# Towards a design concept for rockfall attenuator systems

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ABSTRACT

A joint research program between Wyllie & Norrish Rock Engineers, Ltd. in Canada, Geobrugg North America, LLC, and Geobrugg AG, Switzerland is investigating rockfall dynamics upon impact with a rockfall impact attenuator. The loading of the system, the attenuation processes and the importance of the rotational component are being analysed in a real-scale testing setup in 2015, 2016 and 2017, on a site in British Columbia. The tests were conducted with instrumented concrete blocks and natural rocks, load cells were installed in all support ropes and testing was recorded with two high speed cameras. Five different high-tensile strength structural nets were tested as attenuator systems while rolling more than 200 rocks/blocks.

This contribution provides some insights into the analysis of the loading mechanisms acting on the attenuator system during rockfall impact. Additionally, it provides a comparison method applied to determine the rotational and translational dynamics of the test rocks. Rock motion dynamics are compared between those extracted from the accelerometer and gyroscope sensors embedded in test blocks, high speed video analysis and rockfall simulations with the rigid body rockfall model RAMMS::ROCKFALL. These analyses provide the foundations with which to validate a clear design guide for attenuator systems based on the dynamics of expected rockfall impacts

RÉSUMÉ
La dynamique de chute de blocs et leurs interactions avec un système d'atténuation ou déflecteur sont étudiées dans le cadre d'un programme d'essai entre Wyllie & Norrish Rock Engineers Ltd., Geobrugg North America LLC et Geobrugg AG, Suisse. Les charges absorbées par le système, le processus d'atténuation en lui-même et l'importance de la composante rotationnelle d'un bloc sont analysées par des tests à échelle réelle conduits en 2015, 2016 et 2017, en Colombie Britannique. Les essais ont été documentés par deux caméras à haute vitesse, des cellules de mesures dans tous les câbles du système et des capteurs de mouvements tridimensionnels dans les blocs en béton renforcé. Le reste des blocs provient de la carrière de granite où est situé le site test. Cinq filets en acier à ultra haute résistance ont été testé au cours des années avec plus de 200 impacts de blocs.

Cet article est un premier résumé des résultats de la dernière série de test ainsi qu'une comparaison avec les résultats d'un programme de simulation de chutes de blocs, RAMMS ::ROCKFALL. Le but ultime est de pourvoir un standard pour les système atténuateurs, inexistant pour l'instant. Idéalement il en découlera un cadre pour des critères de conception de déflecteurs.

## 1 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 rotational 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.

### 1.1 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 (Duffy and Glover, 2017 and Balkema et al., 2008). Most recently in 2015/2016/2017 rock rolling experiments were performed in Hope BC, Canada to test the capabilities of an attenuator system (Glover, et al., 2016). 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.

### 1.2 Flexible rockfall protection and attenuators

Attenuator systems 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 (Badger and Duffy, 2012; Muhunthan et al., 2005; Wyllie and Norrish, 1996; Andrew, et al., 2011).

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 (Figure 1). Intercepting rockfall during freefall or after slope rebounds, the mesh system attenuates the rock's kinetic energy and reduces its bounce height (Glover et al. 2012; Glover et al. 2010). Both, the deformation of the netting at impact and the rock-ground contact during transport under the drape, dissipate a great quantity of energy (Badger et al., 2008). 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 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 (Glover et al. 2012). Rockfall attenuators have mainly been applied since the 1990s in North America. Some testing was performed but no appropriate design guidelines exist for them (Muhunthan et al. 2005; Arndt et al. 2009). 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.

