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The Effect of Different Fractures on Propagation Behavior of Blasting Wave in Rock

WANG YANG[1,2], TAO TIEJUN[1,2,3], CHEN XIN[3], CHI ENAN[2], ZHAO MINGSHENG[2], ZHOU JIANMIN[2] AND ZHONG WEN[3]

[1]School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing, 100083, China
[2]Guizhou Xinlian Blasting Engineering Group Co Ltd, Guiyang Guizhou, 550002, China
[3]Jiangxi Key Laboratory of Mining Engineering, School of Resources and Environment Engineering, Jiangxi University of Science and Technology, Ganzhou Jiangxi, 341000, China
Email: *290729639@qq.com*

Abstract: The fractures in rock influence propagation behavior of blasting waves and then it may result in higher blasting boulder yield and affect blasting result. According to the character of rock with closed macro fractures, the features of stress wave propagation in the rock with one inclined fracture, two parallel fractures and two crossed fractures were studied. The numerical models were established in 3DEC combined with LS-DYNA. The explosion wave was simulated by LS-DYNA and transformed into data form readable for 3DEC. Then the propagation behavior of blasting wave was calculated by 3DEC. The computation results show that the stress wave distributed differently in rock with different fractures. Comparing with intact rock, fractures can divide the stress region into parts. The minimum principal stress reduced quickly with the number of fractures increasing. In rock with two crossed fractures, the value of tensile stress near the blasthole reduced about 30 percent.

Keywords: *3DEC, LS-DYNA, Wave Propagation, Fractures, Stress Distribution.*

1. Introduction

Natural rock mass is not homogeneous, and it is full of various weak planes with different structures and geological mechanisms, such as fractures. The fractures in rock may seriously influence the propagation behavior of stress wave and then it may result in higher blasting boulder yield and affect blasting consequence. Theoretical and experimental studies on wave propagation across fractures have been extensively studied [i,ii]. Compared with theoretical and experimental studies, numerical modeling provides a convenient way to study wave propagation across fractures in a rock mass [iii,iv].

Most of the numerical modeling studied on wave propagation across fractures was performed by 2D code UDEC, which treats fractures as interfaces between discrete blocks. In 1971, Distinct Element Method originated by Cundall [v] was used to simulate the response of the discontinuity medium. The rocks with fractures were treated as composition of rock blocks and discontinuity. In 2001, Chen et al. [vi] simulated the responses of rock with fractures under explosion loading by UDEC. In 2008, Zhao et al. [vii] carried out numerical studies of P wave propagation across multiple non-linearly deformable fractures with UDEC. In 2011, Zhu et al. [viii] verified the capability of UDEC to model wave transmission across fractures in rock mass. However, in 2D numerical modeling, it is difficult to fully represent fractures, because fracture planes exist in a 3D space. When there are multiple intersecting fractures, 2D modeling cannot accurately express the spatial configuration of fractures [ix]. Element Code (3DEC) is a 3D numerical code based on the extensively tested numerical formulation used by the UDEC. It should be an appropriate tool to model wave propagation in complicated 3D rock with fractures. In 1993, Kulatilake et al. [x] studied the effect of intermitted fractures on the deformation of rock with fractures through 3DEC. In 2011, Li et a1.[xi]used three dimensional discrete element to simulate the excavation of permanent ship-lock in Three Gorges. All in all, studies on the dynamic responses of rock with fractures by 3DEC are underway.

According to the rock character of blasting excavation field in Guiyang railway station square, the features of stress wave propagation in rock with one fractures, two parallel fractures and two crossed fractures were studied. A numerical model was established in 3DEC combined with LS-DYNA. This study aimed to study the effect of different fractures on propagation behavior of blasting wave in rock so that it can offer effective guidance for blasting design.

2. Study area:

The rock excavation project is located in railway station square in Guiyang of Guizhou Province, stretching 600 m from north to south and 550 m from east to west, and covering about 800,0000 m3 excavation volume. Main excavation volume is located in small mountain with 913.8 m maximum elevation and 47 m excavation height difference. The bedrock of the project is mainly Maokou formation limestone, which is moderately weathered, hard and compact. And its lamellar middle section is full of banded chert and crumb. The tectonic of bedrock is simple, which is monoclinal structure, northwest trend, northeast dip with 20～30°. The characteristic value of limestone's bearing capacity is 3000～4000 KPa. The basic earthquake intensity of this field is less than 6° with stable block and poorly developed fractures.

