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Kaikoura Earthquake 2016: Case Study for the design and installation of a 2000kJ rockfall barrier at Ohau Point

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ABSTRACT

Significant damage was caused to the upper South Islands main transport corridor along the Kaikoura Coastline by the Mw 7.8 Kaikoura Earthquake on 14 November 2016. Both the State Highway (SH1) and Main North Rail Line (MNL) were impacted by landslides, fault displacement and rockfall leading to extensive disruption and closure of both critical transport links. One of the largest landslides developed at Ohau Point, 23 km north of the Kaikoura township, where over 130,000 m3 of debris inundated the transport corridor. Waka Kotahi Transport Agency (Waka Kotahi) and KiwiRail established the North Canterbury Transport Infrastructure Recovery (NCTIR) alliance with the goal of re-opening the infrastructure links along the Kaikoura Coast as quickly as practically possible.

Reviews of the unstable slopes above the road following the earthquake, lead to the decision to relocate SH1 onto a Mechanically Stabilised Earth (MSE) embankment and concrete seawall around the base of Ohau Point. To mitigate rockfall and landslide hazards at Ohau Point slope protection works were installed above the new road alignment. These included anchors and mesh high upslope, repurposing the old SH1 road as a catch bench, and the installation of a 2000 kJ rock fall barrier adjacent to the new road. This paper outlines the design and construction challenges of installing a 600 m long 2000 kJ rockfall barrier on reprofiled landslide debris and the need to work

with the barrier manufacturer during installation to ensure the ETAG 027 certification requirements were met.

1 INTRODUCTION

Ohau Point is a coastal promontory at the eastern end of an east-west trending ridge, cresting up to 180m above sea level. At Ohau Point Pahau Terrane greywacke is overlain by various thicknesses of colluvium (Rattenbury et al., 2006). The greywacke is typically highly fractured and blocky often with open jointing, that was significantly dilated by shaking associated with the Kaikoura earthquake. Site [P6S] is located on the southern face of Ohau Point and comprises three distinct debris chutes (P6A, P6B and P6C). [P6N] is located on the northern face of Ohau Point. Figure 1.

