBK models damage occurs only when strain exceeds the critical value ε_{vcr} and θ_{cr} respectively. On the basis of YBK model, whether the volumetric stress is tensile or compressive, damage may accumulate, which has been verified. Compared with TCK, KUS and LK models, YBK model features broader concept of damage, simple damage evolution equation and easily obtained parameters, making it better describe the changes in mechanical property. Therefore, damage variables defined in YBK model are easily to be used.

2.2 Damage constitutive relations

2.2.1 Constitutive relation of elastic damages

The relation of damage to undamaged modulus can be written as:

$$K = \bar{K}(1-D) \tag{2}$$

$$G = \bar{G}(1-D) \tag{3}$$

$$E = \bar{E}(1-D) \tag{4}$$

In Formulas (2) and (3), $\bar{K}$,$\bar{G}$ and $\bar{E}$ means bulk, shear and elasticity modulus of undamaged rocks respectively, while K,G and E are that of damaged rocks.
In LK and YBK models, damage is supposed not to affect the Poisson's ratio, and the formulas are given as:

$$\mu = \bar{\mu} \tag{5}$$

$$E = 2G(1+\mu) = 3K(1+\mu) \tag{6}$$

$$\bar{E} = 2\bar{G}(1+\bar{\mu}) = 3\bar{K}(1+\bar{\mu}) \tag{7}$$

where $\mu = \bar{\mu}$ is the Poisson's ratio of undamaged rocks.
When stress is resolved into spheric and deviator stresses, constitutive relation of elastic damage in rock can be expressed as:

$$\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3 = K\varepsilon_v^e = \bar{K}(1-D)\varepsilon_v \tag{8}$$

$$s_{ij} = 2Ge_{ij}^e = 2\bar{G}(1-D)e_{ij} \tag{9}$$

where σ_m is the component of spheric stress, σ_1, σ_2 and σ_3 ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) are the maximum, intermediate and minimum principal stresses, s_{ij} is the components of deviator stress, ε_v^e and e_{ij}^e are elastic deformation and elastic deviator strain, and is deviator strain (i, j=1, 2, 3). Accordingly, elastic damage relations are $\varepsilon_v^e = \varepsilon_v$ and $e_{ij}^e = e_{ij}$.

2.2.2 Plastic constitutive relation

In TCK, KUS, LK and YBK models, in case of D=0 and yield in rock units, the stress can be represented as:

$$\psi = \sqrt{J_2} - \frac{\sqrt{3}}{3}\sigma_Y = 0 \tag{10}$$

$$J_2 = [(\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]/6 \tag{11}$$

where ψ is yield function, J_2 is the second invariant of stress deviator and σ_Y is the yield strength under uniaxial loading.
Incremental constitutive relation for yield in rock can be expressed as:

$$d\varepsilon_v = d\varepsilon_v^e + d\varepsilon_v^p = d\sigma_m / \bar{K} + \lambda(\partial\psi / \partial\sigma_m)/3 \tag{12}$$

$$de_{ij} = de_{ij}^e + de_{ij}^p = ds_{ij} / (2\bar{G}) + \lambda(\partial\psi / \partial s_{ij}) \tag{13}$$

where ε_v^p and e_{ij}^p are plastic deformation of volume and deviator stress, and λ is the plastic factor (λ>0).
Formulas (1)-(9) describe the constitutive relations of typical blasting damage models. When a certain damage variable value is reached, unloading occurs. The deformation modulus under unloading is the damage modulus calculated from Formulas (2)-(4) from the damage value.

2.3 Problems in typical rock blasting-induced model

As can be seen from Formulas (2)-(8) and Table 1, typical rock blasting models consider rock damages are caused on the basis of intact state.
Take TCK, LK and YBK as an instance, suppose initial damage is D_0, then, the formulas are given as follows:

$$D_0 = D = 0,\ \varepsilon_v < 0 \text{ (TCK model)} \tag{14}$$

$$D_0 = D = 0,\ \varepsilon_v < \varepsilon_{vcr} \text{ (LK model)} \tag{15}$$

$$D_0 = D = 0,\ \theta < \theta_{cr} \text{ (YBK model)} \tag{16}$$

where D_0 is the damage variable at initial state.
When D_0=0, bulk and shear modulus under initial loading are represented as K_0 and G_0. The following formulas can be derived based on Formulas (2)-(4).

$$K_0 = \bar{K} \tag{17}$$

$$G_0 = \bar{G} \tag{18}$$

$$E_0 = \bar{E} \tag{19}$$

As can be seen from Formulas (17)-(19), bulk or shear modulus at initial state is the same with that at intact state. In typical modes, the initial damage variable is supposed to be 0, namely D_0=0. That is to say, damage evolution is independent of damage history or initial damage has no effect on damage evolution.

