Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Additional assessment of the life-safety risk from rockfalls (boulder rolls)

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GNS Consultancy Report 2012/214
September 2012 FINAL

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BIBLIOGRAPHIC REFERENCE

Massey, C.I.; Gerstenberger, M.; McVerry, G.; Litchfield, N. 2012. Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Additional assessment of the life-safety risk from rockfalls (boulder rolls), *GNS Science Consultancy Report* 2012/214. 18 p + Appendices.

REVIEW DETAILS

This report in draft form was independently reviewed by T. Taig, TTAC Limited. Internal GNS Science reviews of drafts were provided by T. Webb and D. Rhoades.

Rockfall risk calculations were independently checked by T. