ADVANCES IN ROCKFALL PROTECTION:
A PRELIMINARY DESIGN TOOL FOR ATTENUATORS

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D. Wyllie, T. Shevlin, H. Hofmann, J.Glover – Study Conception and Design
T. Shevlin, D. Wyllie, H. Hofmann, J.Glover – Data Collection
T. Shevlin, D. Wyllie, H. Hofmann J.Glover – Analysis and Interpretation of Results
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ABSTRACT

Attenuators are a passive rockfall protection solution sometimes described as a flexible rockfall barrier with a prolonged draped tail. To date there is no formal solutions to their design. In comparison to classical flexible rockfall barriers where only translational kinetic energy is considered and the rockfall is stopped completely; attenuators present a design challenge wherein both the rotational and translational component of rockfall must be considered. In addition, Attenuator Systems are not stopping the rockfall, rather changing the trajectory and moderating the velocity. In order to develop a dimensioning concept that addresses these dynamics, it is important to fully understand the attenuation process. A joint research program between Wyllie & Norrish Rock Engineers, Ltd. in Canada, Geobrugg North America, LLC, and Geobrugg AG, Switzerland investigated this process. The loading of the system, the attenuation processes and the importance of the rotational component have been analyzed in full-scale testing over a three-year period, on a site in British Columbia. This contribution provides insights into the analysis of the loading mechanisms acting on the attenuator system during rockfall impact. Rock motion dynamics are compared between those extracted from the accelerometer and gyroscope sensors embedded in the test blocks, high speed video analysis and rockfall simulations. These analyses provide the foundations with which a dimensioning tool has been created.

Keywords: rockfall, flexible protection system, attenuator, dimensioning, rotation

INTRODUCTION

Rockfall impact attenuators intercept rockfall trajectory, reduce potential bounce height, and dampen the rockfall velocity therefore attenuate the total kinetic energy of rockfall. A controlled guiding of the rock(s) to a designated collecting area is then possible avoiding costly clean-outs, as with standard flexible rockfall barriers. This type of low maintenance, passive rockfall mitigation system is increasing in popularity worldwide but no design guidelines exist. The loading mechanisms and the importance of the angular velocity and directional behaviour of the rocks upon impact have to date been largely unknown. In a joint research program between Wyllie & Norrish Rock Engineers, Ltd. in Canada, Geobrugg North America, LLC, and Geobrugg AG, Switzerland, considerable progress has been made in the understanding of the attenuation process and loading mechanisms of attenuator systems. Notably the importance of a rock's rotational component during impact is being analysed. Full-scale rockfall testing into attenuator systems was performed in 2015, 2016 and 2017 on a test site in British Columbia.

This contribution provides the results of the comparison of the acceleration and rotation components between the rock motion sensors, the video analysis and the RAMMS::ROCKFALL simulation and sets the basis for a dimensioning concept.

Rock Rolling

Full-scale one-to-one rock rolling testing has been central to the understanding of rockfall mechanics both for the development of rockfall protection systems as well as trajectory and impact models. The need to test and understand rockfall has a long history, some of the early efforts to control rockfall date back to the start of railway construction around 1834. Many rock rolling programs have since then been conducted. In the 1960s the US, Japan and Switzerland start with comprehensive rock rolling experiments (1; 2). Most recently in 2015, 2016, and 2017 rock rolling experiments were performed in Hope BC, Canada to test the capabilities of an attenuator system (3). For attenuators with their multi-dynamic interactions between rock and net along with the slope, the need for 1:1 rockfall tests is essential to understand the behaviour of rockfall trajectories and to calibrate simulation models. More importantly, the interaction between rockfall and a flexible protection structure has not been quantified yet and needs 1:1 rockfall tests for data collection in order to develop empirical relationships between the mesh and the rock.

Flexible Rockfall Protection and Attenuator Systems

Attenuators combine two long standing rockfall control methods, namely rockfall barriers and rockfall drapery. Flexible rockfall barrier systems are designed to intercept upslope rockfall and absorb the total energy of a rock impact until it has stopped. Whereas rockfall drapery is placed over an entire rock-mass to control rockfall that occurs within the drapery and direct them to a catchment area at the base of the slope (4; 5; 6; 7).

Attenuator systems therefore offer the interception function of rockfall barriers while, like rockfall drapery, further guide the rocks to a catchment ditch at the base of the slope instead of collecting them (Figure 1). Intercepting rockfall during freefall or after slope rebounds, the mesh system redirects the rockfall trajectory, reduces its bounce height, and can reduce velocity (8; 9). Both, the deformation of the netting at impact and the rock-ground contact during transport under the drape, dissipate a great quantity of energy (10). Attenuator systems are highly applicable to regions with a high rockfall frequency where it would be costly to often clean a standard rockfall barrier that retains rocks in its structure. Moreover, for situations where access for maintenance is difficult, attenuator systems offer a solution to rockfall control that delivers the maintenance needs to a more practical region at the base of a slope. Finally, attenuator systems offer the potential to enhance existing protection structures, such as a rockfall gallery for example, which does not meet the required height or energy level required to meet the actual rockfall hazard. The attenuator dissipates the kinetic energy of the rockfall to the design values of the other protection structure (8). Rockfall attenuators have mainly been applied since the 1990s in North America. Some testing was performed but no appropriate design guidelines exist for them (5; 11). To understand the ability of the attenuator to reduce bounce heights, kinetic energy of rockfall and its efficiency more one to one testing is needed.

