Numerical study of blast-induced rock fractures under different in-situ stress and joint properties conditions

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Abstract. As the excavation depth of underground engineering increases, the influence of in-situ stress on the blasting effect cannot be ignored. Many joints in the natural rock mass, coupled with the initial stress, significantly affect the stress wave propagation process. Therefore, it is necessary to study the blast failure behavior of jointed rock masses under different in-situ stress conditions. In this study, a universal distinct element code-discrete fracture network model was used to examine the failure mode of jointed rock mass induced by blasting under different in-situ stress conditions. The effects of in-situ stress and joint geometric parameters on blast-induced rock fractures were analyzed systematically. The numerical results indicated that in-situ stress conditions would act against the initiation and propagation of blast-induced cracks. The maximum cracking radius and rock breakage area decreased with increasing in-situ stress. The long joints largely prevented the propagation of cracks induced by blasting. However, as a free surface, the joint plane could increase the fracture network scope between the blasting source and joints in the process of blasting. Although it improved the crushing effect of the rock mass considerably, the effect gradually disappeared as the distance between the blasting source and joints or the in-situ stress was increased.

1. Introduction
The drill and blast method is still the primary means of excavating deep rock. The blasting excavation of deep rock results from a combination of in-situ stress and dynamic stress produced by an explosive detonation [1]. The problem of rock blasting under initial stress conditions has attracted considerable attention from researchers because the in-situ stress significantly affects the blasting effectiveness of the rock mass [2-4]. Currently, theoretical analysis, experiments, and numerical simulations are mainly used to study the blasting process of rock mass under in-situ stress and discuss the influence of in-situ stress on stress wave propagation, crack initiation, and propagation. Compared to the previous two methods, numerical simulations are an effective tool for examining these problems. Donze et al. [2] investigated the effect of in-situ stress on the blast fracture patterns using a discrete element model. The simulation results showed that in-situ stress altered the propagation direction and extension length of blast-induced cracks. Based on the Mohr-Coulomb failure criterion, Yilmaz et al. [3] used FLAC3D to simulate the blasting process of a cylindrical charge. They examined the effects of the stress-loading rate, in-situ stress, and lateral pressure coefficient on the fracture zones. The results showed that the shape of the fracture zone was significantly affected by the lateral pressure coefficient of the static stress. Yi et al. [4] adopted LS-DYNA to study the influence of in-situ stress on rock blasting fractures. They reported that the blast load near the blasthole controls crack propagation, while high in-situ stress
affects crack propagation in the far field. The research mentioned above suggests that in-situ stress plays a vital role in blast-induced crack expansion.

In addition, the natural rock mass contains many joints, cracks, and other defects, which makes the rock blasting problem more complicated. Many researchers have also examined the effects of joint parameters on the blasting effects. For example, Ma and An [5] used LS-DYNA software to examine the effects of joint orientation on the blasting effect. Zhu et al. [6] utilized AUTODYN to investigate the effects of the local joint thickness and filling materials (soil and air) on the blasting effectiveness. However, few studies have examined the failure mode of deep jointed rock masses under a dynamic loading.

In this study, the coupled universal distinct element code-discrete fracture network (UDEC-DFN) model was used to simulate the blasting process of granite with joints under different in-situ stress conditions, and the influence of in-situ stress and joint geometric parameters on the blasting effect was studied.

2. Numerical approach

2.1. Generating DFN

Under long-term geological actions, there are a large number of random joints in a rock mass. The geometric parameters of these joints (e.g., size, orientation, and location) are usually considered to obey some probability distributions. In this study, it was assumed that the joint orientation and joint location conform to a uniform distribution, whereas the trace lengths of the joints conform to a power-law distribution [7]:

\[ n(l) = al^{-a} \]

(1)

where \( l \) is the fracture length; \( a \) is the proportionality coefficient; \( a \) is the fracture length exponent.

