Effect of shape on the survival probability of rock replicas during free fall tests

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ABSTRACT: Fragmentation of rocks upon impact is a complex phenomenon that is not well understood. The first question to answer to adequately model fragmentation is whether a falling block is likely to fragment at impact or not. This question can be answered if the survival probability of the rock is known, but this is not trivial as no model or method exists to predict the survival probability of natural rocks. The authors have recently developed a model that can predict the survival probability of brittle rocks under collinear impact, following a preliminary breakthrough for brittle spheres. One complexity associated with irregularly shaped rocks is the possibility of non-collinear or eccentric impacts. The objective of this study is to conduct drop tests on irregularly shaped rocks and highlight the significance of collinear and eccentric impacts on the survival probability in drop tests.

Keywords: Rockfall, Fragmentation, Shape, Survival Probability, Collinear, Eccentric.

1 INTRODUCTION

Rocks commonly fragment during rockfall events, as demonstrated by in situ tests (Matas et al. 2020) or field surveys conducted post events (Evans & Hungr 1993). Understanding and predicting rock fragmentation is non-trivial and there is a lack of data in the literature to assist researchers in developing fragmentation models. One important aspect of this complex phenomenon is to predict the likelihood of fragmentation in a given geological setting. This question can be answered using the survival probability of the rocks but establishing a survival probability is non-practical and very time-consuming. The authors recently proposed a model that can predict the survival probability of brittle spheres in drop tests (Guccione et al., 2021a) and the model was extended to capture some geometrical variability associated with non-spherical shapes. One limitation of the extended model is the assumption of a collinear impact (i.e. the center of mass of the rock is located on the normal of the impact plane passing by the impact point, Stronge, 2000). For many natural rocks, the likelihood of eccentric impacts (where the center of mass of the rock is not located on the normal of the impact plane passing by the impact point, Stronge, 2000) is high. In such case, the falling rock may contact the surface twice or during the impact. The significance of multiple impact points on the survival probability is unknown. This paper presents the results of a series of drop tests on mortar replicas of a natural rock prone to both collinear and eccentric impacts. The objective of the study is to investigate the significance of eccentric impacts on the survival probability of the rock.

2 EXPERIMENTAL METHODS

2.1 Material and specimen preparation

A non-equant (low sphericity) sub-rounded rock of about 8cm in size was selected for this study. The rock was scanned using a EinScan Pro 2x Plus scanner to obtain a 3D mesh. Using the software Meshlab (Cignoni et al., 2008), a homothetic change of dimensions was applied to the rock to obtain a volume equivalent to that of a 50 mm diameter sphere, for comparison purposes with the survival probability of the 50 mm diameter sphere (Guccione et al 2021a). The major, intermediate and small axes of the rock are 50mm, 32mm and 25 mm long, respectively.

Figure 1.Photographs of the replicas of natural rock used for this study. The rock shape is described as low sphericity, sub-rounded.

The 3D digital rock model obtained post-scanning was then used to create 3D printed plastic molds and about 200 mortar replicas were made. For consistency and comparison reasons, the mortar used in previous studies (Guccione et al., 2021a; Buzzi and Guccione, 2023) was used here. It consists of a mixture of sand, cement, lime and water in ratios of 3:1:0.25:1, respectively. All mortar specimens were left to cure in water for 8 weeks at room temperature and to air-dry for 4 weeks.