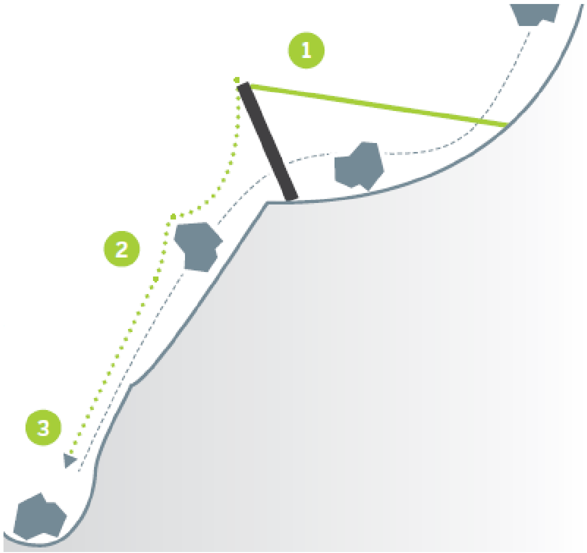


FIGURE 1 Simplified geometry of the attenuator tested in Canada (Geobrugg AG), showing the evolution of a block passing in an attenuator in three steps.

TEST SITE

The Nicolum Quarry in Hope, British Columbia, was chosen as a test site in February 2013, partly based on previous tests carried by the quarry owner, the British Columbia Ministry of Transportation and Infrastructure (MoTI) in the 1990's (12). The initial "proof of concept" full-scale attenuator testing series, performed in 2014 and 2015 by Wyllie and Geobrugg, confirmed the suitability of the Nicolum test site and the instrumentation systems utilized at that time (12). Two large test series were then conducted in January 2016 and subsequently in September 2017.

The slope is 60m high and near vertical with three inclined benches where a thin layer of soil covers the massive bedrock slope. Below the first gully, some rock debris has accumulated. The ground at the bottom of the slope is covered with a layer of soil as well. The rocks are released at the top of the slope with an excavator, approximately 16.5 ft (5 meters) above the ground. After testing in 2015, some trim blasting was undertaken to improve the hit rate on the attenuator system (12). After 2016 testing, the whole system was extended to a greater width to increase the hit rate on the mesh even more. Rockfall modelling contributed to this decision, which was confirmed successfully, during the testing in 2017. Here we present some selected results of the latest testing series.

Natural granitic blocks approximately up to 1.5 ft (0.45 m) in diameter and cubic reinforced concrete blocks 1.8, 2.5, and 3.28 ft (0.55, 0.75 and 1m) in diameter, with a housing for instrumentation, were used for testing. The concrete blocks' corners were painted black and their faces white, to enhance visibility in the videos.

Load cells were installed in all support ropes with two DAS systems (QuantumX MX840-B with eight channels and a HBM Spider system) on either side of the test site to accommodate 10 load cells (Figure 2).

The testing was recorded with two high speed cameras, kindly lent by the Swiss Federal Institute of Forest, Snow and Landscape (WSL) and several other cameras to cover most angles of view (front, side, top; see Figure 2).

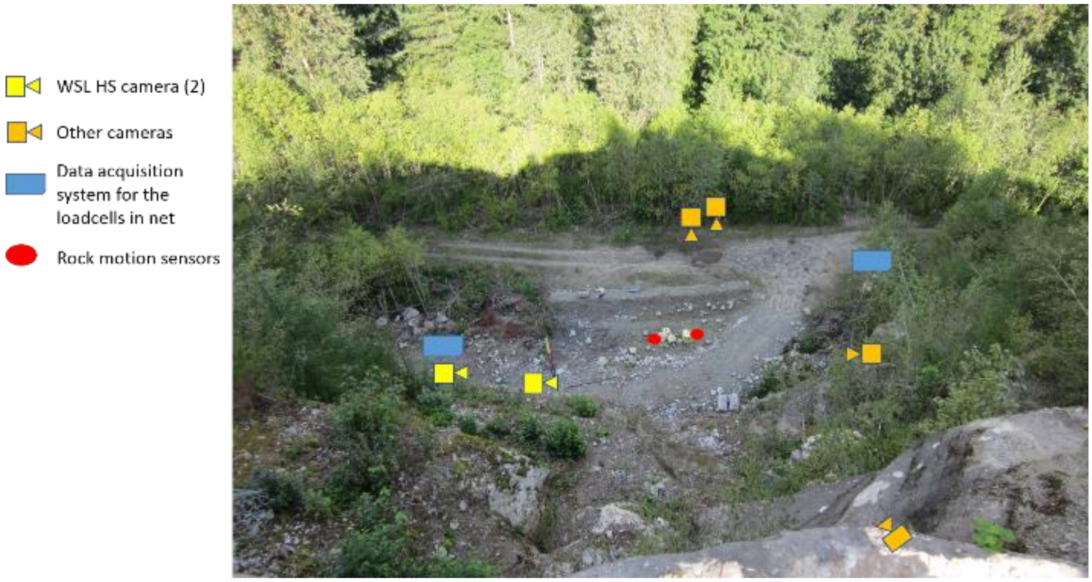


FIGURE 2 Whole instrumentation setup on site. The view looks from the top down onto the slope and the attenuator location.

The main velocity analysis and observations of the rock-net interaction are performed using the data from the high-speed camera with a frame rate of 500 fps. The front view camera is used to document the impact location and the depth of field of the rock, allowing to calculate a correction factor for the side view video analysis.

Four rock motion sensors were used. One was from DTS, a micro slice accelerometer and gyroscope modular unit measuring tri-axial accelerations and rotations at 20 kHz. The sensor is placed into a custom housing and inserted into the test rocks centre of mass (3). The three other sensors were kindly provided by the SLF and were recording at 2 kHz.

ROCKFALL MODELLING

In order to gain insights into the rockfall behaviour at the test site, rockfall modelling was conducted using RAMMS::ROCKFALL (13). Importantly it permits a simulation of rotational behaviour and contact impact forces of rocks during runout (14). Calibration of the rockfall model for the test site was completed in a separate study (15). The rigid body rockfall code considers natural shape of rock blocks and has an extensive rock library to choose from (Figure 3). The simulations assisted in designing the test facility to optimise the placement of the attenuator system in the rock slope and provided valuable data of expected impact velocity distributions, along with angular speeds as governed by different rock shapes. Rockfall modeling was applied both to compare against the measured data and to investigate test site optimization for the most recent testing series in 2017.

