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Diana Falls – Then and now, moving from innovation to improvement.

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1 ABSTRACT

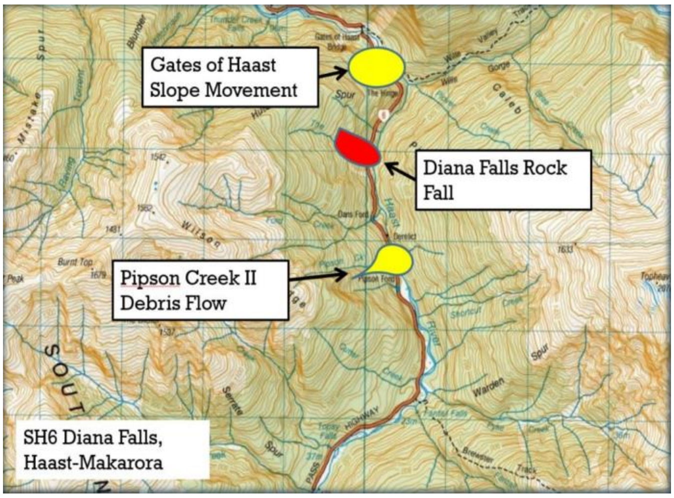
In September 2013 what was described as one of the most extreme rainfall events in New Zealand, hit the West Coast of the South Island. The storm claimed the lives of two Canadian tourists, closed State Highway 6 for two weeks and disrupted traffic on the famous West Coast Highway for nearly 12 months. The largest impact on the route was at Diana Falls, where over 4,000 cubic meters of soil, rock and vegetation slipped and blocked the road. The resultant response to the event became one of the most complex and innovative rockfall mitigation solutions in Australasia. The construction of the Diana Falls Rockfall mitigation system was also a key milestone in the development of a New Zealand design guide for rockfall mitigation and the future design solutions adopted in Kaikoura.

Since 2013, multiple rockfall and landslide events at the Diana Falls site have been successfully attenuated. Diana Falls continues to be a successful and innovative mitigation solution to a complex and extremely active site, with no unplanned road closures having occurred at the site due to rockfall or debris slides since its construction. Routine inspections, monitoring and re-assessment of the hybrid system has enabled it to be modified and improved to meet the challenging and changing conditions of the slip site, adopt new technology and refine its design and operation ensuring its continued effectiveness and efficacy as well as providing data for use in new rockfall protection systems, design guides and guidance documents around the world.

2 SITE SETTING

The Haast Pass in the South Island of New Zealand was converted from a rough track to a passable road by the Ministry of Works in the 1960’s but was not sealed until the early 1990’s. It is one of three mountain passes that cut through the Southern Alps alongside Arthurs Pass and the Lewis Pass.

The State Highway route is cut into the steep side of the Makarora and Haast River valley and the valley is formed of deep incised overly steep mountainous terrain. The road traverses the pass and reaches a maximum altitude of around 563m. As such much of the road is within the densely forested zone.



Multiple rockfall and landslide events occur along the Haast Pass between Makarora and Haast. The slips tend to occur as over slips (landslides or rockfall) on overly steep valley sides and are generally instigated by heavy rainfall and overly dense vegetation where little or no colluvium cover is present. The majority of the failures are typically of the order of 10 to 1000 cubic metres of material being deposited on the road. Road closures are common with one to two closures per annum being normal, however, these events are typically cleared within 24hrs. There are also several slow-moving landslides through the pass, as well as multiple rockfall and debris flow sites.

Figure 1 - Location of Diana Falls

3 THE DIANA FALLS EVENT

The initial failure occurred on the 10th September 2013 during what was described as one of the most extreme rainfall events to have hit the West Coast of New Zealand in recent times with over 300mm of rainfall in 24hrs, with the highest rainfall intensity reaching over 30mm in one hour.

The failure originated at the crest of a vertical face with a large vegetation collapse. The slip quickly regressed upslope by around 100m as a rock and colluvium debris slide. The initial failure deposited around 10,000 cubic meters of colluvium and vegetation directly onto the road, bridge and slope over the Diana Falls stream. Over the following month the failure regressed up the steep slope by a further 100m with subsequent minor failures and slides depositing a total of over 30,000 cubic meters of debris. The failures were mainly associated with periods of heavy rainfall through the months of September and early October.

