Development of a Blasting Simulator Considering Gas-Rock Interaction

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Abstract

Optimization of rock blasting in mining engineering is essential for energy efficiency, cost reduction, and safety. In contrast, the dynamic rock fracture process due to blasting involves highly complex and rapid processes. Thus, it is crucial to develop a reasonable numerical simulator for blasting which can model the following processes: (i)detonation-induced shock wave and gas expansion, (ii)complex dynamic fracture process of rocks, (iii)gas-rock interaction including the impact of shock waves on the blasthole surface and the inflow of blast-induced gas into a dynamically evolving fracture network. Besides, massively parallel computation is indispensable to dealing with the computationally expensive coupling processes (i)~(iii). To this end, this study couples the cubic-interpolated pseudo particle (CIP) method, the combined finite-discrete element method (FDEM) and the immersed boundary method to model the processes (i)~(iii), respectively. A massively parallel computing scheme with general-purpose graphics-processing units (GPGPU) is incorporated for the parallel computation. The applicability of the developed simulator is investigated using a single-hole blasting problem. Although further improvements must be achieved, the proposed blasting simulation results indicate that all the processes (i)~(iii) can be reasonably traced. In conclusion, the developed simulator is expected to help investigate the optimization of rock blasting.

Keywords: FDEM, Fluid-structure-interaction, GPGPU parallel computation, Numerical simulation, Rock blasting

1. Introduction

Optimization of rock fracturing that results from drilling & blasting in mining is essential for improving energy efficiency for fracturing rocks, cost reduction, and disaster prevention by reducing damage to the remaining rock mass. However, since the blasting process consists of high-speed phenomena with a highly complex dynamic fracture process of opaque rocks, the fracture mechanism of rock blasting has not been elucidated, and the optimization of rock blasting has not been achieved yet. Therefore, developing an advanced numerical analysis method for the rapid

and complex dynamic fracture phenomena associated with rock blasting is of engineering importance.

For the reasonable numerical simulation of rock blasting, the following requirements should be considered: (i)rational analysis of the detonation process by explosives, (ii) rational analysis of the complex and fast fracture process of rocks, (iii) rational analysis of the gas-rock interaction (i.e. fluid-structure interaction, FSI), including the impact of detonation waves on the rock mass and inflow of explosion-induced gas products into a dynamically evolving fracture network in the rock mass, and (iv) large-scale parallel computation to deal with the massive amount of computation in the requirements (i)~(iii).

The main aim of this paper is to lay a foundation for developing a reasonable blasting simulation method that can consider the above requirements (i)~(iv). Thus, the main focus is set to two-dimensional (2-D) problems. The applicability of the developed simulator is investigated using a 2-D single-hole blasting problem.

2. Methodology

The requirement (i) is modeled by solving the 2-D Euler equations, i.e. the conservation of mass, momentum, and energy in the following Eqs. (1)−(3), respectively, for an inviscid compressible fluid.

$$\frac{\partial \rho}{\partial t} + v_\alpha \frac{\partial \rho}{\partial x_\alpha} = -\rho \frac{\partial v_\alpha}{\partial x_\alpha} \tag{1}$$

$$\frac{\partial v_\alpha}{\partial t} + v_\beta \frac{\partial v_\alpha}{\partial x_\beta} = -\frac{1}{\rho}\frac{\partial p}{\partial x_\alpha} \tag{2}$$

$$\frac{\partial E}{\partial t} + v_\alpha \frac{\partial E}{\partial x_\alpha} = -\frac{p}{\rho}\frac{\partial v_\alpha}{\partial x_\alpha} \tag{3}$$