2.2. Generating UDEC grain-based model (UDEC-GBM)

UDEC is capable of modeling the quasi-static and dynamic response of rocks. It represents the rock as a combination of discrete blocks, allowing for tensile or shear failure along the boundaries of the block. In UDEC, the sub-blocks can be generated using random-sized triangular or polygonal blocks. As observed in the thin rock section in Figure 1, polygonal grain structures are more appropriate for representing the two-dimensional microstructure of rocks. Therefore, UDEC-GBM was used to model the microstructure of rocks in this study.

![Figure 1](image-url)

**Figure 1.** Schematic diagram of the UDEC grain-based model. (a) Micrograph of granite; (b) UDEC-GBM model considering microstructures; and (c) Finite element meshing (reproduced after Pan et al. [8]).

2.3. Coupled UDEC-DFN

The UDEC-DFN model was implemented using the following steps:

1. Generate DFN samples using UDEC’s built-in programming language.
(2) Generate an intact rock sample (UDEC-GBM) of the same size as the DFN sample, and use the DFN to cut the UDEC-GBM to generate a jointed rock mass model.

(3) The mechanical parameters of the rock and joints are assigned to the contact between the blocks of intact rock and along the fracture, respectively.

Tables 1 and 2 list the mechanical parameters of rock grains and joints determined by reference [9].

Table 1. Micro-parameters used in the UDEC grain-based model [9].

| Contact parameters | $k_{n0}$ (GPa/m) | $k_{s0}$/$k_{n0}$ | $\phi_c$ (°) | $c_c$ (MPa) | $f_c$ (MPa) | $\Phi_r$ (°) |
|--------------------|------------------|-------------------|-------------|------------|------------|------------|
|                    | 78400            | 1.55              | 40.0        | 33.1       | 5.4        | 24.0       |

| Block parameters   | $\rho$ (kg/m$^3$) | $E_p$ (GPa) | $\nu_p$ |
|--------------------|------------------|------------|---------|
|                    | 2600             | 40.0       | 0.252   |

Table 2. Joint parameters used in the discrete fracture network model [10, 11].

| $k_{n0}$ (GPa/m) | $k_{n0}$/$k_{s0}$ | $\phi_c$ (°) | $c$ (MPa) | $f$ (MPa) |
|------------------|-------------------|-------------|----------|----------|
| 20               | 2                 | 35.0        | 6.0      | 1.5      |

3. Numerical simulation and parametric analysis

3.1. Model configuration

As shown in Figure 2a, this study established a 2 m × 2 m two-dimensional blasting model. The model contains 13,300 Voronoi blocks with an average grain size of 0.02 m. The loading process of the numerical model mainly involves two aspects: static stress initialization and blasting stress wave loading. First, the static stress was applied at a specific rate on the boundary of the model until the static force balance was achieved. A borehole with a radius of 19 mm was excavated at the center of the model, and the blasting wave was applied evenly on the inner wall of the blasthole (Figure 2b). In this study, the blasting wave was simplified as a triangular stress wave. As shown in Figure 2c, the peak stress of the blast wave was 100 MPa, and the rise time and total time were 50 μs and 91 μs, respectively [3]. In addition, a viscous boundary was used at all boundaries around the model to eliminate the boundary effects.

![Figure 2](image-url)
3.2. Parametric study

3.2.1. Effect of the joint length. Numerical models with different joint length distributions were established to study the effect of the joint length on blasting-induced fractures generation and expansion (Figure 3). The joint length is assumed to obey the power-law distribution and is controlled by the exponent $a$, which generally varies between 1.3 and 3.5 [12]. Therefore, this section examined three cases with exponents of 1.5, 2.5, and 3.5, respectively. The number of small-sized joints increased with increasing exponent $a$. However, the joint intensity of the model remained the same, and $P_{21}$ (joint length in the unit area) was kept as 2.5 m$^{-1}$.