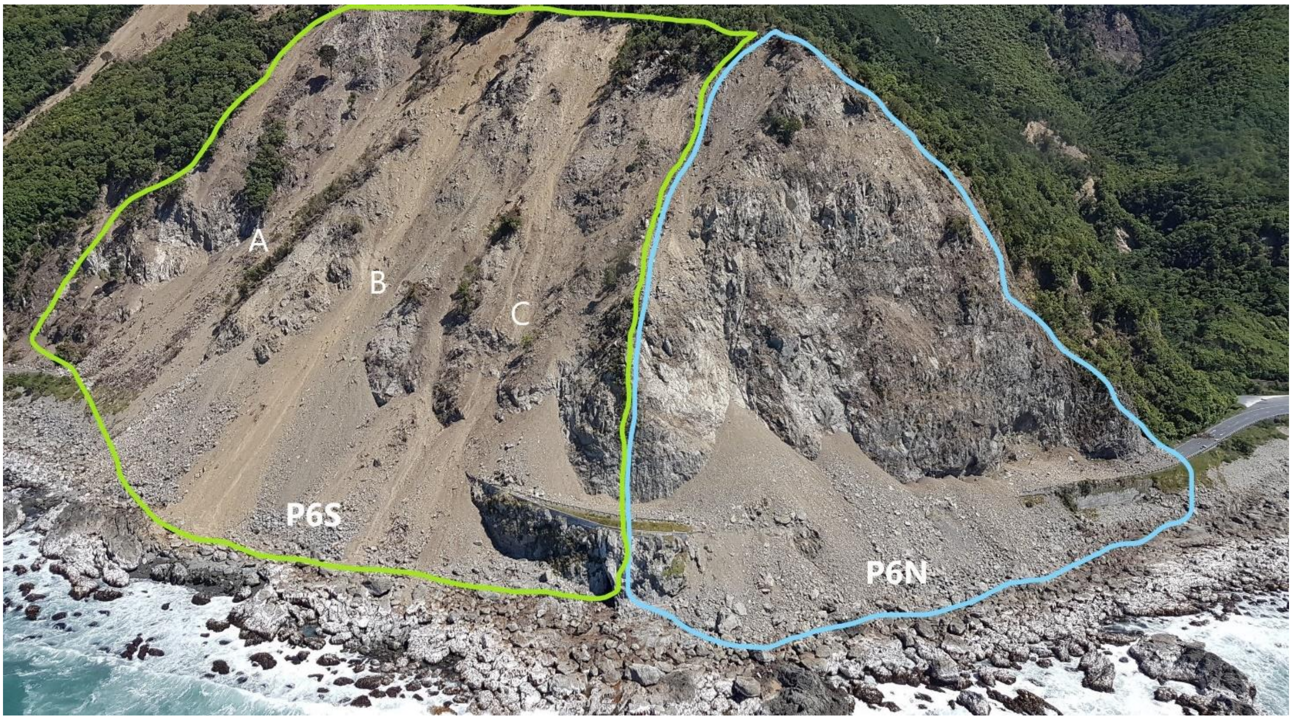

Figure 1: Site overview plan, [P6N] and [P6S] Ohau Point (post-earthquake image)

Landslide clearance and slope stabilisation works now constructed at Ohau Point have been designed to reduce the risk to the road and rail corridors from the identified geo-hazards (rockfall, debris avalanches, and shallow to deep-seated landslides), and to allow reinstatement of the transport corridor. The overarching objective of the design process has been to reduce the likelihood of the geo-hazards affecting the transportation corridor to acceptable levels utilising an "As Low As Reasonably Practicable" (ALARP) approach. Also, NSW RTS ARL and a KiwiRail risk rating schemes have been applied to the site to inform remediation design.

2 PROJECT WIDE DESIGN CONSIDERATIONS AND LIMITATIONS

The NCTIR programme of works is a disaster recovery effort and as such decisions were required to be made at an early stage without the level of supporting information or investigation which would normally be undertaken on the projects if they were pre-planned and constructed in isolation. The key constraints and limitations for the site were.

- Early procurement requirements ahead of design which dictated standardised design approaches.
- Limited timeframes for design and construction in order to meet planned rail and road opening dates.

- Proposed design limited to resources and materials readily available.
- Limited investigations or scoping of works prior to works commencing.
- Consideration of adjacent and conflicting construction works restricting access and/or constructability.
- Culturally sensitive areas within the site.

It is considered that downslope mobilisation of a large single mass (exceeding 500m^3) is unlikely to occur in anything other than extreme rainfall or earthquake events (>1/500 annual probability of exceedance). Mitigation works were not designed prevent a debris avalanche of this volume from intruding into the new highway corridor as this was not considered to be “reasonably practicable” in accordance with the ALARP principle given the anticipated low probability of the triggering event.

A critical aspect of the scope to be managed and delivered by NCTIR was that designs used in the restoration of the transport corridor needed to meet the requirements of KiwiRail and the Waka Kotahi. With the rail entering a tunnel at the southern end of the site and exiting well to the north, it passes behind much of the landslide affected area, and therefore required minimal consideration for the P6N and P6S design process.

Section 2.1.5 of the NZTA Bridge Manual (Third Edition Amendment 2, May 2016) outlines the working life requirements for bridges or earth retaining structures. While rockfall/debris flow barriers are not specifically mentioned NZTA has indicated that their desired design life is also 100 years. Section 2.1.6 also states that “Structures shall be sufficiently durable to ensure that, without reconstruction or major renovation, they continue to fulfil their intended function throughout their design life.”. NCTIR sought departures from the Bridge Manual to reduce the design life from 100 years to 50 years for the European Testing Agency Guideline for rockfall protection kits (ETAG 027) certified barriers and also for the drilled ground anchors to be used for the barrier foundations.

2.1 Departures

Certification to the ETAG 027 provides an assumed working life of 25 years without rock impact under normal environmental conditions and 10 years under aggressive conditions provided that the barrier is regularly maintained.

To extend the design life of rockfall barriers beyond the ETAG 027 25 year certification, regular inspection, maintenance and replacement of components needs to be undertaken. It is considered likely that the rockfall fence will be impacted by debris well within the 50 year design life and major maintenance will be required following these events.

