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Numerical simulation of rock fragmentation by blasting using Discrete Element Method and Particle Blast Method

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Abstract. Blasting is common activity used in quarry to fragment rock which the aim is to obtain maximum yield with desired fragmentation in a safer manner. This study has opened up new possibilities to optimize the blasting in order to achieve the desired fragmentation of rock. Discrete element method (DEM) and particle blast method (PBM) approach was used to investigate numerically the response of rock fragmentation induced by blasting. The numerical simulation performed in this study using the commercial software LS-DYNA. Calibration of the micro-parameters in bonded particle model (BPM) of rock has been conducted. In bench blasting simulation, DEM was used on the modelling of rock media, where PBM was used to simulate the blast loading which capable of modelling thermally non-equilibrium system. This numerical analysis is compared to rock fragment distribution fieldwork data. It shows that DEM-PBM simulation could reproduce the trends observed in fieldwork rock fragment distribution. Comparison between fieldwork data and numerical analyses is presented and discussed.

1. Introduction

Blasting has been widely used for rock breakage especially in mining and civil engineering applications because it is more economical. The aim of blasting is to fragment the rock in a safe, economic and environmentally friendly manner. Poorly conducted blast will be resulting poor fragmentation and other blast results such as ground vibration, flyrock, airblast and backbreak.

One of the major concerns related to blasting operation in mining and civil engineering projects is rock fragmentation. The mean fragment size of rock should not too high or too low. This is because oversize rock and very fines rock will occur. Rock fragmentation plays a critical role in large-scale quarrying operations because of its direct effects on the costs of drilling, blasting, secondary blasting and crushing [1], [2], [3]. The optimum-blasting pattern to excavate a quarry efficiently and economically can be determined based on the minimum production cost, which generally estimated according to rock fragmentation.

Fragmentation of rock means the process of breaking rock into pieces and it can be varying in size, shape and weight. Large-sized of fragment rock known as boulders and this can be fragmentized with or without the use of explosive. Rock fragmentation is the size distribution of the blasted rock fragment which is as an index to estimate the effect of blasting used in the mining and civil industry.

It is normally desired to have uniform fragmentation which the uniformity index (n) values are higher. Uniformity index is the slope of the fragment size distribution curve. Cunningham [4] has suggested that the normal range of n for blasting fragmentation in reasonably competent ground is from 0.75 to 1.5 with the average being around 1.0. More competent rocks have higher values.

2. Bonded particle model

Potyondy and Cundall [5] mentioned that rock behaves like a cemented granular material of complex-shaped grains which the grains and the cement can deform and break. The mechanical behavior of rock is driven by the formation, growth and existing of microcracks. The mechanical properties of rock are determined by its constituent particles and its structure [6], [7].

Bonded particle model (BPM) was defined by Potyondy and Cundall as a model consist of a dense packing of particles either in non-uniform-sized circular or in spherical which the particles are bonded together at their contact points with parallel bond [5] . The mechanical behavior can simulate by DEM using commercialized programs PFC2D, PFC3D[8] and LS-DYNA [9]. Bonded particle model can provide both a scientific tool to investigate micro-mechanisms and an engineering tool to predict macroscopic behaviour. The DEM was introduced by Cundall for analysis of rock mechanics problems and then applied to soils by [10].

The rigid particles interact only at the soft contact which finite normal and shear stiffness. Figure 1 shows the contact bond between particles which the force and moment acting at each contact. Bonded particles in BPM where all of the particles are linked to their neighboring particles through bonds. Bonds represent the complete mechanical behavior of solid mechanics and bonds are independent of the DEM. Every bond between particles is subjected to tension, bending, shearing and twisting [11].

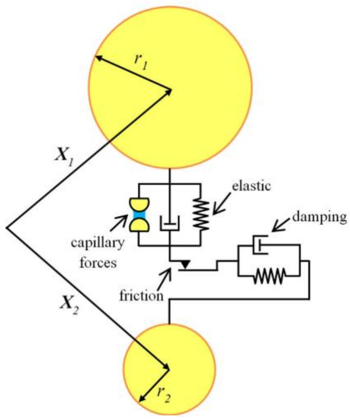


Figure 1. Illustration of contact bond between particles. [12]

3. Particle blast method

Continuum-based Eulerian approach is one of the most accurate technologies to stimulate blast loading. However, this approach has several difficulties in modelling of blast loading. One of the disadvantages is advection error relative to Lagrangian simulations. Both momentum and kinetic energy is not conserved at the same time when advection is used. Next, greater computational effort is needed over Lagrangian simulations due to the advection and geometrical complexities are hard to handle with continuum-based Eulerian approaches [13].