2.2 Fragmentation cell and experimental program

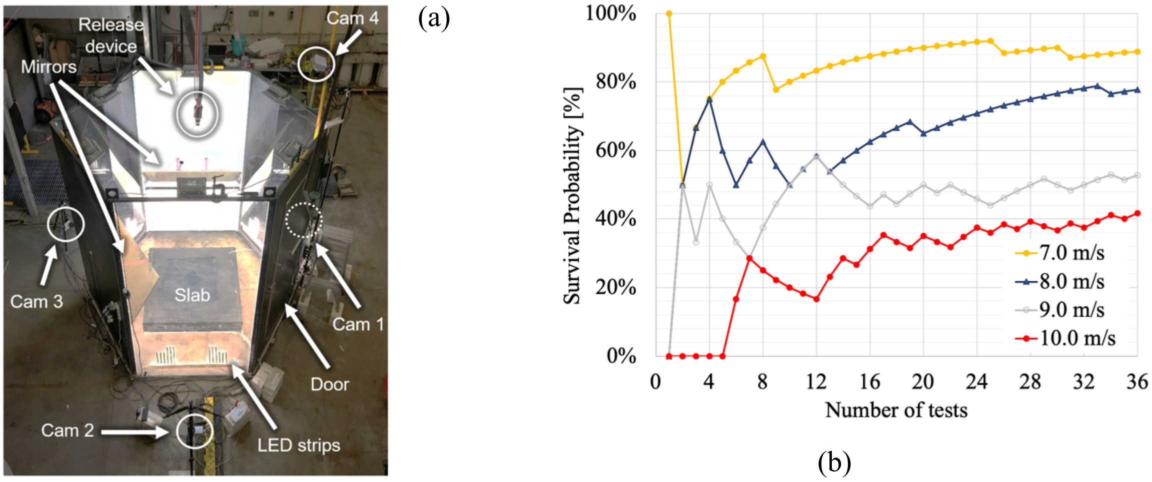
The fragmentation cell developed by Guccione et al. (2021b) was used for this study (see Figure 2a). The set up consists of a concrete slab resting on three 100kN load cells and equipped with an accelerometer and enclosed in a 6-sided frame with clear sides. Four high speed cameras, positioned outside the frame, are used to record the impact and reconstruct 3D trajectories before and after impact, including the rotational movement (Guccione et al. 2021b). The sum of the three load cell measurements is the force transmitted through the slab during the impact. The magnitude of the transmitted force will be discussed in the rest of the paper. The rock or object to be subjected to free fall is held at a predefined height (with 0.5 cm accuracy) using a vacuum cleaner and is released by the turning the vacuum cleaner off. For this study, the sub-rounded rock described in the previous section was subjected to impact at velocities of 7, 8, 9 and 10 m/s. For each impact velocity, 36 drop tests were performed. How this number of tests was decided is covered in section 3. The rock was held and released from all of its six main faces in order to obtain a wide range of impact scenarios. For a matter of page limit, no photograph of the setup is shown, the reader is invited to refer to Guccione et al. (2021b) for more information.

Note that, in the rest of the paper and for comparison purposes, drop test data for 50 mm mortar spheres (from Guccione et al., 2021a) and for mortar replicas of a natural equant rock (referred to as rounded rock, from Buzzi and Guccione, 2023) are used. The principal axes of the rounded rock are

44.5, 51.4 and 65 mm long and its sphericity is high, i.e. 0.92 (estimated as per Wadell, 1933). All three objects have the same volume and same mass (125 g).

3 RESULTS

Figure 2 shows the evolution of survival probability for each impact velocity as the number of drop test increases. These results suggest that with 36 drop tests, the values of survival probability obtained are quite stable and unlikely to vary significantly with additional testing. With 36 drop tests, the values of survival probability obtained are considered reliable.



(a)

(b)

Figure 2. View of the fragmentation cell from Guccione et al. (2021) (a) and evolution of survival probability of the sub-rounded rock with number of tests for impact velocity of 7, 8, 9 and 10 m/s (b).

Figure 3 shows the survival probability in drop tests for the sub-rounded rock of this study, the sphere and the rounded rock. Before discussing these results, it is useful to recall that the degree of variability of material strength or resistance can be appreciated by the steepness of the survival probability: the flatter the curve, the higher the variability. The survival probability of the spheres is the steepest of all three curves, because the main source of variability is the material strength, there is no variability associated with the impact conditions (point of impact and relative position of the object at impact). The survival probability of the rounded rock is flatter than that of the spheres because a geometrical variability is now added to the strength variability. It can also be seen that, for a similar value of survival probability, the velocity required to fragment the rounded rock is slightly lower than for the sphere. Note that for the rounded rock, all impacts were collinear.

The fact that the survival probability of the sub-rounded rock is flatter than that of the sphere and the rounded rock is expected, given the shape of the rock leading to a higher variability of cross sections and possibility of impact geometry. On the other hand, the curve is shifted towards higher values of impact velocity, which implies that more energy is required to fragment the sub-rounded rock. Such outcome was not expected because a mortar of same strength was used.

To explain the results of Figure 3, it is relevant to consider the magnitude of force transmitted through the slab during the impact. Figure 4 shows the cumulative frequency of transmitted force for spheres and sub-rounded rock for all tests with an impact velocity of 7m/s. The spread of forces is much larger for the sub-rounded rock than for the spheres. For 60% of sub-rounded rocks, the transmitted forces are lower than 600 N, which is the lowest value for the spheres (see dashed line on Figure 4). Analysis of high-speed photographs showed that all tests left of the dashed line are eccentric impacts with double contact points and some rotation induced by the impact. In contrast, all impacts (but two) on the right-hand side of the dashed line are collinear with a single contact point and no significant rotation induced by the impact. Examples of such motion are given in Figure 5, for tests on rocks #11 and #129. For the same drop height, an eccentric impact tends to lead to a lower impact force than a collinear impact, which in turns means that the survival probability of an eccentric impact is higher than that of a collinear impact, as per Figure 3.

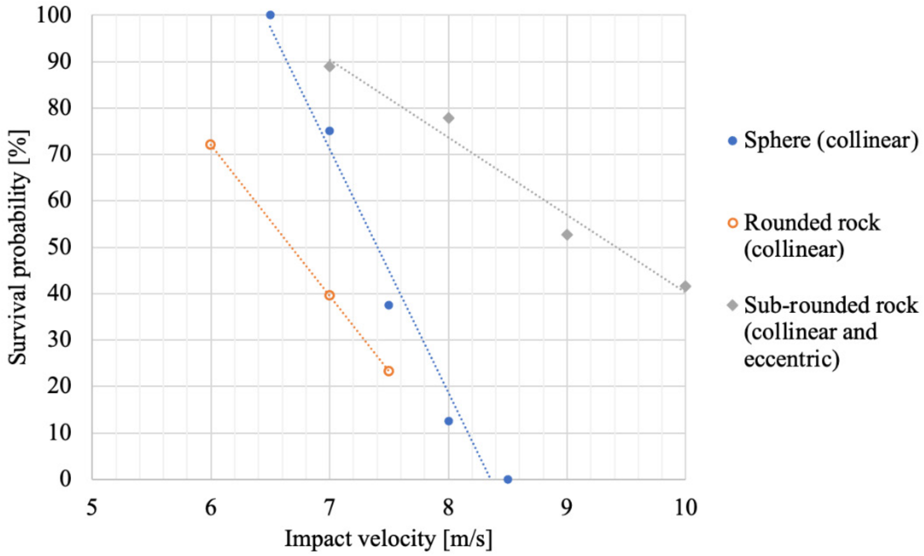


Figure 3. Experimental survival probability in drop tests of the sub-rounded rock replicas (grey diamonds), the 50 mm mortar spheres tested by Guccione et al. (2021a) (blue full circles) and the rounded rock tested by Buzzi and Guccione (2023) (empty orange circles). The impact type (collinear/eccentric) is indicated in bracket for each object. The lines represent a linear fit of the data.

