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Quantification of rockfall breakage in rock engineering through DEM simulations

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Abstract

The present work addresses an interesting numerical perspective to describe and quantify the effects of impact breakage on rockfall phenomena. The objective is to apply computational tools using the discrete element method to predict the dynamics of rockfall on the size distribution after impact.

The numerical model is meticulously calibrated and validated against well-documented real cases in the literature, providing a reliable approach and a solid proposal for analysing these systems.

For the analysis, we apply the definition of relative breakage to determine the degree of fragmentation under various conditions, enabling an accessible quantitative description of rockfall events.

The results of this study present a simple chart that illustrates the degree of breakage in the rock system, considering the initial rock sizes and impact heights. The proposed model contributes to enhancing the evaluation and prediction of fragmentation in such phenomena, strengthening risk analysis and the development of mitigation measures for geomechanical risks associated with rock mass dynamics, both on the surface and in underground environments.

Keywords

Rockfalls, Rock breakage, Numerical modelling, Particle-replacement

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1 Introduction

Rockfall is a common geohazard and physical phenomenon in mountainous regions and rock engineering in general (slope design and underground mining). It is characterised by the sudden release of a volume of rock that impacts the downstream surface, altering both the nature of the environment and human presence in the vicinity of the area of influence. This latter as one of the main reasons why the phenomenon is of great interest in engineering, as it enables the development of safe structures and the design of protective barriers that reduce or mitigate the drastic consequences the process may entail.

A common method for analysing this type of phenomenon is back-analysis, which aims to "learn" and improve various prediction models based on reported rockfall cases. These approaches typically encompass the prediction of rock breakage probability, the influence area of rockfalls, and a dynamic characterisation of the process to quantify the impact forces exerted on cushioning granular layers.

Various authors have conducted experimental and in-situ tests aiming to unravel the kinematics of impact, primarily to design optimal cushioning layers as protective measures against rockfall events. (Pichler et al. 2005; Giacomini et al. 2009; Gili et al. 2022; Meree et al. 2024). These approaches have helped determine the effects of rock block penetration into granular layers and their dynamic response, as well as the potential rock trajectories, based on the geometric characteristics of the system and the mechanical properties of the materials.

An interesting proposal was presented by Ruiz-Carulla and Corominas (2020), where the fractal nature of the fragmentation phenomenon in rockfall was applied. This model, known as the Rockfall Fractal Fragmentation Model (RFFM), was successfully implemented in a series of inventoried cases, providing an accurate estimation of the degree of rock fragmentation.

From a numerical perspective, the phenomenon has been investigated to enhance the understanding of the mechanisms and dynamic interactions underlying the impact (Shen et al. 2019, 2020; Jin et al. 2023). The advantages of DEM tools have provided a wide range of options, allowing for variations in the conditions under which these systems are analysed (primarily rock shapes and sizes). These studies have gained significant relevance due to the rapid advancement of computational science, which facilitates the calibration of models and their respective comparison with real-world tests.

In this work, we propose a new numerical approach to the analysis of rockfall events, providing a rapid assessment of the expected breakage after impact under various initial conditions.

2 Numerical methods

The dynamic behaviour of particulate systems is well described from Newton's second law of motion, which is the basis for the numerical analysis of granular media, a discrete element-based approach initially proposed by Cundall and Strack (1979). In the following, the basis of the numerical model of the breakage is presented, as well as its calibration and validation against tests reported in the literature.

2.1 Particle-replacement method

The idea behind particle breakage models lies in the representation of the fragmentation of the parent particle once a defined criterion has been reached. The fast-breakage model applied in the present work is based on the breakage theory proposed by Vogel and Peukert (2004), and extended by Shi and Kojovic (2007), where a particle breaks when the impact energy threshold is reached. This energy is directly related to the size of the parent particle, where the breakage probability $P(E)$ is defined by the following equation:

$$P(E) = 1 - \exp\left[-SE\left(\frac{d_i}{d_{ref}}\right)\right] \tag{1}$$

Where S is the selection function (kg/J), E the impact energy (J/kg), d_i the initial size of the parent particle (m), and d_{ref} a reference size of a particle of the same material (m). Once the impact energy threshold is reached, the model generates progeny fragments based on the Laguerre-Voronoi tessellation algorithm. This formulation generates a distribution of points in the space from a generator point, which will form part of the centroids of each generated progeny fragment. Formally, given a convex domain $\Omega \in \mathbb{R}^3$, n distinct generator points: $x_1, \dots, x_n \in \Omega$, and corresponding weights (inversely proportional to impact energy) $w_1, \dots, w_n \in \mathbb{R}$, the Laguerre-Voronoi diagram generated by $(x_1, w_1), \dots, (x_n, w_n) \forall j \in 1, \dots, n$ is defined by:

$$L_i = \left\{x \in \Omega: |x - x_i|^2 - w_i \leq \left|x - x_j\right|^2 - w_j\right\} \tag{2}$$

This algorithm is further characterised by the generation of the smallest fragments in the vicinity close to the contact point, and larger fragments far from this vicinity, more realistically imitating the brittle fracture of rock materials, in addition to preserving both mass and volume.

Finally, the fragment size distribution is obtained through the incomplete-beta function, based on the fineness index t_n, and defined as:

$$t_n(t_{10}) = \frac{100}{\int_0^1 x^{\alpha_n - 1}(1-x)^{\beta_n - 1} dx} \int_0^{t_{10}} x^{\alpha_n - 1}(1-x)^{\beta_n - 1} dx \tag{3}$$

Where α_n and β_n are function adjustment coefficients, obtained through experimental tests, for different materials.

Fig. 1 shows the general sequence of the breakage model applied in the present work.

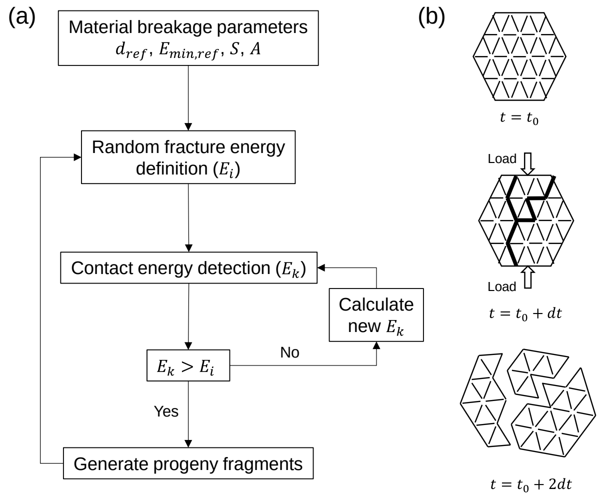

Fig. 1 (a) Working diagram of the fast-breakage model, and (b) graphic representation of the formation of progeny fragments.

2.2 Calibration and validation of the model

The calibration of the numerical model is obtained by carrying out drop weight tests, of which there are a series of results available in the literature for different materials (Jiménez-Herrera et al. 2019). The procedure consists of impacting a grain of defined size and shape with a steel ball. The impact energy is controlled by varying the falling height of the steel ball, and its impact velocity is obtained from the principle of conservation of mechanical energy, $v_{imp} = \sqrt{2gh_{imp}}$. We carried out this type of test for a limestone, considering the presence of this material in the reported phenomena, and whose characteristics are presented in Table 1.

Fig. 2 shows the comparison between the numerical and experimental results, where both the breakage probability and the size distribution present a good fit to the data, while Table 2 is showing the DEM parameters used in all simulations during the calibration process.

Table 1 Material properties for the calibration.

Parameter	**Rock material**	**Steel**
Young's modulus, GPa	52	182
Poisson's ratio, -	0.25	0.30
Specific gravity, g/cm^3	2.93	7.80