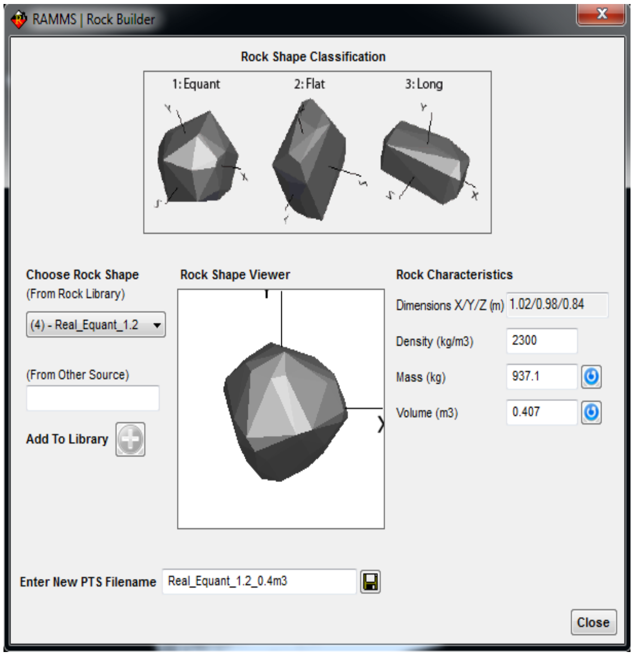
Model Inputs

Input parameters were defined as the following:

- Rock shapes: An equant rock shape was chosen to represent best the cuboid form of the test blocks. A density of 168 pcf (2700 kg/m^3) and 145 pcf (2300 kg/m^3) was selected as this was representative of the onsite lithology along with the density of the reinforced prefabricated concrete blocks used for testing. For the concrete blocks a volume of 14.88 ft^3 (0.4217 m^3) and dimensions x/y/z = 2.46 ft, 2.46 ft, and 2.46.5 ft (0.75 m, 0.75 m, 0.75 m) yielded a mass of 2,160 lbs (970 kg), which reflect a representative mass of the test bodies used (Figure 3).

- Topography was obtained with photogrammetric methods applying structure from motion (SFM) algorithms to obtain digital terrain model (DTM) of the test site. The soil types are defined in three categories depending on slope angle (approximately 0 to 15°; 15° to 40° and 40° to 90°) and are characterized by extra hard, hard and medium hard according to the user manual (Figure 4).

- Protection barrier: of interest for the analysis was to sample the dynamics of rockfalls at the location of the proposed barrier. In order to sample the rockfall dynamics at this location, an artificial wall was created in the DEM with GIS software which acted as a barrier upon which the data could be sampled along a profile line. With the sampling line the rockfall trajectories could be analyzed for the proportion of entering the region of the attenuator and those that potentially missed the structure, along with their dynamics (velocity, angular speed, impact force) at the point of contact.



(4) - Real_Equant_1.2

Dimensions X/Y/Z (m) 1.02/0.98/0.84

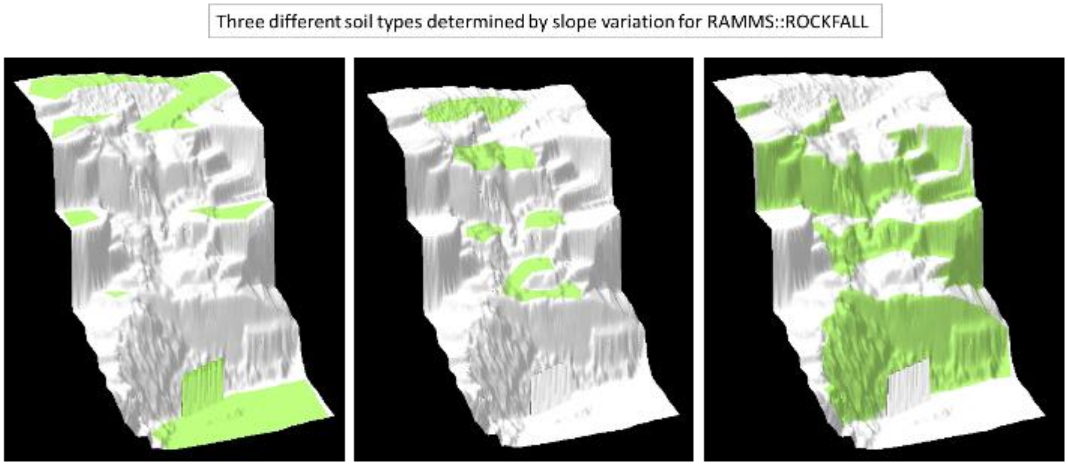
Density (kg/m3) 2300

Mass (kg) 937.1

Volume (m3) 0.407

Enter New PTS Filename Real_Equant_1.2_0.4m3

FIGURE 3 Rock shape library in RAMMS::ROCKFALL. Equant normal was chosen as most rocks and the concrete testing cubes resemble closest this shape. Mass and density are set in this example to fit the concrete test block of test T030, used throughout this contribution for comparison purposes.



1) Relatively horizontal areas 2) Medium slope inclination 3) Very steep sections

Medium hard soil Hard soil Extra hard soil

FIGURE 4 DEM and polygons chosen according to slope angle to define soil types. The steeper the angle the less soil cover does the granite slope have and the above-mentioned soil types in RAMMS::ROCKFALL correspond best to the field description.

Model Results

A total of 1000 rockfall simulations of the test site were conducted and examined for the rockfall hit rate into the attenuator barrier. The simulation results showed that 53.5% of the trajectories impacted the rockfall attenuator system. Compared to the experiments were a 57% hit rate was recorded, the results are close to the 2016 field tests. Additionally, the spatial distribution of the rockfall trajectories is similar in the simulations as in the recorded field tests. It is shown that 8.9% missed to the West and 19.2% to the East of the barrier. Notably the east misses demonstrate the closest parity between the simulations and field tests. On the other hand, 20.6% stayed on the slope or passed over the protection structure, which is almost double the percentage of the field test results.