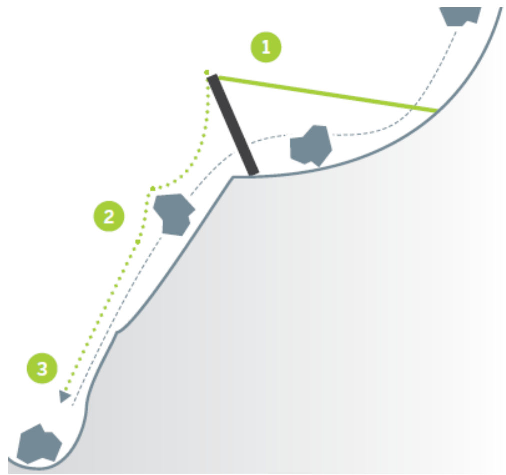


*Figure 1: geometry of the rockfall impact attenuator tested in Canada (Glover, 2016)*

## 2 TEST SITE

The Nicolum Granite 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 (Wyllie et al, 2016).
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 (Wyllie et al. 2016). 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 granite 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 5 meters above the ground. After testing in 2015, some trim blasting was undertaken to improve the hit rate on the attenuator system (Wyllie et al., 2016). 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 0.45 m in diameter and cubic reinforced concrete blocks (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).

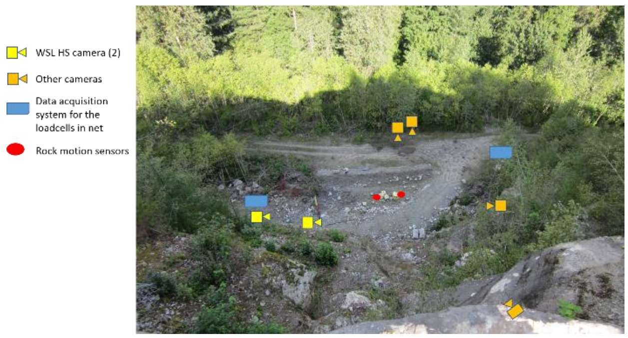


*Figure 2: whole instrumentation setup on site. The view looks from the top down onto the slope and the attenuator location.*

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 (Glover, 2016). The three other sensors were kindly provided by the SLF, and were recording at 2 kHz.

## 3 ROCKFALL MODELLING

In order to gain insights into the rockfall behaviour at the test site, rockfall modelling was conducted using RAMMS::ROCKFALL (Christen et al., 2013). The rigid body rockfall code considers natural shape of rock blocks and has an extensive rock library to choose from (see Figure 3). Importantly it permits a simulation of rotational behaviour and contact impact forces of rocks during runout (Leine et al. 2014). 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 rotational 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.

### 3.1 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 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 0.407 m3 and dimensions x/y/z = 1.02m, 0.98m, 0.84m yielded a mass of 937 kg, which reflect a representative mass of the test bodies used (see 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 characterised by extra hard, hard and medium hard according to the user manual (see 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 analysed for the proportion of entering the region of the attenuator and those that potentially missed the structure, along with their dynamics (velocity, rotational speed, impact force) at the point of contact.

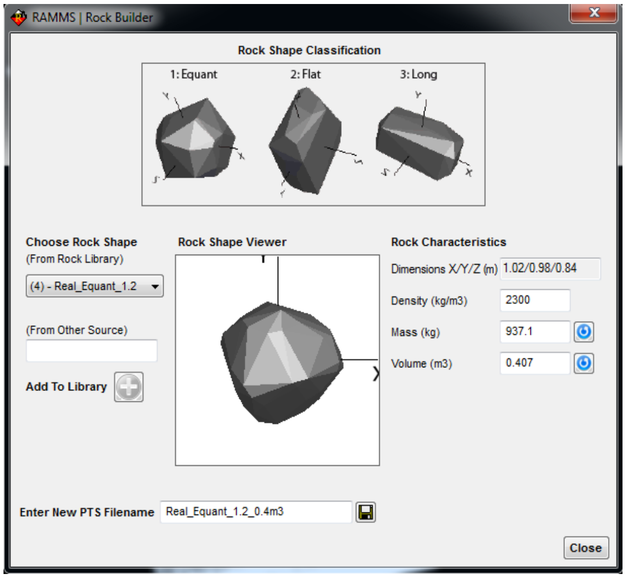


*Figure 3: rock shape library in RAMMS::ROCKFALL. Equant normal was chosen as most rocks and the concrete testing cubes resemble closest this shape. Mass and density are set in this example to fit the concrete test block of test T030, used throughout this contribution for comparison purposes.*