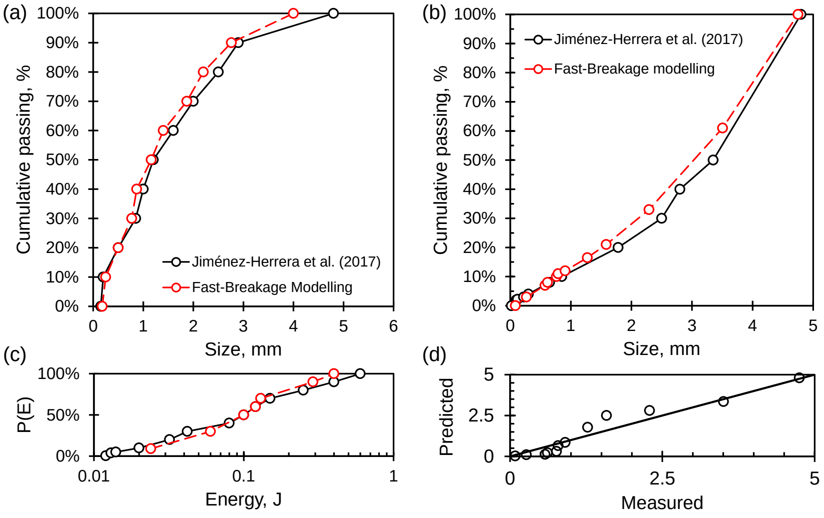

Fig. 2 Calibration comparison: (a) fragment size distribution for a single fragment, (b) fragment size distribution for a multiple impact test, (c) breakage probability as a function of the applied impact energy, and (d) predicted versus measured sizes after impact.

Once the mechanical characteristics of the material were obtained, the breakage model was validated against a series of rock falls reported by Ruiz-Carulla and Corominas (2020).

Table 3 summarises the main characteristics of the inventoried cases.

Table 2 DEM parameters applied in the calibration process.

Parameter	Description	Value
d_{ref}	Reference size, mm	5.00
$E_{min,ref}$	Minimum specific energy, J/kg	100
S	Selection function coefficient, kg/J	0.002
A	Maximum t_{10} value	47.5
d_{min}	Minimum particle size, mm	0.25

Table 3 Summary of the general characteristics of the reported rockfall cases.

	Case I	Case II	Case III
Failure mechanism	Controlled	Toe erosion slide	Toppling
*RBSD, m^3	0.5	4.2	10.7
*IBSD, m^3	0.5	4.2	10.7
RMR	-	64	72
Estimated RBSD n° blocks	63	48	78
Measured RBSD n° blocks	68	49	61
Min. measured vol., m^3	10^{-5}	0.0007	0.0007
Max. measured vol., m^3	0.23	1.1	8.5
Impact height, m	16.5	14.5	6.6

**RBSD: Rockfall Block Size Distribution, IBSD: In-Situ Block Size Distribution.*

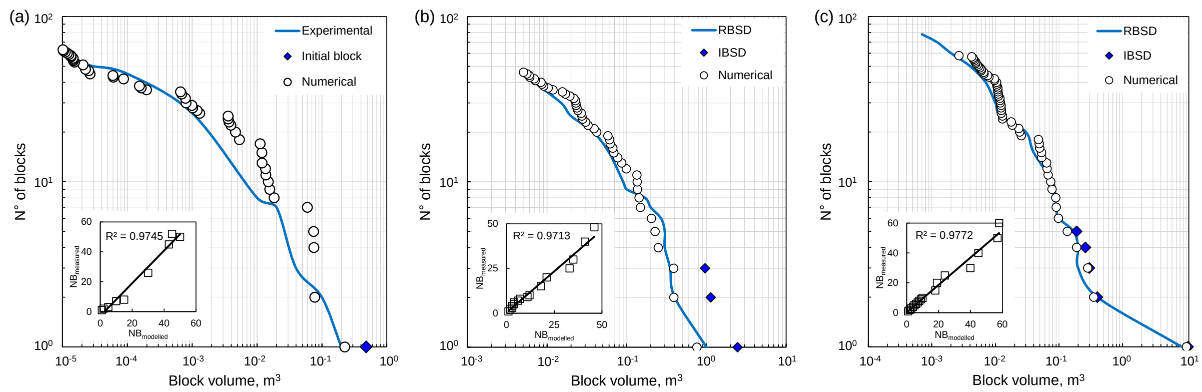

Fig. 3 Validation of the numerical model in the three reported cases. The graphs show the distribution of sizes by number of blocks generated.

2.3 Breakage definition and setup

In order to quantify the degree of breakage of a granular system, Einav (2007) proposes the definition of relative breakage, B_r. This definition is based solely on the relative position of the size distribution curve within the available breakage area (Fig. 4).