Of the n=1000 trajectory simulations modelled with RAMMS::ROCKFALL, the trajectories showed congruence with some of the measured rockfall events during the field testing were selected for analysis. Figure 5 provides an overview of the spatial distribution simulated rockfall trajectories. RAMMS::ROCKFALL saves every calculated trajectory of one run and single trajectories of choice can then be combined on one DEM. In general, the trajectory distribution on the slope matches the field observation (Figure 6).

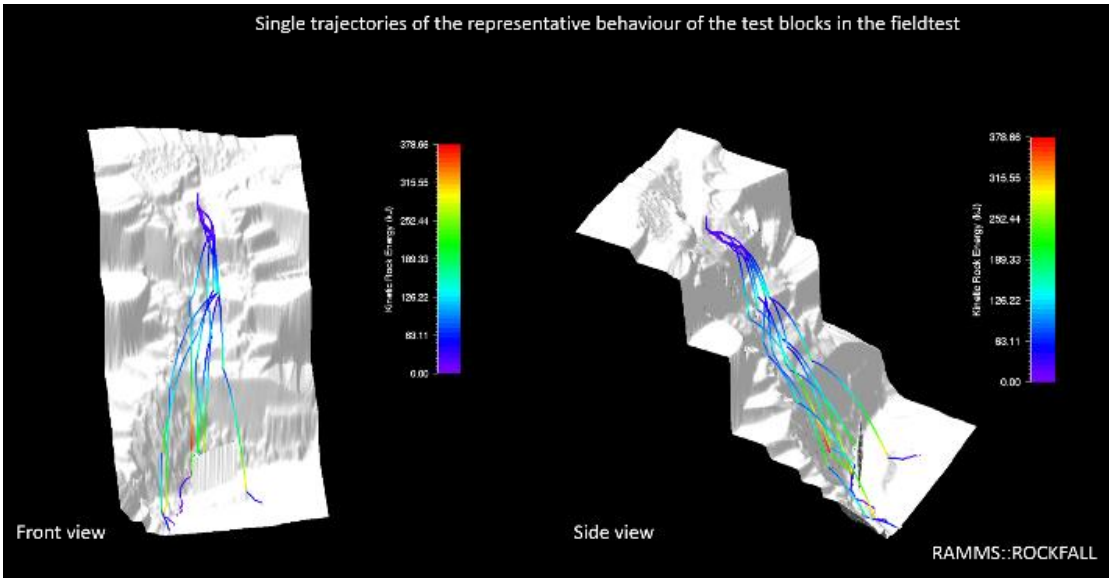


FIGURE 5 Single trajectories modelled, which resemble closely some eccentric behaviour observed while testing, confirming the accuracy of the model.

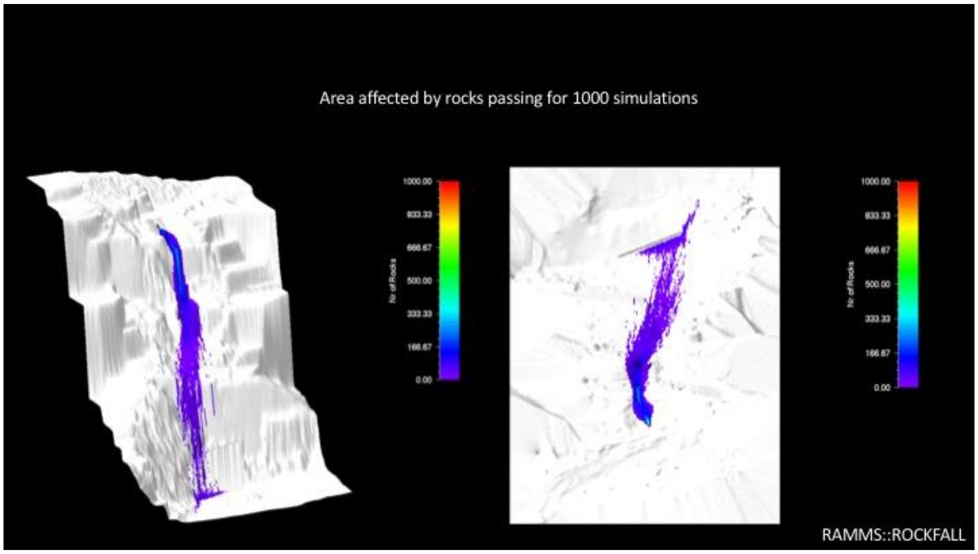


FIGURE 6 Area affected by passing rock, modelled with RAMMS::ROCKFALL for 1000 blocks.

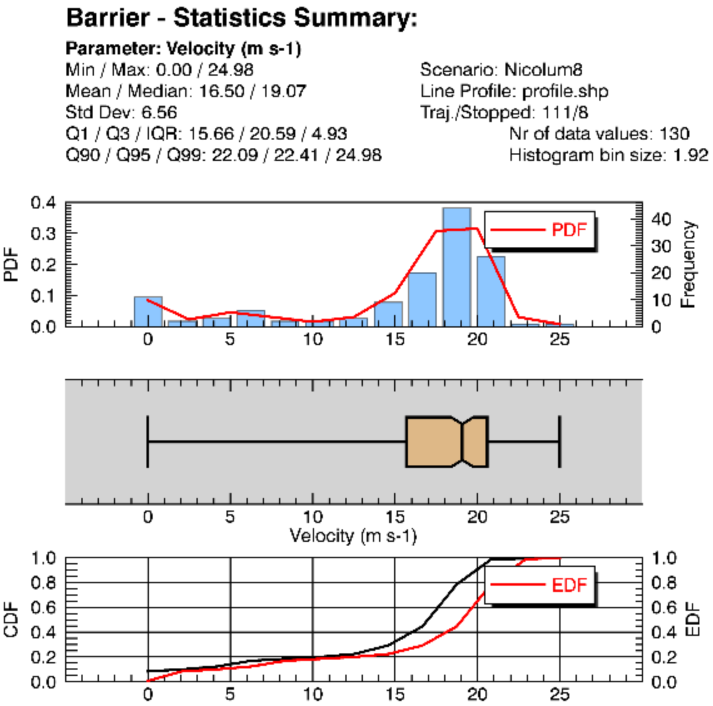
In RAMMS::ROCKFALL velocity and total kinetic energy are always given for the whole trajectory when looking at 1000 trajectories at once. When interested in translational and rotational kinetic energy or the x, y, z, components of the angular velocity, up to hundred trajectories at one time can be studied. Many trajectories stop just short of the improvised barrier, therefore the summary statistics obtained are based on only a small number of impacts and account for a certain amount of error.

