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# Risk and Rockfall: Observations on the Implementation of Rockfall Mitigation at Residential Properties in the Port Hills

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## ABSTRACT

Rockfall has long been recognised as a risk to the community of the Port Hills. The 2010/11 earthquakes triggered rockfall which caused fatalities and damage to property. This event initiated an increased understanding of rockfall risk and the implementation of risk reduction actions.

Area-wide analyses were commissioned following the earthquakes, and were used to assess the risk to residents. These analyses influenced zoning decisions which have had, and continue to have, a significant impact on the recovery process. There has been a corresponding step-change in societal understanding of, acceptance of, and response to rockfall risk.

This paper discusses the key differences between site specific assessment and the area-wide studies, and presents some examples of learnings from projects. Issues encountered in undertaking and arising from rockfall mitigation are discussed. It presents brief case studies illustrating rockfall risk assessment and rockfall protection structure design for residential properties in the Port Hills, and discusses the different approaches to risk observed.

## Introduction

The Port Hills south of Christchurch, New Zealand, form the northern portion of the two former volcanoes of the Banks Peninsula. A number of the valleys of the Port Hills, especially those on the northern faces, have been subject to residential development. The Christchurch suburbs of Cashmere, Heathcote Valley and Sumner are all located in valleys of the Port Hills, and residential areas extend up the sides of these and other valleys. Rock outcrops are commonly encountered up-slope from residences and infrastructure in these areas.

The Port Hills are characterised by rocks of the Lyttelton Volcanic group, which are of Miocene age, approximately 5 to 23 million years old. The basaltic to trachytic lava flows are interbedded with breccia and tuff. Dykes and minor domes occur throughout the group (Forsyth et al., 2008).

Prior to the 2010/11 earthquake sequence the risk from rockfall in the Port Hills was not fully appreciated. As a result of the earthquakes a large number of rocks were dislodged, falling, bouncing or rolling down-slope and causing fatalities and damage to property and infrastructure.

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### *Background*

Following the earthquakes several area-wide studies were commissioned to analyse the risk to residents in the Port Hills from rockfall. A major study was completed by GNS on behalf of Christchurch City Council (CCC), and presented in a series of reports (Massey et al, 2012a, b, c, Taig et al, 2012, and Townsend et al., 2012). The GNS study sets out the principles of the assessment of rockfall risk, defines key reference parameters for use in rockfall analyses, presents risk reference maps, and recommends a tolerable risk level for the Port Hills.

The GNS study was a rigorous peer reviewed assessment, is highly regarded, and acts as a benchmark for subsequent studies in the area. It is required to be referenced when completing risk assessments under the CCC Rockfall Protection Structure (RPS) Guidelines (CCC 2013).

The Port Hills Geotechnical Group (PHGG) was established as part of the response to the 2010/11 Christchurch earthquakes. One of the many tasks undertaken by the PHGG was the recording of fallen boulders in the Port Hills. This information was and continues to be extremely valuable, and forms a vital part of regional and site specific risk assessments. The work undertaken by the PHGG is set out in Macfarlane and Yetton (2013).

A study was completed by Geovert (Avery et al., 2012) on behalf of CERA (Canterbury Earthquake Recovery Authority) using 3D rockfall analyses to indicate areas in the Port Hills likely to be influenced by rockfall run-out. The study was undertaken to aid the preliminary design of area-wide mitigation. The study did not directly present risk levels, but did provide output showing contours of potential rockfall run-out paths and boulder bounce heights, kinetic energies and velocities.

### *Area-wide risk zoning*

CERA zoned residential properties as unacceptable (red-zone) if the long-term annual individual fatality rate (AIFR) at the dwelling was judged to exceed the threshold risk level. According to Jacka (2015), CERA red-zoning status was not intended to be a formal hazard zoning with regard to the Resource Management Act 1991. It was instead intended to *"provide information to the public that could easily be understood about the future performance of land (...) and identify where the Crown should make an offer to purchase"*.

CCC placed uninhabitable (Section 124 or s124) notices on properties if it was concluded that persons at the dwellings would be at an immediate risk of loss of life by remaining in their properties. It should be noted that red-zone status is independent of the s124 process; some properties had both, some had neither, and some had one or the other. A good explanation of the s124 and red-zone processes is provided by Macfarlane and Yetton (2013). According to CERA (CERA website, 30 July 2015), the total number of properties in the Port Hills assigned red-zoning (due to both rockfall and cliff-collapse risk) is 714.