The resultant failure feature measured nearly 250m in height, 50m in width and nearly 5m in depth at select locations. The slip face angle varied between 35 and 42 degrees. The site is dominated by a steep vertical face some 40m high with an upslope above it of around 150m.

The composition of the failure ranged from silty gravel to large schist boulders up to 300t / 125 m3.

Figure 2 - Extent of the failure following repeat upslope failures dated November 2013 through to February 2014.

The failure resulted in an initial closure of State Highway 6 through the Haast Pass for nearly three weeks, further closures occurred throughout November to January 2014 and disrupted traffic to the West Coast Highway for nearly 12 months.

Figure 3 - Example of large boulder.

4 DEFINITION OF THE PROBLEM

Dealing with a landslide or rockfall on to a State Highway is not a new issue in New Zealand. However, the Diana Falls event presented several additional challenges which complicated the remedial actions and posed problems to developing a final remedial solution.

The location and geomorphology of the slip site posed a significant hurdle to the recovery of the road and the installation of the final design. Being over 2hrs away from the closest urban centre, having no mobile phone coverage, limited radio coverage, intermittent satellite coverage and accessed only by a narrow, twisting highway through an alpine pass over multiple single lane bridges all created logistical and health & safety challenges that needed to be overcome. The weather varied from warm sunny days to blizzards and white outs or intense rainfall and low cloud. Visibility on the site and in the area restricted helicopter operations and the site was impacted by at least two magnitude 5 earthquakes during the construction period.

Due to the limited number of highways passing from the West Coast to the tourist centres of Wanaka and Queenstown the importance of the route became very apparent and the tourism industry of both the West Coast (Fox and Franz Josef) and Wanaka/Queenstown were impacted immediately and continued to be affected until tour buses and tourists were allowed to pass through the slip site in mid-2014.

The recovery progress was hampered by ongoing failures and mitigation measures such as targeted scaling and sluicing had little or no effect in reducing the number of regression failures or minor slips and rockfalls that occurred.

The shear overhanging face posed multiple hazards to the single lane passing below due to ongoing rockfalls and limited visibility to the main slip above. Constant observation and monitoring of the slip site was required to enable slip movements to be identified and early warnings afforded to the work crews below.

The site attracted a high media profile due to the impact on tourism and as such every element of the work was scrutinised by the major stakeholders NZTA, DOC and the local government. The profile of the site, the solutions developed and the programme for delivery was therefore extremely sensitive. In addition, there was at the time no New Zealand Standard for the assessment and design of rockfall protection systems as rockfall protection in New Zealand had typically followed international standards and adopted conventional rockfall barrier designs.

The Diana Falls site required a quick, bespoke solution that could be constructed in rural New Zealand using construction equipment that could be transported to the site from either Greymouth or Wanaka and in a tight timeframe driven by the tourist seasons of the South Island.

5 CONCEPT DESIGN OPTIONS

- *Do Nothing* (not permitted to be considered - abandonment was not considered)
- *Realignment* (discounted on the adverse cost of two river crossings - even though consideration had previously been given to a new Haast crossing further downstream)
- *Earthworks* (this option was considered closely in terms of cutting a bench system into the hillside however was abandoned based on the time required to construct a safe bench system. Contractors were invited to site but were surprised by the steepness of the slip and the presence of bedrock in the slip face, eventually the option was discounted on basis of complexity, cost and the time required to achieve a safe outcome).
- *Rockfall Barrier* (large capacity fence was discounted due to the required height and impact energy)
- *Rock Shed/Shield (considered but was discounted due to the time required to construct it and the overall cost).*
- *Rockfall Barrier* (a self-clearing canopy was considered but was discounted as the volume of repeat failures combined with debris slides would most likely exceed the capacity of a canopy)
- *Attenuator* (option 1 (single) / option 2 (two) / Option 3 (three) considered and then passed to detailed design with Geobrugg/WSP and Geovert combining to deliver a workable combination solution)

Cost benefit, ease of construction, speed of construction, life expectancy, impact on road accessibility and level of ongoing maintenance requirements were all key factors that influenced the final design.

6 DETAIL DESIGN

The slip was highly active and geological mapping concluded that further regression of the head scarp was almost certain. Ongoing rockfall including large boulders in excess of $3m^3$ was considered likely to occur on an ongoing frequent basis, namely following a significant trigger event and through erosional processes. Large volumes of slip debris, boulders, gravel and silt were also present across the slip body which were slowly creeping under self-weight, and a waterfall passes through the northern margin bringing debris flow debris and tree debris during storm events.

Drone surveys, topographical mapping as well as periodic prism monitoring of sliding blocks and bedrock heave enabled a full three-dimensional model of the slip to be established. Periodic monitoring of an array of prisms installed on large boulders, bedrock and key features within the slip body soon established that the upper margins of the slip were toppling and would eventually slide releasing large unstable blocks onto the face. The survey and monitoring of debris movement across the slip also identified multiple trajectory paths as well as mass debris slide routes down the slip face. Visual assessment of rockfall trials and monitoring of the slip during periods of heavy rainfall soon identified that the majority of the mobilised materials either rolled or slid down slope as large debris masses, with only occasional large boulder rolls achieving full predicted bounce heights. The boulder rolls that did bounce tended to start bouncing high on the slope and, due to the steep incline in the centre of the slip face and the exposed bedrock faces, catapulted rocks high over the lip and directly toward the State Highway.

The initial designs followed conventional international rockfall design procedures, considering likely seed points, boulder sizes, trajectories and bounce heights. It became apparent through site observations and modelling that any remedial solution had to consider:

a) Large boulders in excess of $3m^3$ being released at the head of the slope with the potential for large bounce heights over 8m at the base of the slip.
b) Large boulders bouncing over large distances and missing the upper lip of the vertical face and directly impacting the road at very high impact energies.

c) Large creep movement of boulder/gravel debris generally mobilised through snow melts and heavy rainfall.
d) The remoteness of the location and the need to provide security to the road user during adverse weather conditions.
e) Difficulty in accessing the slip to complete remedial works or effect repairs.

The site data and models of the rockfall were shared with Geobrugg (Switzerland) and it was realised that either very large rockfall barriers of significant height and capacity would be required or substantial works would be required to lower the potential block energies. This was at the time completed using conventional scaling and blasting techniques to reduce the block sizes and lower the overall energy potentials. However, through various model iterations and consideration of the other debris slide, maintenance and construction issues, it was apparent that a conventional rockfall barrier would not suffice.

The solution adopted in the final design worked on the principle of being self-managing and energy reducing. It was evident that the slip was going to continue to feed large quantities of material and release high energy rock falls over at least the next 5-10 years and the system had to meet the demands of being in a remote location where maintenance could only be periodic.

To achieve this risk reduction a series of hybrid barrier/attenuators were designed to reduce the impact energies and channel debris slide material down the slip and over the lip. There it would be contained against the vertical cut face and be restrained at the roadside in a controlled manner.

Several advantages of the multiple attenuator system became apparent once modelling of the system was completed in that it would reduce the rock fall risk to a manageable level, could be installed quickly with a top down methodology to reduce construction risk to personnel, required less maintenance than a rockfall barrier and provided a large increase in road safety early in the construction phase enabling bridge/culvert works and road surfacing to be expedited.

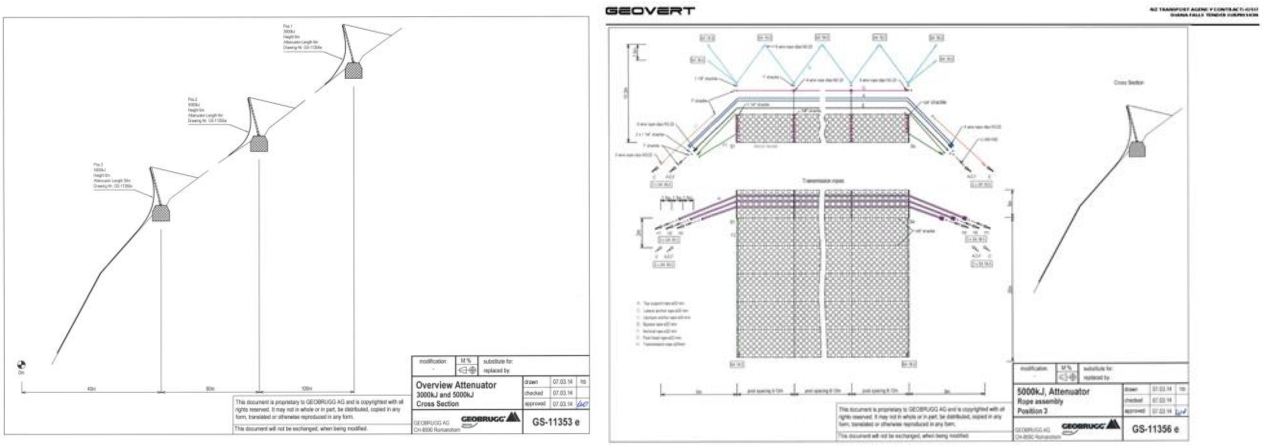


Figure 4 - Attenuator overview and rope assembly drawing of A3

To ensure the hybrid attenuator system was tested and capable of withstanding the rockfall and debris loads, the rockfall barriers were selected by Geobrugg who advised EAD (formally ETAG 27) category A, approved barriers. The barriers were then modified into attenuators by removing the bottom ropes and extending the net downslope (table1).   The following rockfall barriers were selected and modified accordingly:

	Type	MEL Capacity	Barrier Height	Tail Length	ETAG 027 Approved	Residual Height
Upper Slope	GBE-3000A	3000 kJ	5	5	Yes	Category A
Mid Slope	RXE-5000A	5000 kJ	6	6	Yes	Category A
Lower Slope	RXE-5000A	5000 kJ	6	42	Yes	Category A

Table 1 - Modified rockfall barriers.

The three attenuator systems were at the time recognised as being one of the first complex, innovative hybrid systems and are still considered one of the most frequently impacted rockfall mitigation solutions in Australasia.

7 INSTALLATION METHOD

The installation commenced in 2014. The installation of the three attenuators were carried out by the specialist rope access contractor Geovert Ltd with barrier materials being sourced from Geobrugg Switzerland, Australia and New Zealand. The construction required helicopter lifts for the upper two attenuators (A1 and A2) and a crane for the lower attenuator (A3). A top down approach was used to maximise the safety of the installation crew and to enable additional road level works to be advanced on an accelerated programme.

Figure 5 - Helicopter and Crane lifting (courtesy Geovert) And A3 under construction.

The lateral anchors and base plate anchors were installed following a large blasting, scaling and sluicing operation. The 6-8m long 32mm grouted bar anchors were installed with onsite abseil crews and site based geotechnical staff providing full time supervision and observation of rockfall events. Communication to the traffic stop go operators was by radio as no direct line of sight could be achieved. The active monitoring of the works and the slip enabled partial and controlled openings of the road throughout construction. Due to the nature of the site and the environmental conditions, frequent rain, seismic and snow events created rockfall and debris slides throughout the duration of the works. These were managed through a developed site management and operations plan with developed site triggers, inspection policies and safety zones established for both on the slope and at road level operations. Repeater stations and mobile phone communications were temporarily established and maintained throughout the works to enable quick and efficient updates to NZTA, emergency services to be made.

Figure 6 - Extreme working and weather conditions (courtesy Geovert)

8 MANAGEMENT AND MONITORING

Like most rockfall protection systems, the performance and maintenance can be optimised from frequent inspections and post impact analysis. As part of the design development it was determined that due to the active nature of the slip site a regular inspection regime consisting of periodic and repeat inspections be completed including following certain trigger events and that an annual maintenance budget be allocated for the design life of the system.

