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Hybrid fence design for rockfall protection above the coastal highway in Kaikoura, New Zealand

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ABSTRACT

In November 2016, a M7.8 earthquake struck the Kaikoura region resulting in numerous landslides above the main coastal state highway and rail corridor. Two of the sites along the southern section of the Kaikoura coast, known as Site SR18 and SR19 had a complex rockfall issue, which included two large source areas that funnelled through a single gully before exiting onto a wider debris fan. Risk mitigation consisted of a hybrid fence across the narrowest point of the gully where the rockfall is concentrated. The hybrid fence spans a length of approximately 90m with post heights of 4m, and the mesh drape of the hybrid fence extends almost to road level, some 30 m downslope. The long drape is intended to guide debris to a location near the road where it can be removed more easily without the need for roped access construction workers in the impact zone of the hybrid fence.

This paper will discuss the hazard evaluation and decision process for adopting the hybrid fence over a conventional rockfall catch fence or attenuator. Key elements of the design process were the focus on the Safety in Design considerations for both construction and on-going operational maintenance, and fitting the fence to the irregularities of the slope. The use of a hybrid fence enables high dynamic rockfall impacts to be intercepted and guided down slope where the accumulated debris can be removed safely.

Paper 77

1 INTRODUCTION

The M7.8 November 2016 Kaikoura Earthquake struck the east coast of the South Island of New Zealand resulting in widespread damage to the slopes along the coast between Clarence and Oaro. During the initial response efforts numerous landslides were identified along the coastal transport corridors, which includes State Highway 1 (SH1) and KiwiRail's Main North Line (MNL). These transport routes are located on the narrow coastal fringe between the steep slopes to the east and the ocean to the west. The transport network in the Kaikoura region was severely affected and the local communities were effectively cut-off.

The North Canterbury Transport Infrastructure Recovery (NCTIR) Alliance was formed in January 2017 with the task of re-establishing the infrastructure links along the Kaikoura coast as quickly as practically possible. In order to re-open the transport links under these time constraints and deal with the complex rockfall hazards, a disaster recovery approach was adopted which involved procuring a range of rockfall mitigation measures prior to detailed design in order to ensure the availability of materials. This resulted in a number of challenges and opportunities for innovation during the design and construction phases.

The intent of this paper is to provide an insight into the hazard evaluation and design process for adopting a hybrid fence over a conventional rockfall catch fence or attenuator at two complex sites along the southern section of the Kaikoura coast, known as Sites SR18 and SR19 (SR18/19).

2 BACKGROUND

2.1 Geology

The Kaikoura Coast is dominated by the north-east trending Seaward Kaikoura Range. The slopes rise from the sea along the coastline, and the transportation corridor is located on a narrow width of flat land between the foreshore and the toe of the hillslopes. The steep and rugged slopes adjacent to the corridor rise to over 300 m above sea level. Slope angles are typically 35^o to 50^o, with localised short sections of near-vertical cliffs along the coastline.

Basement 'Greywacke' of the Pahau Terrane forms the hills along the coast south of Kaikoura and much of the North Kaikoura Coast. The Greywacke typically comprises slightly weathered sandstone and mudstone (argillite), often with a mantle of moderately weathered rock close to the ground surface. The mudstone is typically weak and the sandstone is moderately strong to strong.

Colluvium overlies the Greywacke and is typically a mixture of rock fragments, silt and sand. It is widely distributed over the basement rock throughout the project area, where slope angles are less than 45°. The colluvial mantle is typically 0.5 m to 1 m thick near the ridge tops, and increases in thickness downslope, with a maximum observed thickness of approximately 15 m.

2.2 Site Description

The combination of rapid tectonic uplift, coastal erosion and oversteepening of the slopes to form the road and rail corridor had rendered the slopes vulnerable to instability.

The majority of the slope failures caused by the 2016 Kaikoura Earthquake were evacuative rock and debris avalanches, that, in some cases, involved the release of large volumes of material (in excess of 50,000 m^3 at some locations). In addition, widespread hillside and ridge cracking occurred during the earthquake, without downslope release of material.

At SR18/19, earthquake shaking ground damage effects on the hillslopes included denuding of soil slopes, tension cracking and dilation of rock outcrops, all of which have increased the potential for future rockfall onto the transportation corridor, see Figure 1.

