Development of design method for rockfall Attenuators

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ABSTRACT

A five year research program is nearing completion to develop improved rockfall mitigation structures that only absorb a portion of the impact energy, such that the net deflects the rock into the ground where the balance of the energy is absorbed. The structures are termed Attenuators. The research has involved theoretical studies of impact mechanics, laboratory experiments, and full-scale testing where blocks of rock and concrete cubes weighing up to 950 kg (2200 lb) were dropped down a steep, 60 m (200 ft.) tall rock face. The tests were documented in detail with high speed cameras, load cells on the support ropes recording at 2000 Hz, as well as rock motion sensors with 3D accelerometers and gyroscopes embedded in the blocks. The results have provided a unique insight into the interaction between translating and spinning blocks impacting flexible nets, including the distribution of energy losses in the system and the deflection of the net. It is found that the nets are self-cleaning, which minimizes maintenance costs. This test data with state-of-the-art data acquisition methods are being applied to develop a design tool for estimating the performance of Attenuator Systems. Herein we present the design method concept.

INTRODUCTION

Over the past five years, a research program, comprising theoretical studies, model experiments and full scale testing has been carried out to develop improved rockfall protection structures, termed Attenuators. The principle of Attenuators is that the rock is deflected by the net into the ground such that the net structure only absorbs a portion of the impact energy, with a major portion of the energy being absorbed by the ground. This is in contrast to conventional nets where all the impact energy is absorbed by the net. Significant advantages of Attenuators are that they can be constructed with lighter structures compared with conventional fences, in addition they are self-cleaning which minimizes maintenance costs.

ATTENUATOR PRINCIPLE

Figure 1 shows the typical features of Attenuators comprising a freely hanging, flexible, but impact resistant steel net suspended from a pair, or series, of steel posts with hinged bases bolted to the rock face. Each post is supported with four support cables anchored to the rock face with cable loop anchors and cement grout (Wyllie, 2014).

As can be seen in Figure 1, cleaning of the accumulated rock in the ditch can be readily carried out with equipment located beside the ditch without having to dismantle the structure. Another feature of Attenuators is that the deflection of the net during impact is often limited to about 1 to 2 m, but can be greater depending on impact location and other factors. The limited deflection values means that the structure can be located close to the highway or railway without deflection interfering with traffic. An advantage of this condition is that construction and maintenance costs of Attenuators are significantly less than structures that have larger deflections, and need to be located at a greater distance from the facility being protected.

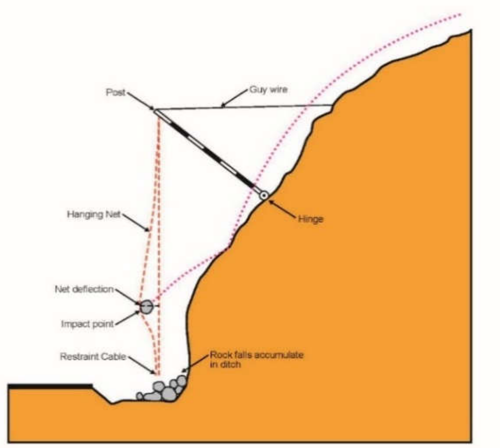

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Figure 1.Typical Attenuator configuration

EXISTING ATTENUATOR INSTALLATIONS

The primary author has experience with the design and installation of approximately 24 freely hanging style Attenuators in North America over the last 20 years approximately, and many of these have been impacted hundreds of times over their operational life. This experience has shown that virtually no maintenance is required, and that removal of the accumulated rock can be readily carried out. Significant maintenance was only required when structures were impacted by snow avalanches that encompassed the entire net. However, even in these events, the avalanche was mostly contained in the ditch.

Figure 2 shows an Attenuator installed to protect a railway close to a tunnel portal where the source of rockfalls is about 450 m above railway. The design procedure for the Attenuator was to closely study the rockfall trajectories in the lower 50 m of the slope to identify both the path of the rockfalls, and their trajectories, i.e., height above the ground, in order to position the structure correctly on the slope, and that the top of the net would be high enough to contain rocks that could impact the track. The required momentum capacity of the net was calculated by studying the site geology and existing rockfalls to determine the design mass (*m*), and the trajectories to determine the design velocity (v).

Construction of the ditch required to contain rockfalls that impact the net required trim blasting to excavate rock at the base of the rock face, and placement of concrete blocks to form a vertical face along the outside of the ditch.