3. Modelling procedure:

Because of the three-dimensional geometry of the problem, 3DEC was selected, which is a three-dimensional distinct element code which utilizes a Lagrangian calculation scheme to model large movements and deformations of a blocky system [xii].

3.1. Geometry and constitutive models:

Maokou formation limestone which is the most abundant rock in the area is considered in this section. Figure 1 shows the 3DEC model of blasting bench with a width of 10 m, a height of 10 m and a slope angle of 60o. The length of model basis is 13 m.

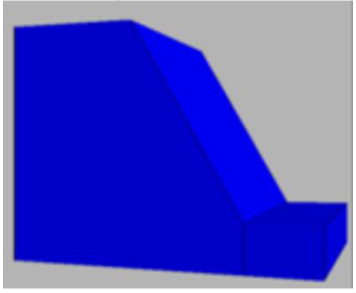
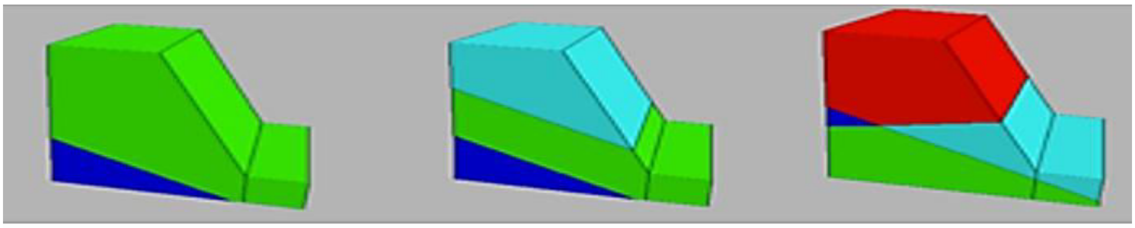


Figure 1. *Geometry of the 3DEC model of study area with intact rock*

The mechanical properties of rock blocks used for the simulations are summarized in Table 1.

Table 1: *Properties of rock blocks used in the 3DEC model*

Density/ kg/m^3	Young's modulus/ GPa	Poission's ratio	Cohesion/ MPa	Internal friction angle /°	Tensile strength / MPa
2200	27	0.29	0	55	25



a. one inclined fracture b. two parallel fractures c. two intersectant fractures

Figure 2. *Geometry of the 3DEC model of rock with different fractures*

In 3DEC model, the geometric parameter of fractures is a very important factor. For the determination of fracture, it was suggested that the accuracy and numerical efficiency should be both considered. Thus only part of fractures, which have important effect on mechanical response and are sensitive to explosion load, were shown in this model. According to structure fractures of rock masses in real project, the model of rock with one inclined fracture, two parallel fractures and two crossed fractures were studied, as shown in figure 2.

After the geometries of fractures were determined, the relative parameters must be input into this model. In the model of rock with fractures, there are two important parameters: *K*n, normal stiffness; *K*s, shear stiffness. The virtual fractures between surrounding blocks must be cohered together in case of slide and gaping. And the value of normal stiffness and shear stiffness must be high enough on the prevention of fracture slide.

In general, *K*n and *K*s are ten times of maximum stiffness equivalence value between adjacent units. The stiffness equivalence in normal direction is[xiii],

$$\max\left[\frac{K+\frac{4}{3}G}{\Delta Z_{\min}}\right]$$

Where, *K*, *G* are bulk modulus and shear modulus respectively; $\Delta Z_{\min}$ is minimum width in vertical direction (0.4).

The fractures generated in the model are considered to be fictitious. Specific mechanical properties must be assigned to these sections of "fractures" that are related to the properties of the intact rock [xiv]. Table 2 presents the mechanical properties assigned to fictitious fractures in this case.

Table 2: *Characteristics of rock fractures used in the 3DEC model*

Kn / GPa	*Kn* / GPa	*Kn* / MPa	Internal friction angle/°	Tensile strength /MPa
1	1	0	35	0

3.2. Mesh size:

The blocks are meshed into triangular elements. The size of elements has a great influence on the computational results. For the determination of the mesh size of the ground, it was suggested that the accuracy and numerical efficiency should be both considered. In 1973, Kuhlemeyer and Lysme [xv] showed that for the accurate representation of wave transmission through a model, the mesh size (Δl) must be smaller than approximately one-tenth to one-eighth of the wavelength,

$$\Delta l \le \lambda/10 - \lambda/8$$

Where, λ is the wave length corresponding to the dominant frequency.

