

# Rockfall Protection Structures on a Critical Lifeline in Christchurch

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## ABSTRACT

Following the 2010/11 Canterbury Earthquake Sequence in Christchurch, significant rockfall, cliff collapse and mass movement features occurred around the Port Hills. The Sumner-Lyttelton Corridor is a critical link between Lyttelton Port and Christchurch CBD for transportation of oversized and hazardous goods and suffered extensive rockfall and slope failures from the earthquakes. Sections of the Sumner-Lyttelton Corridor have been kept operational through the use of temporary rockfall protection measures in the form of ballasted shipping containers. The Wakefield Avenue section of the Sumner-Lyttelton Corridor had three areas affected by rockfall and cliff collapse, which were temporarily protected by ballasted shipping containers. This paper focuses on the design of the permanent rockfall protection structures at two sites along Wakefield Avenue which will allow the removal of the shipping containers and mitigate the rockfall and cliff collapse geo-hazards in the long term. The project involved carrying out geotechnical investigations, identifying the rockfall sources, mapping existing rockfall, modelling rockfall trajectories, ground truthing modelling outputs, design of rockfall protection structures and providing assistance to the client during consenting and construction. It is concluded that important considerations for the design and construction of rock fall protection structures include detailed topographic surveys, stormwater management, service clashes and safe construction methodology.

*Keywords:* rockfall, protection, critical lifeline, Canterbury Earthquake Sequence

## 1 INTRODUCTION

The 22 February 2011 M6.3 earthquake event in Christchurch, part of the 2010 – 2011 Christchurch earthquake sequence (CES), caused significant damage to the Christchurch area with damage and collapse of buildings in the city centre and significant rockfall, cliff collapse and landslides in the Port Hills south to southeast of Christchurch's CBD. The 13 June 2011 M6.4 aftershock had peak ground accelerations (PGAs) exceeding 2g at a seismograph in the Heathcote Valley (Geonet 2011) which created considerable rockfall and cliff collapse especially around the Sumner area. A critical link between Lyttelton Port and Christchurch CBD, referred to as the Sumner-Lyttelton Corridor, was affected by cliff collapse, rockfall and mass movement. Temporary protection in the form of ballasted double and single stacked containers was put in place in the highest risk areas to allow use of the road until permanent remediation or protection measures could be implemented.

This paper will focus on the site work carried out, including shallow investigations and mapping, rockfall modelling and design of the rockfall protection structures for the two highest risk sections along a 1.1 km section of Wakefield Avenue. Jacobs developed a concept design involving two rockfall bunds along Wakefield Avenue to reduce the risk of rockfall to the road corridor for Christchurch City Council (CCC). The concept design was then taken through to a detailed design solution for tendering and construction.

## 2 SITE DESCRIPTION

### 2.1 Geology and Topography

Wakefield Avenue runs approximately north-south along the western side of Sumner at the base of Richmond Hill as shown in Figure 1. The slope above Wakefield Avenue rises from approximately 3 m above sea level (masl) at Wakefield Avenue to 170 masl at the crest of the slope. The site geology is typical of the Port Hills and predominantly consists of loess (wind-blown silt), underlain by the Lyttelton Volcanic Group basaltic to trachytic lava flows interbedded with breccia and tuff (Forsyth, P.J. et al, 2008). The joints and defects within the basalt and pyroclastic deposits generally form tabular or

equidimensional blocks, however the jointing is irregular and generally does not form persistent joint sets. The northern end of Wakefield Avenue is dominated by cliffs approximately 60 m tall below Richmond Hill while the majority of the site is typically moderately steep slopes (25-30°) with discrete bluffs along the slope (Engel, 2015). Where the basalt and pyroclastics outcrop on the slopes they form prominent rock bluffs that run across the slope. The loess slopes have developed shallow soil failures, tunnel gullies and debris flows predominantly along ephemeral drainage lines.

## 2.2 Geohazards

The three main geo-hazards affecting Wakefield Avenue are rockfall or boulder roll, cliff collapse and debris flow. During the 2011 CES, notably the 22 February and 13 June aftershocks, over 15,000 m<sup>3</sup> of debris (Massey et al. 2014) fell from the cliff collapse at the northern end of Wakefield Avenue (Figure 1). Significant ground cracking was mapped through the properties above the cliffs extending up to 50 m back towards Richmond Hill Road (Massey et al. 2014). The results of GNS mapping, modelling and investigations of the area identified 10 debris avalanche (cliff collapse) sources and thus the area was designated a Class 1 Mass Movement Area (Massey et al. 2014). The modelling of the 10 debris sources by GNS identified that only two of the sources have the potential to impact Wakefield Avenue.