A corpuscular particle method (CPM) has been proposed for airbag deployment application to overcome those difficulties. The CPM considers the effect of transient gas dynamics and thermodynamics by using a particle to represent a group of gas molecules. Each particle carries translational energy as well as spin energy [13].

CPM assumes that the system is always thermal equilibrium. This is a reasonable assumption for airbag simulation with moderate temperature and low pressure. But for blast simulation where gas flow is extremely high, the assumption of thermal equilibrium is invalid [14].

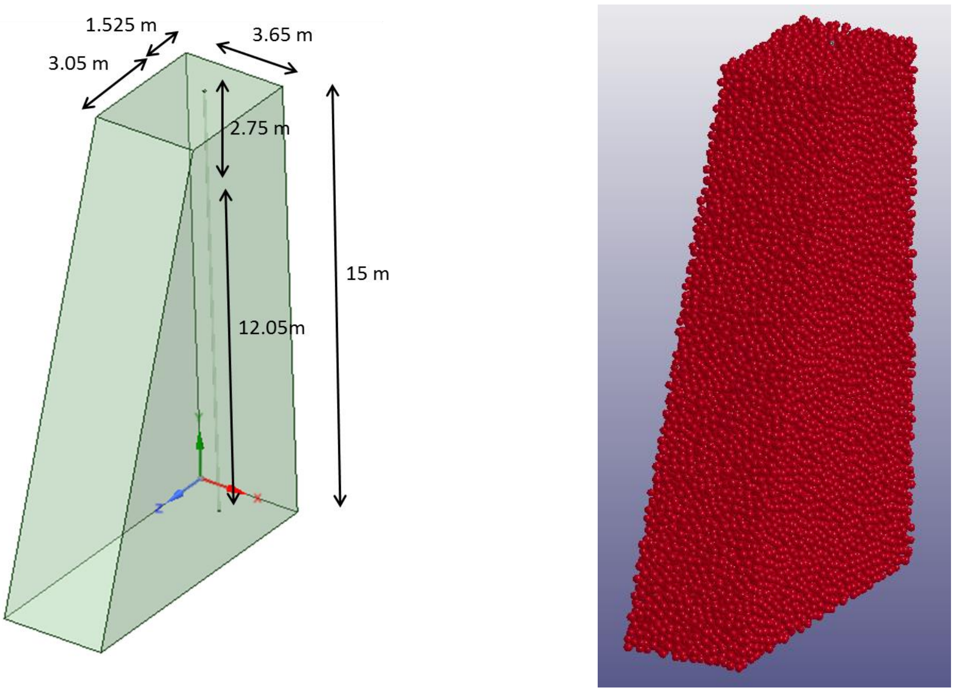
A particle blast method (PBM) has been proposed to model the interaction between detonation products, air, and structure. This method improves corpuscular method to account for the thermally non-equilibrium behaviour. Furthermore, to better represent gas behaviour at high temperature, co-volume effects have been considered [14].

4. Numerical model

Bench blasting numerical simulation performed in this study using the commercial software LS-DYNA. A one-borehole model was constructed to model the field test. Figure 2(a) shows the model geometry and the sizes of rock mass. The borehole diameter is 89 mm. The bench height is 15 m and the borehole depth is 14.8 m. 2.75 m from the borehole depth is the length of stemming. The burden and spacing length are 3.05 m and 3.65 m.

Bonded particle model combined with particle blast method were used to model the rock mass as shown in Figure 2(b). Calibration procedures have been done to meet elastic modulus and UCS tolerance of intact rock specimen form the laboratory test. The uniaxial compression strength, shear strength and uniaxial tensile strength were set to 90 MPa, 30 MPa and 20 MPa respectively. In discrete element modelling of geomaterials, there are microproperties that need to be specified. These properties cannot be measured in the laboratory test. Therefore, in order to calibrate the numerical model, some initial values for the microproperties must be examined to create model similar to the actual rock. Trial and error method are needed to calibrate the numerical model. Input parameters of calibrated models are shown in Table 1 below.

The numerical model to stimulate bench blasting is shown in Figure 2(b). The explosive was modelled by PBM using 50000 HE particles and the particle parameters are listed in Table 2. The rock mass were modelled by 36158 DEM. The density of DEM is adjusted such that total mass of DEM equal to the total mass of rock.