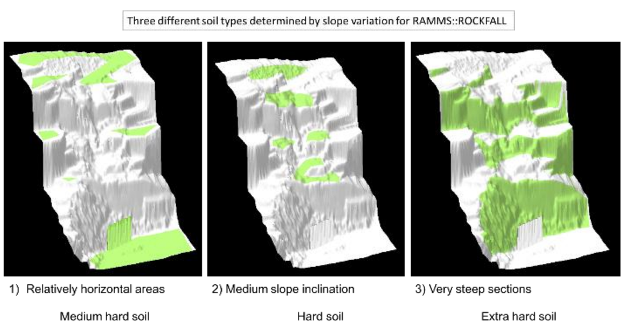


*Figure 4: DEM and polygons chosen according to slope angle to define soil types. The steeper the angle the less soil cover does the granite slope have and the above mentioned soil types in RAMMS::ROCKFALL correspond best to the field description.*

### 3.2 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).

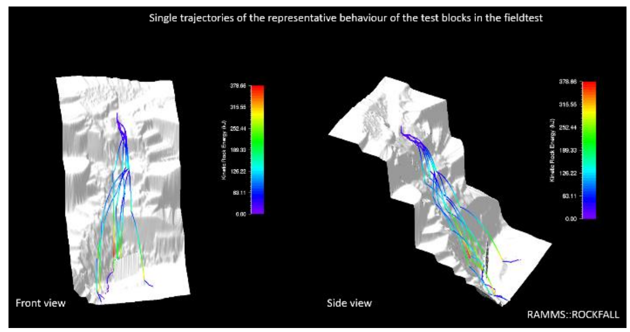


*Figure 5: single particular trajectories modelled, which resemble closely some eccentric behaviour observed while testing, confirming the accuracy of the model.*

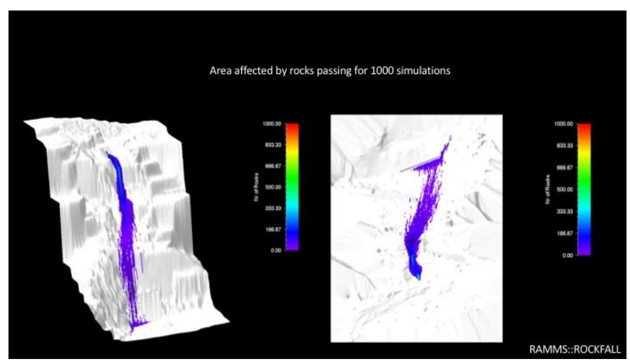


*Figure 6: area affected by passing rock, modelled with RAMMS::ROCKFALL for 1000 blocks.*

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 rotational 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 little number of impacts and account for a certain amount of error.

The translational velocities in RAMMS::ROCKFALL range between 0 and 30 m.s$^{-1}$. This range is visible in Figure 7. The average maximum velocity is of 32.38 m.s$^{-1}$, getting close to the maximum values of the field test, but the frequency distribution ranges with most values placed around 18/19 m.s$^{-1}$, show an underestimation of the bulk velocities.

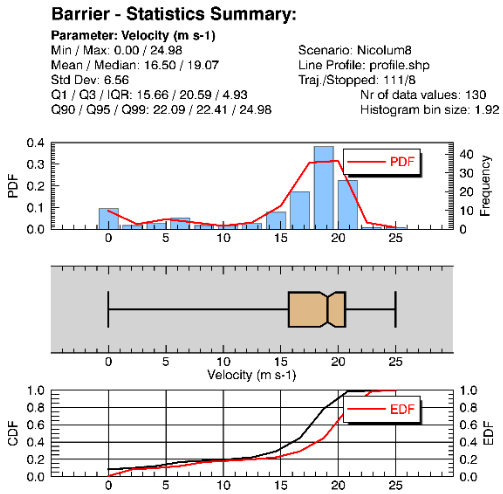


*Figure 7: statistical distribution of the translational velocities modelled for 119 blocks.*

The rotational velocity in RAMMS::ROCKFALL for 1000 simulated trajectories range between 0 to 49.8 rad.s$^{-1}$ (Figure 8). The model overestimates the maximum values from 37 rad.s$^{-1}$ to 50 rad.s$^{-1}$. The frequency distribution is better with the main values ranging around 20 to 24 rad.s$^{-1}$. Knowing that even the fieldtest results might be slightly overestimated due to the video analysis, the maximum rotational values are rather overestimated.