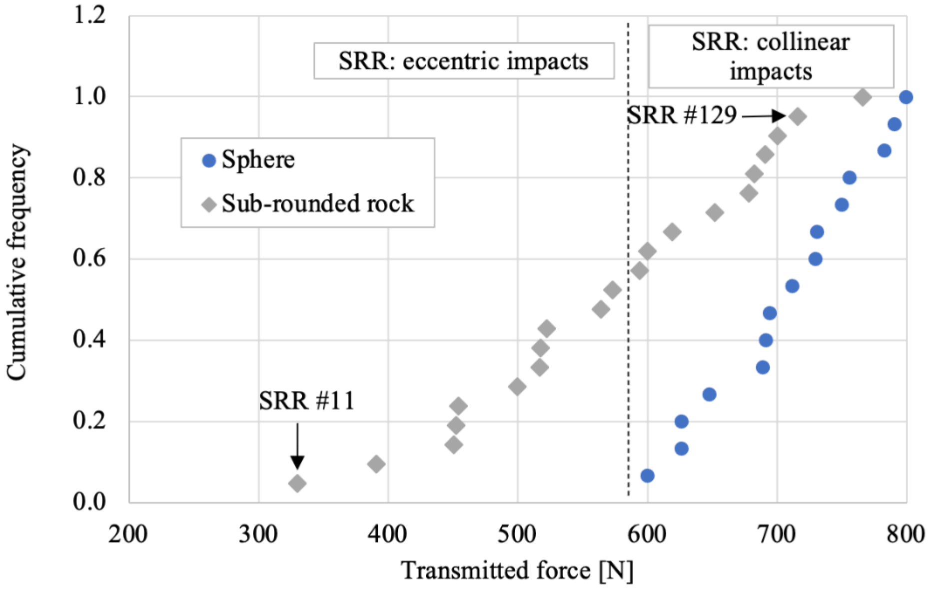


Figure 4. Cumulative frequency survival probability of the sub-rounded rock replicas subjected to drop tests and of the 50 mm mortar sphere tested by Guccione et al. (2021a). Impact velocity of 7m/s. The vertical dashed line separates the tests with eccentric impacts (left hand side) and collinear impacts (right hand side) for the sub-rounded rocks.

The high-speed photographs were processed with the software TEMA (Image Systems Motion Analysis 2019) to track trajectory and compute velocity in all directions. When comparing the trajectory of a sphere (collinear impact) and of sub-rounded rock #11 (eccentric impact) in Figure 6, one can see that the sub-rounded rock rebounds much less than the sphere, which indicates that a larger fraction of the incident kinetic energy is dissipated during the impact.

Table 1 reports the computed values of translational kinetic energy pre and post impact, as well as the percentage of incident kinetic energy lost upon impact. For the collinear impact (sphere), 76% of the energy is dissipated at impact, which is consistent with estimations from Guccione et al. (2021b). However, for the sub-rounded rock #11, subjected to an eccentric impact, up to 93% of energy is dissipated at impact. The extra 17% of energy loss is attributed to the rolling motion visible in Figure 5 and this energy dissipation mechanism explains the results of Figure 3. Because the eccentric impact generates additional energy dissipation, more impact energy (or velocity) is required to achieve fragmentation, resulting in a shift of the survival probability towards higher velocity, compared to the sphere.

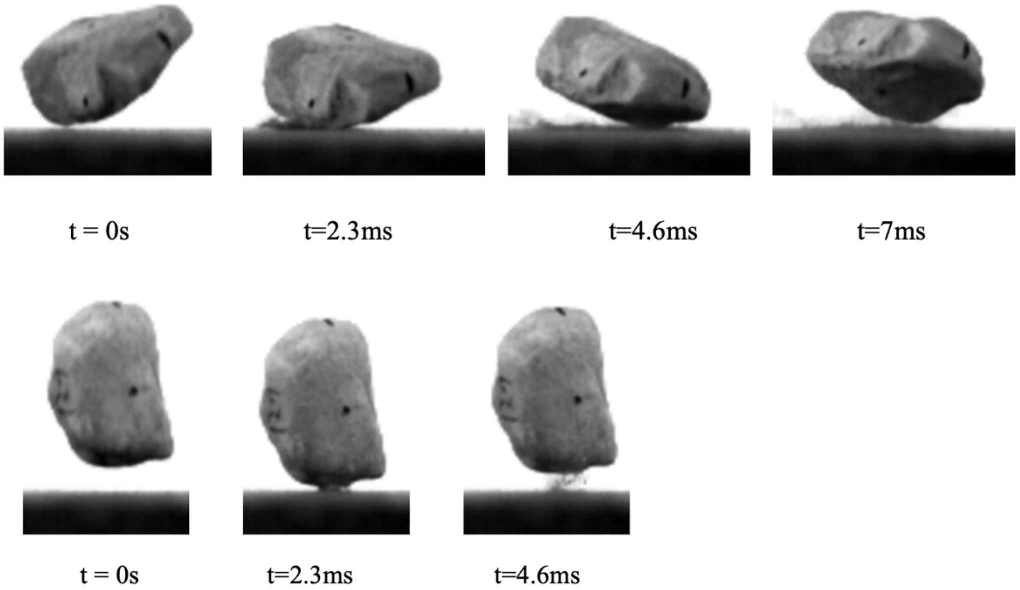


Figure 5. Sequence of photographs showing the impact and post-impact motion of sub-rounded rock #11 (top) and sub-rounded rock #129 (bottom). The initial time t = 0s is arbitrary and not the same for both tests. Both rocks were subjected to an impact velocity of 7m/s.