(a) Geometry of bench blast model (b) Bench blast model using DEM/BPM

.Figure 2. One borehole bench blast model.

Table 1. Input parameters of the calibrated model.

Properties	Value	Properties	Value
Particle radius/mm	100-125	Maximum gap between two bonded spheres (MAXGAP)	-1.31
Parallel-bond normal stiffness (PBN) / GPa	20.76	Normal damping coefficient (NDAMP)	0.7
Parallel-bond shear stiffness (PBS)	0.25	Tangential damping coefficient (TDAMP)	0.01
Parallel-bond maximum normal stress (PBN_S)	0.03	Friction coefficient (Fric)	0.99
Parallel-bond maximum shear stress (PBS_S)	0.02	Rolling friction coefficient (FricR)	0.98
Bond radius multiplier (SFA)	1.31	Normal spring constant (NormK)	0.1
Numerical damping (ALPHA)	0.5	Shear spring constant (ShearK)	0.4

Table 2. Particle parameters of high explosive.

Parameters	Value
Density, ρ (kg/m)	1200
Energy, E (GJ/m)	3.2
Detonation velocity, D (m/s)	4500
High Explosive fraction, γ	1.4
Co-volume, b	0.3

5. Results and analysis

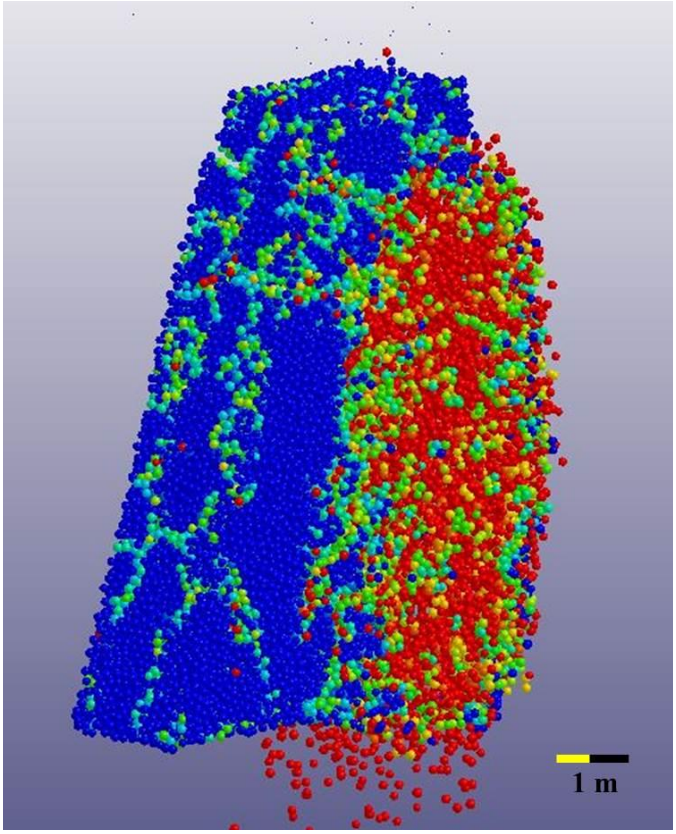
Digital image processing in fragmentation assessment techniques allows rapid and low cost of blast fragmentation size distribution [15]. There are several software namely Split Desktop, Wipfrag, GoldSize to obtain fragment size distribution. In this study, GoldSize software was used for size distribution computation in Gemencheh Granite quarry. Figure 3(a) shows the image taken of rock pile after blasting process. Rock fragment from numerical simulation is shown in Figure 3(b). To determine the size of rock particles, scaled object in the image were required as a reference. Then, the rock fragment from rock pile and particles that form a fragment need to be identify. The particle edge was outlined manually in a continuous line. Once the binary image was completely edited, computation of size distribution can be carried out. In this study, simple estimation was used which applied a fines correction formula to increase the amount of fine material at sizes below a specified threshold.