Figure 2. Typical Attenuator installation showing a series of hinged posts with support cables, and a freely hanging net.

FULL SCALE TESTING OF ATTENUATORS

Full scale testing for Attenuators described in this paper has been carried out to verify the detailed mechanics of their behavior during impact with respect to such factors as net impact, load transfer into the support cables, and net deflection. This information provides design parameters for future installations, consistent with the performance of the previously constructed installations described in Section 3 above. The testing was performed by dropping rocks down a natural slope, impacting the rock face as they fell so that they were translating and rotating when they impacted the net.

The test facility was constructed in a quarry where the test blocks could be dropped from heights up to 60 m down an irregular rock face at an overall slope angle of 60 degrees (Figures 3 and 4). The Attenuator was constructed with two, 8 m long steel beams attached to hinged bases bolted to the rock face. The posts were 12 m apart, and the 12 m wide by 11 m long (vertically) net was suspended from a 19 mm diameter steel cable strung between the tops of the posts. Each post was supported with two up-slope support cables and two lateral support cables attached to anchors drilled into the rock face. Figure 4 shows a 40 ton crane lifting the posts into place; a man-lift was used to install the support cables and hanging net.

A laser scan was carried out to produce detailed topography of the site, and to accurately locate the anchors for the support cables. The scanner was located at the base of the slope, and because some areas of the face were in occlusion zones, a drone was used to take images of the slope from above the crest. The point clouds from the scans and the images were combined to produce a topographic plan of the site.

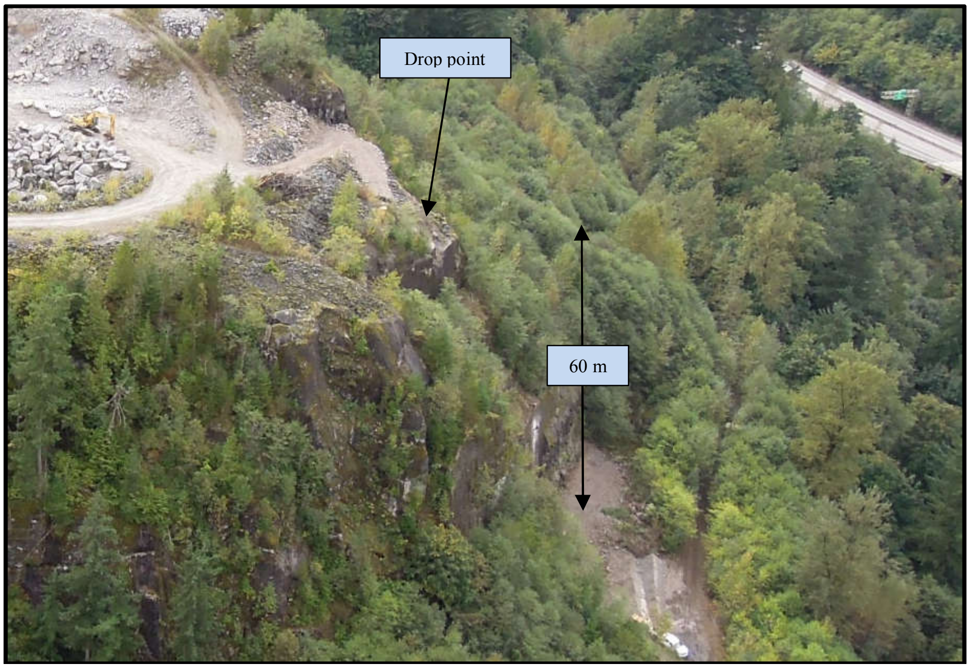

Figure 3. Image of test site

Two types of blocks were used for the testing. First, blocks of rock, with dimensions of between 0.5 and 0.8 m and weighing up to 200 kg were available in the quarry. Although the rock was a very strong, massive crystalline rock, some fragmentation of the blocks usually occurred as they impacted the rock face. Second, heavily steel reinforced concrete cubic blocks, with dimensions of 0.75 m and a mass of 950 kg, were specially fabricated for the tests. These blocks withstood many impacts, with only chipping of the corners. An electronic crane scale was used to weigh each block after the test.