Table 1. Values of translational kinetic energy before and after impact, and energy loss (computed as the energy difference over the translational kinetic energy before impact, expressed in percentage) for a 50 mm sphere and sub-rounded rocks #11. Note that the rotational component of kinetic energy post impact is negligible for SRR #11. S: Single, C: Collinear, E: Eccentric, R: rotation.

		Sphere	SRR #11
Impact type		S, C	E, R
Kinetic energy before impact	[J]	2.98	2.98
Kinetic energy after impact	[J]	0.71	0.21
Energy loss	[%]	76	93

4 CONCLUSIONS

This paper presents the results of an experimental study focusing on the determination of the survival probability in drop test of replicas of a natural rock. The rock has low sphericity and is sub-rounded. This study is part of a current research by the authors on the prediction of survival probability of rocks during rockfall. For the rock selected, it was observed that the impact can be collinear (center of mass located in the line of impact force) or eccentric (center of mass outside the line of impact force). When the impact is eccentric, an additional portion of the incident kinetic energy (estimated to up to 17% for one test) is dissipated during the impact, compared to a collinear impact. The outcome of this extra dissipation is that the magnitude of the impact (measured via the transmitted force) is reduced, and the rock is more likely to survive the impact. This mechanism explains why the survival probability curve of the sub-rounded tested in this study is shifted towards higher values of impact velocities, compared to a sphere of same mass and strength. Although this paper brings new insight into the significance of rock shape for the survival probability, more research is needed to fully understand the role of rock curvature (convex, flat or non-convex surfaces) and to compute the amount of energy dissipated upon non-eccentric impact.

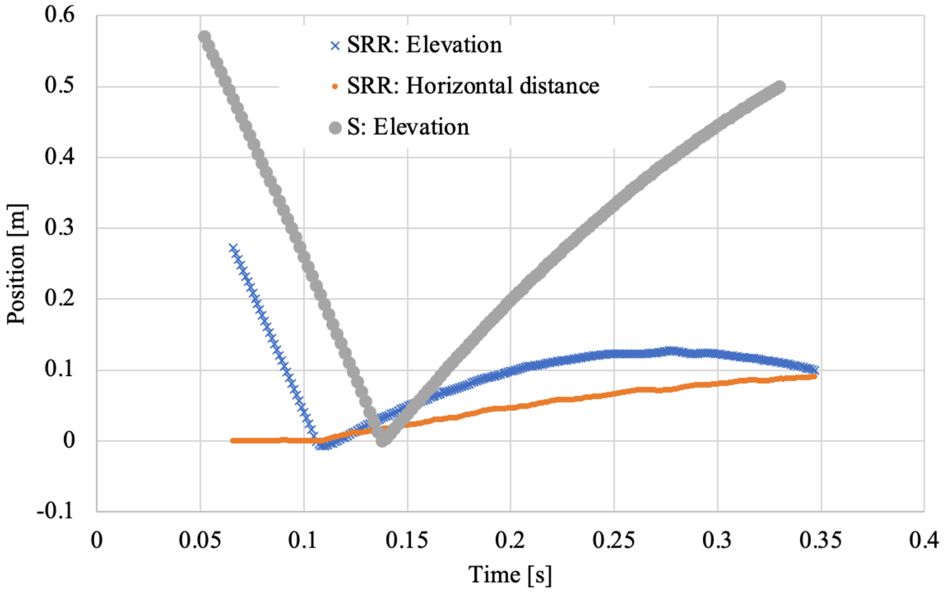


Figure 6. Evolution of object position (vertical and horizontal) in free fall, before and after impact with time. SRR: sub-rounded rock, S: sphere. The origin of elevations (0 m) corresponds to the position of the center of a 50 mm sphere resting on the slab. The origin of horizontal distance (0 m) is the initial position of the object before being released. No horizontal movement was observed for the sphere.

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