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A study of the sensitivity of rolling behaviour to block shape

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ABSTRACT: Rolling of rocks during rockfall events is an important phenomenon in a country like Australia, where cliffs are rare, but steep rocky slopes are common. This paper presents an experimental study to investigate the influence of both coarse and subtle changes in shape on rolling motion of blocks during rockfalls. Experimental tests involve blocks with different shapes, rolled down a 5m wooden ramp with varying slopes. Autoclaved Aerated Concrete (AAC) which is easily cut and abraded was used to create blocks with different coarse shapes, being elongated hexagonal and octagonal prisms. Blocks of each shape were repeatedly rolled down the ramp, for chosen inclinations, and the changes in rolling speed were recorded as the edges of the blocks were abraded, and the blocks became rounder. The results demonstrate that both block form and block roundness are dominant factors in the speed of a rolling block. The relatively mild change from hexagonal to octagonal for an equant block is sufficient to change the rolling velocity by a factor of 2. Similarly, a rounding of edges of just 2mm on a block of gross dimensions of 200mm is sufficient to change the rolling velocity by 20%, and a loss of 4mm is sufficient to change it by 50-100%. The results confirm the need to a better understanding of rolling phenomena in rockfall studies.

1 INTRODUCTION

Rockfall phenomena are a source of serious hazards for both facilities and people. The motion of falling rocks includes, falling, bouncing, sliding and rolling of rock blocks over a substrate. (Hunger et al. 2014). Numerical simulation programs are widely used to study hazard assessment of rockfall, however most of rockfall simulation programs are unable to represent the full mechanical and geometrical properties of both blocks and substrate rigorously, at least for rolling motions.

Generally, the lumped mass and rigid body approaches are widely used to simulate rockfall (Volkwein et al. 2011). Lumped mass models consider the blocks as a single, dimensionless points which inherit all mechanical properties of the actual blocks via the empirical coefficients adopted to describe block-substrate interactions. Rigid body models use ideal shapes such as a sphere, cube or ellipsoid to represent the block shape, and take direct account of these shapes in interactions with the substrate. Hybrid models use a lumped mass model to simulate free falling motions and a rigid body representation to model bouncing, rolling or sliding motions (Mitchell and Hunger 2017).

Bouncing interactions are usually modelled using restitution coefficients (Asteriou 2015, Azzoni 1995) which seem to take reasonably good account of the associated energy transformations during impact. Energy dissipation during rolling is usually accounted for by a generic rolling coefficient (Giani 1992) which is defined as the tangent of the slope at which blocks will roll at a constant rate. Rolling coefficients are a crude parameter to describe the complex phenomena of rolling, taking little account of the shape of blocks and how this affects the style, speed and sustainability of rolling motions

Although rigid body approaches represent a more realistic model of rockfall, the use of a simple rolling friction coefficient (Bozzolo, et al. 1988; Azzoni et al. 1995) is not able to correctly explain the energy dissipation process during rolling. To improve the reliability of rockfall simulations on different slope types, the effect of parameters like the size and shape of blocks must be considered with greater detail (Dorren et al. 2006).

Experimental and field results show that nature of rockfall is strongly affected by the shape and size of blocks, and these are dominated by their parent rock mass geology (Fityus et al. 2013). The geometry of blocks not only affects rockfall trajectories, but it also this controls whether a block will bounce or roll, since transition between translational and rotational motions is controlled by the block angularity (Ritchie 1963, Pfeiffer and Bowen, 1989).

In this paper, the effect of block shape on rolling motion over a sloping, flat substrate is investigated. Specifically, the aims of the study were to explore the sensitivity that both coarse and subtle changes to the shape of blocks have on their rolling motion; namely, their rolling velocity.

2 METHODS AND APPROACH

The outcomes presented here are based on the results of an experimental program wherein prismatic blocks of two different basic shapes were rolled down the same surface, so that their rolling velocities could be measured and compared. By making the blocks from soft material, and rolling them repeatedly causing their edges to become worn, the change in rolling speed was correlated to more subtle changes in shape as the blocks were progressively abraded.

The rolling surface used in this study was an adjustable planar ramp, 5m long by 1.2m wide, with a thick wooden surface supported by a stiff steel-framed structure, as shown in Figure1 and 2. The ramp is raised and lowered from one end using a simple lifting system, consisting of chains and rollers, with four vertical feet at intermediate positions used to increase the stability of ramp. The ramp has a high surface roughness to promote rolling over sliding, achieved by covering the ramp with a sand-based paint.

The velocity of the rolling blocks is measured throughout their motion over 6 different pairs of segments down the ramp using pairs of laser indictors installed at different positions on the ramp. Timing is triggered when the rolling block breaks the beam between the first pair of indicators at the top of the ramp, with the time then recorded as the rolling block breaks the beam between subsequent pairs of sensors.

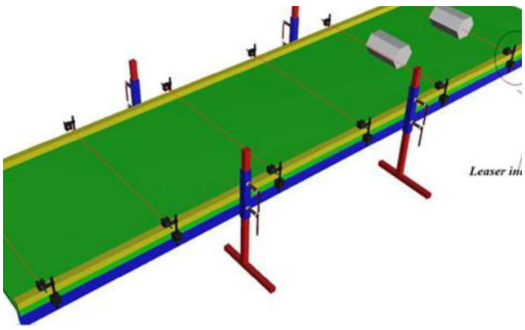

Figure 1. Schematic arrangement of the ramp used as the substrate in the experimental program.

Figure 2. Photograph of the ramp used for the experimental testing (having its inclination adjusted).

The two different shapes of blocks studied were octagon and hexagon. Elongated prisms were chosen, and rolled with the long axis perpendicular to the steepest direction, to achieve greater consistency in the rolling direction. This choice took account of previous experience that more equant blocks have a greater tendency to roll in a more unstable manner, with occasional rotations that are not perfectly consistent with the direction of motion in the steepest direction down the ramp.

In each case, the cross-sectional shapes of the prisms were derived by cutting the edges from a basic square prism of 200 x 200 x 300 mm. The resulting cross-sections are shown in Figure 1.

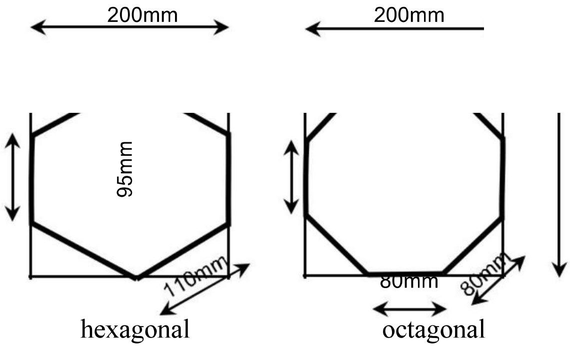

Figure 3. Geometry of the prismatic sections used.

To achieve relatively rapid shape evolution through abrasion during rolling, Autoclaved Aerated Concrete (AAC) was used to create the blocks. Due to the low hardness of AAC, block edges were easily abraded during rolling, allowing the blocks to evolve from angular to rounded after 100-300 repeated rolls on the ramp.

ACC is an ideal material for this study as it is easily shaped by cutting, it is a lightweight material that can be easily lifted, and despite being soft it is sufficiently strong to avoid fracturing during its motion. Figure 4 shows the stock of AAC bocks from which the prisms were cut, and some of the prisms that were tested.

