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A probabilistic fragmentation-based rockfall model for open-pit and natural slopes

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Abstract

Accurate prediction of rockfall propagation is critical for designing safe slopes in open-pit mines as well as in other engineered or natural environments. Fragmentation during impact significantly alters runout distances, energy dissipation, and the hazard footprint, yet most trajectory models neglect this phenomenon or treat it empirically. This study applies RockFRAG, a novel probabilistic 2D lumped-mass model, developed by the author and implemented in a code, that explicitly incorporates fragmentation processes informed by laboratory experiments accounting for impact energy, block shape and rock-mass structure through probabilistic fragment trajectories.

Applied to synthetic open-pit bench profiles, fragmentation-aware and intact-block simulations are compared across different bench configurations, showing that neglecting fragmentation is not inherently conservative: depending on face angle and bench geometry, breakage can either extend runout and increase pit-floor arrival probability, or promote earlier arrest through fracture-energy dissipation. These geometry-dependent, non-monotonic effects cannot be captured by non-fragmenting assumptions and lead to significant differences in runout envelopes and impact conditions. These findings underscore the need to account for fragmentation in runout-based design checks and bench performance evaluation. A probabilistic treatment is essential to cover uncertainty in fragment behaviour and slope interaction, enabling risk-informed design beyond deterministic assumptions, with implications extending to mountainous environments where impact-induced breakage commonly influences runout variability and the performance of protective measures.

Keywords

Fragmentation, Trajectory analysis, Rockfall, Open pit, Hazard assessment.

1 Introduction

Rockfall is a major safety concern in both engineered and natural slopes, with significant operational implications in open-pit mines and mountainous terrain (Macciotta et al., 2021). Blasting, evolving bench geometries and rock-mass variability drive event frequency in mines, while lithological contrasts and discontinuity networks govern instability on natural slopes (Ferrari et al., 2016).

Trajectory models range from lumped-mass formulations, which treat the block as a point mass, to rigid-body approaches that resolve shape-dependent dynamics (Li and Lan, 2015). Lumped-mass models are computationally efficient and well suited for probabilistic analyses where block shape or release conditions are poorly constrained, as is common in open-pit mines and on natural cliffs with diffuse source areas (McNabb et al., 2025). Their ability to accommodate parameter variability makes them widely used in probabilistic hazard studies. Accurate prediction of rockfall propagation requires an adequate representation of slope geometry and block–slope interaction parameters, as both strongly control impact conditions and mobility. In open-pit mines, operational modifications such as crest loss and debris accumulation frequently produce deviations from ideal geometries (Darling, 2011), and comparable complexity characterises natural slopes. These geometric and material uncertainties, together with variability in impact conditions, have motivated probabilistic approaches capable of yielding distribution-based estimates of runout and velocities (Wang et al., 2014).

Synthetic bench profiles have been widely used to derive design charts for pit-slope layouts and protective measures (Alejano et al. 2007; Marchelli et al. 2023), yet impact-induced fragmentation, a key control on mobility, energy dissipation and trajectory patterns (Ruiz-Carulla et al., 2020; Gili et al., 2022), is rarely included. Breakage redistributes energy among multiple fragments and can either increase or reduce runout depending on the impact configuration, making explicit probabilistic treatment of fragmentation essential. This work applies RockFRAG (Marchelli, 2026), a new lumped-mass model with an energy-based fragmentation module calibrated on laboratory drop tests (Marchelli et al., 2025), to idealised open-pit geometries to quantify how fragmentation alone alters runout distributions and impact velocities, with implications for both engineered and natural slopes.

2 Methodology

The study focuses on variability introduced by impact-induced fragmentation. To isolate the effect of fragmentation, eight three-bench synthetic geometries representative of typical open-pit environments are analysed, combining two bench heights h_b (15 m, 20 m), two bench widths w_b(7 m, 10 m) and two face angles β (55°, 85°), consistent with previous parametric studies (Alejano et al., 2007; Marchelli et al., 2023). Such idealised layouts provide a controlled and reproducible basis for assessing slope-scale kinematics and retention capacity. For each geometry, non-fragmenting (N.F.) and fragmenting (F) simulations are compared, the latter governed by the probabilistic energy-based module described in Section 2.1.