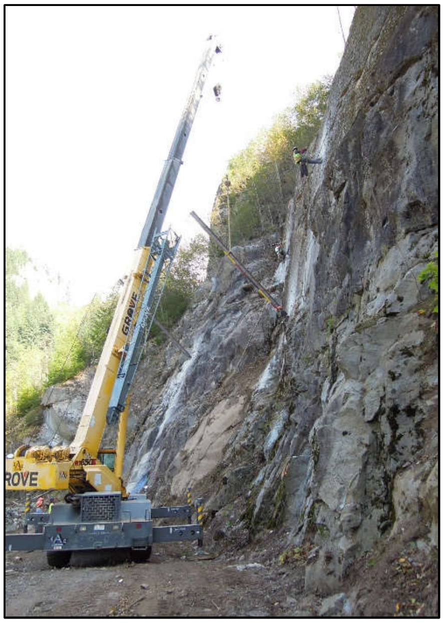

Figure 4. Construction of test Attenuator

The following is a summary of the instrumentation used to document testing, with emphasis on how the impact momentum is transferred into the net and the cables supporting the posts and net.

Cameras

The rockfall motion was recorded with three video cameras. The first camera, running at 30 fps, was located near the drop point to record the trajectories prior to impact with the net. The second camera, running at 60 fps, recorded a face-on view of the test blocks impacting the net. The third camera, running at either 250 fps or 1000 fps, recorded the impacts from a side-on view aligned parallel to the net.

Load cells

The load in each support cable was measured with a Z-type tension load cell, while compression load cells were placed on the bolts holding the hinged base of one of the posts. All the load cells were connected to a data acquisition system running at 2400 Hz; it was necessary to collect data at this rate in order to capture the very short duration impact loads. A trigger was used to start the side view camera and the load cell data acquisition system simultaneously so that observations of the interaction of the test block with the net could be correlated with measured load in the support cables.

Accelerometers and gyroscopes

A sensor, manufactured by Diversified Technical Systems (DTS), incorporating 3-D accelerometers, 3-D gyroscopes (angular rate sensors), a data acquisition system running at 20,000 Hz and a programmable gravity trigger was used to record the translational and rotational motions of the concrete blocks. The sensor, measuring 60 mm by 25 mm, had calibrated sensor range of up to 500 g, but was shock proof up to 1500 g which was necessary to ensure it would survive impact with the rock face. The sensor was used in selected concrete blocks that incorporated a steel pipe in which the sensor could be positioned at the center of the block to minimize centrifugal accelerations. The sensor was mounted in a custom housing that ensured direct transfer of rock's motion to the sensor; minimizing any sensor noise through shaking.

RESULTS OF ATTENUATOR TESTING

During testing carried out in January 2015 and 2016, a total of 46 tests provided dynamic measurements of rockfalls attenuator interaction. These measurements captured rock impacts into attenuator nest filmed with video whereby the system loads were recorded in the support cables and select experiments also included rock motions captured with the embedded sensor device. The following is a brief description of the results.

Translational and rotational velocity

ProAnalyst software was used to analyze the side view video and calculate the translational velocity and where necessary the rotational speed of the blocks from the time just before impact with the net, to time of impact with the ground. The procedure was to track the motion of the block frame by frame (every 0.004 seconds for 250 fps). The video images were scaled using a dimension scale painted on the posts supporting the net. The scaling was also corrected for depth of field with respect to the rock's lateral position passing through the posts. With the correct scaling applied over image frames, it was possible to calculate the velocity (Glover et al., 2012).

On net impact, the rock decreased its velocity rapidly. The rapid deceleration showed correlation with force peaks recorded in the load cells (see discussion below on load cells). During an approximate 0.2 second time interval, the translational speed decreased by about 50 per cent, and from this time the speed remained approximately constant until impact with the ground occurred. Importantly the velocity vector was deflected to the ground during this time.

With respect to the rotational speed, the videos clearly showed that the frictional contact between the rotating, irregular blocks and the openings in the wire mesh, caused the rotational speed to be reduced to zero in a period of 0.15 to 0.2 seconds. Following this rotation of the block is induced in the opposite direction before impacting the ground.

The significance of these velocity observations is that about 50 per cent of the translational momentum and 100 per cent of the rotational momentum of the blocks are lost during the period of 0.2 seconds after impact. During this time period the block is in contact with the net, which means that the loss of momentum of the test blocks is equal to the gain in momentum in the net and load cells.

Loads in support cables

Figure 5 shows typical loads induced in the support cables during impact on the net. It was found that the peak load occurred at a time of about 0.2 seconds after impact, and that most of load is in the up-slope cables. The duration of peak loading is coincident with the most rapid reduction and deflection of translation velocity, and the attenuation of rotational speed. This demonstrates that the greatest momentum transfer from the test block to the Attenuator system occurs within the initial impact period.