Red-zoned property owners in the Port Hills generally received an offer from the authorities for the purchase of the property, typically at the 2007 rated property value. The red-zoning potentially had other effects, for example on insurance premiums, re-sale values, and the future use of the properties and land.

In 2014 CCC commenced a review of its District Plan (the Christchurch Replacement District Plan), which provides a framework for development and resource management within the area of CCC's jurisdiction. The natural hazards information contained within this plan is subject to revision as part of this review. Relating to rockfall, two categories have been established (CCC 2014), based on the assessed risk at the property in question:

- *Rockfall Hazard 1:* Areas where the risk from rockfall is considered intolerable, and that sub-division, use and development is to be avoided.
- *Rockfall Hazard 2:* Areas where the risk from rockfall can be reduced to a tolerable level. Sub-division, use and development in these areas is to be controlled.

It is understood that areas that will be categorised as Rockfall Hazard 1 broadly, but not exactly, correspond to those areas which were red-zoned by CERA.

***Re-zoning***

The policy wording regarding the CERA zoning is important. It is noted on CERA's website that *"*[a] *property may only be re-zoned green if the Minister* [for Canterbury Earthquake Recovery] *is satisfied that the risk affecting* [a] *property has been* ***entirely*** *removed* (…)*"*. CCC, however, will allow re-zoning under the District Plan if the level of risk can be shown to have been reduced to below the threshold level. The assessment process includes the requirement for an independent peer review.

A significant issue is presented in that these two authority bodies didn't have policies that agreed, and some home owners were left in the middle. It is acknowledged, as stated above, that the CERA red-zoning and CCC District Plan serve different purposes.

It should be noted that red-zoning follows property boundaries (that is, a property will either be entirely red, or entirely green), whereas CCC District Plan hazard areas can cross boundaries.

## Case Studies

Arup has undertaken site specific assessments and rockfall risk mitigation designs for some twenty Port Hills houses over the last two years. This paper discusses the key differences between site specific assessment and the area wide studies, and presents two case study examples drawn from projects of what we have learned in completing this work:

**Case study 1:** A residential property on Avoca Valley Road, in Avoca Valley. The risk to the property is driven by the presence of a number of rock outcrops up-slope of the dwelling. Boulders were observed passing the property following the 22$^{nd}$ February 2011 earthquake, and a number of boulders were stopped up-slope by trees.

**Case study 2:** A residential property on Bowenvale Avenue, in Bowenvale Valley. The property was initially assigned a CERA green-zoning, but this was subsequently revised to red following the December 2013 CERA zoning review. Following a site specific assessment, it was established that the risk to the property was being driven by four individual rock sources above the property.

## Site Specific Assessment vs Area-Wide Models

The primary purpose of the area-wide analyses was to inform decision making regarding rockfall risk in the Port Hills. Both the GNS and Geovert studies acknowledge that they are area-wide studies. The CCC RPS Guidelines specify that a site specific geotechnical assessment is required to provide the basis for mitigation designs (CCC 2013).

Through comparison to a number of site-specific assessments, key differences between the site specific and area-wide approaches and the resulting implication to risk are highlighted below.

### *Rockfall source characterisation*

In the area-wide studies the source areas were considered to be a continuous cliff band across the entire valley. Potential rockfall sources were defined in the Geovert analysis as any slope greater than 45 degrees (Avery et al., 2012). Whilst both are effective first pass methods of establishing the position of potential source zones, site specific mapping shows that the assumption of constant rockfall sources could not be validated in many areas. A good example of a false source derived from slope angle was encountered during Case Study 2, whereby a slope at the rear of the property was identified as a rockfall source (Figure 1).