The evolution of roundness of each block with repeated rolling was assessed by physical measurement of the extent to which its edge were

Figure 4. Stock AAC blocks from which test blocks were cut (left), and the cut prisms used in this study (right).

removed after a particular number of rolls down the ramp. A simple adjustable angle gauge was fitted to touch each of two adjacent faces, so that a gap was evident between the vertex of the gauge and the rounded edge. Then, a calibrated thin taper was in-

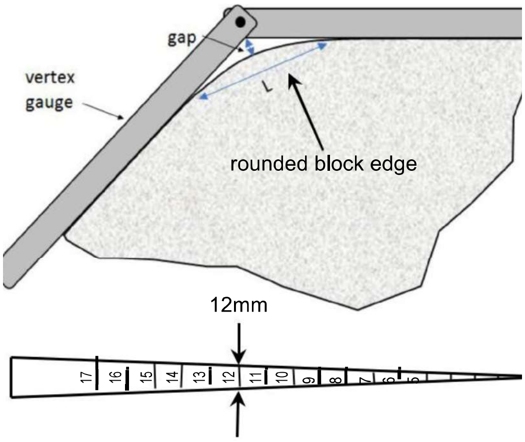

Figure 5. Arrangement for measurement of block round-ness using the vertex gauge (top) and the graduated taper inserted to measure the "gap" (bottom).

serted into this gap to determine the maximum value of the gap, in a direction perpendicular to the block surface. The arrangement is shown in Figure 5.

Roundness measurements were taken after 10, 25, 50 and 100 repeated rolls of each block, except for the first octagonal block, where a total of 360 rolls were undertaken. Measurements were made of each edge around the centre of the block, and the results expressed as the average of the 6 (hexagon) or 8 (octagon) readings taken on each occasion.

Two different ramp slopes were tested for each block shape. It was found that the tendency for each shape to roll continuously to the bottom of the ramp was different, with the octagonal block rolling more readily than the hexagonal block. Hence, the first slope tested for each was that slope at which each block would just consistently roll to the end of the ramp without stopping: 3.1 degrees for the octahedral block, and 6.9 degrees for the hexagonal block.

Then a second slope was tested for each: 6.9 degrees for the octagonal block (so the result could be compared directly with the hexagonal block at 6.9 degrees) and 11.8 degrees for the hexagonal block, which is similarly greater than the first tested slope for the hexagonal prism, as is the difference between the two slopes tested for the octagonal prisms. Table 1 summarises these arrangements.

Table 1. Details of the tests performed

block	slope (degrees)	measurement points
Hexagonal 1	3.1	10, 25, 50, 100
Octagonal 1	6.9	10, 20, 36, 60, 100, 160, 250, 300
Hexagonal 2	6.9	10, 25, 50, 100
Octagonal 2	11.8	10, 25, 50, 100

A key aspect to be considered in the experimental design was the way in which the blocks would be released. It was important that blocks were released in a consistent way each time, so that the subsequent rolling behavior was not biased by differences or inconsistencies. It was decided that each block should be consistently released from the same edge each time, and that it should roll onto the same face (that is, rotate in the same direction). For the octagonal blocks, release from any edge produce similar rolling, but because of asymmetry in the hexagonal blocks, they rolled differently depending upon which edge they were released from, and which edge they rolled onto. Release from the edge between two long faces, to fall onto a long face, was found to be least likely to lead to sustained rolling, whereas release from an edge between a long and short face, to fall onto the long face, was found to be the most likely to lead to sustained rolling. The latter was selected as the release condition.

In all tests, a unique position on the ramp was determined such that when the block was balanced on the chosen edge, it could be gently released to fall downslope to begin rolling, and in doing so, break the laser beam to initiate the timing sequence.

3 ROLLING SENSITIVITY TO BLOCK FORM

Even before any rolling velocity measurements were made, it was apparent that block form has a profound influence on rolling behavior. This was evident through the finding that the octagonal block would roll sustainably to the bottom of the ramp at just 3 degrees, but the hexagonal block would not roll consistently until the slope reached 6.9 degrees; almost double.

Figure 6 compares the average velocities of the two block forms with respect to slope. So that the effects of roundness are excluded, the values in Figure 6 represent those from the initial rolls of the blocks in their pristine condition, before any abrasion had occurred. It is apparent from the results that the octagonal block rolls significantly faster for a given speed; from the data at the common slope value of 6.9 degrees, it would seem to be about twice as fast.