The translational velocities in RAMMS::ROCKFALL range between 0 and 82 ft/sec (0 and 25 m/s). This range is visible in Figure 7. The average velocity is of 62 ft/sec (19 m/sec), getting close to the maximum values of the field test, but the frequency distribution ranges with most values placed around 59 to 62 ft/sec (18 to 19 m/sec), show slowerbulk velocities than from the video analysis.

The angular velocity in RAMMS::ROCKFALL for 1000 simulated trajectories range between 0 to 49.8 rad/sec (0 to 6 rev/sec); (Figure 8). The frequency distribution gives the main values ranging around 20 to 24 rad/sec (3 to 4 rev/sec).

It is notable is that the translational kinetic energies ranged between 0 and 485 kJ, the average maximum translational kinetic energies for 1000 simulated trajectories is 463 kJ with a standard deviation of 13.7. While the rotational kinetic energy ranges between 0 and 111 kJ with an average of 93 kJ and a standard deviation of 10.1. The rotational kinetic energy makes up to 20% of the total kinetic energy.

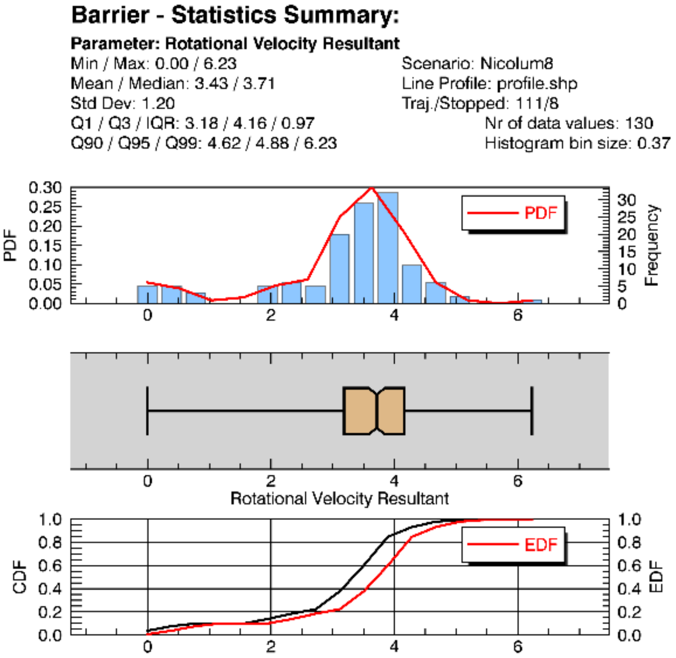
Total kinetic energy (Figure 9) being a function of translational kinetic energy (depending on velocity) and rotational kinetic energy (depending on angular velocity), its distribution is slightly underestimated with most values around 230 kJ whereas 300 kJ would be more realistic when compared to the field test.


Barrier - Statistics Summary:

Parameter: Velocity (m s-1)
Min / Max: 0.00 / 24.98
Mean / Median: 16.50 / 19.07
Std Dev: 6.56
Q1 / Q3 / IQR: 15.66 / 20.59 / 4.93
Q90 / Q95 / Q99: 22.09 / 22.41 / 24.98

Scenario: Nicolum8
Line Profile: profile.shp
Traj./Stopped: 111/8
Nr of data values: 130
Histogram bin size: 1.92

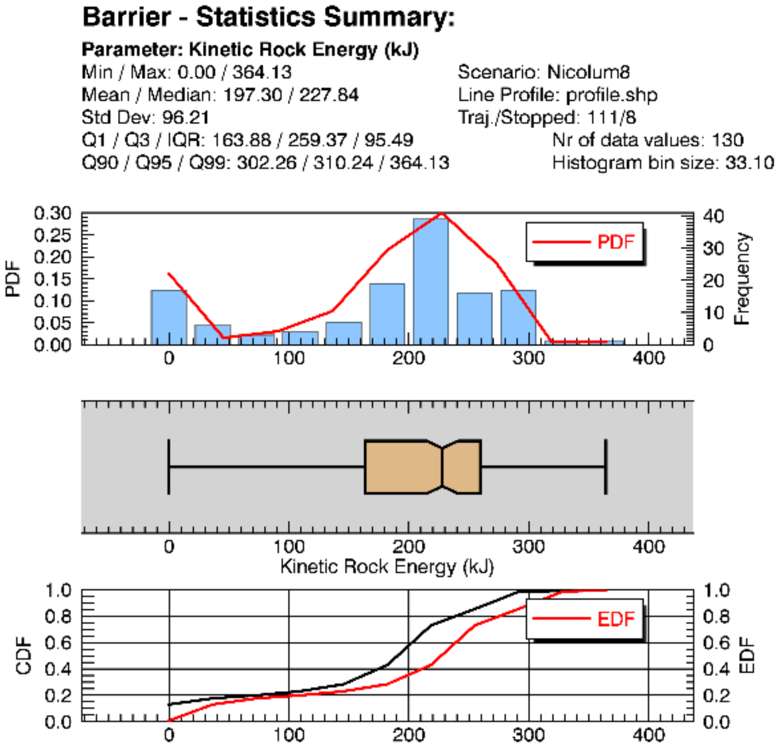
FIGURE 7 statistical distribution of the translational velocities modelled for 119 blocks with associated probability density function (PDF), cumulative distribution function (CDF) and empirical distribution function (EDF).