After rock size distribution for both rock fragments of fieldwork and numerical results were obtained. Figure 4 shows the comparison of both rock fragment distributions. [16] suggested experimental equation (1) and also was used by [17], which the uniformity parameter (n) can be calculated and compared with the real value based on d_{50} (size at which the passing fraction is 50%) and d_{80} (size at which the passing fraction is 80%). Table 3 shows the values of d_{50} and d_{80} that were recorded from curve Figure 4 for fieldwork and numerical results. The uniformity parameter (n) was obtained from equation (1) below:

$$n = 0.842/(\ln d_{80} - \ln d_{50}) \tag{1}$$

By evaluating the size distribution curves (Figure 4) and the table information (Table 3), it can be seen that the curve graph trend of particle size distribution between numerical and fieldwork are similar. However, numerical results show bigger fragmentation size compared to fieldwork rock pile. In Table 3 shows the value of d_{50}, d_{80} and n for numerical results are higher compared to fieldwork. The possible reasons of the difference because the DEM particles in the numerical model are not fine enough i.e. 100-125 mm is not sufficient [18]. Higher computer performance is needed for numerical simulation. Smaller DEM particles and large scale of model are time consuming for analysis.

(a) Fieldwork rock pile.



(b) Fragment of rock from numerical simulation.

Figure 3. Image of fragment rock induced by blasting for calculation of size distribution.

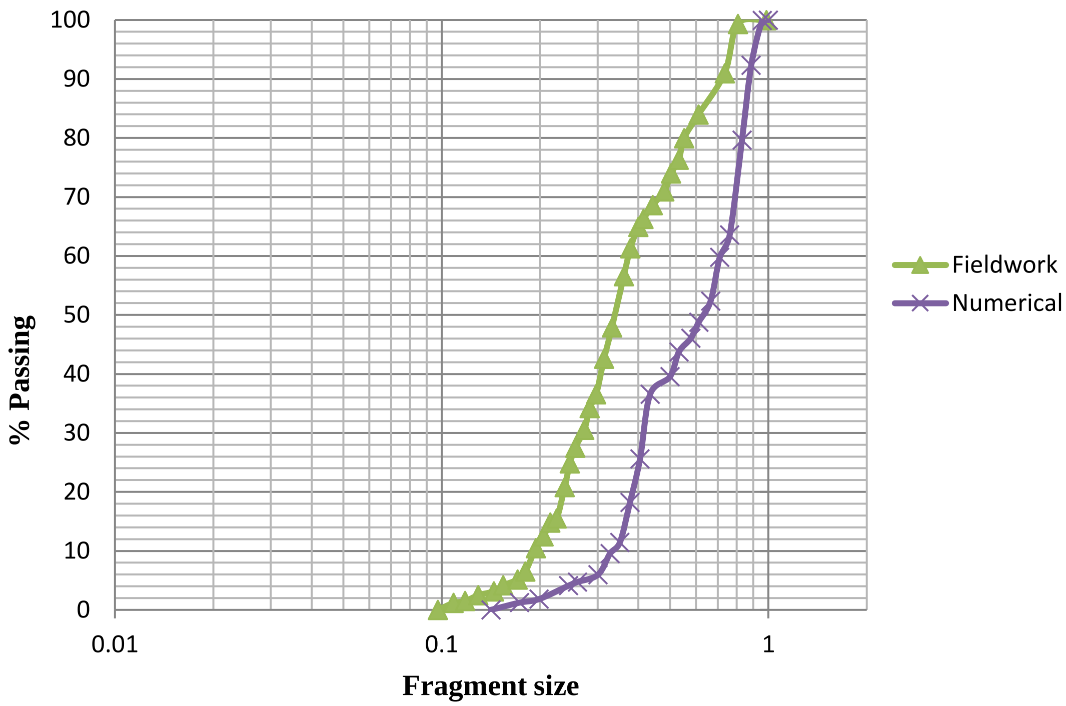


Figure 4. Comparison of rock fragment distribution between fieldwork rock pile and numerical results using LS-DYNA.

Table 3. Comparison of particle size distribution results.

	d_{50}	d_{80}	n
Fieldwork rock pile	0.35	0.55	1.86
Numerical results	0.62	0.84	2.77

6. Conclusion

In this study, combination of DEM-PBM was used to simulate rock fragmentation by blasting. Size distribution of the rock fragmentation was analysed by image digital processing using GoldSize software. Comparison of rock fragment distribution between numerical results and fieldwork rock pile was conducted. It can be seen that DEM-PBM simulation could reproduce similar curve trend for fieldwork fragment size distribution. However, the value of d_{50}, d_{80} and n for numerical results are higher compared to fieldwork. This is because the size of DEM particles are not fines enough due to computer limitation. In conclusion, DEM-PBM can model detonation of explosive and blast gas behaviour. The combination of PBM and DEM using BPM is suitable for numerical simulation of rock fragmentation by blasting.

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