Application of FDEM to Blasting-Induced Rock Fragmentation in Jointed Rock Masses: A Postprint

Authors: Xu Chenyu, Hu Yingguo, Li Peng, Liu Meishan, Li Gengquan

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Abstract

Finite-Discrete Element Method (FDEM) is an advanced numerical computational method highly suitable for simulating the complete process of rock blasting and fragmentation. Considering that natural rock masses contain numerous joint surfaces, this study introduces a realistic joint constitutive model to reproduce the transmission and reflection phenomena of blasting stress waves when they reach joint surfaces. Simultaneously, based on the original FDEM code, an optimized blasting computational model is proposed. This model accounts for the effects of explosion gases and accurately describes the physical relationship between explosion gas pressure and the change in blast cavity volume induced by crack propagation. This study optimizes the criteria for crack coalescence detection and the calculation method for blast cavity area, thereby enabling efficient computation of the influence of explosion gas penetration on fracture propagation. Finally, through two numerical examples, the transmission and reflection patterns of blasting stress waves at joint surfaces and the complete process of rock mass throw blasting are simulated. The results demonstrate that the improved FDEM can be utilized to assist in analyzing the complete process of rock fragmentation by blasting in jointed rock masses, significantly revealing its application potential in blasting engineering.

Full Text

Application of FDEM in Blasting Fragmentation of Jointed Rock Mass

Chenyu Xu, Yingguo Hu, Peng Li, Meishan Liu, Genquan Li
Key Laboratory of Geotechnical Mechanics and Engineering of the Ministry of Water Resources, Changjiang River Scientific Research Institute, Wuhan, Hubei 430010, China

Abstract

The finite element and discrete element coupling method (FDEM) is an advanced numerical calculation method highly suitable for simulating the entire rock blasting process. Considering that rock masses contain numerous joints, this study introduces a realistic joint constitutive model to reproduce the transmission and reflection phenomena of blasting stress waves at joint interfaces. Based on the original FDEM code, an optimized blasting calculation model is proposed that considers the effect of detonation gas and accurately describes the physical relationship between detonation gas pressure and changes in blasting chamber volume caused by crack propagation.

This study optimizes the criteria for crack penetration and the calculation method for blasting chamber area, enabling efficient computation of how the embedding effect of detonation gas influences fracture propagation. Finally, two examples simulate the transmission and reflection laws of blasting stress waves at joints and the complete process of rock mass throw blasting. Results demonstrate that the improved FDEM can assist in analyzing the entire blasting fragmentation process in jointed rock masses, revealing substantial potential for application in blasting engineering.

Keywords: FDEM; jointed rock mass; rock blasting; detonation gas

Current simulation methods for rock blasting fragmentation can be divided into three major categories [**?**, **?**]: continuous simulation methods based on continuum mechanics (FEM, BEM, etc.), discontinuous methods based on Newtonian mechanics (DDA, DEM), and coupled continuous-discontinuous methods (SPH-FEM, FDEM, etc.). Continuous simulation methods offer greater numerical stability and shorter computation times compared to the other two approaches, providing good stability for far-field blasting simulation and satisfactory fragmentation effects. However, the blasting process involves numerous discontinuous phenomena, and these methods lack quantitative description of crack initiation and propagation.

Discontinuous simulation methods excel in phenomenological representation of blasting processes but suffer from much longer computation times and higher costs. Moreover, the stability and accuracy of mechanical indicators such as stress, velocity, and acceleration time-history curves are less than ideal. While these methods demonstrate clear advantages in simulating blasting throw and crack propagation, their accuracy heavily depends on element or block size and contact parameter settings.

Both continuous and discontinuous numerical simulation methods have inherent limitations when modeling blasting processes, making it significant to establish coupled continuous-discontinuous simulation methods that combine their respective advantages. Two main solution strategies exist for such methods. The first involves coupling established continuous and discontinuous methods: Saiang [**?**] coupled PFC2D and FLAC2D to investigate the spatial distribution characteristics of blast-induced damage and parameter degradation mechanisms; Wang et al. [?] and Huang et al. [?] implemented SPH-FEM coupling for rock blasting simulation by employing SPH in the near-field and FEM in the far-field. The second strategy involves developing new computational methods: Feng et al. [?] simulated three-dimensional bench blasting in open-pit mines using CDEM; Yan et al. [?] proposed a rock fracture simulation method within FDEM that considers gas-driven crack propagation; Ren et al. [?] simulated rock foundation pit blasting using CDEM and conducted comparative analysis of average fragmentation size, limiting fragmentation size, boulder yield, and system fracturing degree. Such methods, which combine the advantages of continuous and discontinuous simulation approaches, are becoming important tools for rock blasting fragmentation simulation.