Barrier - Statistics Summary:

Parameter: Rotational Velocity Resultant
Min / Max: 0.00 / 6.23
Mean / Median: 3.43 / 3.71
Std Dev: 1.20
Q1 / Q3 / IQR: 3.18 / 4.16 / 0.97
Q90 / Q95 / Q99: 4.62 / 4.88 / 6.23

Scenario: Nicolum8
Line Profile: profile.shp
Traj./Stopped: 111/8
Nr of data values: 130
Histogram bin size: 0.37

FIGURE 8 statistical distribution of the angular velocities computed for 119 blocks.



Barrier - Statistics Summary:

Parameter: Kinetic Rock Energy (kJ)

Min / Max: 0.00 / 364.13
Mean / Median: 197.30 / 227.84
Std Dev: 96.21
Q1 / Q3 / IQR: 163.88 / 259.37 / 95.49
Q90 / Q95 / Q99: 302.26 / 310.24 / 364.13

Scenario: Nicolum8
Line Profile: profile.shp
Traj./Stopped: 111/8
Nr of data values: 130
Histogram bin size: 33.10

FIGURE 9 Calculated kinetic energies by RAMMS::ROCKFALL for 119 trajectories.

FULL-SCALE TESTING

Methodology

The impact velocity and angular velocity are measured from the videos, with the help of a video analysis software. In this case, Kinovea (16) was used as it is an open source software and relatively easy to handle as a beginner. Originally it is a sport motion analysis software but can be used for rock rolling experiments. Once a certain distance was calibrated (here the post of 26.25 ft (8m) length, the rock can be tracked automatically and manually, depending on lighting conditions, from first appearing in the frame all the way down to the ground through impact with the net (Figure 10). The velocity is then computed from the x and y points obtained from tracking and corrected for depth as described as in (17).

The rock motion sensor data is downloaded from the sensor using the proprietary software and processed to remove signal noise

FIGURE 10 Tracking of a block throughout its fall with the software Kinovea.

Results

The velocity evolution throughout the fall is represented in Figure 11. Velocity at impact is of 88.5 ft/sec (27 m/sec) and decreases towards 19.7 ft/sec (6 m/sec) just above ground. This illustrates the attenuation process, it is observed how the block does not come to a full stop, but only attenuates its dynamics as the rock passes through the system.

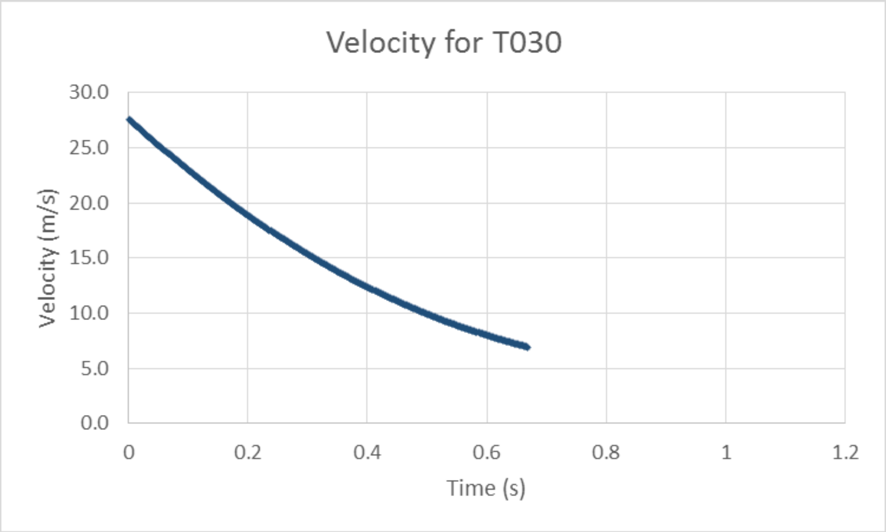


FIGURE 11 Velocity in m/sec for block T030 from impact with mesh until shortly above ground.

It is possible to compare the theoretical freefall of block T030 with its actual trajectory, illustrating the attenuation process in the perspective of distance travelled. Figure 12 shows how the trajectory of the block is intercepted, and its anticipated height is considerably dampened when impacting the attenuator instead of freefalling without any protection structure.

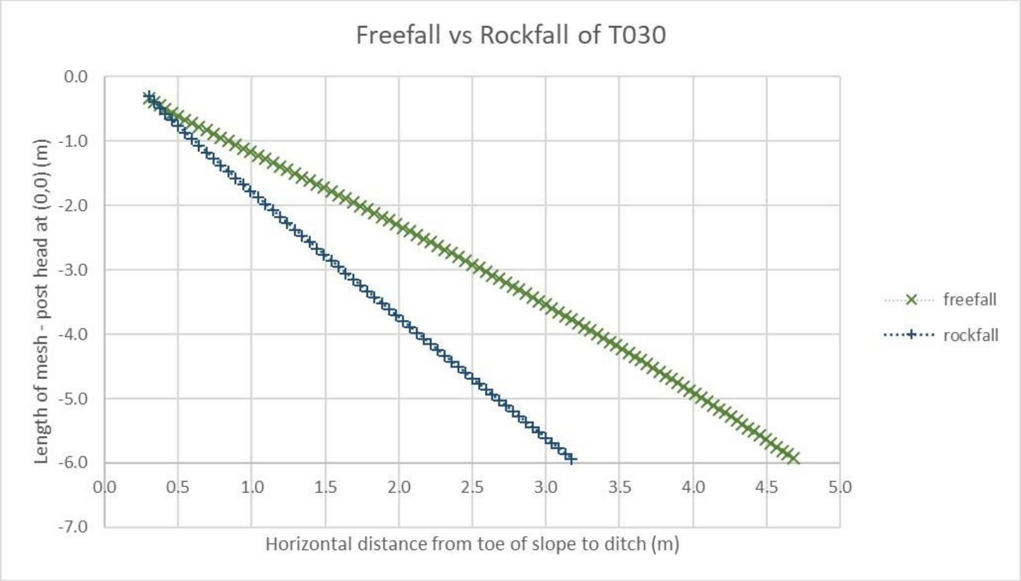


FIGURE 12 Comparison between theoretical freefall behaviour of block T030 versus the actual trajectory with impact of the protection structure from time of impact onwards.