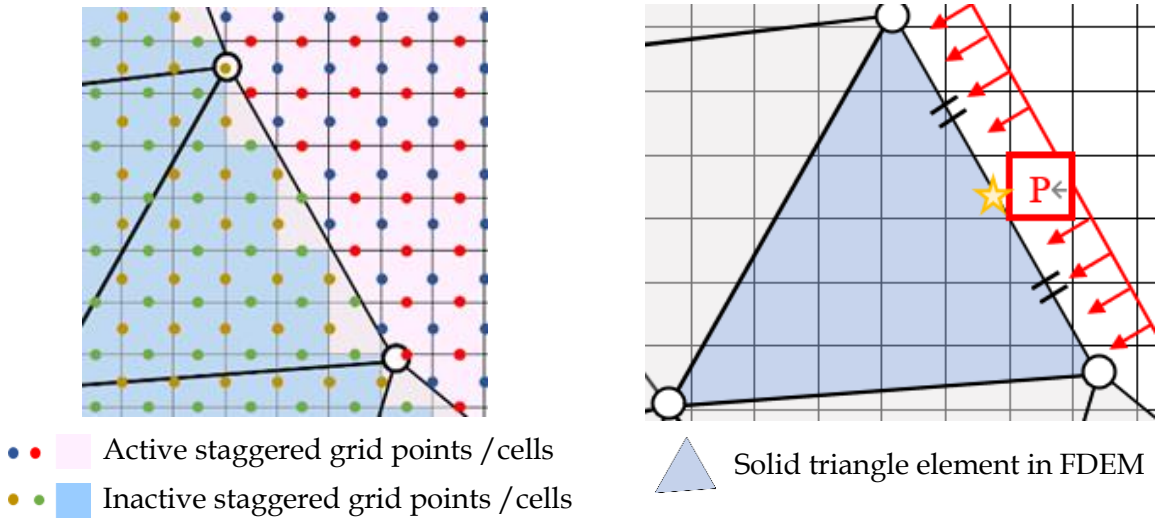
where ρ, v, p, and E are density, particle velocity, pressure, and internal energy of fluid, respectively. The subscripts α and β in these equations refer to the spatial direction and summation convention applies for the repeated index. In this study, the cubic-interpolated pseudo particle (CIP) method [1] is applied to solve the governing equations of the compressible fluid. Compared with other computational fluid dynamics approaches, the CIP method can reduce numerical diffusion by including the information of spatial derivative values in spatial interpolation. The fluid particle velocities are calculated on staggered grid points, while the density, internal energy, and pressure are calculated in each fluid cell. In addition, to handle the shock wave without numerical instability, an artificial viscosity q is added to the pressure terms in Eqs. (2) and (3), and q is given in the following Eqs. (4) [2]:

$$q_{ij}^n = \begin{cases} c_1 \rho_{(i,j)}^n c_s \left|\Delta U\right| + c_2 \rho_{(i,j)}^n \Delta U^2 & (\Delta U < 0) \\ 0 \quad (\Delta U \geq 0) \end{cases} \tag{4}$$

$$\Delta U = u_{(i+1/2,j)}^n - u_{(i-1/2,j)}^n + v_{(i,j+1/2)}^n - v_{(i,j-1/2)}^n \tag{5}$$

where c_s, c_1, c_2, and n are the speed of sound, artificial viscosity coefficients and time step, respectively. It must be noted that the subscripts i and j in these equations refer to the location of fluid cells or staggered grids. In addition, u and v in Eq. (5) correspond to the fluid particle velocities v_1 and v_2, respectively, in Eqs. (1)−(3). The above fluid simulation method is implemented utilizing the parallelization scheme using a general-purpose processing unit (GPGPU) for the requirement (iv).

The requirement (ii) is modeled by the 2-D combined finite-discrete element method (FDEM) [3]. FDEM is a hybrid method combining the advantages of the continuum-based finite element method and the discontinuum-based discrete element method. It aims to simulate the complex transition process of rock mass from a continuum to a discontinuum using three mechanical modeling concepts, i.e. continuum mechanics, nonlinear fracture mechanics based on the cohesive zone model, and contact mechanics. It enables highly sophisticated numerical modeling of the dynamic fracture process of rocks. Despite its capability, the FDEM is notorious for its significant computational cost. This study applies the GPGPU-based FDEM simulator "Y-HFDEM" code developed by Fukuda et al. [4][5] for the requirement (iv). Interested readers are



(a) (b)

Figure. 1: Overview of FSI calculation model. (a): the influence of the existence of the solid on the fluid, (b) the influence of the existence of the fluid on the solid.

referred to the literature [4][5] for the full detail of the theory and implementation detail of the applied FDEM code.

The requirement (iii), i.e. FSI, is modeled based on the immersed boundary method. In the FSI, it is necessary to consider "the influence of the existence of the solid (i.e. rock) on the fluid (i.e. gas)" and "the influence of the existence of the fluid on the solid". For the former aspect (see Fig.1(a)), we consider the "active" and "inactive" fluid staggered grid points/cells. The active staggered grid points/fluid cells that do not overlap with the solid region are solved only by the CIP method. On the other hand, if the four staggered grid points comprising each fluid cell are included in the area occupied by the solid triangular elements used in FDEM, the corresponding fluid cell is judged as the inactive cell to which the ambient condition is assigned. The particle velocities of inactive fluid staggered grid points are interpolated using the shape functions and nodal velocities of the solid triangular element inside which the inactive fluid particles are located. For the latter aspect (Fig.1(b)), at the edge of an FDEM solid triangular element which is the fluid-solid interface, the fluid pressure of the active fluid cell (e.g. the fluid cell "P" in Fig.1(b)), which exists nearest to the midpoint of the solid element edge is applied using 1-point Gauss integration theorem (e.g. the star mark in Fig.1(b)). This FSI is also implemented using the GPGPU-based parallelization for the requirement (iv).

It should be noted that the implemented code can entirely run on GPGPU except for the input and output stages of the blasting simulation.

3. Two-dimensional blasting analysis

The developed blasting code is used to simulate a 2-D single-hole blasting problem numerically. The simulation model is shown in Fig. 2 based on Munjiza et al. [6]. In the model, the grey part is the cylindrical rock part with a single blasthole. The blasthole is initially filled with a high-energy gas source with high pressure, as shown by the red color. On the other hand, all the other fluid parts, including the outer region of the rock part, as shown by the blue color and the region overlapping with the rock part, are initialized to the ambient condition, i.e. low pressure. An ideal gas is assumed for all the gas parts with Courant number = 0.1, and the initial conditions for fluid simulation are summarized in Table 1. The most outer boundary of the model is assumed to be a continuous (non-reflecting) boundary.

On the other hand, the FDEM input parameters assuming an intact rock are shown in Table 2. The time step increment

Δt is fixed at 20 ns. Note that this Δt condition fully satisfies the Courant condition for both the fluid and solid analyses. For the FDEM element size, an average element size = 9.5 [mm] is used, resulting in a total number of triangular elements = 69,871. To increase the resolution of the FSI calculations, 25,010,001 (=5001×5001) fluid cells are used in the CIP-based fluid simulation.

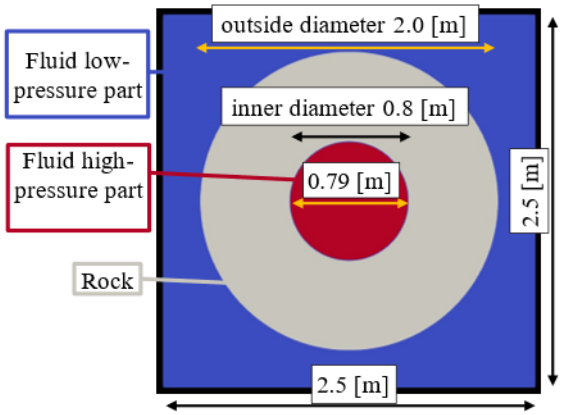


Figure. 2: 2-D single-hole blasting simulation model based on [6]

Table 1: Initial conditions for fluid analysis by CIP method

	High-pressure part	Low-pressure part
Density ρ [kg/m^3]	1.63×10^2	1.20
Internal energy E [J/kg]	4.29×10^5	2.09×10^5
Particle velocity u, v [m/s]	0.00	0.00
Pressure P [Pa]	2.80×10^7	1.01×10^5
Spatial derivative of ρ, E, u, v	0.00	0.00

Table 2: Input parameters for dynamic fracture process analysis by FDEM

Density [kg/m^3]	2.60×10^3	Microscopic tensile strength [MPa]	6.30
Young's Modulus [GPa]	5.50×10^1	Microscopic Cohesion [MPa]	1.82×10^1
Poisson's ratio	0.30	Microscopic internal friction angle [°]	3.00×10^1
Dynamic contact friction coefficient	0.60	Mode I fracture energy [J/m^2]	5.00×10^1
		Mode II fracture energy [J/m^2]	2.50×10^2

3. Results

Figure 3 shows the spatial distribution of fluid particle velocity at time t = 1.04 ms, 1.70 ms, 2.60 ms, and 3.14 ms after the onset of the simulation. In addition, Fig. 4 shows the spatial distribution of fluid pressure (compression: negative value) and minimum principal rock stress "PS3" (most compressive stress with compressive stress shown by negative value) immediately after the shock wave propagating in the fluid in the blasting hole starts to load the blasting hole wall at t = 0.02 ms.

First, before crack initiation and propagation, the fluid and solid behaviors must be circumferentially symmetric due to the geometric symmetry of the problem with respect to the blasting hole center. Besides, the fluid pressure and radial compressive stress must be equal on the blasting hole wall interface. From these perspectives, Fig. 4(a) shows that the distributions of the rock stress and the fluid pressure around the blasthole center are circumferentially symmetric. Furthermore, Fig. 4(b) shows that the fluid pressure and radial compressive rock stress (i.e. PS3 in this case) are very close on the blasting hole wall, indicating that the implemented FSI is modeled appropriately. After the stress waves are induced in the rock mass due to the shockwave on the blasthole, the result at t = 1.04 ms in Fig. 3 shows that complex macroscopic fractures are generated in the rock mass. These fractures are initiated from blasthole by the shockwave-induced dynamic loading as well as the from the outer free face due to the reflection of the stress wave. Then, the results at t =1.70 ms and 2.60 ms show that high-pressure gas flows into the macroscopic fracture network generated from the blasthole side, and the FSI further extends these fractures toward the outer free face of the rock part. At t = 3.14 ms, it is observed that the gas starts to eject from the outer boundary of the rock part. Note that the nominal gas flow speed is roughly 214 m/s. The validity of the evaluated nominal gas flow

speed must be investigated in our future study.

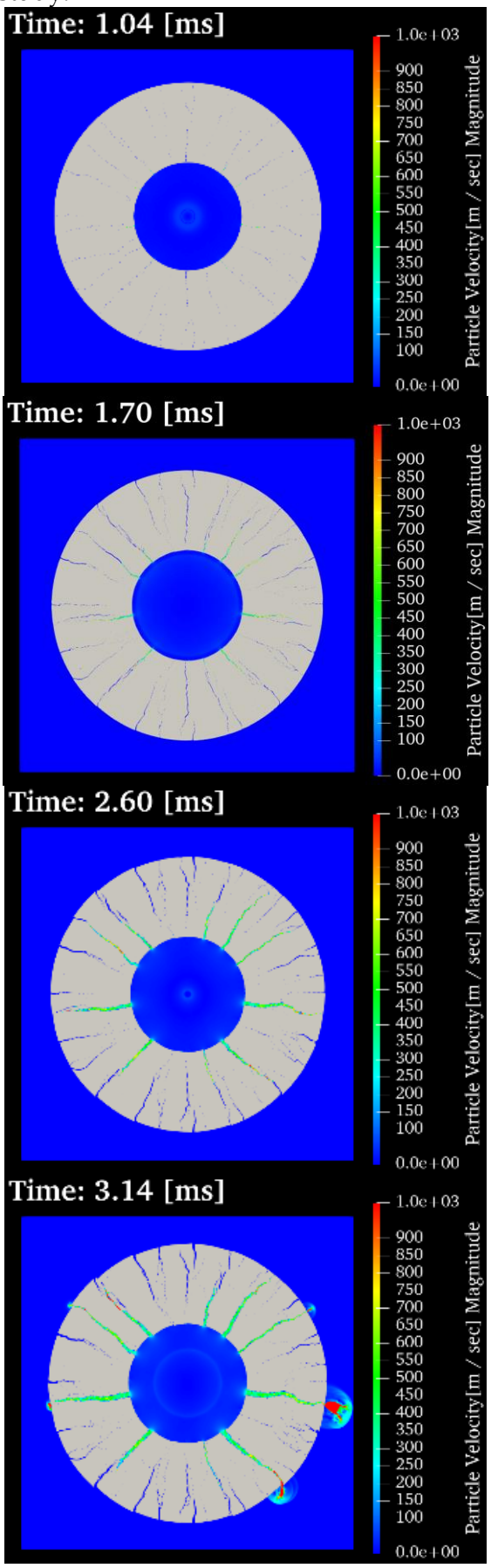


Figure. 3: Spatial distribution of fluid particle velocity at selected timesteps

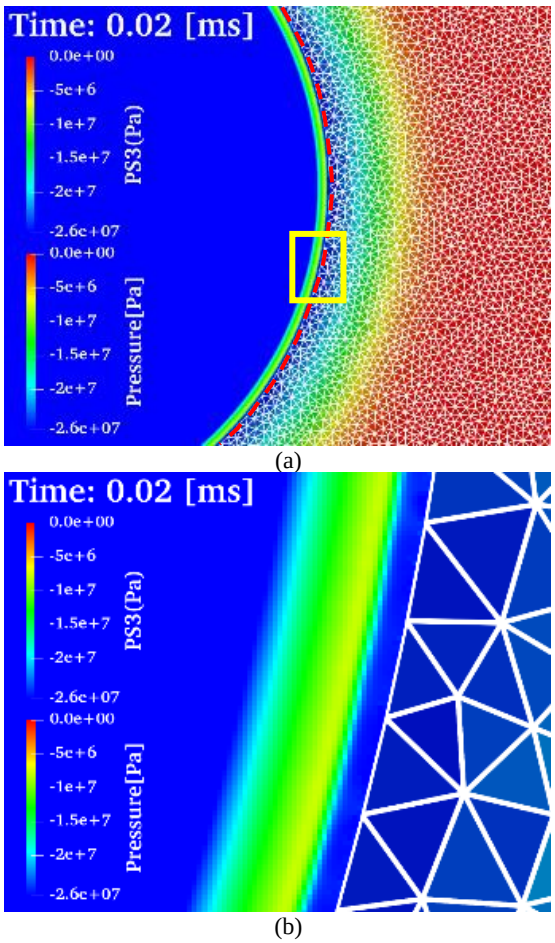


Figure. 4: (a)Fluid pressure and minimum principal rock stress (PS3) at t = 0.02 ms (red dotted curve is the interface between rock and gas), (b) a zoom-up of the yellow box in (a).

From the presented blasting simulation results, it is clear that the fundamental basis for the reasonable blasting simulator, which can consider all the requirements (i)~(iv), has been laid out to model the entire process of rock blasting.

5. Conclusions

In this contribution, we proposed a reasonable numerical simulation method for blasting to lay a foundation for explicitly representing all the elementary processes. The proposed blasting simulation method was implemented with GPGPU-based parallel computation.

The implemented blasting simulator was applied to a 2-D single-hole blasting problem. The simulated results indicate that the proposed blasting simulator can successfully trace all the essential

elementary processes of rock blasting. Thus, the developed simulator is expected to be an essential basis for promoting the development of the practical blasting simulator. Future works include "incorporating other equations of state, such as the JWL equation of state", "extension of the current implementation to three-dimensional problems", and "checking the validity of the results obtained from the proposed blasting simulation based on the experimental observation".

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