This paper improves the FDEM source code by introducing a realistic joint constitutive model and a blasting calculation model that considers the dynamic effect of detonation gas on rock masses. Through examples, the improved FDEM is shown to accurately reproduce the complete rock blasting process and demonstrate sufficient application potential.

2.1 Representation of Structural Planes in FDEM

Currently, structural planes (faults, joints, bedding planes, weak layers) in FDEM are represented as shown in [Figure 1: see original paper]. Thickened solid elements comprising triangular and joint elements are primarily used for simulating weak underlying layers, while zero-thickness joint elements can simulate realistic joints (bedding) through parameter redefinition and modification. Based on the cementation and filling conditions between actual joints, these can be further classified into rigid structural planes and weak structural planes. Rigid structural planes are considered as already-failed joint elements, whereas weak structural planes have intact joint elements with parameter values determined according to actual joint conditions. This study selects weak structural planes to represent realistic joints.

Utilizing established and validated realistic joint constitutive models (linear elastic model [?], BB model [?], etc.), this paper introduces a stress-based failure criterion and incorporates a linear joint constitutive relationship into FDEM. The relationship is expressed as follows:

Where d and s are the normal and shear displacements of the joint; σ and τ are the normal and shear stresses; k_n and k_s are the normal and shear stiffnesses of the joint; and τ_s is the maximum shear stress.

3 Blasting Process Simulation Considering Detonation Gas

Numerous studies [?, ?] have demonstrated that rock failure results from the combined action of stress waves and detonation gas. However, nearly all current commercial software [?] cannot accurately characterize both the action process of detonation gas on rock fracture and the complete evolution of cracks.

As previously noted, FDEM is an advanced numerical method highly suitable for simulating the complete blasting process, but the original FDEM requires optimization to achieve refined simulation of the entire blasting process. This study improves upon the single-hole blasting simulation method of Yan et al. [?], simplifies the blasting chamber area calculation process to facilitate multi-hole blasting scenarios, and further extends this method to additional application contexts.

[Figure 2: see original paper] shows a cross-sectional schematic of borehole chamber expansion during rock blasting in FDEM. R_0 is the initial borehole radius, R is the diffusion radius of detonation gas in fractures at time t, where $R = V_p \cdot t$ and V_p is the gas diffusion velocity. The detonation gas is assumed to be ideal gas diffusing outward uniformly at constant speed. The blasting chamber area calculation assumes: (1) triangular elements are relatively rigid, ignoring area changes from mutual embedding; (2) triangular elements on the gas diffusion line are counted as half area. The final blasting chamber area is given by Equation (2), approximating the area after gas diffusion minus the initial area and triangular element area.

After determining the total area occupied by detonation gas, the current pressure is determined based on the ratio of current area to initial gas area. Equation (3) presents an exponential detonation pressure equation of state to determine instantaneous chamber pressure [?]. Gas pressure is then applied to all fracture boundaries connected to the chamber, and for isolated blocks surrounded by detonation gas, gas pressure is applied uniformly to their outer boundaries.

Where P and P_0 are the current and initial detonation gas pressures, V and V_0 are the current and initial chamber areas, and γ is a constant related to explosive and rock properties.

Existing joint element constitutive models in FDEM establish force-displacement relationships, where elastic, yield, and failure stages are determined by displacement (strain) magnitude. However, this approach neglects the effect of normal stress on shear strength and cannot determine the total area occupied by detonation gas when applied to wave propagation problems.

4.1 Propagation of P-Waves at a Single Linear Deformable Joint

Schoenberg et al. [?] and Pyrak-Nolte et al. [?] derived transmission and reflection coefficients for normally incident harmonic P-waves crossing a single linear deformable joint using a displacement discontinuity model:

Where T_{lin} and R_{lin} are the transmission and reflection coefficients for stress waves crossing a single linear joint; k_n is the joint normal stiffness; ω is the angular frequency of the harmonic wave; z_p is the P-wave impedance, defined as the product of P-wave velocity and rock density; $|T_{lin}|$ and $|R_{lin}|$ are the transmission and reflection coefficients, respectively, depending on normalized joint normal stiffness $K_n = k_n/(\omega z_p)$. $|T_{lin}|$ increases with increasing K_n, approaching 1 when K_n is large, and satisfies $|T_{lin}|^2 + |R_{lin}|^2 = 1$.