For each geometry, 1000 realisations are run from the upper bench crest for both N.F. and F. conditions. Classical lumped-mass block–slope interaction parameters, i.e. normal and tangential restitution coefficients (COR_n, COR_t) and friction angle (φ)are sampled from Gaussian distributions consistent with values calibrated for lumped-mass rockfall models under open-pit conditions. These parameters reflect impacts on rocky faces and debris-covered treads and reproduce typical block–slope interactions reported in mining environments (Alejano et al., 2007; Marchelli et al., 2023). A deliberately low friction angle is adopted to account for rolling behaviour, which is not explicitly represented in the lumped-mass formulation, and a small surface-roughness variation is included to mimic local topographic irregularities. To limit uncertainty sources and input complexity, in this stage, the block is modelled as a spherical element (≈1 m³), with mechanical properties consistent with those of the rock-face material and no internal structural features. Input parameters for the geometric configurations and block–slope interaction are summarised in Table 1, together with the fragmentation-related parameters used in the analyses (as detailed in Sec. 2.1).

Table 1. Input parameters for the geometric configurations and block–slope interaction.

Parameter	Value
Bench height heights h_b (m)	15, 20
Bench height width w_b (m)	7, 10
Bench face angle β (°)	55, 85
N° of benches (-)	3
Block diameter (m)	0.62±0.06
Tensile strength σ_t(MPa)	7±0.7
Block density (kg/m^3)	2700
Block shape factor $k_{s,E_{th}}$ (-)	1

Parameter	Value	
	Face	Bench
COR_n (-)	0.4±0.03	0.35±0.03
COR_t (-)	0.85±0.03	0.8±0.03
ϕ (°)	8±1	8±1
Young modulus (GPa)	50±5	20±2
Poisson ratio (-)	0.2	0.2
Surface roughness (°)	±1	±1

2.1 Trajectory model

Fragmentation is evaluated at every impact using an energy-based criterion applied to the normal component of the pre-impact kinetic energy $E_{k,n}^{b}$. Breakage occurs when the ratio $\epsilon = E_{k,n}^{b}/E_{\text{th}}$ exceeds unity, where the threshold E_{th} depends on the effective tensile strength $\tilde{\sigma}_t$, the contact modulus Y_{eq}, an equivalent diameter d_{eq}, and a shape factor $k_{s,E_{th}}$ that lowers the threshold for non-spherical blocks (details in Marchelli, 2026). Structural effects are introduced by assigning $\tilde{\sigma}_t$according to rock-mass class (intact, moderately fractured, highly fractured) and, for the moderately fractured class, by sampling joint orientation θ and applying an orientation-dependent reduction consistent with drop-test evidence (Marchelli et al., 2025; Marchelli et al., 2026). Once $\epsilon > 1$, resulting fragment masses are sampled via Monte Carlo from a bilinear complementary cumulative distribution fitted to laboratory drop tests on intact and pre-fractured samples, with the slopes and breakpoint of the distribution depending on ϵ and on rock-mass class. Mass conservation is enforced, and a minimum fragment mass prevents excessive multiplicity. The remaining kinetic energy after fracture is distributed among fragments proportionally to their mass, consistent with observations of energy partitioning. Post-impact fragments velocities (v_f^a) are assigned through an energy-balanced rebound rule that accounts for deformation and fracture-energy loss via an effective normal restitution $COR^* = \psi\, COR_n$, where ψ scales calibration values to the target substrate. The post-impact velocity vector due to normal impact is $\tilde{v}_f^a = v_n^b\, COR^*$, while directions are sampled from ejection-angle ranges that depend on rock-mass class, joint orientation and ϵ. Tangential components inherit the parent term $v_t^b COR_t$. Each fragment then propagates as a new body within the same lumped-mass framework, inheriting the parent's rock-mass and shape class. The current implementation is two-dimensional for computational efficiency; a 3D extension including lateral dispersion is planned. RockFRAG has been validated against laboratory drop tests on specimens with controlled discontinuities (Marchelli et al., 2025), large-scale field fragmentation experiments, and full-scale propagation tests (Bourrier et al., 2021; Gili et al., 2022); full details are reported in Marchelli (2026). As a representative example, Table 2 compares simulated and observed fragment runout statistics at Vallirana Site 4 (Barcelona, Spain; Gili et al., 2022; Matas et al., 2020), where 24 limestone blocks were released and 22 fragmented producing 1241 fragments. Restitution parameters were calibrated independently on the fragmentation-free Site 1 and transferred without adjustment to Site 4, isolating the fragmentation module performance. Errors remain below 10% across the maximm runout and the 50% cumulative-mass distance, confirming field-scale physical reliability.