2.1.1 ETAG 027

The European Organization for Technical Approvals (EOTA) endorses the European Technical Approval Guideline “Falling rock protection kits” (ETAG 027), where a testing procedure for CE marking of a net fence has been defined (Peila and Ronco 2009). It is noted that ETAG 027 was superseded by European Assessment Document EAD 340059-00-0106 in July 2018, after the barrier design phase was complete.

3 UPSLOPE WORKS – THE TOP DOWN APPROACH

Following the iterative and systematic design optioneering process (Saul and Anderson 2019) and (Horrey and Saul 2020) slope remediation commenced. Works completed at the [P6S] and [P6N] zones followed a ‘top down’ approach, where slope instability was mitigated before work directly below commenced.

Extensive slope treatment of upper source areas by helicopter sluicing and roped access scaling was initiated first. At the steeper [P6N] zone a draped ring net and high tensile mesh wrapped over the upper north face to stabilise the area and facilitate roped access to the lower slopes. Once that access was established, remote monitoring and rock dowel stabilisation of specific features below the meshed area were installed.

Removal of landslide debris by armoured excavator once ALARP risk mitigation was achieved in the upper source areas. As debris removal continued, a realignment of the highway away from the slopes onto a bedrock shore platform (raised by the earthquake) was undertaken to reduce the rockfall risk to traffic. The road realignment was progressively routed over the MSE embankment and concrete seawall around the base of Ohau Point as lifts progressed. Unearthing of the old road bench and establishment of a continuous earth bund along its outer edge, effectively re-purposed the old road as a rockfall and debris catch bench. Reprofiling of remnant colluvium and landslide debris below the old road bench to provide a uniform grade, acts as a retarding zone to any material bypassing the catch bench. These works were completed by December 2018. Figure 2.

Figure 2: Works completed prior to commencement of 2000kJ barrier construction (Dec 2018)

Localised scaling and rock dowels were installed where slopes below the old road bench comprise in-situ rock not suitable for reprofiling. With the upslope rockfall protection structures in place and the final alignment of the new SH1 defined, installation of a high resistance rockfall barrier (fence) between the highway corridor and the toe of the profiled slope could commence.

4 HIGH RESISTANCE ROCKFALL BARRIER (HRRB) DESIGN

The HRRB fence is the final line of defence and will intercept any rockfall arriving at the inside edge of the new SH1 road corridor. This type of fence has been chosen because:

- Observations during storm events while upslope works were in progress indicated that material could bypass the catch bench and bund if it becomes overwhelmed in extreme events These were noted to occur at a variety of locations along the [P6S] and [P6N] zones.
- Flexibility to position the fence on a variable slope adjacent the road

- The rockfall fence does not require any additional footprint. To accommodate any alternative structure (wall or bund) the slopes above would need to be steepened to an unacceptable angle.
- The deflection zone required on the downslope side of the fence (1.2 x fence height) is provided by the swale drain included in the SH1 road corridor design, so no additional space is required.
- Good construction and maintenance access is available from the new SH1 road corridor. Ongoing access behind (upslope of) the fence is not required as debris clearance can be achieved by releasing individual fence panels and removing debris from the new SH1.

4.1 Rockfall Modelling

Two dimensional rockfall modelling was carried out to inform design of the fence, details of the methodology are provided in Colgan (2018). Rockfall modelling proved a particularly useful tool in the design of rockfall interception structures (Figure 3), when calibrated against rockfall trajectories determined from field trials of varying dimensioned boulders released from likely source areas (Horrey and Saul 2020).

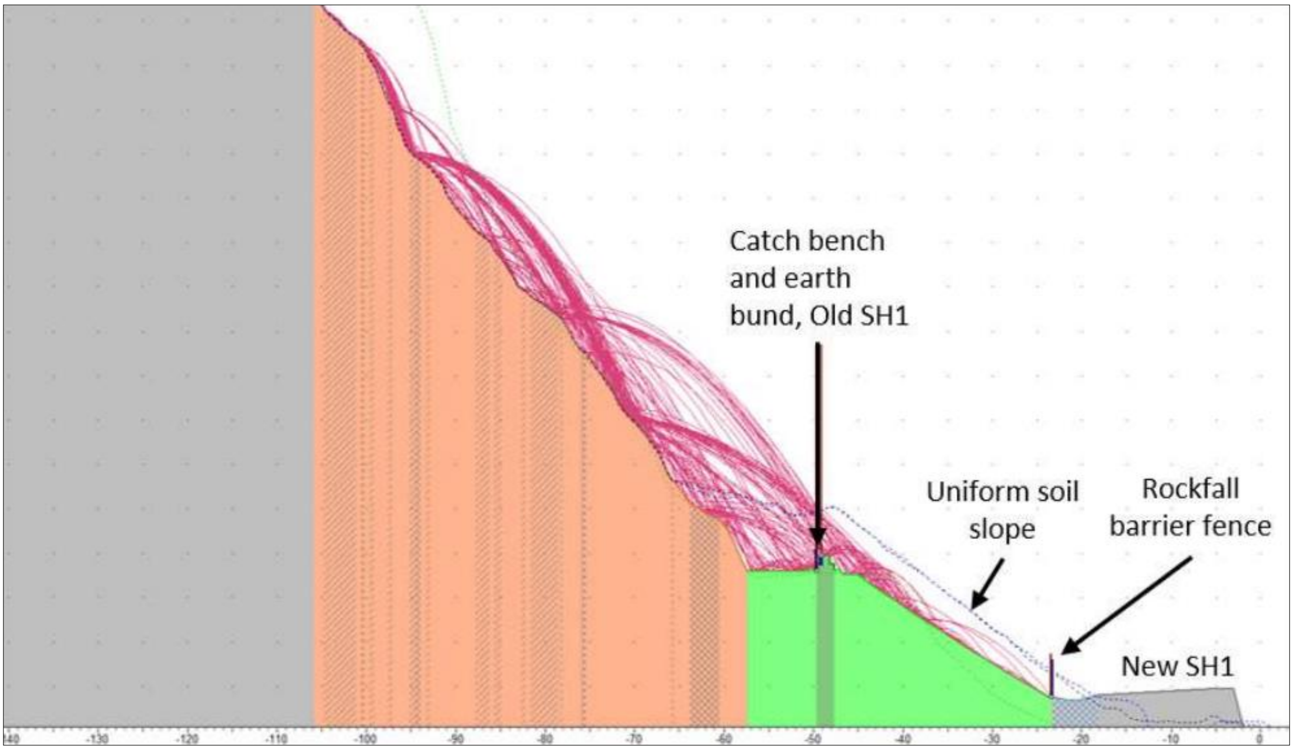

Figure 3: Example rockfall simulation showing the effect of the proposed rockfall protection measures, [P6N]

2D Rockfall modelling results from identified preferential rockfall paths are summarised in Table 1, with those preferential trajectories shown on the 3D rockfall trajectory analyses of Figure 4. Block size distributions were refined based on field observations and vary across the site. Modelling indicates that < 1% of 95 percentile size boulders will pass the fence if they have bypassed the catch bench, bund and profiled uniform slope above.

Table 1: Summary of the f individual rockfall analyses results at site P6.

Section*	% passing bund	95% bounce height at bund (m)	95% kinetic energy on bund (kJ)**	% passing fence	95% bounce height at fence (m)	95% kinetic energy on fence (kJ)**
A_1	< 1%	0.5	200	< 1%	< 1	< 10
B	1%	4	100	< 1%	< 1	< 10
D_1	10%	7	155	< 1%	< 1	< 50
G***	12%	10-21	650-1000	< 1%	0.2-3.0	65-1105
H	16%	10	100	< 1%	1.9	115
J	25%	15	100	< 1%	3.25	145

*Section matches Figure 4 trajectories. ** Translational kinetic energy *** Multiple sources considered

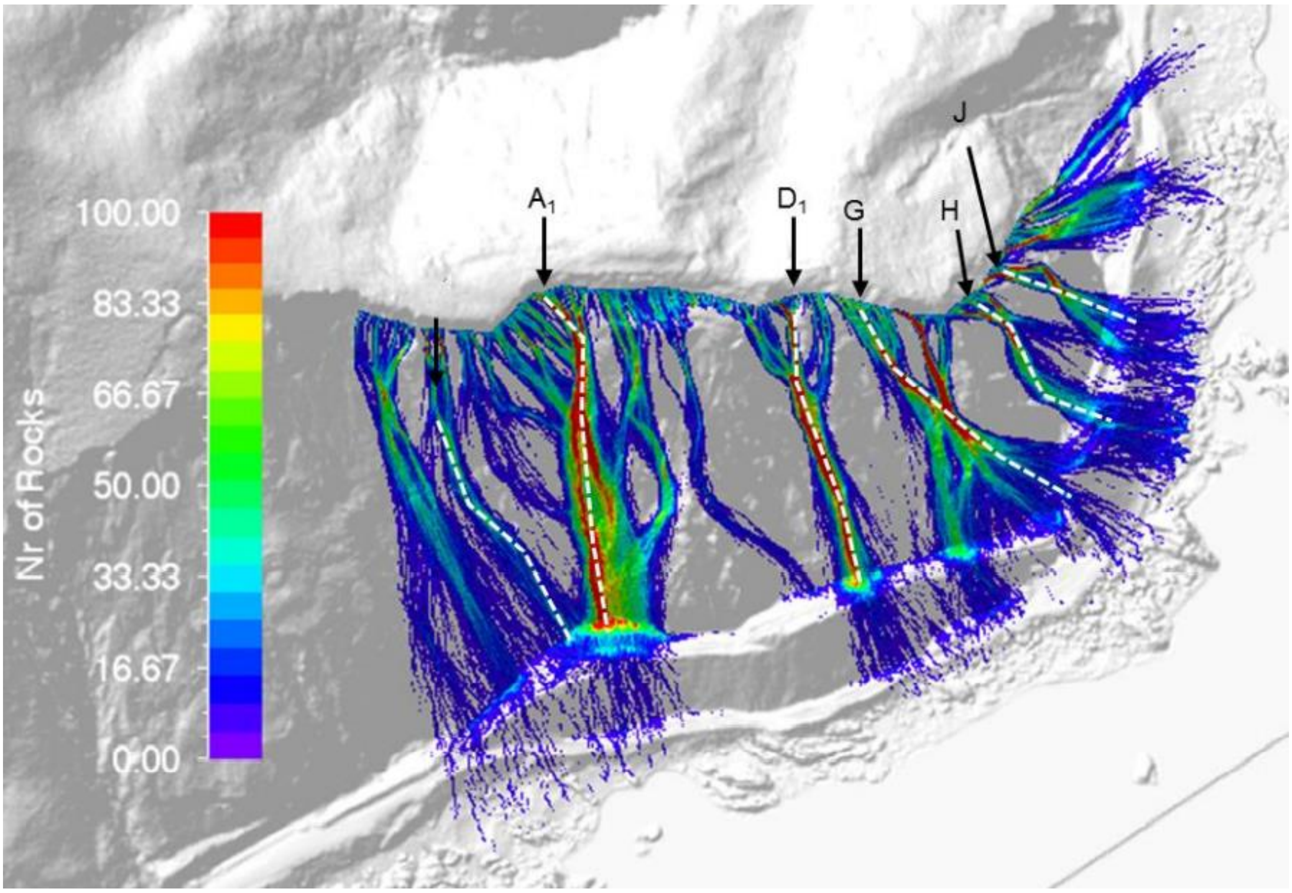

Figure 4: Rockfall hazard heatmap showing preferential rockfall paths (after Colgan 2018)

4.2 HRRB Design Matched Bounce Height and Impact Loads

The 4 m high, 2000 kJ Maccaferri RMC 200/A HRRB was adopted early in the design process to allow for procurement lead times and leveraged benefits of providing a standardised product being deployed at similarly impacted sites along the NCTIR project corridor. The Maccaferri RMC 200/A will accommodate the modelled impact energy and bounce heights from individual rockfall (95th percentile block size) assuming this as representative of the MEL (analogous to a ULS impact). MBIE guidelines ("Design considerations for passive protection structures", 2016) suggest a serviceability energy limit (SEL, analogous to an SLS impact) of 0.33 x MEL. The fence readily complies with this in all but the most extreme design case for rockfall path G (Table 1).

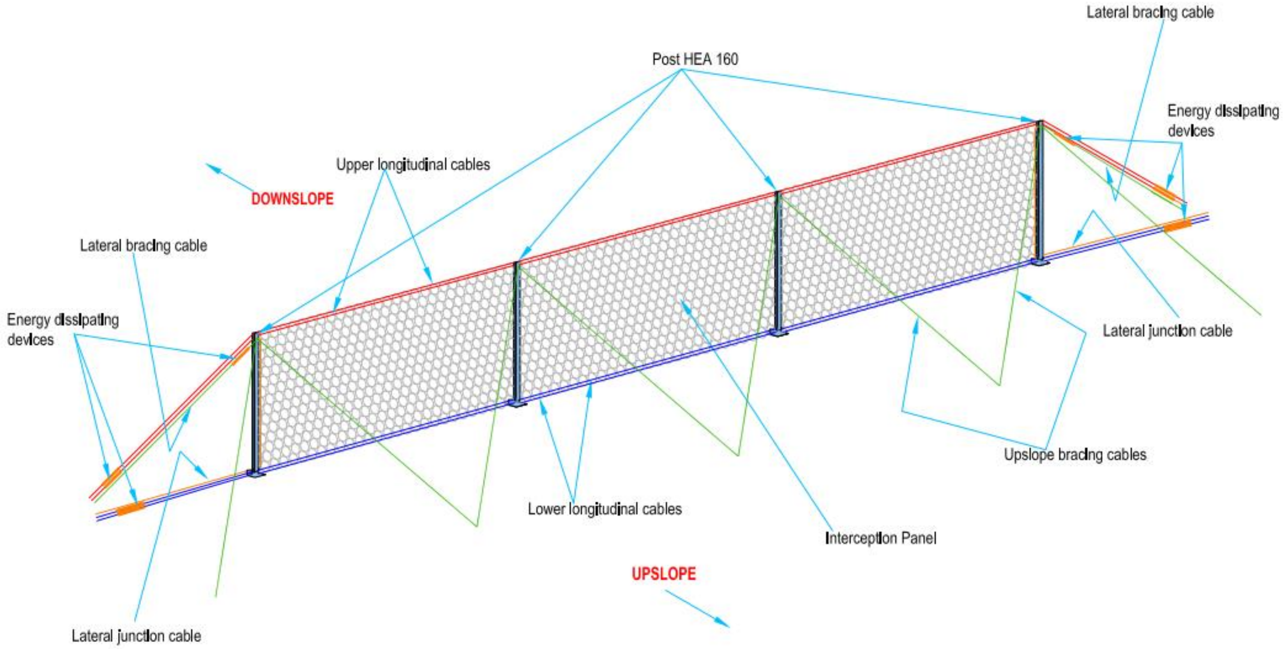

Figure 5: Maccaferri RMC 200/A configuration elements (Maccaferri 2013)

4.3 Fence Anchor Loads

Loads for the anchors and foundations are sourced from manufacturers documentation (Maccaferri 2014). These reference loads are unfactored loads based on MEL testing of the fences as part of ETAG 027.

The design criteria used to calculate the required minimum bond length for the anchors is based upon Table 2 of BS8081:2015, a minimum Factor of Safety (FoS) of 2.0 has been used for the ultimate grout/ground bond capacity of the anchors. Anticipated ground conditions were interpreted from ground investigation boreholes, site specific investigation anchor testing, and anchor testing results from other sites in the NCTIR project.

5 MACCAFERRI RMC 200/A 2000KJ HRRB CONSTRUCTION

The Maccaferri RMC 200/A HRRB is a modular system that can be adapted to suit the site requirements and is provided in a standardised kitset form to facilitate ease of construction. Variations can be incorporated into the system to maintain performance where obstructions or slope geometry prevent the use of standard components. The Ohau Point 2000kJ fence used standard supplied component kits provided in 50m long sections. The barrier was installed with an intermediate post between the adjacent 50m sections allowing the barrier to extend the required 600 m and provide a near continuous barrier adjacent the road.

