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# Analysis of impact-induced rock fragmentation using a discrete element approach

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## 1. Introduction

Rockfalls involving abrupt movements of rock masses detached from steep slopes or cliffs[1] are widely observed in mountainous areas. These events can cause significant hazards to human lives and lifeline facilities.[2,3] Among various types of rock block motion (e.g. freefall, bouncing, and rolling), bouncing (impact) is the most complex, uncertain, and poorly understood one.[4,5] During impacting, the kinetic energy dissipates and the direction of motion changes. Depending on the mechanical properties of the terrain and the rock block, the impact angle, and the block shape, mass, and velocity, the impact process can vary from the elastic to plastic.[5,6] In addition, during impact, the rock block tends to break, this is especially true for weak rocks.[4] After fragmentation, the trajectories of rock fragments are very difficult to predict, increasing the probability of damage to human lives and properties.[7] In this process, the position and the extent of the debris accumulation zone are strongly affected by rock fragmentation. This phenomenon has been observed by Crosta et al.,[8] and they concluded that rock fragmentation influences the runout extent and trajectory of rockfall.

Several parameters can influence the fragmentation process,[9,10] namely, the pre-existing joints and micro-fractures, the ground conditions, the impact energy and angle. Through numerical analyses and laboratory tests, several researchers[11–13] have investigated the impact-induced fragmentation for granular agglomerates, concluding that the breakage intensity of agglomerates mainly depends on the normal component of the impact velocity. Wang and Tonon[9] analysed the effect of impact angle on the rock fragmentation using discrete element method (DEM), and their results indicate that the magnitude of the normal velocity is the main factor influencing the rock fragmentation. Paluszny et al. [14,15] employed the combined finite element method and impulse-based discrete element method to study rock fragmentation. They concluded that the impacting velocity strongly controls the final fragment size distribution. De Blasio and Crosta [16] point out that the fragmentation is mainly due to the effect of normal stress acting on the impacting plane. Consequently, it can be concluded that the normal component of the impact velocity plays an important role in rock fragmentation.

This paper presents a model of the fragmentation induced by normal impact of a synthetic spherical rock block under different impact loading rates, using the open source DEM code ESyS-Particle.[17,18] It is true that a spherical rock block is not commonly found in nature. However, the block shape has a significant influence on the rock fragmentation due to impact induced stress concentration,[19,20] and the spherical block can effectively avoid this effect.[20] Therefore, this model is considered as a reasonable initial proxy to study impact-induced rock fragmentation. The paper is organized as follows: in Section 2, the DEM model configurations of impact-induced rock fragmentation are presented. In Section 3, the obtained numerical results are illustrated with respect to the fragmentation process, the fragmentation intensity, the fragment number, and the fragment size distribution. Finally, in Section 4, some conclusions reached in this study are provided.

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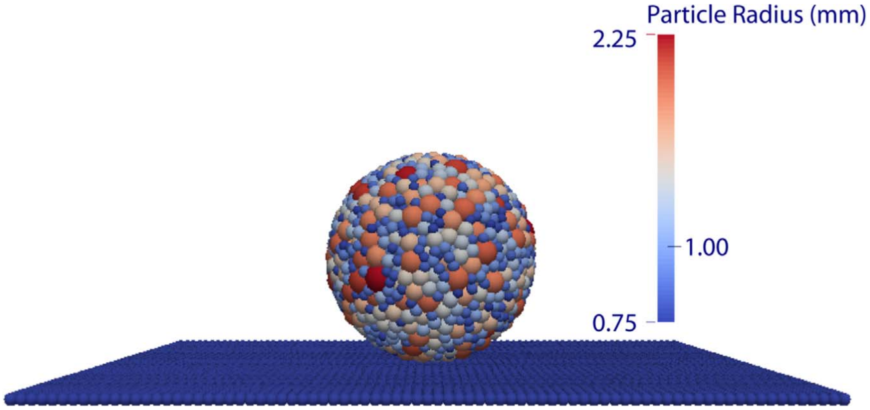

**Fig. 1.** Configuration of the three dimensional DEM model for rock fragmentation analyses. The rock block is ball-shaped consisting of closely packed spherical particles (particles are colored based on their radii). The rigid ground is mimicked by a layer of fixed particles.

## 2. DEM model configurations

In this study, the impact of a rock block with a rigid ground is analysed to investigate the fragmentation characteristics by a numerical model configuration as shown in Fig. 1. In the DEM model, the spherical rock block is represented as an assembly of densely packed and bonded spherical particles with a diameter ($D$) of 10 cm. It consists of 48,987 randomly distributed spherical particles with the average radius of 1.5 mm, and the ratio of the largest to smallest radius equal to 3. The rigid ground is represented by a layer of fixed particles with a radius of 0.75 mm.