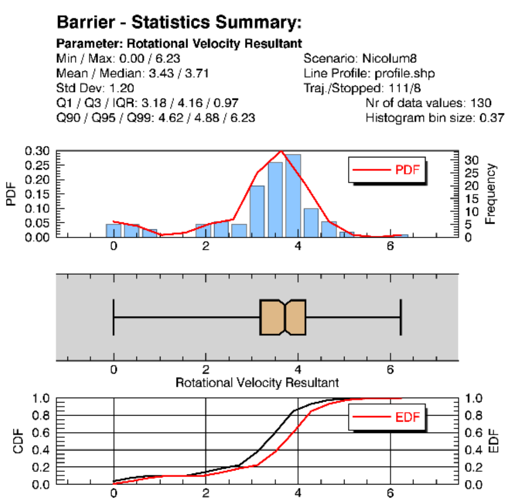


*Figure 8: statistical distribution of the rotational velocities computed for 119 blocks.*

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 rotational velocity), its distribution is slightly underestimated with most values around 230 kJ whereas 300 kJ would be more realistic compared to the field test. But with the range of translational and rotational velocities being slightly underestimated this is only the logical consequence.

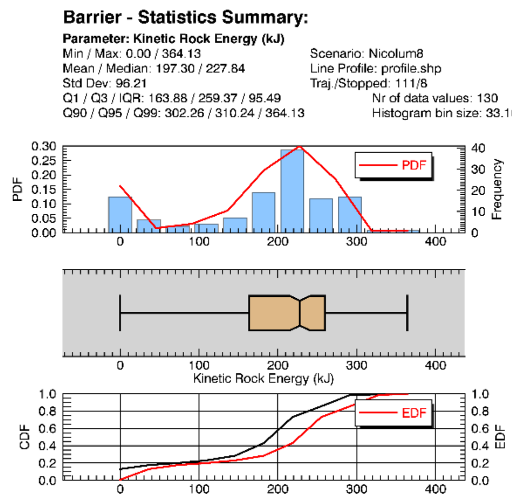


*Figure 9: Calculated kinetic energies by RAMMS::ROCKFALL for 119 trajectories.*

## 4 REAL-SCALE TESTING

### 4.1 Methodology

The impact velocity and angular velocity are measured from the videos, with the help of a video analysis software. In this case, Kinovea 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 perfectly used for rock rolling experiments. Once a certain distance was calibrated (here the post of 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 Glover (2015).

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.*

4.2 Results

The velocity evolution throughout the fall is represented in Figure 11. Velocity at impact is of 27 $m.s^{-1}$ and decreases towards 6 $m.s^{-1}$ 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.

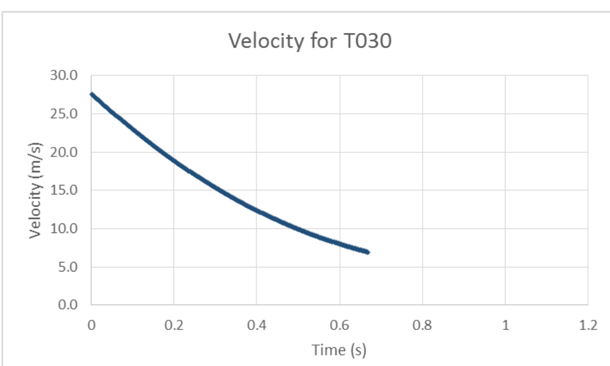


*Figure 11: Velocity in $m.s^{-1}$ for block T030 from impact with mesh until shortly above ground.*

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 height is considerably dampened when impacting the attenuator instead of freefalling without any protection structure.