5.1 RMC200A Setout

The proposed fence alignment covered the entirety of the [P6S] and [P6N] footprint, immediately upslope of the new SH1 road alignment drainage swale. A 5 m minimum offset from the edge-of-seal for the alignment was used where the swale drain geometry changed along its length. Natural and adjacent project construction features that needed to be accommodated in the alignment were:

- At the southern end of [P6S] the fence needs to overlap the northern end of an upslope Terramesh rockfall bund. In this location the swale drain terminated against the northern end of a raised pile wall embankment.
- At the junction between [P6S] and [P6N] is a sub vertical rock bluff (Figure 1) which pinches out the swale drain immediately north and south of its location. At this location, the fence was terminated on both the southern side and northern side of the bluff, leaving a 25 m section with no fence.
- Mid way along the [P6N] a rehabilitated crib wall encroaches to within 1800 mm of the new SH1 road alignment. At this location, the drainage swale terminated into a catch pit which is also fed by subsoil drainage pipe running along the edge-of-seal to the north.
- At the northern end of [P6N] a maintenance ramp accessing the new upslope catch bench meets road level, open access to this by off road haul truck is required.

Incorporating the outline features meant the 2000kJ fence alignment would be constructed in 3 sections: B1 - all of [P6S] between the southern terra mesh bund and the central rock bluff; B2 - southern part of [P6N] between the central rock bluff and the rehabilitated crib wall; B4 - the remaining northern part of [P6N] between the rehabilitated crib wall and the northern access ramp for the new catch bench. A redundant alternative alignment section B3 parallel to B4 but slightly upslope on the edge of the new catch bench was initially considered but had lower performance identified in the rockfall modelling.

Maximum elevation change between adjacent posts is suggested to be within +/- 0.5 m. Elevations of each post along the alignment were confirmed and where required iteratively adjusted using an optical level.

5.2 Anchor Drilling

Anchor drilling was completed with two excavator mounted top hammer hydraulic rigs, which facilitated ease of positioning setup for the various anchor installation geometries required.

Figure 6: Excavator mounted drill rig installing self-drilling foundation micro-piles at Ohau Point

5.2.1 Bracing and Lateral Anchors

Lateral and bracing anchor bars were predominantly installed into landslide debris using a self-drilling method under grout flush, with the locations directly into rock drilled by an open-hole drilling method. The anchor bars used were Ischebeck Titan 40/16 bar with a Maccaferri flexible anchor heads used to enable attachment of the barrier support cables.

5.2.2 Post Foundation Anchors

Barrier post foundations were located predominantly in landslide debris and comprised a reinforced concrete plinth anchored to the ground by one vertical micropile (compressive forces) and two splayed upslope anchors (tensile forces). The same bar type Titan 40/16, was used in both cases. Baseplates for the posts are connected to the plinth foundation by four Reid RB32 bars embedded in the reinforced concrete plinth.

For the few post foundations located on rock, four 1.5 m long anchor bars were installed perpendicular to the slope into competent rock. A reinforced concrete plinth was used to provide a level surface for installation of the post bearing plate which was connected directly to the anchor bars.

5.2.3 Anchor Acceptance Testing

The objective of the anchor acceptance testing is to demonstrate the anchor can sustain the design loading. As part of the final works, 10% of installed anchors were subjected to testing in accordance with BS EN 8081:2015 Section G.4. Additional anchors with construction issues or had previously failed were also selected for acceptance testing. Selection of the anchors to be tested was carried out by reviewing the drilling logs and assessing the ground conditions that may impact the grout ground the bond capacity, where the ground was assessed to be poor the anchors were tested.

5.3 Post Plinth Construction

Plinths were constructed inclined to match the slope geometry, facilitating load transfer from fence post baseplate to ground bonded anchors, typical examples of plinths under construction shown in Figure 7.

Figure 7 Plinth construction, note the variable particle sizes in the excavations. A) Landslide debris plinth detail B) Rock plinth detail C) Poured plinth awaiting backfill D) Bracing anchor flexhed plinth detail.

5.4 RMC200/A Assembly

As sections of bracing anchors and plinths were completed, construction of the HRRB fence could begin. This allowed construction personnel to be installing the barrier posts, associated cables, mesh and energy dissipating elements while anchor drilling continued for another section of the HRRB fence.

Figure 8: Partially constructed barrier, posts, foundations and bracing cables in place

5.5 Construction Challenges

Construction challenges for the project can be broadly separated into two categories, issues with drilling conditions or issues with geometry.