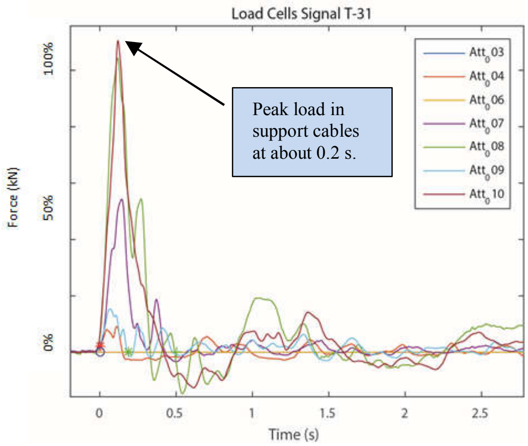

Figure 5. Typical results of forces in load cells during impact.

Accelerometers

Figure 6 shows the acceleration of the test block from the moment of release to impact with the ground in the ditch; a duration of about 6.5 second. The plot on the left shows the impacts with the rock face where accelerations of between 100% and 15% g are generated, and that the acceleration on impact with the ditch is 30%.

The plot on the right shows the acceleration components of the block during a 0.5 second period after impact with the net. Prior to impact during free fall of the block, the acceleration components are greater than zero, representing centrifugal forces of rotation, resulting from the sensor not being precisely in the center of the block. After impact with the net, for a time of 0.2 seconds, accelerations change due to the frictional contact between the irregular, rotating block and the openings in the net.

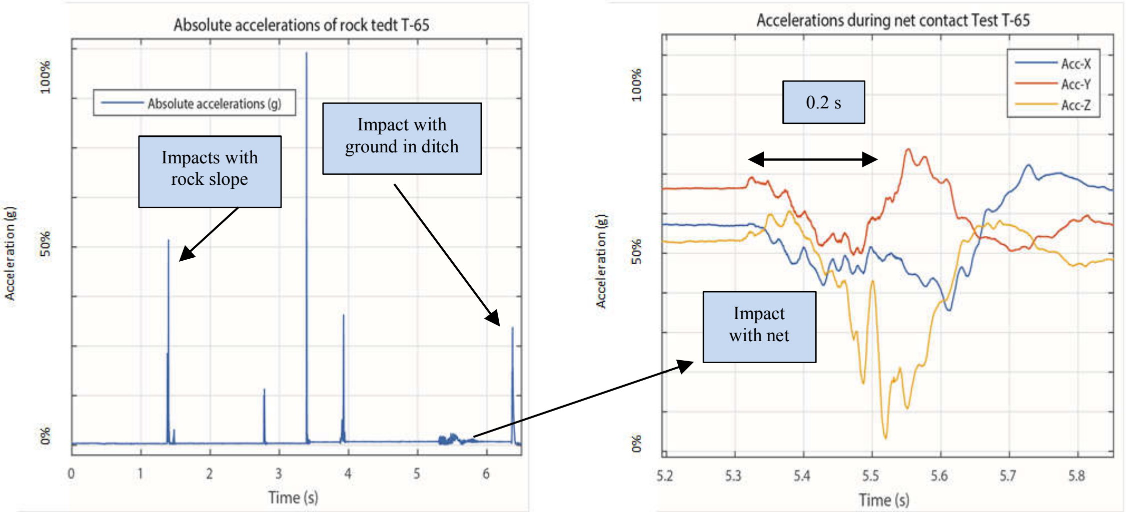

Figure 6. Typical results of accelerometers

After the impact duration of 0.2 seconds, the accelerations of the block decrease as it rolls down the net into the ditch as the gravitational force of the falling block is opposed by the frictional force between the block and the net.

Gyroscopes

The 3-D gyroscopes embedded in the test blocks recorded the rotation of the blocks throughout the 60 m fall. This is respectively, the transfer of translational kinetic energy into rotational momentum on impact with the rock face. The consecutive impacts of the rock with the rock face caused a stepped increase in rotational speed up to a maximum of about 22 rad s^{-1}. The rotational speed during free fall periods remained constant. Once the block impacted the net, the shear force between the irregular block and the net reduced the rotational velocity to zero at 0.2 seconds. The rotational velocity then reversed and increased to more than the impact rotational velocity until it impacted the ground. The significance of the change in rotational direction is first, that all the rotational momentum is absorbed by the net during the initial 0.2 second contact period. Furthermore, the reverse rotation of the block when it impacts the ground causes it to roll back towards the slope and not roll out of the ditch.