Table 2. Observed vs. simulated fragment runout distances at Vallirana Site 4 (data from Matas et al., 2020).

Statistic	Observed (m)	Numerical (m)	Error (%)
Runout at 50% cumulative mass	≈13.5	14.6	8.1
Maximum runout	35.2	33.6	4.4

3 Results and Discussion

The simulations are performed using a tailored script implementing the trajectory model (RockFRAG) in Matlab (R2023b). All the kinematic parameters and block-reaching probability (p_r)are recorded along the slope and at the pit floor, where block or fragment arrivals are most critical for operational safety and for the preliminary definition of mitigation measures. As pit-retention capacity is a key aspect of open-pit slope design, the results can be analysed in light of the acceptance criteria of Read and Stacey (2009): at the bench scale, acceptable failure probabilities range between 10–20 % (80–90 % reliability), while at the overall slope scale a reliability requirement of up to 90-95 % may be appropriate. For the purpose of designing protection structures, the 95th-percentile values of the main kinematic quantities (trajectory h_{95}, velocity v_{95} and kinetic energy E_{95}) are evaluated.

Across the eight synthetic geometries, the comparison between non-fragmenting (N.F.) and fragmenting (F.) simulations highlights two fundamentally different behavioural regimes, controlled primarily by the bench-face angle and secondarily by bench width and height. A first regime, typically associated with shallow face angles (β = 55°), shows that fragmentation increases the runout distance and leads to a higher proportion of trajectories reaching lower benches or the pit floor. In these cases, fragmentation generates a large number of small fragments, characterised by low individual masses, that travel efficiently across bench treads. At the same time, the breakage process occasionally produces rare but dynamically significant high-energy fragments, as reflected in the upper-tail values of the 95th-percentile velocity and kinetic energy profiles. These isolated events extend the extreme

runout envelope well beyond the intact-block prediction, demonstrating that the assumption of a single non-fragmenting block does not safely bound the runout in shallow-slope geometries. The h_b =15 m-w_b =10 m β = 55° geometry (Fig. 1.a) offer clear examples of this behaviour: substantial portions of F case trajectories exceed the 10 % reliability threshold at both intermediate benches and at the pit floor, even when the corresponding N.F. simulations indicate limited mobility.

A contrasting regime emerges for steep face angles (β = 85°). In these configurations, fragmentation predominantly enhances retention rather than mobility. The steep geometry promotes near-normal impacts on the upper bench, resulting in substantial fracture-energy dissipation during breakage. The post-impact velocities of the resulting fragments are generally lower than those of the intact block, producing reduced flight heights and shorter downslope travel distances. As a result, the F curves lie consistently to the left of the N.F. curves, indicating improved bench effectiveness. For wide benches (w_b= 10 m), the fragmenting simulations often eliminate pit-floor arrivals entirely, whereas the N.F. runs may still include a small number of exceedances. The h_b =20 m-w_b =10 m β = 85° geometry (Fig. 1.b) exemplifies this effect, where the fragmentation model yields $p_r$values well below the acceptance thresholds across all slope sectors.

The variability observed in the full dataset is summarised in Table 1, reporting, for each geometry, p_r, h_{95}, v_{95}, and E_{95} at the end of bench 1, end of bench 2 and the beginning of the pit floor. Reaching probabilities below 5% are reported for completeness but do not affect reliability assessment. Considering a 95% reliability target (p_r, ≤ 5%), only two configurations ($\beta = 85°, h_b = 10$m) satisfy the criterion regardless of fragmentation; while twofurther geometries meet it in the non-fragmenting case only, confirming that intact-block assumptions can be non-conservative. Two systematic trends emerge. First, in shallow-angle geometries, fragmentation raises $p_r$across all slope sectors and increases both h_{95}, and v_{95}, at the pit floor, confirming that neglecting fragmentation is non-conservative when the slope promotes shallow impacts and long bench-tread traversal. Second, in steep-angle geometries, fragmentation reduces $p_r$and maintaining similar h_{95} and v_{95}, at each bench, indicating improved retention and demonstrating that fracture-energy dissipation can dominate over the mobility-enhancing effects of small fragment generation. Across all configurations, the N.F. case consistently exhibits the highest E_{95} as the very small masses generated by fragmentation inherently limit the energy carried by single fragments. This aspect is fundamental for assessing bench performance and the expected loading on pit-floor protection measures.