Figure 4 shows the results of the blasting-induced crack distribution. The numerical results indicated that the joint length affects the fracture shape, number of cracks, and maximum crack length. The number of cracks and the maximum crack length increased with decreasing joint length (Figure 4). When the joint length exponent was increased from 1.5 to 3.5, the number of cracks increased by 4.6%, whereas the maximum crack length increased by 23.1%. Although the number of cracks increased slightly when the exponent $a$ changed from 1.5 to 3.5, there was a significant difference in the fracture mode. When long joints dominate the model, dense cracks are formed between the joints and the blasthole (Figure 4b). However, as the length of the joints became shorter, the type of microcracks gradually changed from reflective tensile cracking at the joint surface to winging crack at the end of the joints (Figure 4d).

![Figure 3](image_url)

**Figure 3.** Universal distinct element code-discrete fracture network models with different joint length exponent. (a) Intact model; (b) $a = 1.5$; (c) $a = 2.5$; and (d) $a = 3.5$.

![Figure 4](image_url)

**Figure 4.** Effect of the joint length exponent on blasting fracture. (a) Intact model; (b) $a = 1.5$; (c) $a = 2.5$; and (d) $a = 3.5$. ($T$ is tensile crack, $S$ is shear crack, and $ML$ is maximum crack length)

3.2.2. Effect of joint location. The simulation results in the above section show that the length of the joint has a significant influence on the blasting effect. This section examines the influence of the distance between the long joint and the blasthole on the blasting effect. Three models were developed...
with the same joint intensity and length distribution exponent, as shown in Figure 5. The joint intensity and length distribution exponent of these models were 2.5 m\(^{-1}\) and 1.5.

The hindering effect of the joints on stress wave propagation was influenced by the distance, as shown in Figure 6. As the distance increased, the reflective tensile damage owing to the joints gradually decreased until it disappeared.

![Figure 5. Universal distinct element code-discrete fracture network models with different joint locations.](image)

![Figure 6. Effect of the joint location on blasting fracture.](image)

![Figure 7. Effect of the joint intensity on the blasting fracture. (a) P_{21} = 2.5 \text{ m}^{-1}; (b) P_{21} = 5.0 \text{ m}^{-1}; and (c) P_{21} = 10.0 \text{ m}^{-1}. (T \text{ is tensile crack, } S \text{ is shear crack, and } ML \text{ is maximum crack length})](image)
3.2.3. **Effect of joint intensity.** The effect of joint intensity was studied while keeping the joint length exponent at 2.5. Figure 7 shows the failure modes. The number of microcracks increased with increasing joint intensity, regardless of whether they were tensile cracks or shear cracks. However, the maximum crack length decreased with increasing joint intensity. This was attributed to the increase in the density of joints, leading to an increase in the number of joints. As a weak structural plane, joints can hinder the propagation of stress waves and are prone to damage [13].

3.2.4. **Effect of in-situ stress.** In this section, the blasting behavior of intact rock and jointed rock

| Intact rock | Jointed rock mass |
|-------------|-------------------|
| (a) $\sigma_h = \sigma_v = 2\text{MPa}$ | (g) $\sigma_h = \sigma_v = 2\text{MPa}$ |
| (b) $\sigma_h = \sigma_v = 5\text{MPa}$ | (h) $\sigma_h = \sigma_v = 5\text{MPa}$ |
| (c) $\sigma_h = \sigma_v = 10\text{MPa}$ | (i) $\sigma_h = \sigma_v = 10\text{MPa}$ |
| (d) $k = 2$ | (j) $k = 2$ |
| (e) $k = 0.5$ | (k) $k = 0.5$ |
| (f) $k = 0.33$ | (l) $k = 0.33$ |

**Figure 8.** Effect of in-situ stress on blasting fracture.
masses under two different groups of geostress conditions was investigated. One group had a constant lateral pressure coefficient \( k \) of 1.0, and the vertical stress \( \sigma_v \) was 2MPa, 5MPa, and 10MPa, respectively. For the other group of models, the horizontal stress \( \sigma_h \) was fixed to 5MPa, and the lateral pressure coefficient \( k \) was 2.0, 0.5, and 0.33, respectively. The joint intensity and length distribution exponent of the jointed rock mass models were 2.5 m\(^{-1}\) and 1.5, respectively.