DESIGN METHOD FOR ATTENUATORS

The impact of rockfalls with an Attenuator net system as shown in Figure 1 can be analyzed using the conservation of momentum principle as follows.

Momentum lost by the rock body

For an impacting rock body (mass m_r, moment of inertia, I), with translational and rotational velocities ($v_{r(t=0)}$, $\omega_{r(t=0)}$), the total momentum (P_r)at the moment of impact ($t = 0$) is:

$$P_{r(t=0)} = \left(m_r \quad v_{r(t=0)}\right) + \left(I \quad \omega_{r(t=0)}\right) \quad (1)$$

At time $t = 0.2$ seconds, when the loads in the support cables are at the maximum values, the translational velocity of the body has been reduced to $v_{r(t=0.2)}$ and the body is not rotating ($\omega = 0$) the momentum of the body is:

$$P_{r(t=0.2)} = \left(m_r \quad v_{r(t=0.2)}\right) \quad (2)$$

Therefore, the momentum lost by the body to time $t = 0.2$ seconds is equal to the change in velocity and rotational speed during this time period:

$$\Delta P_r = m_r\left(v_{r(t=0)} \quad v_{r(t=0.2)}\right) + \left(I \quad \omega_{r(t=0.2)}\right) \quad (3)$$

Momentum gain by net system

According to the principle of conservation of momentum, the momentum lost by the impacting body to time $t = 0.2$ seconds is equal to the momentum gained by the net and support cables during this time period. The momentum gain in the net and the load cells is calculated as follows.

First, at time $t = 0.2$, the body and the net are in contact so the velocity of the net as it moves horizontally is equal to the horizontal component of the velocity of the body ($v_{rH(t=0.2)}$) and the momentum of the net is:

$$P_{n(t=0.2)} = \left(m_n \quad v_{rH(t=0.2)}\right) \quad (4)$$

where m_n is the mass of the net that is engaged by the impacting rock at $t = 0.2$ seconds.

Second, at time $t = 0.2$ seconds, the total force in the eight support cables, as measured by the load cells, is $\sum_1^8 F$. The force in the load cells acts over time Δt, so the increase in momentum in the net support system over this time interval is:

$$P_{LC} = (\textstyle\sum_1^8 F) \quad t \ (5)$$

This momentum is made up of two components comprising the sudden movement of the net due to impact, and the oblique, impact between the rotating body and the net that generates a frictional force in the net. Both these actions generate reaction forces in the net, which are recorded by the load cells in the supporting cables (Figure 5).

The resultant acceleration of the block due to the frictional contact between the body and the net is measured by the accelerometers (Figure 6) and is the Euclidean sum of each acceleration axis. The force generated by this frictional contact is the product of the resultant acceleration and total of the mass of the block and the mass of the net engaged by the impact. Therefore, momentum of the contact force is given by:

$$P_{contact} = \left[\left(a_x^2 + a_y^2 + a_z^2\right)^{0.5} \quad (m_r + m_n) \quad \Delta t\right] \ (6)$$

Based on these equations, the conservation of momentum is given by:

$$\Delta P_r = \left[P_{n(t=0)} + P_{LC} \quad P_{contact}\right] (7)$$

Examination of the equations shows that the correct function of Attenuators depends on the ratio of the mass of the rockfall to the mass of the net engaged during impact to deflect the rock into the ditch.

CONCLUSIONS

The integrated test information on the mass and shape of the test blocks and the mass of the net, and data from the video cameras, load cells, accelerometers and gyroscopes has provided a unique insight into the performance of Attenuator net systems under full scale rockfall impact conditions. This information showed that the following features of Attenuator performance:

- Nets fabricated with high strength steel wire and weighing 3 kg m-2 can withstand impact forces generated by translating and rotating blocks of rock and concrete with masses up to 1000 kg.
- The foundation of Attenuator design is to apply an appropriate ratio between the mass of the rockfall and the mass of the net.
- The rotation of the blocks was reversed during impact with the net which helps to contain the rocks in the ditch.
- Because the velocity of the blocks is only reduced by their impact with the net, only a portion of the impact momentum (and energy) must be absorbed by the net and support system.
- The net is self-cleaning because the rocks fall out of the lower edge of the net into the ditch.
- A nearly maintenance free flexible rockfall system, was developed and tested by these tests.

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