Table 3. Probability of reaching each slope sector (p_r), and 95th-percentile trajectory heigh (h_{95}), velocity (v_{95}) and kinetic energy (E_{95}) at the end of bench 1, end of bench 2, and at the beginning of the pit floor. n.a.=no arrivals. Values of p_r <5%, (underlined) are reported for completeness but are not relevant for reliability assessment.

h_b-w_b-β	1st bench				2nd bench				Pit-floor			
N.F – F.	p_r (%)	h_{95} (m)	v_{95} (m/s)	E_{95} (kJ)	p_r (%)	h_{95} (m)	v_{95} (m/s)	E_{95} (kJ)	p_r (%)	h_{95} (m)	v_{95} (m/s))	E_{95} (kJ)
15-7-55	93-86	0.0-0.2	3.8-5.2	19.8-2.7	23-54	0.0-0.15	2.7-9.4	10.2-0.8	23-54	0.2-4.6	7.4-16.5	326.6-4.9
15-10-55	19-53	0.0-0.0	2.5-3.7	8.9-0.7	<0.1-17	0.0-0.1	3.5-7.9	22.3-0.7	<0.1-16	0.1-2.3	10.2-15.4	250.2-0.6
20-7-55	100-99	0.9-0.9	5.7-8.0	35.4-3.2	40-63	0.0-0.7	2.9-11.6	10.9-0.8	40-63	0.0-11.6	18.8-19.9	502-1.7
20-10-55	21-20	0.0-0.0	3.7-5.1	18.2-0.8	15-34	0.0-0.1	2.6-10.1	10.5-0.4	15-34	0.0-9.4	18.8-19.7	504-1.1
15-7-85	35-3	0.0-0.0	1.9-2.2	10.3-0.4	5-<0.1	5.2-5.1	6.6-7.4	57.3-0.6	5-<0.1	14.9-14.9	14.7-10.4	270-1.2
15-10-85	<0.1-n.a.	5.5-n.a	10.4-n.a	147.0-n.a	n.a.-n.a				n.a.-n.a			
20-7-85	66-27	6.6-6.6	10.1-10.2	30.0-1.2	42-16	9.3-6.7	10.7-9.0	210-0.9	42-15	19.2-17.3	15.6-12.3	310-2.6
20-10-85	20-<0.1	2.8-2.8	4.4-3.6	25-0.4	<0.1-<0.1	4.5-2.5	6.6-4.8	59.4-0.0	<0.1-<0.1	20-17.4	18.8-11.1	260.2-0.4

Overall, the results show that fragmentation produces geometry-dependent, non-monotonic changes in mobility that intact-block assumptions cannot capture. Breakage spreads energy among many low-mass fragments with limited rebound, yet it can still generate rare high-energy trajectories that drive long-runout extremes. Shallow faces enhance the mobility of small fragments, whereas steep faces favour energy dissipation and improve capture. These outcomes underline the need to include fragmentation in probabilistic analyses and runout-based reliability checks for open-pit slope design.