At the southern end of Wakefield is a 170 m long continuous bluff below Richmond Hill Road and a smaller mid-slope bluff that were sources of a significant amount of rockfall during the CES (Figure 1). The majority of boulders that fell from these sources during the CES accumulated on the slope and park area at the base of the slope, however approximately 20-25 discrete boulders and some fly rock came to rest on the road with at least 7 boulders rolling across Wakefield Avenue into properties on the eastern side of the street.



Figure 1. The rockfall and cliff collapse hazards affecting Wakefield Avenue are indicated in yellow and red respectively. (Image courtesy of Google Earth Pro, 30 June 2016).

A risk assessment of future rockfall to the Wakefield Avenue portion of the Sumner-Lyttelton Corridor was undertaken (Swatton 2014) and identified four sections where the risk was classed as high to very high. GNS undertook research (Massey et al. 2012) and provided advice to CCC on acceptable levels of risk for different activities to allow CCC to identify what an acceptable level of risk for normal use of Wakefield Avenue would be. The sections of the Sumner-Lyttelton Corridor where the risk was assessed to be higher than medium, some form of remediation or rockfall protection structure was required. This paper focuses on two of the high risk sections on Wakefield Avenue (below the highlighted areas in yellow and red in Figure 1).

### 3 FIELD INVESTIGATIONS

The majority of the work undertaken on site prior to Jacobs's involvement centred around GPS mapping of rockfall boulders and some at source remediation of rockfall hazards. After the 22 February 2011 event, contractors undertook at source remediation of the continuous bluffs at the southern end of the site, including blasting and rolling loose boulders to the bottom of the slope. The highly fractured nature of the bluffs made this kind of at source remediation difficult, as removing unstable material at the surface often uncovered more unstable material behind. Jacobs mapped fallen boulders – refer Figure 2(a) and (b) – to identify run out distances and sizes of the boulders which were compared to the information used in the GNS pilot study (Massey et al 2012a) to determine what size boulders the remediation solution would be required to stop. It was difficult to determine which boulders fell as a result of the earthquakes and which had fallen from the source treatment works. Regardless, they all provided information on the size of boulders and run out distances that could be expected at road level.



Figure 2. (a) This boulder is approximately 3 m<sup>3</sup> and is the result of rockfall from the continuous bluffs at the southern end of Wakefield Avenue; (b) This boulder fell as a result of the cliff collapse at the northern end of Wakefield Avenue. The boulder has landed at the base of the cliff immediately below where it was located; it has not rolled out towards Wakefield Avenue.

### 4 ROCKFALL ANALYSIS

Rocscience ® RocFall 5.0™ software was used to analyse the rockfall hazard along seven cross sections at the two locations where rockfall protection structures were proposed. Ground profiles were generated using LiDAR data flown by the Earthquake Commission (EQC) with the slope surface material properties used in the model based on information published by GNS (Massey et al. 2012a, Townsend et al. 2012a) and from Jacobs's site investigations. RocFall™ models rockfall trajectories from designated sources on the slope profile and considers how the boulders interact with the materials they impact on the slope and calculates bounce heights, kinetic energy (translational and rotational) and velocity (translational and rotational). Multiple boulder paths can be analysed simultaneously with the software (in our case 2000 boulder paths per model run). The modelling requires a design boulder size to be defined; for this project the design boulder size was assumed to be the 95<sup>th</sup> percentile, i.e. only 5% of the boulders that could fall from the site have the potential to exceed that size. In our area there were two different scenarios, cliff collapse and rockfall so two different boulders sizes were used for the modelling.

GNS carried out slope stability modelling of the cliff collapse hazard at the northern end of the site for the 10 individual cliff collapse sources (red and black areas in Figure 1) and identified the potential run out distance of slip material and debris. To determine the energy level and bounce height of boulders that could impact a protection structure during a cliff collapse event, rockfall modelling was undertaken. The 95<sup>th</sup> percentile boulder for modelling the cliff collapse scenarios was assumed to be the largest mapped boulder that was generated from the cliff collapse, which was 8 m<sup>3</sup>.

CCC engineers (Port Hills Geotechnical Group) mapped the boulders that fell as a result of rockfall or boulder roll during the Canterbury earthquakes and aftershocks to produce a database of boulder sizes and run out distances. Based on the database of mapped boulders, GNS determined the 95<sup>th</sup>

percentile boulder size for the rockfall hazard in Sumner (yellow areas in Figure 1) was 3 m<sup>3</sup> (Massey et al. 2012a).