The video analysis was also applied to measure the block's angular velocity. This was achieved by tracking given face of the block and marking every 90° rotation in the software. The time stamp of these frames then allows the computation of the angular speed in rad/sec. Figure 13 illustrates the evolution of T030 and T062 from impact with mesh onwards. The angular velocity extracted from the video analysis could then be compared with the measurements made with the gyroscope measurement of the rock motion sensor (Figure 14).

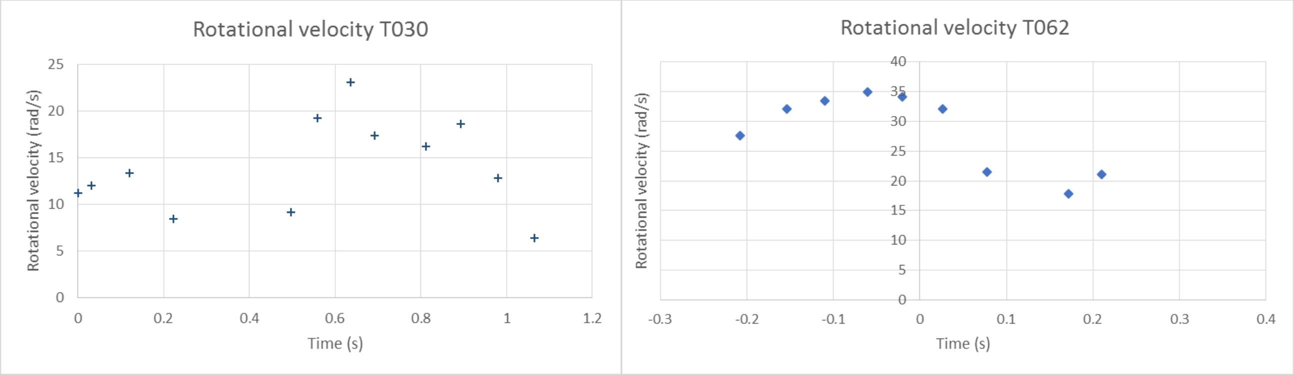


FIGURE 13 Angular speed (rad/sec) of block T030 (left) and T062 (right). Time of impact at T= 0s.

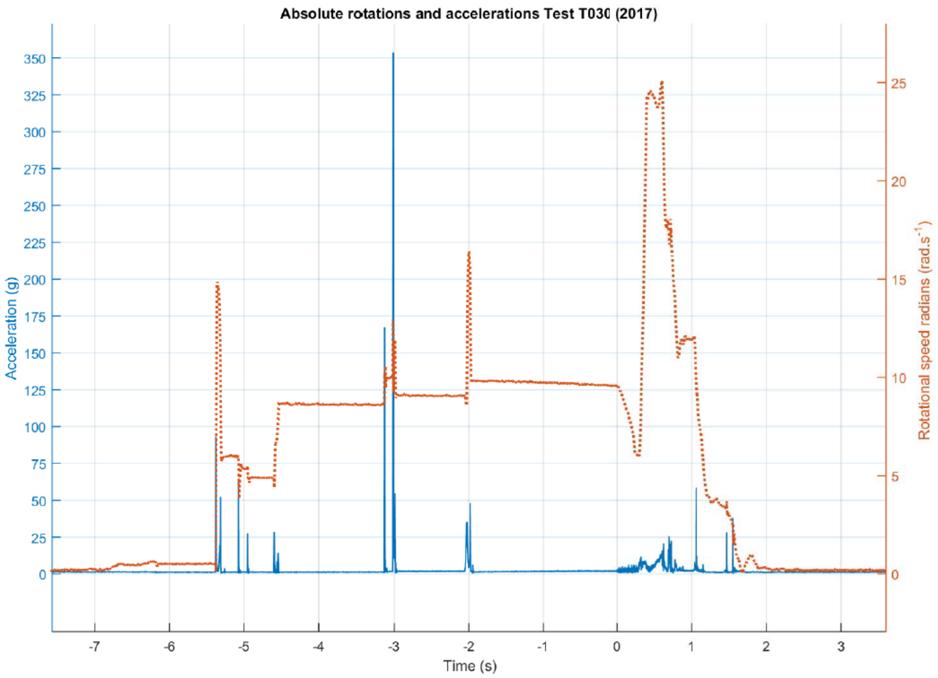


FIGURE 14 Plot of the three-axis gyroscope resultant positioned in the concrete blocks. Example of test T030.Angular velocity evolution ranges in the same order of magnitude then for the video analysis. Time of impact is t = 195.2 Ms.

The gyroscope measurement shows the same evolution of angular velocity to the video analysis results yield. Block T030 and T062 comes into the mesh with an initial clockwise rotation of respectively 10 rad/sec and 35 rad/sec, decreases and then increases in a counter-clockwise reverse rotation again up towards approximately 25 rad/sec before decreasing in steps (slightly visible as well on Figure 13) towards 0 eventually when reaching the ground. The left part of figure 13 and figure 15 show a similar evolution for test T062, therefore the angular velocities through video analysis seem to be coherent and the video analysis method can be applied when no rock motion sensor data is present.

Discussion

First analysis of the load cell data captures well the classic behavior of attenuator systems (Figure 16). The first peak corresponds to the initial impact of the block with the mesh and the second peak corresponds to the peak torque generated as the friction between the attenuator netting and the rock causes a reversal of the rocks rotational direction while rolling along the mesh (time steps match between the load cell graph and the video analysis where the reversal in rotational direction is observed).

Both the translational impulse and rotational impulse of the rock interacting with the attenuator system form the principal load cases attenuators should be designed for and are the basis of the proposed attenuator design concept conserving momentum (18). These two load cases seem to correspond to the boundary conditions of the mesh.

1. Maximum translational impulse presents a puncturing risk through the mesh, and
2. A high rotational component of rockfall can shear the mesh open while being contained behind it.

Further, the load cell readings have confirmed these load cases which is forming the basis of the design principles for attenuators.