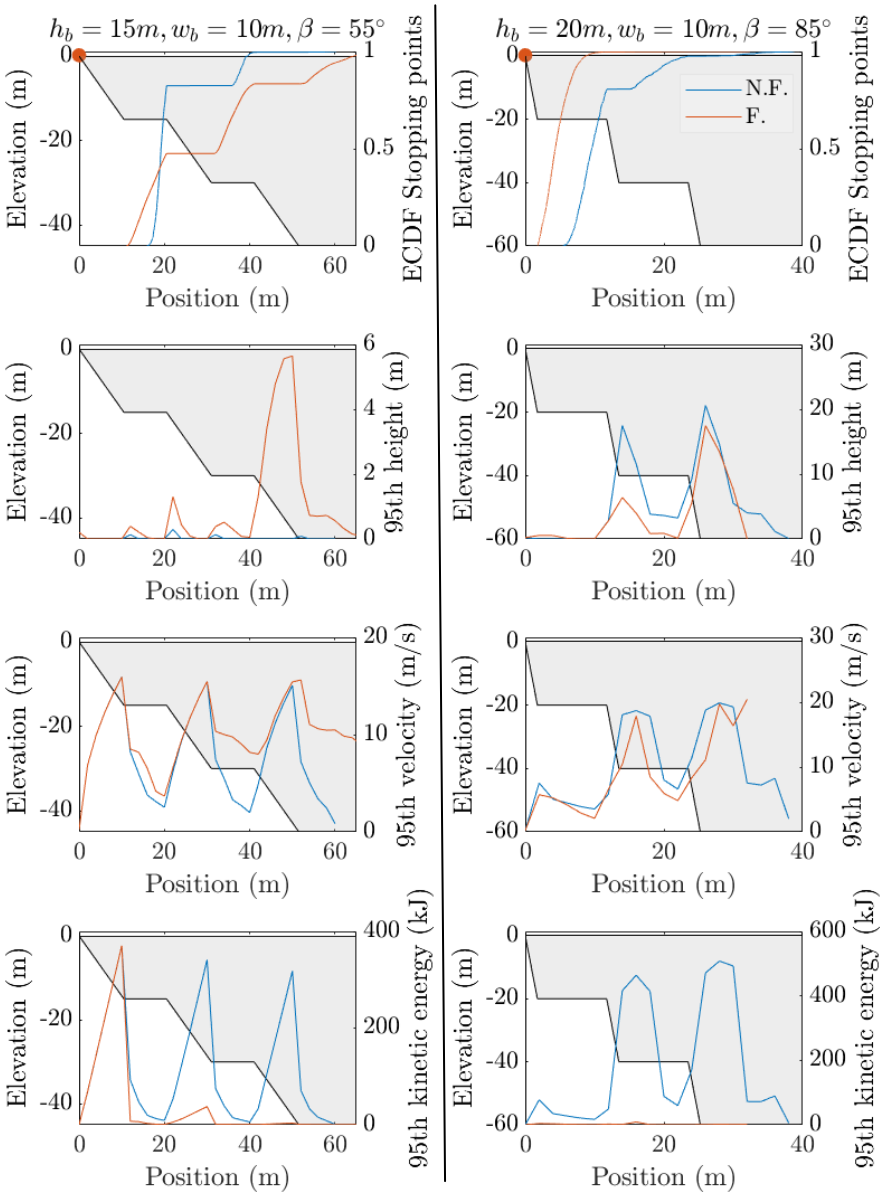


Fig. 1 Comparison between N.F. and F. simulations for:(a) h_b= *15 m,* w_b = *10 m,* β = *55°* and (b) h_b = *20 m,* w_b= *10 m,* β = *85°*. Panels showstopping-point profiles (empirical cumulative density function ECDF), 95th-percentile height, velocities, and kinetic energies along the slope. Red dots represent the source area.

4 Conclusions

The analyses performed on ideal synthetic bench geometries demonstrate that fragmentation exerts a systematic and geometry-dependent influence on rockfall propagation and pit-floor hazard. For shallower faces, fragmentation markedly increases run-out distances, arrival probabilities and upper-tail impact velocities, indicating that neglecting breakage can result in non-conservative design assessments. Conversely, for steep faces, fragmentation may have a limited effect or even improve retention when benches are sufficiently wide, as fracture-energy dissipation promotes earlier stopping, although some very high-velocity trajectories may still arise.

These findings underscore the need to account for fragmentation in runout-based design checks and in evaluating bench performance. Fragmentation can alter conclusions on catch-bench effectiveness and

the loading conditions for protective measures, as its effects on mobility are geometry-dependent. In contexts with uncertain inputs or structural conditions, analysing both fragmenting and non-fragmenting scenarios provides a more robust basis for design, ensuring that the full range of plausible runout and impact conditions is captured.

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