Alternatively, in order to accurately simulate the transmission of shock wave in rock fractures and eliminate the wave distortion, the maximum input frequency of the wave should be less than a maximum frequency of $f_{\max}$ which is determined by the following equation [xvi],

$$f_{\max} = \frac{c}{\lambda} = \frac{c}{10\Delta l}$$

Where, C refers to the smaller value between C_p and C_s which are velocity of P and S waves, respectively.

According to supersonic field test, C_p is 4232 m/s and C_s is 1869 m/s. Thus, if $\Delta l = 0.4$ m was adopted, $f_{\max}$ calculated as 373 Hz. Because the numerical simulations of blasting wave are carried out based on the transient dynamic finite element program LS-DYNA. The velocity temporal is recorded by using of MATLAB and then transform into data form readable for 3DEC. The waves with frequencies from 60 Hz up to 70 Hz were recorded after filtration. Thus the elements size was selected fine enough to make sure that the waves with frequencies from 60 Hz up to 70 Hz could be transmitted without distortion.

Eventually, a uniform mesh of tetrahedral elements with the average edge length of 0.4 m was adopted by computations.

3.3. Additional damping:

Natural dynamic systems contain some degree of damping of the vibration energy within the system; otherwise, the system would oscillate indefinitely when is subjected to driving forces. Damping is due, in part, to energy loss as a result of internal friction in the intact material and slipping along interfaces, if these are present. For a dynamic analysis, the damping in the numerical simulation should be reproduced in magnitude and form of the energy losses in the natural system subjected to a dynamic loading.

In 3DEC model, Rayleigh damping is commonly used to provide damping that is approximately frequency-independent over a restricted range of frequencies. The idea is to try to get the right damping for the important frequencies in problem. The required input parameters to specify Rayleigh damping in 3DEC are the central frequency, $f_{\min}$ and the critical damping ratio, $\xi_{\min}$ [xvii],

$$f_{mm} = \omega_{mm} / 2\pi = \sqrt{\alpha / \beta} / 2\pi$$

$$\xi_{mm} = \sqrt{\alpha\beta}$$

Where, α is proportionality coefficient of quality damping; β is proportionality coefficient of stiffness damping. Their values can be obtained by the following formulae,

$$\begin{cases} \alpha = \dfrac{2\omega_m\omega_n}{-\omega_m^2 + \omega_n^2}(\xi_m\omega_n - \xi_n\omega_m) \\ \beta = \dfrac{2\omega_m\omega_n}{-\omega_m^2 + \omega_n^2}\left(\dfrac{\xi_n}{\omega_m} - \dfrac{\xi_m}{\omega_n}\right) \end{cases}$$

Where, ω_m, ω_n, is natural frequency; ξ_m, ξ_n is damping ratio.

For fracture system in this model, according to engineering experience, m=1, n=5, and the damping ratio is 5%.

3.4. Boundary conditions:

In deep underground mining, it is usually assumed that specific model is surrounded by infinite medium, and the surface structure is analyzed to be in a half infinite space. In static analyses, fixed or elastic boundaries can be realistically placed at some distance from the region of interest. In dynamic problems, however, such boundary conditions cause the reflection of outward propagating waves back into the model and do not allow the necessary energy radiation. The use of a larger model can minimize the problem, since material damping will absorb most of the energy of the waves reflected from distant boundaries. However, this solution leads to a large computational burden [13]. One alternative solution is to use absorbing boundaries for which several formulations have been proposed; the viscous boundary developed by Lysmer and Kuhlemeyer [15] was used in our simulations. It is based on the use of independent shock absorbers, which is almost completely effective for incident wave with incidence angle more than 30° when it reached the boundary. For incident wave with incidence angle less than 30°, the energy absorption is only an approximation and it can be ignored. It is regarded as an effective technique because it can be used for time-domain analysis. Its effectiveness has been confirmed in the finite element method and finite difference method.

In this model, as shown in figure 3, the left side, the back, the front side and the ground side were setting as viscous boundary. But top side and right side were defined as free surface.