Figure 1: Earthquake damaged slopes above the coastal transport corridor, the approximate site location of SR18/19 is outlined in red

At SR18/19 two large source areas funnel material through a single broad gully before exiting onto a wider debris fan. Rock avalanching (rather than individual boulder release) has been the typical style of release observed during and since the initial earthquake. The scale of individual rocks observed ranged from fist-sized cobbles to large boulders up to several metres across. Failure volumes under relatively frequent rainfall events (1 in 5 year to perhaps 1 in 25 years, regardless of rainfall duration), are typically be expected to be between 1 m^3 to 50 m^3. This failure type and large variation in debris size indicates a complex hazard which originates from multiple sources.

3 MITIGATION OPTIONS PROCESS

A number of design options were considered prior to selecting a hybrid fence. These included:

- Sluice and scale to remove the source material – overall scope of works for complete hazard removal was considered too great and contained a high uncertainty as to a long term successful outcome. Notwithstanding this, an extensive scaling and sluicing program was undertaken to reduce the hazard and thus the expected number of impacts on the barrier, as much as possible;
- Install a rockfall catchment fence on the slope – boulders impacting the fence would be stopped. However due to the required fence location on the slope this option was discounted as maintenance and debris clearance of a catchment structure would be time consuming, costly and pose significant safety issues.
- Install a rigid barrier at the toe of the slope – this option was briefly considered, but in the post-disaster environment proprietary products that could be ordered and installed rapidly without a long design lead time were necessary. There are also a number of buried services adjacent to the road which would have needed relocating if this option was pursued.
- Daylighting of the road tunnels and benching of the rockmass – this option was discounted due to the high costs and time implications associated with the major earthworks involved.

Following assessment of these options, a hybrid fence was selected as the most practical option, whilst recognising that significant maintenance will be required due to the frequent impacts anticipated and the proximity to the coast. A large part of this decision was based on the expectation that boulders impacting the hybrid fence will pass through the tail and be able to be removed at or near road level. It was also expected that this longer tail, approximately 30m in length, would provide a longer time for deceleration for the boulders thus reducing impact loads on the structure when compared to a rockfall catch fence.

The hybrid fence was selected to be installed at a narrowing of the two upper gullies as this provided well defined end points as well as allowing the shortest possible length, approximately 90m. This also matched a location where rockfall modelling demonstrated that the bounce heights and kinetic energies of falling rocks were likely to be in a reasonable range. While installing the structure lower down the slope would have been easier, the road is located immediately at the toe of the slope (with no shoulder) and the structure was not allowed to deform into the road corridor. This meant that an on-slope location was necessary.

Safety in design was considered during design development and guided a number of key decisions:

1. The choice to use an hybrid fence instead of a rockfall catch fence means that on-slope maintenance is reduced and thus the time of exposure for workers is lower post-construction compared to a catch fence
2. Extensive scaling and sluicing was undertaken to reduce the number of impacts on the barrier, and to reduce construction related risks
3. Works were only undertaken during dry weather, when the likelihood of rockfall is lower

4 DESIGN OF HYBRID FENCE SYSTEM

4.1 Overview

The hybrid fence selected is a modified standard ETAG-27 certified rockfall catch fence. The main difference with the hybrid fence, is that it does not stop the rocks at the interception zone, but instead attenuates the impact energy and guides the rocks down to the toe of the slope. Therefore the best locations for hybrid fences are typically across gullies or at the crest of steep slopes with continuous flatter angled slopes above. The essential zones and their functions are described in Figure 2 below.

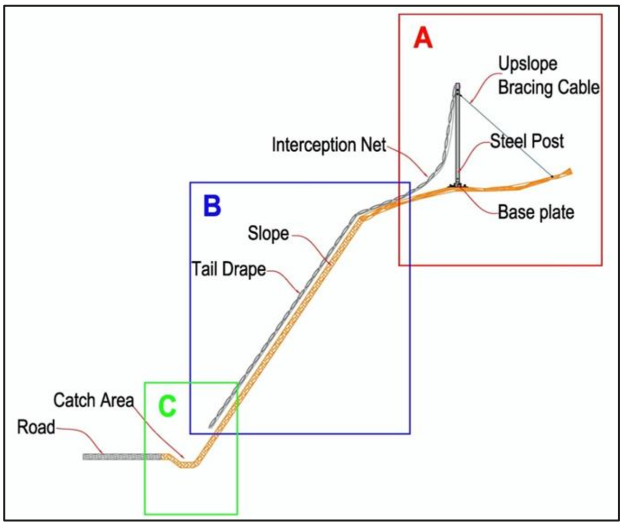

Figure 2: Hybrid barrier zones: ***A*** *- Rock interception and energy dissipation,* ***B*** *- Rock bounce control and further energy dissipation;* ***C*** *- Collection area (catch area, ditch, embankment, flexible rockfall barrier)*