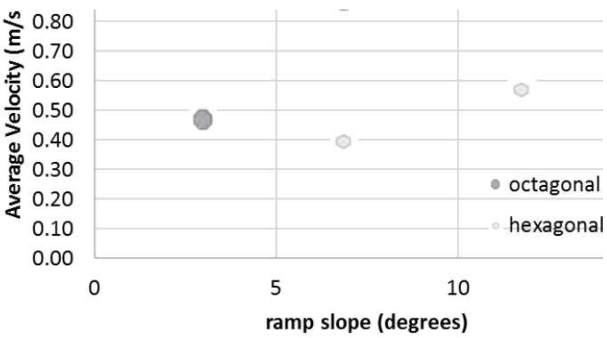

Figure 6. Comparison of average rolling velocities for initial rolls over 5m, for the two tested shapes, as a function of slope.

4 ROLLING SENSITIVITY TO ROUNDNESS

4.1 *The nature of abrasion of rolling blocks*

By rolling the same soft block repeatedly down the same ramp, the block became progressively rounder. Before considering the effect of this on the rolling motion of the blocks, some observations are made regarding the trends in roundness achieved.

It might be expected that rounding of the prism edges might produce an approximately circular surface, which meets the faces of the prism at a tangent, and that the radius of the circle would increase with progressive abrasion. Figure 7 shows the relationship between the gap and the distance L for an assumed circular rounding surface of increasing radius. The relationship between the gap and L is given by

$$L = 2\sin\theta / (1-1/\cos\theta) \times \text{gap} \qquad (1)$$

where θ is the complement of the angle between the faces of the prism (60 degrees for a perfect hexagon, and 45 degrees for an octagon). Figure 8 compares the theoretical relationships between the abrasion length L and the gap with the measured data from the study. It is apparent that both theoretical relationships and measured data give bigger gaps for the

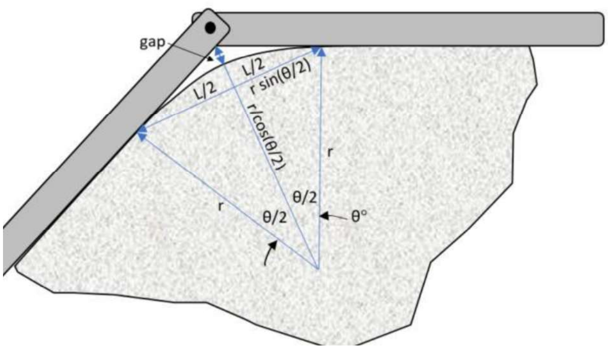

Figure 7. Geometry for an assumed circular edge rounding, showing the relationship between L and the gap.

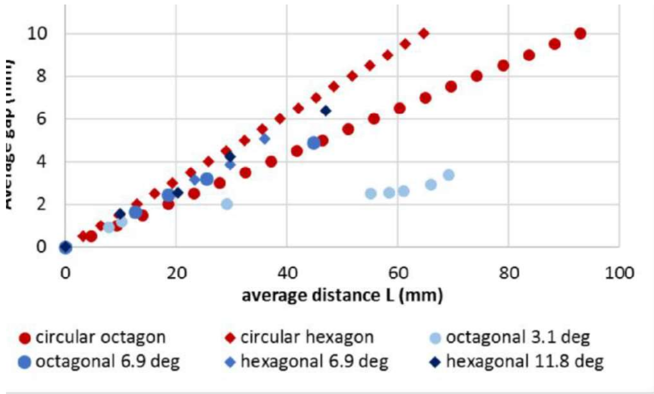

Figure 8. Comparison of theoretical and measured relationships between the length of the abraded edge and the gap.

same length for hexagonal prisms than for octagonal prisms. The theoretical circular relationships are good approximations in all but the octagonal block tested on the 3 degree ramp, where the measured gap for a given abrasion length is smaller than that predicted by a circular rounding assumption.