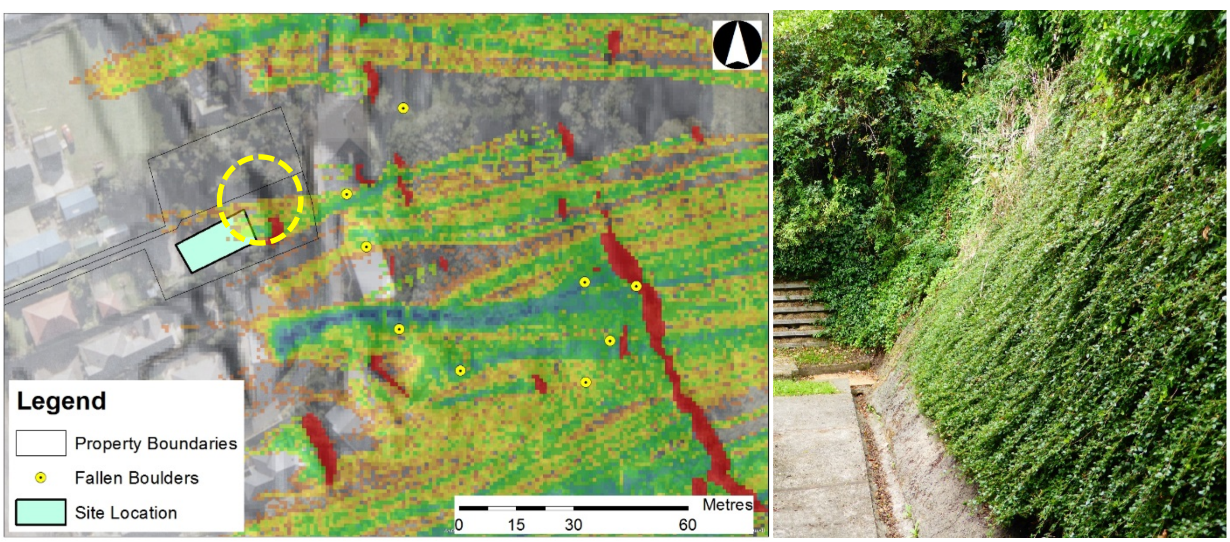


Figure 1: Retained slope behind Case Study 2 property identified as source (circled). Blue shading shows a concentration of boulder transit paths, red areas identify rockfall source zones (Avery et al., 2012).

The area-wide analyses defined long bands of source zone based on topography, but site specific mapping often showed a series of discrete sources with soil slopes in-between rather than a single long source. Whilst this does not greatly affect the run-out calculations, as run-out directions can vary by up to +/- 30 degrees (Macfarlane and Yetton 2013), it does mean that on occasion, the results of studies show potential boulder paths originating from sources that do not exist. If not picked up by cross-checking or field verification, this could lead to an increased perception of risk.

Geological mapping of the source zones was able to identify rock sources that would likely cause more rockfall versus others which were less likely to produce rockfall. The mapping was able to discern structural control (blocky vs. brecciated or pillow flows), evidence of recent falls (easy to identify from weather discolouring and vegetation) and the distribution of observed rockfall below the source to compare site specific rates of rockfall versus area-wide rates.

Another consideration was the total volume of modelled rockfall source. The risk calculation assumed a potential volume of rockfall that would be triggered following a specific earthquake ground motion. In some cases, when applying the rate of rockfall (derived from valley wide assessment and averaged over all potential source areas on a given slope) to a local rockfall source for the large events, it was clear that the volume of source present was insufficient, implying that the area-wide average rockfall rate was not applicable to the source in question.

***Topographic forcing***

The influence of topography was modelled by Geovert through the use of 3D rockfall modelling (Avery et al., 2012). This work gives an indication of the likely path of boulders, but did not quantify effect or calculate risk. Drainage path models undertaken during the case studies tended to support the results presented by Avery et al. (2012). It is acknowledged that both of these types of analysis do not take account of boulder shape.

Several studies (Massey et al, 2012a, and Macfarlane and Yetton 2013) note that the effect of topography can be relatively minor. Macfarlane and Yetton (2013) note that the influence of topography is related to the momentum of the boulder. It can be reasonably inferred that larger boulders travelling at greater speeds will be less influenced by topography, while smaller boulders travelling more slowly are more likely to be influenced by topography.

Topographic forcing factors were applied in site specific assessments where mapping showed dispersing or concentrating rockfall relative to a dwelling. These factors were only applied where it was assessed that boulders would be nearing the end of their run out, and would therefore be likely to be losing momentum. On many Port Hills slopes, reference to the fallen boulder record and topography indicates that prominent natural drainage gulley and ridge features clearly control rockfall. This is supported by evidence of concentrations of observed boulder run-out paths below gulley features, and reductions in the number of boulders (relative to the valley-wide distribution) below ridge features (refer Figure 2).

Where appropriate, factors were applied in the site specific assessments to represent the concentration of boulder paths towards or away from houses. The latter applied to Case Study 1, for which the natural slope orientation encouraged boulders away from the dwelling.