An annual budget of circa $100,000 was allowed for in the first five years of the design life and this was to be re-appraised after year 3. The design life of the system was established as being less than 50 years with a large portion of the components to the upper and middle attenuators likely to be replaced within 3-10 years.

After replacing several posts due to rockfall damage over the first 3 years the system was modified to remove the frequently impacted posts completely. This design change required re-assessment of rockfall impacts on the posts and barriers recorded over the previous 3 years and review of the management of sliding boulders above the attenuators. The accepted re-design allowed for additional top rope sag of 0.5m, reduced the post replacement programme and made significant savings on maintenance operations and component replacements.

Figure 7 - Examples of post impacts and component failures due to static and dynamic loads

Figure 8 - Debris catch in A3 following heavy rainfall

The barrier impact's and attenuator loads have been monitored annually enabling a full assessment of component failures and design alterations to be instigated as the system has been activated. Examples of changes include removing the posts on A1, adapting the bottom rope of A3 to facilitate easier clearing of slip debris and replacing the secondary mesh on A3 to reduce puncturing and tearing by tree fall. This level of monitoring and continual improvement is key to developing a successful and economic rockfall protection system.

Figure 9 - completed Attenuators A3 left A2 middle A1 Right

9 IMPROVEMENT AND DEVELOPMENT IN BARRIER DESIGN

Since the Diana Falls attenuators were constructed, further research, testing and performance evaluations have led to an evolution in the attenuator design methodology. When designing an attenuator, the impact energy should not be solely used. The attenuator does not completely decelerate the rock at initial impact but alters its trajectory and guides it to the bottom. Given this added complexity the forces exerted on the structure are very different to a rockfall barrier and can only be accurately determined from 1:1 testing and subsequent Finite Element Modelling (FEM). Given that the attenuator does not completely stop the impact block, it should not be designed or classified solely by the Impact energy (kJ) and rather by the rocks mass, velocity and shape (puncturing resistance).

To further understand the forces acting on attenuators, in 2018 Geobrugg completed a 3-year research project to develop an attenuator design model. The model is based on over 200, 1:1 instrumented field tests in conjunction with Duncan Wyllie, President of Wyllie & Norrish Rock Engineers and considered data collected from the Diana Falls rockfall and debris slide events.

The key learnings from the 1:1 attenuator testing included significantly lower anchor forces with no requirement for braking elements or transmission ropes. These simplifications make the new style attenuators more economic compared to the equivalent modified EAD rockfall barrier. These findings are in line with the performance of the Diana falls attenuators as to date only the top transmission ropes U brakes on attenuator 2 (A2) have slightly elongated after many design level impacts.

The majority of EAD approved barriers have a maximum post spacing of 10-12m whereas attenuators can extend to around 16m spacing (limited by rope sag) this has also been observed at Diana Falls where posts have been removed resulting in an up to 18m span. Other learnings conclude that high tensile chain link mesh is the most suitable attenuator mesh due to being easier to install than ring nets due to no necking (hourglass shape when lifted), being lighter so on shallower slopes it allows debris to pass underneath, having a uniform puncturing resistance over the entire mesh and due to the aperture size being <80mm so a secondary mesh is not required. Recent remedial repairs at Diana Falls also include lacing the mesh panels as opposed to shackling and redesign of the upslope stay wires to remove them from slip debris aggradation. All these advantages and developments continue to reduce overall maintenance costs, reduce repairs and maintain an effective RPS which may extend the systems design life.

Figure 10 - 400mm elongation of a 3000mm U-brake at Diana Falls.

10 SIMILAR SYSTEMS ADOPTING THE DIANA FALLS RPS PRINCIPLE

The Diana Falls approach to energy dissipation and control of debris has enabled several systems to be developed and adopted across New Zealand.

In 2017/2018 two similar attenuator systems were installed in Kaikoura. The Kaikoura systems were based on 4m high RXE 2000 EAD class A approved rockfall barriers. The main difference with the Kaikoura systems are that the impact block size is smaller than that for Diana Falls (<1m^3) and only a single attenuator was required. Although likely over engineered the systems are working well.