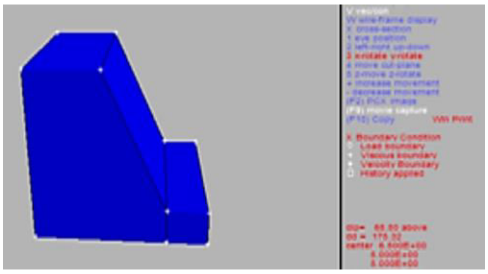


Figure 3. The viscous boundary of the 3DEC model

3.5. Dynamic load input:

The determination of dynamic loads is the basic information and a difficult problem to study the dynamic response of rock slopes under explosion. In 3DEC model, the commonly used method is treating the load as the input of velocity temporal or strain [xviii]. The first method required specific velocity temporal. The disadvantage is its boundary cannot be defined as transmitting boundary. And it will put any stress wave reflected back through the border in model. Thus it requires setting viscous boundary separately [xix]. The second method can solve this problem. It transforms velocity temporal into strain. It should note that additional normal stress should be double than stress in viscous boundary. In this case, applied velocity temporal maybe different with original velocity temporal because both methods are calculated by linear formulas.

In 3DEC model, method one was adopted in dynamic load input and the vibration velocity was imported in the form of TABLE. The numerical simulations were carried out based on the transient dynamic finite element program LS-DYNA. The velocity temporal was recorded by using of MATLAB and then transformed into data form readable for 3DEC. Even the explosion wave calculated by LS-DYNA was an approximate value; this error could be ignored if the recorded location was near enough from explosion point.

Material Type 8 of LS-DYNA (*MAT_HIGH_EXPLOSIVE_BURN) was used for emulsion explosive. The detailed model parameters of emulsion explosive are shown in Table 3.

Table 3: *Model parameters of emulsion explosive*

Density/*kg/m*^{3}	**Detonation velocity/ *m/s***	**PCJ**
1300	4533	1.1×10^{10}

The Jones–Wilkens–Lee (JWL) equation of state was used to calculate the pressure generated by the expansion of the detonation products of the chemical explosive. The JWL defines the pressure as [xx].

$$P_{eos} = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E_O}{V}$$

Where, P_{eos} is the pressure induced by donation, E_o is the internal energy per initial volume, V is the relative volume, A, B, R_1, R_2, ω, are the user defined input parameters related to charging explosives. The material parameters for emulsion explosive used in the present study are as follows,

Table 4: *Material parameters for emulsion explosive*

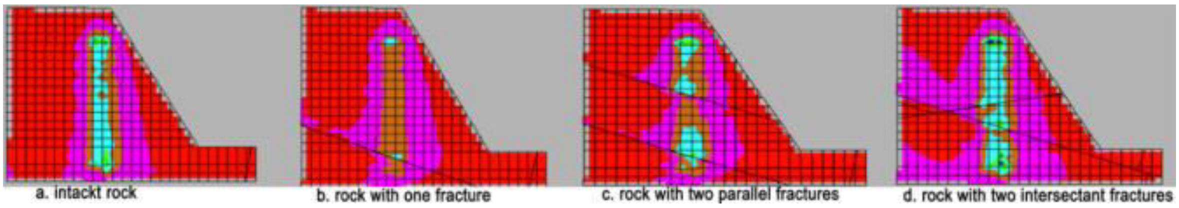
***A*/GPa**	***B*/GPa**	**ω**	**R_1**	**R_2**
391	4.400	0.191	6.070	1.510

For the accuracy, in LS-DYNA model, the mesh size was the same as in 3DEC model. And the rock was used by elastic/plastic Mohr-Coulomb material model. In the end, the explosion stress wave was transformed into EXECL and then converted it into TXT.

4. Computation results:

For accurate computation of stress wave in this discrete element model, the frequency and wavelength of stress wave were limited artificially, the rock mass was defined to be a deformable body to adapt the mesh size., and the elasticity modulus and contact stiffness of the block were determined by longitudinal wave velocity. For there was a dynamic input of peak velocity and instantaneous rise time, the very fine spatial grid and the small time step were required objectively. This was because when the waves transmit through the discontinuous body, it can produce higher frequency. Thus the fine mesh can filter the high-frequency wave, while the coarse mesh will affect the results.

The bedrock of the project is mainly limestone, which is moderately weathered, hard and compact. The static tensile strength is 3.5 MPa and dynamic tensile strength is 1 to 10 times of the static tensile strength, which is 25 MPa here. For computation result, there are stress distribution of 2000, 4000 and 6000 time-steps, which is shown in figure 4, figure 5, and figure 6.



a. intackt rock b. rock with one fracture c. rock with two parallel fractures d. rock with two intersectant fractures

Figure 4. *The stress distribution of 2000 time-steps*

It is shown in figure 4: a. in the brown area, the values of tensile stress are all greater than 25 MPa and the stress in blasthole center reaches 70 MPa. According to the maximum tensile stress failure criterion, the rock is crushing.; b. in the brown area, the values of tensile stress are all greater than 25 MPa and the stress trends to be stable; c. in the green area, the values of tensile stress are all greater than 25 MPa and blasting wave is cut by fractures into pieces; d. in the green area, the values of tensile stress are all greater than 25 MPa and the scope of rock damage is shrinking. From four pictures, we can see that fractures can affect the propagation of stress wave and the minimum principal stress is in downward trend.