The numerical analysis model for stress wave transmission across a joint is shown in [Figure 3: see original paper]. The coordinate origin o is located at the lower left corner of the model. The model dimensions are 300 m in length and 1 m in width, with the joint positioned at the center. A half-cycle sinusoidal wave with frequency 20 Hz and velocity amplitude 1 m/s is incident vertically from the left boundary propagating in the x-direction. Viscous boundary conditions are applied at both ends to avoid artificial boundary reflections. The entire model restricts displacement in the y-direction while allowing free displacement in the x-direction. Monitoring points A (75, 0.5) and B (225, 0.5) record time-history curves of incident, reflected, and transmitted waves. During numerical simulation, rock material is assumed to be perfectly elastic because wave attenuation in rock masses is primarily caused by geological structures such as joints [**?**, **?**], with material attenuation having minimal effect. As this study focuses on joint effects on stress wave propagation, rock material attenuation is neglected. Transmission (reflection) coefficient variations are investigated through changes in joint normal stiffness from 5E7 to 5E9 Pa/m (corresponding to normalized joint normal stiffness of 0.049–4.989). Specific parameters are listed in .

[Figure 4: see original paper] shows velocity time-history curves at monitoring points A and B for P-waves crossing single joints with different normal stiffness values. [Figure 5: see original paper] compares theoretical solutions and FDEM numerical solutions for transmission coefficients at different normalized joint normal stiffness values. Results indicate that when the incident wave reaches the joint, transmitted waves (monitored at point A) and reflected waves (monitored at point B) are generated, both with peaks smaller than the incident wave. As k_n increases, transmitted wave peaks increase while reflected wave peaks decrease, meaning transmission coefficients increase and reflection coefficients decrease with increasing k_n. FDEM-derived transmission coefficient variations with normalized joint normal stiffness agree well with theoretical solutions.

4.2 Throw Blasting

A rock blasting model is established ([Figure 6: see original paper]) with dimensions 16 m in length and 7 m in height. The borehole radius $R_0 = 0.05$ m, borehole center coordinates $O(0, 0)$, and minimum burden distance of 2 m. The model contains 8,950 triangular elements and 13,542 zero-thickness joint elements. Joint elements employ the realistic joint constitutive model introduced above with normal stiffness of 6E9 Pa/m. Initial peak detonation gas pressure $P_0 = 0.2$ GPa, gas diffusion velocity $v_p = 200$ m/s, and constant $\gamma = 1.4$ related to explosive and rock properties.

Two scenarios are simulated: without and with detonation gas consideration. The complete blasting process is illustrated in [Figure 7: see original paper]. Evolution of blast-induced fractures is shown in [Figure 8: see original paper].

Rock mass around the borehole first develops radial initial shear fractures under blasting stress waves, with tensile fractures in the far-field. Detonation gas diffuses slower than stress waves, subsequently generating numerous tensile fractures that play a primary role in rock fragmentation. [FIGURE:8(a)] shows time-history curves of fracture counts for both scenarios: 1,901 fractures in the final stage without detonation gas versus 3,367 with detonation gas, indicating that detonation gas significantly increases fracture numbers. [FIGURE:8(b)] presents velocity time-history curves at monitoring point A, demonstrating that detonation gas accelerates rock block throw processes. [FIGURE:8(c)] shows time-history curves of chamber area and detonation gas pressure during the complete blasting process. Due to approximate chamber volume calculations, detonation gas pressure curves exhibit significant fluctuations but show an overall exponential decay trend consistent with Equation (3). Overall, the improved FDEM proposed in this paper can capture the complete process of stress wave propagation, gas wedge effects, crack initiation, propagation, penetration, and subsequent block separation and throw in rock masses during blasting, demonstrating the method’ s potential for blasting simulation. The limitation of this example is that it does not comparatively analyze blasting effects with and without joints, which will be investigated in future studies.

Conclusions

1. The representation method of realistic joints in FDEM was established, and a realistic joint constitutive model was implemented to simulate the complete transmission and reflection process of blasting stress waves at joint interfaces. Simulation results demonstrate that FDEM can accurately reproduce stress wave propagation laws and attenuation characteristics in joints, providing a necessary computational foundation for subsequent research on complete blasting processes in jointed rock masses.

2. The FDEM blasting calculation model was further optimized based on previous work. This model considers detonation gas effects, optimizes criteria for crack penetration and calculation methods for blasting chamber area, achieves accurate capture of chamber volume and detonation gas pressure, and thereby reproduces the promoting effect of detonation gas on fracture development and propagation, demonstrating the method’ s potential for blasting simulation.

3. The rock mass failure mechanism in blasting was discussed, revealing that after stress waves generate initial radial fractures, detonation gas expansion and embedding into fractures play a primary role in rock fragmentation and throw.

Future research will focus on three-dimensional FDEM, GPU acceleration for large-scale computations, and further promotion of FDEM applications in practical blasting engineering.

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