3. Blasting damage model considering initial damage

3.1 Damage evolution equation and constitutive relation

It can be seen from the above analysis that damage variable defined in YBK model is relatively reasonable. To this end, this paper modified the YBK model to establish a model considering the effects of initial damage.
Damage evolution undergoes on the basis of initial damage. Therefore, damage evolution equation in YBK model shown in Table 1 was modified into:

$$D = 1-(1-D_0)\cdot \exp(-C_{\mathrm{d}}^2) \tag{20}$$

where D_0 is the parameter for initial damage. If D_0=0, Formula (20) is degraded as the damage evolution equation of YBK model in Table 1. The evolution equation of YBK model is a special form of Formula (20).
Like equation for YBK model, crack density parameter C_{d} can be formulated as:

$$C_{\mathrm{d}} = \int_0^t A_{\mathrm{Y}}(\theta - \theta_{\mathrm{cr}})^{B_{\mathrm{Y}}}\,\mathrm{d}t \tag{21}$$

Equivalent tensile strain θ can be calculated as:

$$\theta = \sum_{i=1}^{3}[(\varepsilon_i + |\varepsilon_i|)/2] \tag{22}$$

where ε_i is the principal strain in i direction.
At initial damage state, C_{d}=0. Then, the following formula can be derived from Formula (20) and (2)-(4).

$$K_0 = \bar{K}(1-D_0) \tag{23}$$

$$G_0 = \bar{G}(1-D_0) \tag{24}$$

$$E_0 = \bar{E}(1-D_0) \tag{25}$$

$$\mu_0 = \bar{\mu} = \mu \tag{26}$$

where μ_0 is the initial Poisson's ratio.
If bulk, shear and elastic modulus are constant for intact rocks, the modulus, according to Formulas (23)-(25), depends on the initial damage variable at initial sate.
Combining Formulas (8)-(13), (20) and (23)-(25) can derive the constitutive relation between elastic and plastic damages, with initial damage taken into account.

3.2 Blasting damage criterion considering initial damage

Damage variable increases with loading. When the damage variable reaches a certain value between 0 and 1, relatively serious damages will occur to rock units exactly seeing the emergence of inner macro-cracks. Based on Formula (20), the critical damage variable and crack density can be expressed as:

$$D_{\mathrm{lim}} = D_0 \exp(-C_{\mathrm{dlim}}^2) + [1-\exp(-C_{\mathrm{dlim}}^2)] \tag{27}$$

Where D_{lim} is the critical damage variable, showing the damage state in which macro-cracks are generated; and C_{dlim} is the critical crack density, which can indicate the critical state of damage.
When damage variable satisfies the Formula below, rock unit is within the range of fracture or the area of macro-cracks. Criterion for fracture can be described as:

$$D \geq D_{\mathrm{lim}} \tag{28}$$

For a certain rock, C_{dlim} is generally a constant. As can be seen from Formula (24), $\mathrm{D}_{\mathrm{lim}}$ is a function in which D_0 is the variable. D_{lim} increases as D_0 increases. In this paper, the proposed blasting damage criterion is a function of damage history. However, D_{lim} is a constant, i.e. 0.2, 0.2 and 0.22 in TCK, KUS and YBK models, which neglect the effects of initial damage history.

3.3 Confirmation of calculating parameters

3.3.1 Confirming θ_{cr}, E_0, and μ_0 (or θ_{cr}, G_0 and K_0)

As the threshold value for equivalent extensile strain, θ_{cr} can be calculated as:

$$\theta_{cr} = \varepsilon_t^e = \sigma_t^e / E_0 = -2\mu_0 \varepsilon_c^e = -2\mu_0 \sigma_c^e / E_0 \quad (29)$$

where σ_t^e and σ_c^e are the stress of linear elastic limit under uniaxial tension and compression; and ε_t^e and ε_c^e are the strain of linear elastic limit under static uniaxial tension and compression. “-” means compression is negative but tension is positive.
Compression test is easier to be conducted than tension test. Therefore, a laboratory test for static uniaxial compression can be conducted to determine the stress of linear elastic limit σ_c^e, the strain of linear elastic limit ε_c^e, the initial elastic modulus E_0 and initial Poisson's ratio μ_0. Then, Formula (29) can be used to deermine the threshold value for equivalent extensile strain θ_{cr}, E_0 and μ_0. Based on Formulas (6)-(7) and (23)-(25), G_0 and K_0 can be confirmed.
The relation ε_c^e to D_0 can be described as:

$$\varepsilon_c^e = \bar{\varepsilon}_c^e (1 - D_0)^n \quad (30)$$

where $\bar{\varepsilon}_c^e$ is the strain of elastic limit for intact rocks under uniaxial compression, and n is a material parameter. $\bar{\varepsilon}_c^e$ and n can be determined through the uniaxial compression test for intact rocks under static loading,