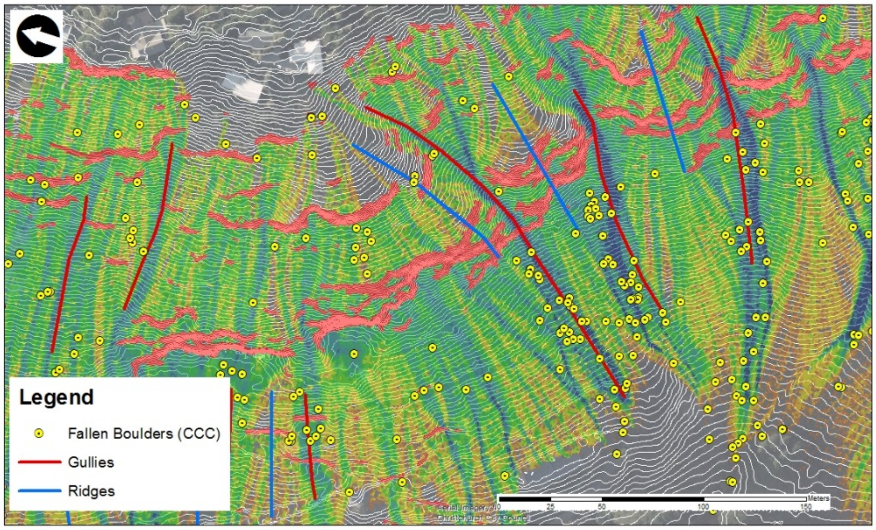


Figure 2: The influence of topography on boulder distributions (Heathcote Valley). Blue shading shows a concentration of boulder transit paths, and red areas identify rockfall source zones (Avery et al., 2012).

It is concluded that topographic forcing can influence the assessed risk to a specific dwelling, however careful assessment is required in order to rely on this factor for risk reduction.

## RPS and Mitigation: Discussion

### ***Common RPS and mitigation designs***

Common RPS include bunds, rockfall fences, terraces, or combinations of these structures. The common design aim of these structures is to absorb the energy of the boulder and stop it, thus preventing it from reaching the property or infrastructure protected by the RPS. Mitigation options, which are also covered under the CCC RPS funding agreements, include scaling, bolting and meshing, and source removal. These options aim to reduce or entirely remove the hazard, with a consequential reduction in risk.

For Case Study 1, although in Avoca Valley the area-wide rockfall rate was high, the site specific assessment showed that the source rate was not consistent across the rockfall catchment, there was topographic forcing, and the dwelling was far enough down the slope that rolling boulders were close to the end of their run-out paths. For this location, a terrace that would stop a significant percentage of boulder rolls was deemed to provide considerable risk reduction to bring the risk to an acceptable level.

A terrace was created with a small bund at its downslope end. Rockfall modelling during the design process demonstrated the effectiveness of the terrace (without the bund) in reducing the risk to well below the acceptable threshold. The small bund was added to provide additional protection. The client was informed that a larger bund would reduce the risk at the house to an even lower level, but in balancing the risk with their continued enjoyment of the property, they elected to accept a higher (but still below the threshold) risk in return for a smaller bund. Other structures (for example a fence or a primary bund) would have been feasible, but the property owners chose the terrace as it gave them a flat area, was less visually obtrusive than a bund, and will require less maintenance than a rockfall fence.

For Case Study 2, the site specific mapping showed a discrete number of rockfall sources above the property. It was considered technically and economically feasible to remove four source zones assessed as presenting a hazard to the property (Figure 3). Access to these properties was not difficult and the volume of material was not excessive. A new access track and the remediation of an old access track were included in the design. The rock sources were mitigated by milling (cutting) them back to an angle approaching the natural grade. This treatment rendered the outcrops to be non-credible sources of boulders, therefore reducing the risk to the property to a non-credible level.

Other areas of rock were present on the slope above the property, but based on geological mapping these were not considered to be credible rockfall source zones during the site specific assessment. These rocks had limited rock volume, no evidence of failure, irregular joints, and were located in a place with a low probability of impacting the dwelling. The singular rock sources were also assessed following the AGS Guidelines (AGS 2007) to present an individual risk to the property of less than $1 \times 10^{-6}$, and as such they were left in place. One of these sources was subsequently required to be mitigated by CERA to meet their requirements for re-zoning.

Figure 3. Case study 2: Example of rock source milled back to slope, Bowenvale Valley.