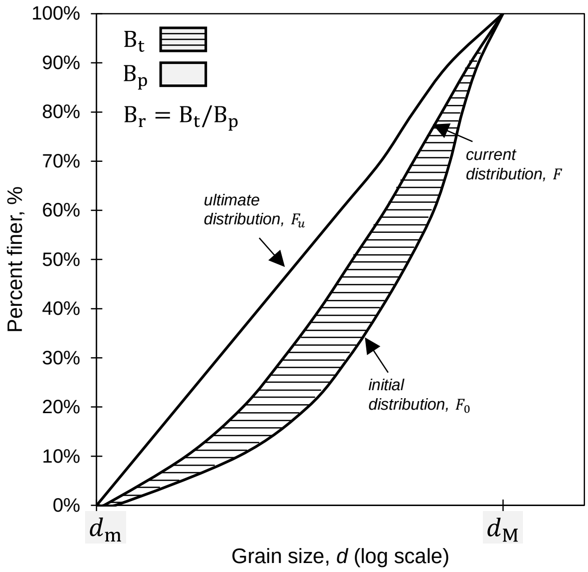

Fig. 4 Definition of relative breakage from the size distribution curve.

Therefore, the formal definition of the relative breakage is presented as:

$$B_r = \frac{\int_{d_m}^{d_M} \left(F_c(d) - F_0(d)\right) d^{-1} \mathrm{d}d}{\int_{d_m}^{d_M} \left(F_u(d) - F_0(d)\right) d^{-1} \mathrm{d}d} \tag{4}$$

Numerical simulations are based on the free fall of a defined volume of rocks on a soft surface of the same material, emulating the conditions of rockfalls in mountainous areas or in underground environments. Table 4 shows the different geometric conditions of the modelling, covering a wide range of rock sizes, as well as impact heights.

Table 4 Initial conditions of the simulations.

Parameter	**Range**	**Unit**
Initial block size, d_i	[0.5 – 4]	m
Initial impact height, H_i	[5 – 200]	m
Froude number, $v^2/(gd_i)$	[2.5 – 100]	-

3 Results

3.1 Fragment size distribution

Fig. 5 shows the behaviour of the size distribution of the fragments after the impact, for different initial heights. This shows how as the initial size of the rock increases, the fragmentation curves tend to couple, showing that larger rocks tend to form smaller and "uniform" fragments.

For each of the cases, it is plausible to visualise the effect of the impact height, where higher heights imply the formation of smaller fragments, due to the amount of kinetic energy involved in the most critical cases (energy proportional to the square of the velocity), where a proportion of such energy is used to break the initial fragments (impact energy).