It is worth noting that when the abraded edges of the prisms were inspected, a degree of asymmetry was observed.

Figure 9 shows the trends in rounding of the prisms with repeated rolling.

The upper figure indicates that hexagonal prisms abrade more quickly than octagonal blocks to lose the sharpness of their edges. Generally, the loss of edge depth is very rapid for the first 10 rolls, before showing to a steady rate of loss. For the octagonal prism at a very low slope, the rounding rate becomes very slow after around 60 rolls. The lower rates for

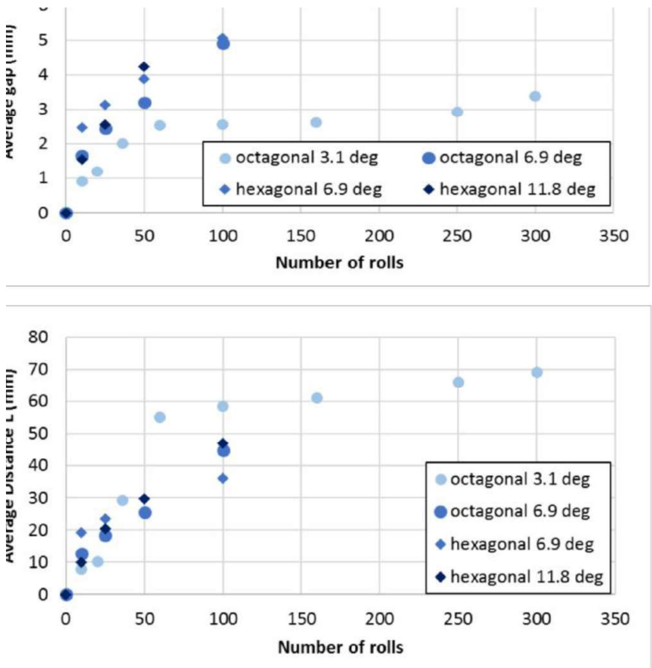

Figure 9. The relationship between abrasion length (top) and gap size (bottom) with number of rolls for the tested blocks.

the octagonal shape is due to the greater number of faces and the broader face-to-face angles, which result in gentler impacts as successive faces contact the ramp. The lower abrasion for lower sloping surfaces is consistent with the expectation that abrasion is decreased for slower rolling on milder slopes.

The increase in abrasion length L is generally consistent for both shapes and all slopes for the first 50 rolls, but there is a trend for this length to increase more quickly for octagonal prisms than for hexagonal prisms with increasing repetitions.

4.2 *The effect of abrasion on rolling*

Figure 9 shows the evolution in rolling velocity for the octahedral block on the 11.9 degree ramp. Velocity values are plotted for both the individual ramp segments as well as an average value for the entire length of the ramp. From the figure, a number of observations can be made.

- For any given roll of the block, the velocity increases with distance down the ramp, though decreasingly so with distance.
- The velocity values scatter with increasing distance (due to the increased likelihood there will have been a perturbation in the rolling motion, or a rolling direction change)
- All measured velocities evolve most rapidly at the beginning, and the evolution slows down as the number of rolls becomes large, particularly for more than 20 rolls.
- The velocity over the first metre is least affected by block rounding increasing only from 0.6m/s for the first roll to 0.8 after 100 rolls.
- The velocity over the last 0.5m is most affected, increasing from 0.8m/s for the first roll to 2.1 m/s after 20 rolls and 2.6m/s after 100 rolls.