It is shown in figure 5: the color become be brown in free surface. It means that the stress wave reflex in the free surface and then overlap with the transmitting wave. It results in the phenomenon of stress concentration in the free surface. However, for the stress in the whole region, the stress values are all decreased and fractures prevent the propagation of stress wave. At the same time, blasting wave in rock with two intersecting fractures reduced fastest and shows a fragmented shape.

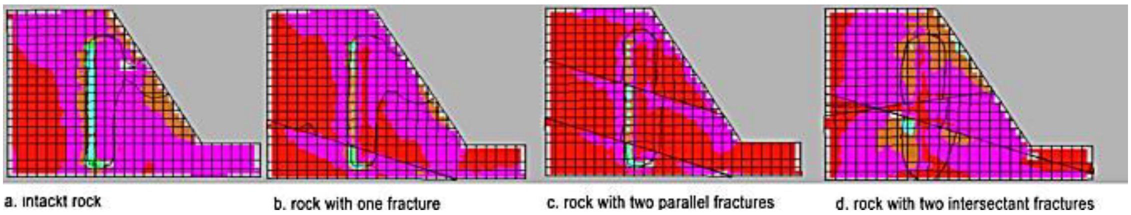

a. intackt rock
b. rock with one fracture
c. rock with two parallel fractures
d. rock with two intersectant fractures

Figure 5. *The stress distribution of 4000 time-steps*

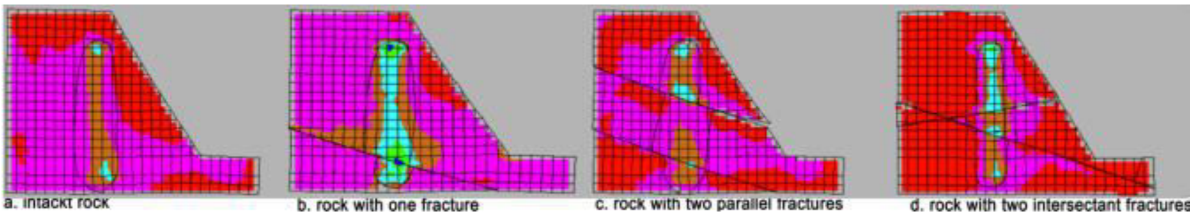

a. intackt rock
b. rock with one fracture
c. rock with two parallel fractures
d. rock with two intersectant fractures

Figure 6. *The stress distribution of 6000 time-steps*

It is shown in figure 6: tensile stress around blasthole center is smaller when two fractures exist and the value of stress is reduced to about 30%, thus the rock is not easy to be destroyed. In Engineering, there often are these types of closure fractures and it should increase the amount of charge for avoiding large break-stones.

5. Conclusions:

a. Referencing blasting excavation project in Zunyi railway station square in Guizhou Province, LS-DYNA combining discrete element method software 3DEC was used to study the blasting mechanism of closed macroscopic fractured rock. The explosion wave was simulated by LS-DYNA and transformed into data form readable for 3DEC. Then the propagation behavior of blasting wave was calculated by 3DEC.
b. In order to reasonably model the propagation behavior of blasting wave with the 3DEC method, the rock mass should be divided into discrete blocks by one inclined fracture, two parallel fractures and two crossed fractures were studied which exist in the real geometry. And the mesh size is determination to be 0.1 m for consideration of the accuracy and numerical efficiency
c. Closed macro-fractures hamper blasting wave propagation and the stress wave which is not well-distributed mainly spreads toward free surface.
d. The number of closed macro-fractures can affect the blasting wave propagation. Comparing with intact rock, two parallel fractures divides the stress region into three parts and the crossed fractures divides the stress region into more parts. Additional the fractures can affect the amplitude of minimum principal stress wave. When fractures exist, minimum principal stress reduces; it is dropped to 20% for the rock mass with two parallel fractures and 30% for the rock mass with two crossed fractures.

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