***Tolerable and residual risk***

A suggested tolerable risk was stated by GNS as being of the order $10^{-4}$ (Taig et al., 2012). The value $1 \times 10^{-4}$, at the lower end of this order, is commonly adopted as the threshold level. This number is comparable to the annual individual risk of being killed in a car accident in New

Zealand, and also to similar comparable international thresholds (Taig et al., 2012). When implementing rockfall mitigation the aim should always be to reduce the risk to as low as reasonably practicable (ALARP), a limit which is most often determined in practice by a balance between risk reduction and cost.

The requirement by CERA to mitigate a single source at Case Study 2 with a risk of less than $1 \times 10^{-6}$ (subsequent to completion of the designed mitigation) to meet their requirements for re-zoning highlights the difference in approach between CERA and CCC. CCC permit re-zoning under the District Plan in the event that a risk reduction can be demonstrated. Residual (non-zero) risk is therefore permitted by CCC. CERA however will only permit re-zoning with risk removal, despite the threshold risk of $1 \times 10^{-4}$ being used in the original zoning decisions.

It is again acknowledged that CERA red-zoning was designed to serve a different purpose to District Plan zoning. CERA's policy does however cause the situation to arise in which a red-zoned property can undergo mitigation, be demonstrated to have undergone risk reduction to several orders of magnitude below the threshold, but still remain red-zoned. This appears to contrast with risk management best practice, and could result in property owners facing ongoing issues, for example with respect to finance and insurance relating to their property.

***Conflicting aims and progressive mitigation***

It is common for the hazard to neighbouring properties to comprise the same rockfall source zones. A situation was encountered in which the owners of two neighbouring red-zoned properties had conflicting aims. The owner of property A aimed to use their red-zone offer to apply for RPS funding to undertake source removal, reducing the risk to the property to a non-credible level. The owner of property B, next door, initially commissioned an engineer to try to show, for insurance reasons, that the risk was such that a s124 notice should have been placed on the property.

This situation highlights important drawbacks in the system. Firstly, the fact that RPS funding is on an individual property basis means that individual property owners must assess mitigation feasibility with respect to the value of their property alone. There is no simple mechanism for combining funding with neighbours. Secondly, it highlights that property owners may have to make a decision on whether to accept red-zone buy-out offers without fully understanding the mitigation options available to them.

Continuing with the example of properties A and B, the owner of property B, having failed to secure a s124 notice, then proceeded to explore the possibility of mitigation. In the meantime the owner of property A had secured RPS funding and commissioned the mitigation work. The cost of the work exceeded the RPS funding cap, and the owner therefore had to fund the difference. A significant proportion of the cost involved the creation of access tracks down onto the slope.

The completion of the mitigation work for property A meant that mitigation was now economically feasible for property B. The source zones removed for property A also posed a hazard to property B; the risk to property B had therefore been reduced by the work for property A.

There is currently no mechanism for the owner of property A to recover the excess costs incurred, despite the work subsequently benefiting other property owners. An unzipping effect is observed, whereby as mitigation is completed, the mitigation feasibility for adjacent properties increases. In the example discussed, it would be economically feasible to mitigate least four more properties by continuing rock removal works along the slope. As more properties are added to the project, the cost/benefit ratio increases.

## Conclusions

Public and professional understanding of rockfall risk has greatly improved following the 2010/11 earthquakes, but it is apparent that policy relating to rockfall risk mitigation could be improved.

Area-wide analyses provide a sound basis for risk assessment, however the detail provided by a site specific assessment is required to allow the design of RPS or mitigation. Key aspects of a site specific assessment include the confirmation of source zones, and the consideration of topography.

The differing approach to risk between organisations causes difficulty in assessing the feasibility of mitigation, and causes uncertainty for engineers when satisfying themselves that mitigation has been achieved to a level that will meet the property owner's ultimate goal within the legislation. The requirement to remove risk in its entirety is considered overly conservative, and contrary to best practice.

The conflicting aims of the owners of adjacent properties with overlapping source areas could cause opportunities for mutually beneficial solutions to be missed. Additionally, the RPS funding agreements do not encourage multi-dwelling mitigation, as feasibility is assessed on an individual property basis. It is acknowledged that there are legal and funding difficulties in pursuing multi-dwelling mitigation.

Progressive mitigation could be considered as a procurement model that satisfies the existing funding mechanisms, whilst allowing feasibility to be established for multiple properties with interdependent mitigation designs.

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