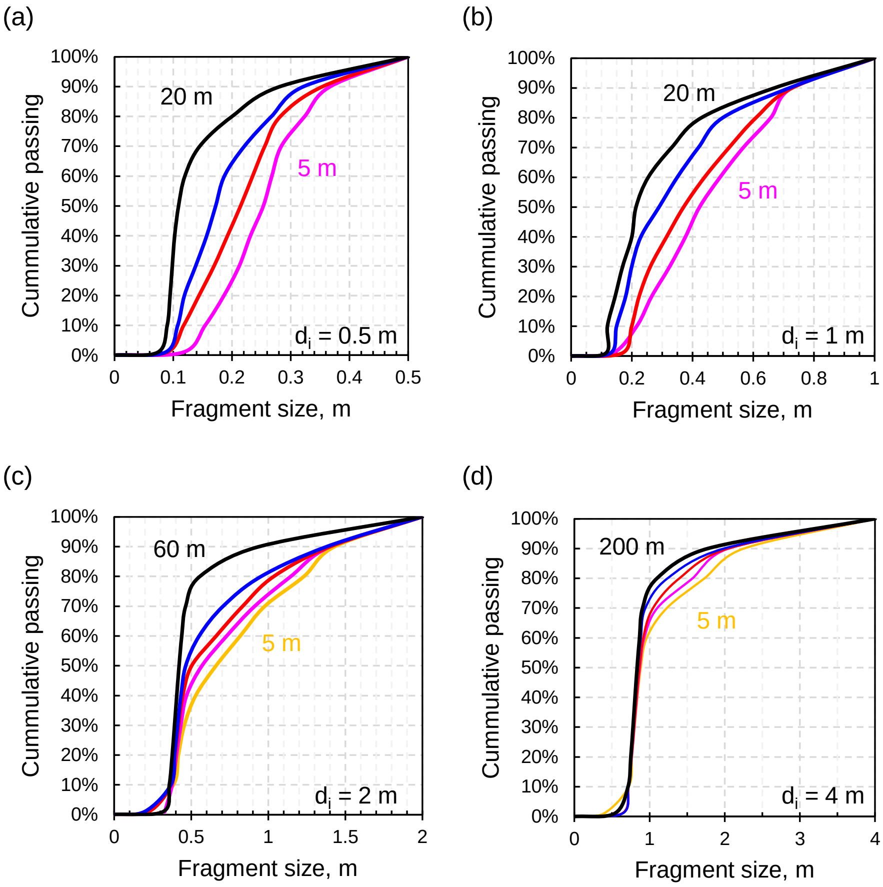

Fig. 5 Fragment size distribution curves for initial block sizes from 0.5 to 4 m (a-d respectively).

3.2 Relative breakage

The quantification of the relative breakage is based on the definition shown in Eq. 4, where the initial curve F_0 corresponds to a vertical line whose intersection with the abscissa is d_i, while the ultimate curve F_u is considered as those fragments that are within the range 5-15% of the initial size, both due to the computational restrictions and the effect of the rockfall itself.

Based on the fragmentation curves presented above, Fig. 6 shows a proposal for estimating the relative breakage. These graphs represent in a dimensionless way the effects of rockfalls through the definition of two parameters: the dimensionless velocity (also known in fluid mechanics as the Froude number), and the characteristic length, defined as the ratio between the initial impact height and the expected average size of the fragments.

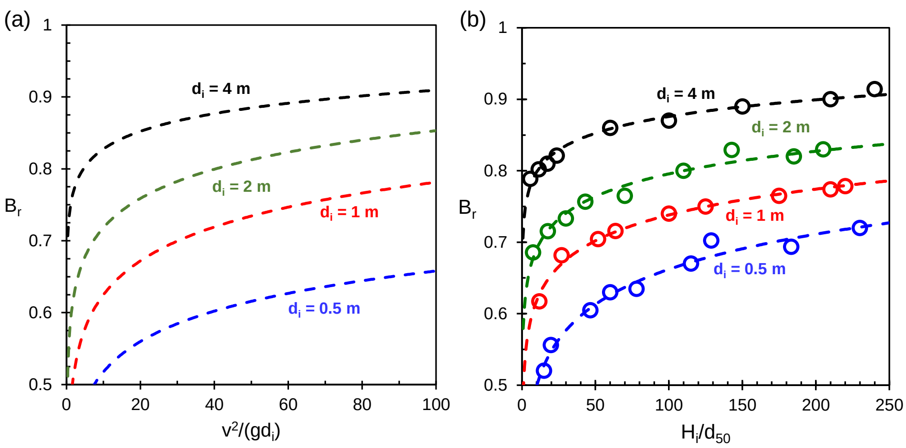

Fig. 6 (a) Relative breakage as a function of the dimensionless velocity, and (b) relative breakage against the characteristic length. Both graphs show a family curves based on the initial size of the rocks.

In this way, we propose two simple alternatives for a preliminary evaluation of relative breakage in rockfall systems. Although both cases assume an initial mono-size distribution of the rocks, it is possible to consider a variable distribution considering the average size of the system, $d_{50,i}$, as the initial parameter.

The difference between both curves is that Fig. 6(a) is clearly based on the initial conditions of the phenomenon, while Fig. 6(b) is based on the average size of the fragments after the impact, giving both alternatives a valid proposal as a preliminary estimate of the degree of fragmentation.

4 Conclusions

In the present work, an attractive numerical tool has been applied to quantify the degree of breakage in impact-induced rock systems, based on a framework of discrete elements, calibrated and validated against a series of experiments and reported data.

From the results obtained, the phenomenon shows that larger rocks fracture in a pattern that tends to a more homogeneous distribution independent of the impact height. This phenomenon is related to the sensitivity of the rock size to increases in impact energy, where larger fragments are more likely to experience fracture.

The relative breakage has been quantified from the size distribution curves, where we have provided a simple proposal to quickly evaluate the degree of fragmentation, either from its initial conditions, or from the desired sizes, depending on the context in which rockfall is evaluated.

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