- **Zone A: Interception Zone** – The interception panels (usually consisting of ring nets with double twist mesh overlain) are hung between the fence posts, and designed to intercept the falling rocks. At this point, the fence behaves similar to a standard catch fence but with more flexibility due to the elasto-plastic deformation of the intercepting panels with a longer drape. A standard catch fence has slightly restricted movement within the interception panel as it is restrained by a lower longitudinal cable. The largest dissipation of kinetic energy will occur in this zone.
- **Zone B: Transition Zone** – Following on from the interception zone, the falling rocks with much dissipated energy, enter the longer drape section of net and mesh. The length of the draped panel guides the rocks toward the toe of the slope. The self-weight of the ring nets plus the friction between the rocks and drape net further reduces the velocity and energy to a minimum for collection at the toe.
- **Zone C: Collection Zone** – The tail of the hybrid fence’s draped section extends down the slope where it is either open without restraint or loosely secured with wire ropes. This maintains the system’s flexibility and allows the drape to elevate during impact thereby dissipating energy. The guided rocks have minimal energy after the dissipation in Zones A & B. However, a collection area is still required and can be designed as either a catch ditch, small rigid barrier or even a flexible catch fence.

At this stage, there is no international guideline or certification for hybrid fences. The approach adopted was therefore to use an ETAG-27 fence components for the similar energy capacity fence as the deceleration will be slower and thus loads lower.

4.2 Design considerations

The design of the hybrid fence is categorised into two design states; *dynamic* and *static*.

The dynamic design uses a similar approach to a standard catch fence. The minimum energy capacity and height of fence post is determined from trajectory (rockfall) analysis. This standard approach is combined with the observed behaviour and internationally documented performance of hybrid fences to form part of the design considerations. In particular, the published results from the full scale trial undertaken by Arndt et al. in 2009 “Colorado’s Full-Scale Field Testing of Rockfall Attenuator System”. It can be concluded from this testing that the impact forces on hybrid fences can be half that of a standard catch fence due to the attenuation of impact duration. However, considering the absence of an international guideline for hybrid fences, the design uses similar anchors and foundation load requirements applied from a standard fence design – in this case, the 2000kJ - RMC200A ETAG-27 certified rockfall fence.

The static design follows the recommendation from Washington DOT Research Report - “Analysis and design of wire mesh/cable net slope protection”, which considers the structure as a simple drapery application.

4.3 Site specific design elements

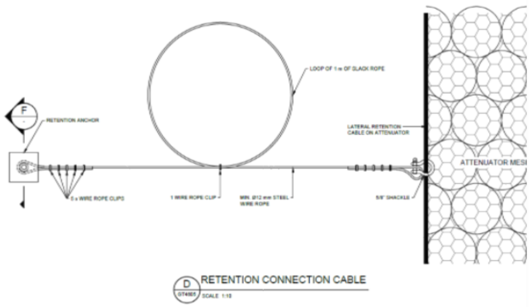

Figure 3: Example of retention connection cable detail

The topography at site SR18/19 is such that it is crucial to prevent the drape from ‘necking’, in order to enclose the potential trajectory rockfall path. For this site, lateral retention ropes were therefore required to connect to the sides of attenuator net to hold ‘open’ the drape to prevent them from closing in across the widening portion of the hourglass shaped slope. The lateral retention anchors were necessary at 4m intervals down the slope, see Figure 3.

These lateral anchors designed to ‘hold’ the drape open are non-structural and therefore have been designed to have a minimum pullout load slightly greater than the ring nets tensile strength, so that in the event of an impact the anchors remain intact. Lateral retention ropes were then designed to be connected between the lateral retention anchors and edge of the ring nets with a 1m loop loose connection. The design consideration is for the lateral retention ropes to rupture during a severe impact that would allow the drape to lift.

5 CONSTRUCTION PHASE

The construction of the hybrid fence at SR18/19 began in November 2017. The initial stages included sluicing, scaling and draping temporary mesh across the headscarp areas, to reduce the rockfall risk to the contractors working below. Several constructability issues arose during the construction phase, mainly a result of the complex terrain, and included:

- Providing appropriate access via a construction bench
- Closing out gaps that formed at the corners of the fence
- Modifying the bottom of the attenuator tail

5.1 Construction Bench

Figure 4: The bench and access ramp enable for improved access for the fence installation

To provide temporary access and a suitable construction area, a narrow 2.5 m width bench was constructed at the proposed fence location (Figure 4). Installing a bench on the slope initially provided a clear working platform on which to construct the hybrid fence, which enabled access without the need of daily helicopter transportation. The bench also enabled the use of excavators for installing the plinth foundations, reducing the construction time which was critical to road reopening.