3.3.2 Confirming D_0, C_{dlim} and D_{lim}

According to the one-dimensional theory of longitudinal wave, the following formula can be given.

$$D = 1 - (c / \bar{c})^2 \quad (31)$$

where c is the longitudinal wave velocity in a damaged rock.
In light of Formula (31), the initial damage variable can be calculated as:

$$D_0 = 1 - (c_0 / \bar{c})^2 \quad (32)$$

where c_0 is the longitudinal wave velocity in a rock at initial damage state.
D_0 can be calculated according to Formula (32). In nature, there are almost no intact rocks. In this case, sampling can be used for statistical analysis. As a result, sample with the fastest longitudinal wave velocity can be used as intact material, of which the bulk, shear and elastic modulus as well as longitudinal wave velocity are deemed as parameters for intact material.
Descent rate of the longitudinal wave velocity can be formulated as:

$$\varpi = (c_0 - c) / c_0 \quad (33)$$

where ϖ represents the descent rate of the longitudinal wave velocity relative to the initial state.
Existing research has shown that when ϖ achieves some extent that the damage in rock unit will be in a critical state. Then, the following formula works:

$$\varpi_{lim} = (c_0 - c_{lim}) / c_0 \quad (34)$$

where ϖ_{lim} is the critical value for the descent rate of the longitudinal wave velocity, c_{lim} is the critical value for the longitudinal wave velocity in rock damage, and $\varpi_{lim}$and c_{lim} represent the critical state of damage.
Combining Formulas (31)-(34) can obtain the formula below:

$$D_{lim} = 1 - (1 - \varpi_{lim})^2 + D_0 (1 - \varpi_{lim})^2 \quad (35)$$

The following equation is given by comparing Formula (35) and (27).

$$C_{dlim} = \sqrt[2]{-2 \ln(1 - \varpi_{lim})} \quad (36)$$

According to *Construction Technical Specifications on Rock-Foundation Evacuating Engineering of Hydraulic Structures* (DL/T5389-2007, CHN), C_{lim}=0.57 can be calculated by substituting $\varpi_{lim} = 0.15$ in Formula (36).
When $\varpi_{lim} = 0.15$, Formula (35) can be changed into:

$$D_{lim} = 0.28 + 0.72 D_0 \quad (37)$$

3.3.3 Confirming A_Y and B_Y

Under the loading of normal stress rate, Formula (21) can be rewritten as:

$$C_d = \int_0^{\theta} A_Y(\theta - \theta_{cr})^{B_Y} d\theta / \dot{\theta}_{con} = A_Y(\theta - \theta_{cr})^{B_Y+1} / [\dot{\theta}_{con}(B_Y + 1)] \quad (38)$$

where $\dot{\theta}_{con}$ represents a constant extensile strain rate of equivalence.
In case of critical damage, the following equation can be derived according to Formula (38).

$$C_{dlim} = A_Y(\theta_{lim} - \theta_{cr})^{B_Y+1} / [\dot{\theta}_{con}(B_Y + 1)] \quad (39)$$

where θ_{lim} means the equivalent extensile strain in the critical state of damage.
In case of constant strain rate under uniaxial compression, $\dot{\theta}_{con}$ and θ_{lim} can be represented as:

$$\dot{\theta}_{con} = -2\mu_0 \dot{\varepsilon}_{con} \quad (40)$$

$$\theta_{lim} = -2\mu_0 \varepsilon_{clim} \quad (41)$$

Where $\dot{\varepsilon}_{con}$ is the constant strain rate under the dynamic loading of uniaxial compression, ε_{clim} is the critical strain at the direction of principal stress on uniaxial compression test.
At last, A_Y and B_Y are confirmed based on Formulas (39)-(41) and the results from uniaxial compression tests at different strain rates. Overall, when rock unit is at an initial damage state, there are only 5 numbers of parameter in the proposed model, including θ_{cr}, E_0, μ_0, D_0, A_Y and B_Y (or θ_{cr}, K_0, G_0, D_0, A_Y and B_Y).

4. Conclusion

(1) Typical blasting damage models in fact neglect the effects of initial state of rock on damage, so elastic, shear and bulk modulus in the initial state are identical with that in the intact state.
(2) The proposed model improved by YBK model still retains features of the old one broader. It has a wide concept of rock damage, simple damage evolution equation and easily obtained parameters through compression tests (or uniaxial tension test) and sound wave velocity test. The numbers of parameter are so low (only 5 parameters) that the proposed model is easy to be used.
(3) The damage evolution relation considers the effects of initial damage on damage evolution, so the proposed model can consider the effects of initial damage on the blasting-induced damage in rocks.

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