When the lateral pressure coefficient equaled 1, the length and number of cracks produced by blasting decreased with increasing in-situ stress, as shown in Figure 8(a)-(f). When the lateral pressure coefficient was not equal to 1, the propagation of cracks deviated to the direction of the maximum principal stress. Similar phenomena were observed in the jointed rock masses, as shown in Figure 8(g)-(l). In addition, the reflection–stretching effect of the joint surface gradually disappeared with increasing in-situ stress. At the same time, the difference between the blasting effects of the jointed rock mass and intact rock gradually decreased.

4. Conclusions
(1) The long joint affected the expansion of the blasting-induced main crack, but the reflected tensile stress wave generated at the joint surface strengthened the damage to the rock mass between the blasthole and the joint. The reflection tensile failure of the joint surface was affected by many factors, such as the distance between the explosion source and the joint and in-situ stress.

(2) The joint intensity affected the number and maximum length of microcracks. In particular, the number of microcracks increased with increasing intensity of the joint, regardless of whether they were tensile or shear cracks. However, the maximum crack length intensity of the joint increases.

(3) In-situ stress had a significant influence on the blasting effect of jointed rock masses. As the in-situ stress increased, the difference between the blasting effects of the jointed rock mass and intact rock decreased.

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References
[1] Xie L X, Lu W B, Zhang Q B, Jiang Q H, Chen M and Zhao J 2017 Analysis of damage mechanisms and optimization of cut blasting design under high in-situ stresses Tunnel. Underground Space Technol. 66:19-33.
[2] Donze F V, Bouchez J and Magnier S A 1997 Modeling fractures in rock blasting Int. J. Rock Mech. Min. Sci. 34(8):1153-1163.
[3] Yilmaz O and Unlu T 2013 Three dimensional numerical rock damage analysis under blasting load Tunnel. Underground Space Technol. 38:266-278.
[4] Yi C P, Johansson D, Greberg J 2018 Effects of in-situ stresses on the fracturing of rock by blasting Comput. Geotech. 104:321-330.
[5] Ma G W and An X M 2008 Numerical simulation of blasting-induced rock fractures Int. J. Rock Mech. Min. Sci. 45:966-975.
[6] Zhu Z M, MOHANTY B and Xie H P 2007 Numerical investigation of blasting-induced crack initiation and propagation in rocks Int. J. Rock Mech. Min. Sci. 44(3):412-424.
[7] Yang P, Lei Q H, Xiang J S, Latham J P and Pain C 2020 Numerical simulation of blasting in confined fractured rocks using an immersed-body fluid-solid interaction model Tunnel. Underground Space Technol. 98:103352.
[8] Pan C, Li X, Li J C and Zhao J 2021 Numerical investigation of blast-induced fractures in granite: insights from a hybrid LS-DYNA and UDEC grain-based discrete element method Geomech. Geophys. Geo-energ. Geo-resour. 7:49.
[9] Pan C, Li X, He L and Li J C 2021 Study on the effect of micro-geometric heterogeneity on mechanical properties of brittle rock using a grain-based discrete element method coupling
with the cohesive zone model *Int. J. Rock Mech. Min. Sci.* 140: 104680.

[10] Zhu J B, Li Y S, Peng Q, Deng X F, Gao M Z and Zhang J G 2021 Stress wave propagation across jointed rock mass under dynamic extension and its effect on dynamic response and supporting of underground opening *Tunnel. Underground Space Technol.* 108:103648.

[11] Shang J, Hencher S R and West L J 2016 Tensile Strength of Geological Discontinuities Including Incipient Bedding, Rock Joints and Mineral Veins *Rock Mech. Rock Eng.* 49:4213-4225.

[12] Lei Q H, Latham J P and Tsang C F 2017 The use of discrete fracture networks for modelling coupled geomechanical and hydrological behaviour of fractured rocks *Comput. Geotech.* 85:151-176.

[13] Chai S B, Li J C, Zhang Q B, Li H B and Li N N 2016 Stress Wave Propagation Across a Rock Mass with Two Non-parallel Joints *Rock Mech. Rock Eng.* 49:4023-4032.