The results of the modelling were compared to onsite observations of rockfall run out and the mapped boulder database to calibrate the modelling. In general there was good agreement between the modelling and the mapped rockfall giving us confidence the modelling was realistic. A boulder in the order of 3 m<sup>3</sup> was identified in an aerial photo taken after the 13 June earthquake on Wakefield Avenue against a container which compared well with run out distances identified in the modelling. Discussions with residents suggested that the boulder may have been rolled by contractors remediating source material however it provided valuable information on expected run out distance and the size of boulders that could be released from this source. A summary of the modelling results taken approximately from the back (slope side) of the protection structure footprint are provided in Table 1.

Table 1. Summary of modelling results

Location	Bounce Height (m) <sup>a</sup>		Total Kinetic Energy (kJ) <sup>a</sup>	
	Minimum	Maximum	Minimum	Maximum
Cliff Collapse Northern End	1.0	1.5	2,200	2,600
Rockfall at Southern End	1.4	4.4	800	1,200

<sup>a</sup>Bounce height and total kinetic energy values are taken at the back of proposed rockfall protection structure locations.

## 5 ROCKFALL PROTECTION STRUCTURES

Two options were considered for remediating the cliff collapse and rockfall hazards above Wakefield Avenue: 1) at source treatment, 2) rock fall protection structures, including rockfall bunds and rockfall catch fences. At source treatment of the hazard was ruled out at the cliff collapse site due to the scale of the tension cracking behind the crest of the bluff and the high risk environment for any workforce. At source treatment of the rockfall hazard had been trialled on the continuous bluffs previously and was judged to be unsuccessful.

Both the cliff collapse and rockfall sources have the potential to release multiple boulders in a single event therefore a rockfall protection structure (RPS) in the form of a bund or a fence would provide the most efficient method of reducing the risk to the road. A key requirement of any RPS at this site is the ability to withstand multiple impacts during a single event plus further impacts during aftershocks or prolonged weather events following the main event, before being repaired or cleared. Other important requirements set by CCC for RPS on this project included the design life of the structures to 100 years and the consideration of ongoing maintenance and repair costs in the overall cost of the structure.

### 5.1 Green Terramesh Bunds

A comparison between rockfall bunds and fences was undertaken to look at the best option for this site. The advantages of a bund over a rockfall catch fence included its ability to withstand multiple impacts without losing too much capacity or height, installation and maintenance did not require specialist contractors or plant, and the costs and time associated with repairing the structure after an impact were lower in most cases. Based on these advantages a decision was made to go with a rockfall bund which could withstand multiple impacts before requiring repair. Research into the type of rockfall bunds typically used for this sort of environment and hazard was undertaken and Green Terramesh (GTM), a product supplied by Geofabrics used both locally and globally to form reinforced rockfall bunds, was identified. The manufacturer of GTM bunds have undertaken full scale field tests on the bunds and the results have been modelled and analysed using Finite Element Method (FEM) to support the design philosophy based on boulder energies and bounce heights. Two options were considered for the finished face of the bund; 1) vegetating the face with grass or native plants to give a more natural, softer appearance, 2) facing the bunds with larger rocks.

Jacobs worked with Geofabrics to design the rockfall bunds using their GTM units. GTM bunds are a modular design meaning they can be scaled to suit the requirements for each site and can be constructed across uneven terrain. The modular nature of the GTM units means that individual sections can be repaired without deconstructing large sections of the bund to make repairs. Repair in a lot of cases, is as simple as stitching a new double twist mesh section and edge cables across the damaged area.

Jacobs worked with Geofabrics to design the bunds to meet the height and impact requirements identified in Table 1. The height of the bund was determined by assuming the modelled impact point occurs at the midpoint of the boulder, then adding the radius of the boulder (to get to the top of that boulder impact) plus a minimum “freeboard” equivalent to one boulder radius above the top impact point of the boulder (Maccaferri 2012). For example, if the boulder is 3 m<sup>3</sup> with the dimensions 2 m x 1.5 m x 1 m and a bounce height of 1.2 m, 1 m is added to get the top point of the boulder that impacted the bund half the longest side of the boulder) then 1 m freeboard is added for the radius of the boulder, meaning the minimum bund height needs to be 3.2 m tall. The minimum crest width of a GTM bund is determined by the amount the design boulder would penetrate into the bund and the modelled bounce height. The minimum width at the point of impact recommended by Geofabrics is 2 times the penetration depth determined from a correlation between boulder radius and energy level (Maccaferri 2012).