5.2 Close out details

Prior to the construction of the hybrid fence at SR18/19, a similar hybrid fence had begun to be installed at a nearby site (SR14). The partially completed installation of the hybrid fence at SR14 provided the basis of the construction assumptions for the hybrid fence at SR18/19. However, at SR14 the slope is simple and planar allowing the hybrid fence to be extended across the full extent of the identified hazard, whereas the fence at SR18/19 is limited by the complex topography and constrained to the narrow gully, as shown in Figure 5.

Figure 5: (Left) SR14, installed across a planar slope (Right) SR18/19, constrained by complex topography

To ensure the maximum coverage of the hazard at SR18/19, the hybrid fence was designed to be installed across the full width of the gully with the border posts installed at the furthest possible extents on the installed bench. During the installation of the ring-net panels it became apparent that, even with the end posts at their furthest possible location, the linear fence installed at the narrowest point of the widening gully resulted in sizable gaps existing between the draped ring net panels and the ground. These gaps were observed on the northern and southern edges and mapped by the site team, see Figure 6.

Figure 6: The mapped hazards resulting from the gaps at the edges of the hybrid fence at SR18/19

To remediate this issue the NCTIR designers collaborated with Maccaferri and Geofabrics to design a close-out detail that would form "wings" on the structure and close out the identified gaps. These close-out elements attached to the hybrid fence would reduce material travelling through the gaps, and importantly act independently from the installed system. Independence was key as it has not been field tested how these close-out elements will ultimately behave, and it was important not to interfere with the known performance of the rockfall fence upon which the design is based.

Figure 7: An example of the initial drawings of the close out detail

The design intent of the close out attachments is to act as a funnel, diverting rockfall paths directly into the catchment area of the hybrid fence, reducing the possibility of material bypassing the fence, see Figure 7. These additions enabled the linear fence to fit better within the topography of the narrow gully.

The close out details were installed and completed during the final stages of construction, and were installed independently to the hybrid fence. The additional mesh panels, wire ropes and braking elements were fitted to the slope and closed out the critical areas reducing the potential for rockfall reaching the road.

5.3 Attenuator tail section

As can be seen in Figure 5 and 6 above, the toe of the slope was obscured throughout the design and construction by the row of temporary protection containers. This presented a challenge for the tie in detail of the attenuator tail.

During the initial design process, it was assumed that once the containers were removed and the slope cleared back to its pre-earthquake profile, there would be sufficient space at the base of the slope to install a small catch fence. The initial design included a low-energy catch fence installed at the toe of the slope outside the operating roadway. The fence would then capture material that passed through the attenuator tail. As the project progressed and containers removed, it became apparent that there was insufficient space for any dynamic or rigid catch structure at the base of the slope.

This change required a modification in the attenuator tail. The draped tail was extended in length to reach within 2m of the base of the slope and secured with an anchored bottom rope. This secured tail is supportive enough to retain the attenuated material at the base of the slope, while maintaining the required flexibility for the attenuation. The safety in design aspect was also achieved by enabling maintenance and material clearance to be undertaken from road level, without the need to access the slope or interception zone.

6 CONCLUSION

In conclusion, the magnitude of the damage caused, scale of the project and complexities of the site lead the design team to adopt an innovative hybrid fence design. The design elements of the hybrid fence enabled the complex risk at SR18/19 to be reduced for the road users below. Several design and construction challenges were presented throughout the project. Each of these challenges were overcome and provide the basis to share valuable lessons on the design and construction of hybrid fences. In summary the key lessons learnt were:

- The decision process to select a hybrid fence is based on the specific limitations of the project such as, cost, construction times, topographic restrictions and product availability. However, the hybrid fence provides a good solution to overcome a number of these limitations.
- Installing a bench on the slope initially provided a clear working platform. This improved access and ease of construction enabling the use of machinery for excavating the plinth foundations, reducing the construction time, which was critical to reopening the road. However, the cut bench in the talus slope resulted in minor erosion issues on both the downslope and upslope edges. This resulted in additional temporary measures having to be installed.
- Installing a barrier at the neck of an hourglass shaped gully means that the tail of the barrier is narrower than the gully below the barrier. This required innovative design to close the small gaps without compromising the main barrier's function.

The success of this project is in thanks to the collaboration of all parties involved including the NCTIR Design Team, NCTIR Delivery Team, Maccaferri, Geofabrics, Heads Up Access and SRG Ltd.

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