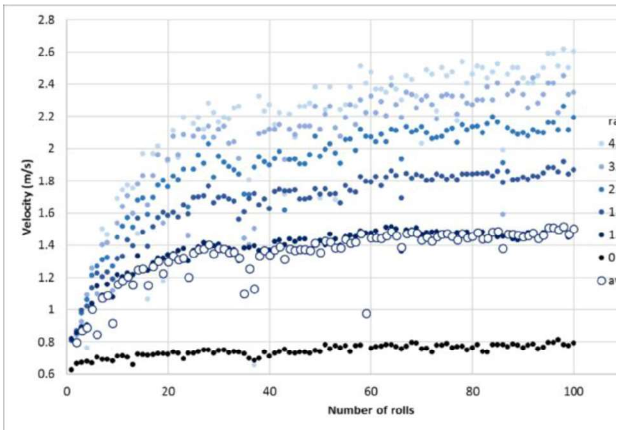

Figure 10. Velocity over different ramp segments with number of rolls for the octahedral block on the 11.8 degree ramp.

Figure 11 correlates the relative change in velocity (velocity of abraded block / velocity of pristine block) as a function of the size of the gap, or more significantly, the amount of edge loss.

Generally, edge loss leads to an increase in rolling velocity. Edge loss seems to causes a bigger change in velocity for blocks rolling on steeper surfaces; the blocks on surfaces that were just steep enough to sustain rolling (octagonal 3.1 degrees and hexagonal 6.9 degrees) experienced velocity increases of up to 20% for an edge loss of 2mm, whereas the blocks that were rolling on steeper surfaces (octagonal 6.9 degrees and hexagonal 11.8 degrees) experienced velocity increases of up to 50% for an edge loss of 2mm. With edge losses of only 4mm, all blocks experiences velocity increases of at least 50%, with the hexagonal prism on the steeper 11.9 degree slope rolling more than twice as fast due to the loss of 4mm of edge thickness.

The influence of subtle edge rounding on rolling speed is profound, and of a similar order of magnitude to the influence of overall block shape, which also caused a factor of between the rolling speeds of hexagonal and octagonal blocks on surfaces with the same slope.

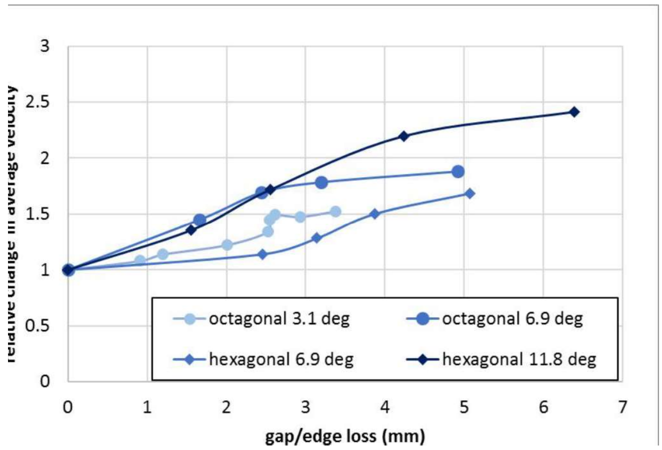

Figure 11 Relative increase in velocity as a function of edge loss (increasing gap) for all blocks.

5 CONCLUSIONS

The present study demonstrates that the shape of blocks is a dominant factor in the rolling motion of rock blocks during rockfall events. Despite little rigorous account being taken of block shape in most rockfall simulations, the experimental results presented here demonstrate that relatively small changes in shape can profoundly affect the speed of rolling.

The results demonstrate that both form and roundness are significant parameters for rolling motion, and are potentially of similar importance. The two forms studied, hexagonal and octagonal) were not greatly different, with both being equant and having the same values and ratios of orthogonal dimensions for the prism section. Although they differed only in the number of faces and their interfacial angles, the difference in form were enough to cause a factor of 2 difference in their rolling velocities, and a factor of 2 in the slope required to cause them to roll consistently and sustainably.

Similarly, even though the sections tested were of the order of 200mm x 200mm, the loss of just 2mm from the edges caused the rolling velocity to increase by up to 20%, and a loss of 4mm caused the velocity to further increase by at least 50% and as much as 100%.

These outcomes suggest that more research is needed to better understand the sensitivity of rolling block motions to block shape, so that better numerical models of rolling behavior can be formulated.

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