## **5.2 Cliff Collapse Hazard**

A rockfall bund at this location would need to withstand bounce heights up to 1.5 m above ground level (magl) with a total kinetic energy up to 2,600 kJ as indicated in Table 1. The RPS designed for the cliff collapse hazard was a 3.6 m high GTM bund 132 m long with 70 degree slopes. A minimum crest width of 1.5 m was specified to accommodate the high energy levels and maintain the minimum width of the bund at the location of a boulder impact. Based on feedback from the community, this rockfall bund was to be faced with greywacke cobbles.

## **5.3 Rockfall Hazard**

The length of area affected by rockfall hazard is 252 m and the distance the road is from the base of the slope varies considerably. As indicated in Table 1, the bund would need to be able to accommodate boulders with bounce heights between 1.4 and 4.4 m and with a total kinetic energy up to 1,200 kJ. At the northern end of the affected section, the road is as close as 5 m to the base of the slope, compared to up to 55 m at the southern end. At the northern end, the boulders are modelled as bouncing off the steep rock and soil faced bluffs and impacting the bund at 4.4 magl, these boulders aren't actually bouncing 4.4 m. At the southern end of the section the bounce heights are up to 1.4 magl.

The GTM bund designed to mitigate the rockfall hazard at this area is 3.6 m high with 70 degree slopes and a minimum crest width of 1.5 m from the southern end until the bund is 10 m from the toe of the slope. When the bund was within 10 m of the toe of the slope, the bund is stepped up to 6 m high to accommodate the higher bounce heights. Due to the limited space between the base of the slope and the road, the sides of the bund needed to be steepened to 80 degrees to minimise the footprint and still maintain the minimum crest width of 1.5 m. Based on the consent requirements, this bund needed to have a vegetated face where possible. Where the bund has 70 degree slopes, the face was to be vegetated by native plantings. Where the bund face is steeper than 70 degrees, to maintain stability, the face was finished with greywacke cobbles.

## **6 IMPORTANT CONSIDERATIONS FOR ROCKFALL BUNDS**

Through the process of designing and constructing the rockfall bunds a few key design considerations and lessons were learnt. A detailed topographic survey of the bund footprint and the surrounding area is recommended as small variations in topography along the length and width of the bund can have a significant impact on the volume of soil to be excavated. As rockfall bunds are typically installed at the base of, or on a slope they will affect stormwater flow. Stormwater design is important to ensure the bunds don't start acting as a dam, retaining water. This is also where a detailed topographic survey becomes important. As the bunds can cover a large area, both in length and width, it is crucial to identify any services in and around the bund location. Both underground and overhead services can have an impact on the bund location or, if the location can't be altered, relocating affected services which can lead to significant programme delays and costs if not addressed early in the design.

Rockfall bunds are only constructed in areas where there is a risk of being hit by boulders, therefore developing appropriate construction, maintenance and repair methodologies during the design phase is important. Safe construction methodologies, reducing the risk to the construction team, may impact the layout of the bund and should be considered early in the design.

## 7 CONCLUSION

The 2010/11 CES, notably 22 February and 13 June 2011, created significant instability in the Port Hills and along the Sumner-Lyttelton Corridor. The Wakefield Avenue section of the Sumner-Lyttelton Corridor was affected by cliff collapse, in particular at the northern end of Wakefield Avenue and rockfall or boulder roll, in particular at the southern end. Jacobs were involved in taking a concept design of mitigation measures to reduce the risk to Wakefield Avenue and develop it into a detailed design and supporting the client with construction supervision. Rockfall modelling of the 95<sup>th</sup> percentile boulder for the two different hazards was undertaken to determine the bounce height and energy levels of boulders that could impact Wakefield Avenue. The results of the modelling were compared to mapped boulders (i.e. real data from the earthquakes), to check that the results were realistic.

After considering remediation options including at source treatment of the hazard, rockfall catch fences and rockfall bunds, it was determined rockfall bunds would best meet the design life and multiple impact requirements. Jacobs worked with Geofabrics to design GTM bunds for the cliff collapse hazard and rockfall hazard. The results of the modelling of the energy levels at the cliff collapse were used to design a 132 m long, 3.6 m high rockfall bund with 70 degree, rock faced slopes to reduce the risk to an acceptable level. The results of the modelling for the rockfall hazard indicated higher bounce heights at the northern end due to the closer proximity to the bluffs at the base of the slope. The rockfall bund at the southern end is 252 m long, 3.6 m high with 70 degree slopes until the boulder gets 5 m from the base of the slope where it steps up to 6 m high with 80 degree slopes.

Important considerations identified during the design of the rockfall bunds were that a detailed topographic survey is required, stormwater needs to be managed and that service clashes need to be identified early to allow changes to the design or relocating the services. Safety in construction, maintenance and repair in case of impact needs to be addressed early during the design phase.

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