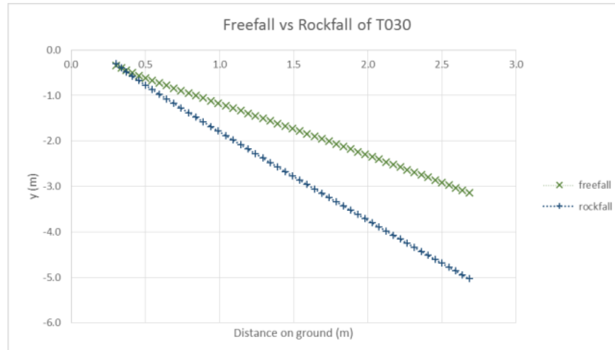


*Figure 12: comparison between theoretical freefall behaviour of block T030 versus the actual trajectory with impact of the protection structure from time of impact onwards.*

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.s-1. Figure 13 illustrates the evolution of T030 from impact with mesh onwards. The rotational velocity extracted from the video analysis could then be compared with the measurements made with the gyroscope measurement of the rock motion sensor (see Figure 14).

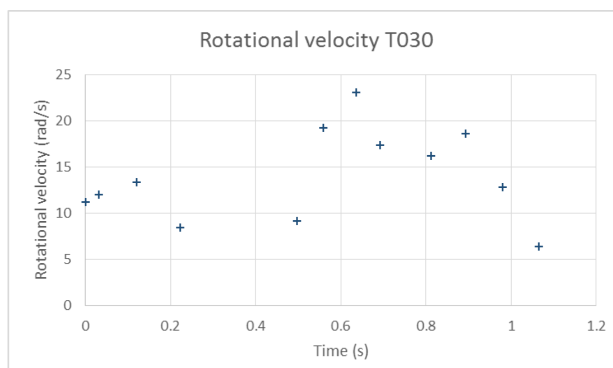


*Figure 13: Rotational speed ($rad.s^{-1}$) of block T030. Time of impact at t= 0s.*

The gyroscope measurement shows the same evolution of rotational velocity then the video analysis results yield. The block comes into the mesh with an initial rotation of approx. 10 $rad.s^{-1}$, decreases and then increases up to 25 $rad.s^{-1}$ before decreasing in steps (slightly visible as well on Figure 13) towards 0 eventually when reaching the ground.

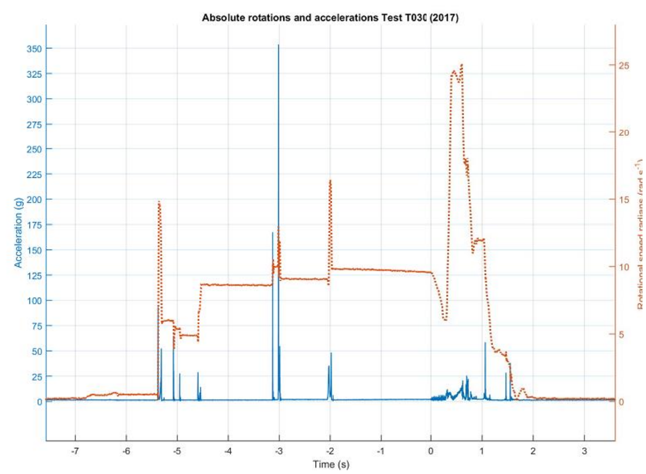


*Figure 14: plot of the three-axis gyroscope and three-axis accelerometer, positioned in the concrete blocks. Example of test T030.Angular velocity evolution ranges in the same order of magnitude then for the video analysis. T=0 is time of impact.*

## 5. CONCLUSION

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 obviously 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 test a without a rock motion sensor recording, as the comparison between both is satisfactory. Accelerations are still in the process of being analysed.

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 and will lead to a design concept for rockfall impact attenuators.

## ACKNOWLEDGEMENT

We would like to acknowledge the kind help of the WSL for lettings us borrow the high speed cameras and thank you to the RAMMS team at the SLF for lending us the sensors and the license for RAMMS::ROCKFALL.

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