The adjacent block particles are bonded together by a bond particle model (BPM). The bond breakage criterion[21,22] used in this paper is as follows:

$$\frac{F_{bn}}{F_{bnMax}}+\frac{F_{bs}}{F_{bsMax}}+\frac{M_b}{M_{bMax}}+\frac{M_t}{M_{tMax}}\geq 1 \tag{1}$$

where $F_{bn}$ and $F_{bs}$ are normal and shear bond forces, $M_b$ and $M_t$ are the bending and twisting moments, respectively; $F_{bnMax}$ and $F_{bsMax}$ are the maximum normal and shear forces, $M_{bMax}$ and $M_{tMax}$ are the maximum bending and twisting moments, respectively. A detailed description of the BPM can be found in a recent work by Zhao et al.[22]

After bond breakage, the particles will experience cohesionless frictional interaction (CFI) if they come into contact with each other. At each contact, a linear contact viscous damping[23] is employed to dissipate a small amount of energy due to elastic wave propagation and particle asperities being sheared off. The interaction model between the rock block and rigid ground is of CFI type as well. A more detailed discussion of CFI models can be found in the work of Wang and Mora.[21]

A detailed calibration of the above mentioned DEM bonded particle model for coal rock via the numerical uniaxial compression and Split-Hopkinson Pressure Bar (SHPB) tests has been presented in Zhao et al., [22] and will not be repeated in this paper. However, the same type of coal rock will be employed in the simulations because of its low strength and brittle nature, and the availability of some well-established dynamic testing data. The input parameters of the DEM model are listed in Table 1.

**Table 1**
Input parameters used in the DEM model.

| DEM parameters | Value | DEM parameters | Value |
|---|---|---|---|
| Particle radius, $r$ (mm) | 0.75–2.25 | Young's modulus of bonds, $E_b$ (MPa) | $1.25\times10^3$ |
| Particle density, $\rho$ (kg/m$^3$) | 2650 | Cohesion of bonds, $c$ (MPa) | 14.25 |
| Young's modulus of particle, $E_p$ (MPa) | $5\times10^3$ | Bonds friction angle, $\varphi$ (°) | 45 |
| Particle Poisson's ratio, $\nu$ | 0.25 | Viscous damping coefficient, $\beta$ | 0.01 |
| Particle friction coefficient, $\mu$ | 0.58 | Time step size, $\Delta t$ (s) | $5\times10^{-8}$ |

**Table 2**
Range of initial impact velocity and the corresponding impact loading rate used in the tests.

| | | | | |
|---|---|---|---|---|
| $v_0$ (m/s) | 20 | 30 | 40 | 50 |
| $\dot{\varepsilon}$ (s$^{-1}$) | 200 | 300 | 400 | 500 |

## 3. Results

In the analyses, the impact loading rate ($\dot{\varepsilon}$) is defined as $v_0/D$, with $v_0$ being the initial impact velocity, $D$ being the diameter of the rock block. The ranges of initial impact velocity and the corresponding loading rates examined in the numerical model are listed in Table 2. For simplicity, the time scale used in the analyses is defined as T = 5 × 10$^{-6}$ s.

Fig. 2 illustrates the rock impacting and subsequent radial spreading for impacting loading rate of 500 s$^{-1}$. According to the figure, it can be observed that the radial displacement of rock fragments is very small before 100 T, while the displacements increase gradually after 100 T as the fragments are ejected. This indicates that the rock fragmentation occurs before fragment ejection, and the fragments ejected by the impacting energy of fragmentation. This phenomenon has been discussed by De Blasio and Crosta [16] and Zhao et al. [22] as momentum boost effect, by which the fine fragments can spread long distances. After the impact, some fine fragments can also be generated by subsequent collisions between large fragments and ground between 200 and 400 T.

Fig. 3 shows the evolutions of the fragment number, normalized kinetic energy ($E_k$), and the damage ratio ($\alpha_b$) over time, for the impact loading rate of 500 s$^{-1}$. The normalized kinetic energy is the ratio of the total kinetic energy of the fragments to the initial kinetic energy. The damage ratio, or bond breakage ratio ($\alpha_b$)[24] (i.e. the ratio of the number of broken bonds to the initial number of bonds) has been used to quantify the rock fragmentation intensity. As shown in Fig. 3, once the rock block impacts upon the ground, the damage ratio and the fragment number increase sharply to the peak values at 100 T, and the kinetic energy decreases gradually. The subsequent sliding and collision of fragments also lead to further decrease of kinetic energy, while the damage ratio remains almost unchanged. The slight decrease of fragment number during 100–200 T is due to the disaggregation of relatively small fragments to the size smaller than our statistical