5.5.1 Drilling challenges

At Ohau Point the landslide debris is generally comprised of loose non-cohesive material with a wide variety of particle sizes, from very large boulders (sometimes several metres in diameter) to sands and silts, there was also present large voids within the material. Using open hole drilling methods were not considered feasible in this material due to potential hole collapse prior to installation of the bar and grouting. Self-drilling was the preferred method by the specialist installers, however the ground conditions created issues with the self-drilling technique and there were challenges achieving grout return. This became evident early into the project. with volumes of grout greatly exceeding the theoretical grout volume To mitigate this issue identified early in the construction phase, all anchors were drilled under grout flush to target depth with a Water Cement ratio (W/C) = 0.7 "runny mix", the self-drilling anchor bar retrieved and grout in the hole allowed to "cure" for 24 hrs. After the 24 hr period re-drilling attempted to get return with a 300% maximum of the theoretical grout volume using a thicker grout with a W/C = 0.4 ratio. This was attempted twice and if grout return could not be achieved the anchor was left in place and subject to acceptance testing to verify their load carrying capacity, any that failed the acceptance testing were rejected and a replacement anchor installed.

Over a 40m portion of the 2000kJ fence B1 section a subsurface obstruction was encountered, potentially metallic and possibly a displaced remnant of Armco traffic barrier which prevented the vertical plinth anchors achieving their target depth. Given the upslope anchors for all affected plinths had already been successfully installed in this location the concrete plinth dimensions were increased to provide adequate vertical load carrying capacity for the post foundations and no vertical micropile anchor installed.

5.5.2 Geometry challenges

Apart from the southernmost 30 m, at Ohau Point the fence alignment is on a convex geometry for its entire 600 m length. The recommended fence layout (Maccaferri 2013) is a straight horizontal line, offsets can be accommodated, but usually requiring additional bracing anchors and cabling to be constructed on intermediate post positions. As the 2000 kJ fence was supplied in a series of standardised 50m long kits, where possible the alignment was 'straight-lined' into 50 m runs with all orientation changes accommodated at the shared end posts of each run. With this principle the alignment was able to be constructed requiring only two additional downslope bracing anchors/ropes on the intermediate posts. The use of shared end post, with lateral anchors on both sides of the shared post enabled the continuous long length of fence. A benefit of using shared end posts is to minimize and contain the maintenance or repair to the particular section of the fence that has been impacted by rocks.

While the 2000kJ fence alignment accommodated the prominent features outlined in 5.1, the lateral and in particular the upslope bracing cables encountered more discrete features that necessitated modified anchor set out locations. Resolution was achieved by separating the single shared upslope anchor into two independent upslope anchors located where the projection of a standard bracing cable geometry intercepts the obstruction, thereby maintaining the geometry of any applied loads. This technique was utilised nine times across the three fence segments, an example of one shown in Figure 9.

Figure 9 Southern end of 2000kJ B2 segment with modified upslope bracing cable geometry

Figure 10: Looking north along an upslope portion of the completed barrier B1

6 CONCLUSIONS

In conclusion, the scale of the damage caused by the Mw 7.8 earthquake combined with the compressed timeframe to reopen the transport corridor lead the design team to adopt an innovative multi-faceted top-down rockfall protection system design. These include multiple ‘at source control’ measures on the slopes and moving the road away from the rockfall and landslide threat by constructing the MSE sea wall. A key facet of the system is the 4 m high 2000kJ Maccaferri High Resistance Rockfall Barrier RMC 200/A constructed adjacent to the new SH1 road alignment, being the final passive rock fall protection structure to catch any material that may bypass or overwhelm the upslope protection measures.

Using a pragmatic approach to deal with the grout loss into the landslide debris during anchor installation, supported by a rigorous acceptance testing regime where grout return was not achieved, has meant the design objectives could be met while managing the time/cost impact to the project.

The modularity and inherent flexibility afforded by the 2000kJ fence system meant that geometric alignment issues could be readily mitigated without the need for sourcing customised componentry, achieve the design intent, and maintain the ETAG 027 certification of the product.

Collaboration across several teams including the NCTIR Design Team, NCTIR Delivery Team, Maccaferri, and Geovert, enabled the successful construction of the Maccaferri RMC 200/A HRRB at Ohau Point.

Figure 11: Ohau Point with the completed rockfall mitigation works in place.

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