Figure 11 - Kaikoura Modified RXE2000 Attenuators

In 2019 a new Style ATT-60 was installed in Kaikoura. The system was selected over an EAD modified barrier due to the faster and lower cost installation with no need for a secondary mesh. The ATT-60 also has a lighter tail so the frequent low mass high velocity impacts on the shallower ~45 slope can pass through.

Two ATT-40's have also been installed in Cobb Valley, NZ the systems utilise a fixed post (no upslope ropes) which meant they could be installed from the road with an excavator mounted drill.

Figure 12- ATT-60 (left) and ATT-40’s(right)

In Australia the design approach is much the same as New Zealand. A Stainless-steel ATT-40 was recently installed (2020) on the Great Ocean Road. Stainless steel and galvanised epoxy posts with isolators were selected to meet the design life in the aggressive coastal environment. Several more ATT systems are in the planning and installation stage across Australasia.

Figure 13 - (left) Stainless steel ATT-40.

North America likely has the most attenuators in the world due to their wide road verges which can easily accommodate runout catchment. Their design style slightly differs from that adopted in New Zealand, as they rotate the post forward even on the shallower slopes to create a hanging net rather than the drape the tail on the slope, however, the design principles are effectively the same. The benefits of a hanging net are that it allows the mesh to be extremely flexible which can reduce plastic deformation of the mesh. The hanging net also reduces the chance of material getting caught up in the tail and the requirement for future vegetation control. The disadvantage of a hanging net is that less energy is absorbed from rock and slope interaction, so the exit velocity may be higher. If the catchment is narrow or the exit velocity is too high, then tethers or weights can be installed to fine tune the attenuator. If the attenuator is dimensioned correctly then any blocks that exit the attenuator with some residual velocity should have a reverse rotation which will encourage the block to roll back towards the slope. Attenuator 3 at Diana Falls adopts the hanging mesh principle due to a near vertical slope. The attenuator is frequently impacted with large boulders that are then successfully deflected to ground under the mass of the mesh. Frequent material clearance at both Diana Falls and Kaikoura has proved to be the most effective method due to limiting road closure durations and minimising the time that the material has to consolidate.

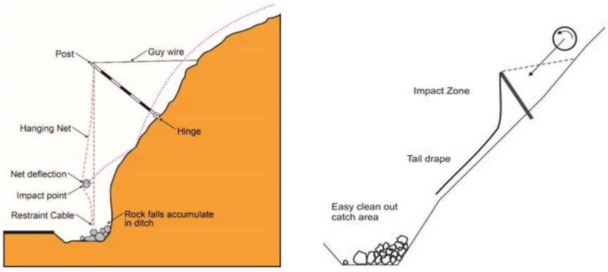


Figure 14 - Hanging net (left) and net draped on slope (right)

In Switzerland, Germany, Austria and France attenuators are less common over rockfall barriers due to the extensive steep mountainous regions, with narrow roads and less space to control the rockfall. In these regions it is also a common and standard procedure for rope access and helicopter work, so maintenance is less of a consideration and is a somewhat normalised procedure. The higher populations and settlement density also means they are less restrictive and remote than sites such as Diana Falls in New Zealand.

11 CONCLUSIONS

The design, development and installation of the Diana Falls Hybrid system was a significant milestone in the adoption and development of standard design for Rockfall Protection Systems in New Zealand. With constant monitoring and data recording of its performance, the system is an excellent example of building network resilience, being innovative, adapting to natural hazards and environmental constraints, adopting new and emerging technologies and developing remote construction methodologies.

The continuous monitoring and improvement of the system has enabled the needs of an ever-changing environment to be met as well as provide substantial long-term cost savings to be realised in terms of component or system replacement and ongoing maintenance.

Since its design and development in 2013 and construction in 2014/15 the Diana Fall attenuators have been subject to multiple impact events and are performing extremely well with only a modest maintenance budget.

The Attenuators are likely the most frequently impacted rock fall protection system in New Zealand and attract global interest and the system continues to provide reliable rockfall and debris slide data enabling constant opportunities for improvement as well providing confidence in the future design and adoption of similar Rockfall Protection Systems around the world.