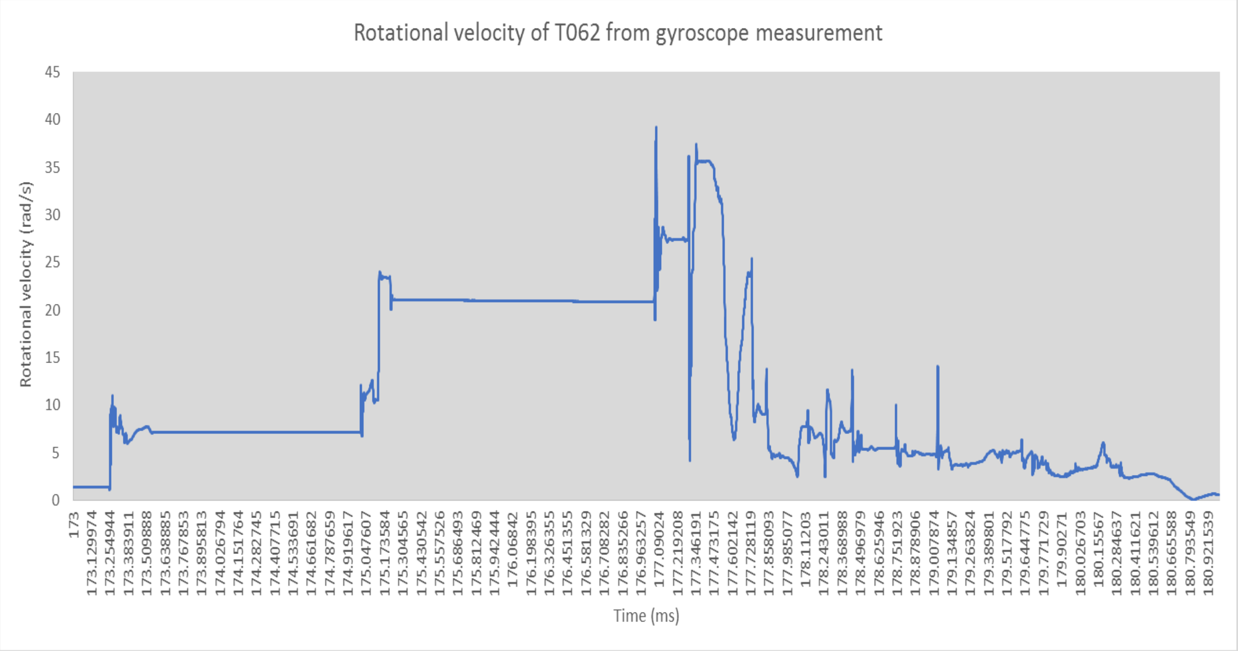


FIGURE 15 Plot of the three-axis gyroscope resultant, positioned in the concrete blocks. Example of test T062. Angular velocity evolution ranges in the same order of magnitude then for the video analysis. Time of impact at t = 177.4 ms

CONCLUSION

Attenuators are an interesting addition to flexible protection structures for rockfall hazard and a formal design procedure is important. To conclude, the rockfall simulations indicate similar results to the measured values and permit further insights into the full range of rockfall dynamics to be expected at the test site. Moreover, the simulation results assisted in developing test site design changes for the September 2017 tests in which the width of the attenuator system was increased. The widening of the attenuator test barrier successfully increased impact rate of the 2017 testing series. Rockfall dynamics are situated in a realistic range. The video analysis is associated with some error but in the case of angular velocity it is possible to compare the values with rock motion sensors. Although the resolution is not the same between the time steps of the video analysis and the 20kHz sampling rate of the rock motion sensor, it is possible to use the values obtained from video analysis for tests without a rock motion sensor recording, as the comparison between both is satisfactory.

Overall the combination of rockfall modelling and 1:1 real scale testing allows to understand rockfall dynamics better, as well as the general attenuation process. The proof of concept and advantages of attenuators have long been known, now the concept for a design approach is being assembled with these latest results, in order to build standardized systems. The necessity of high strength nets to cope with shearing load because of rotation is evident from the results obtained in this study. The dimensioning tool will be presented at the conference with a detailed explanation of the two-step verification of translation and rotational impulses for several types of rock properties found in nature.

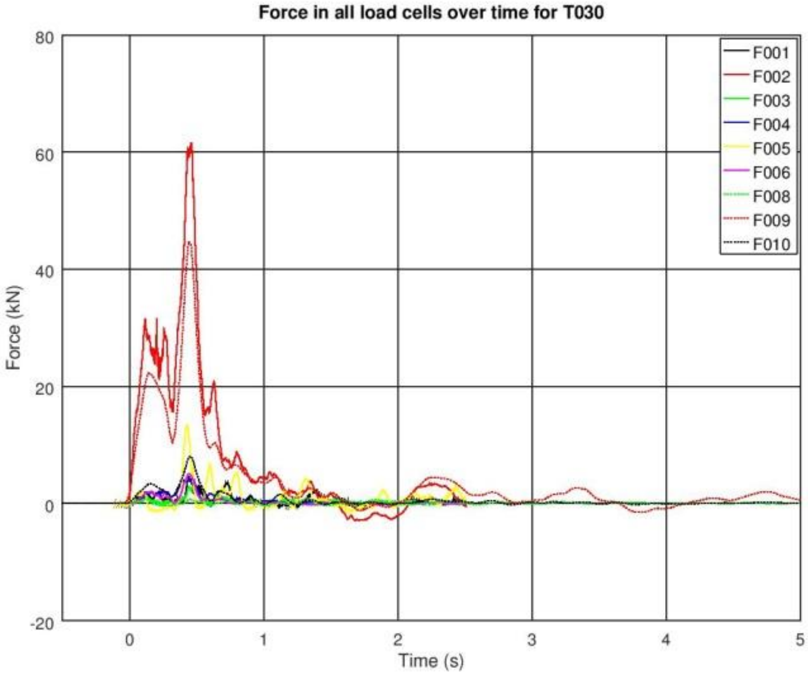


FIGURE 16 Two peaks recorded with load cells (F002 and F009 correspond to the top rope), t=0 corresponds to the time of impact.

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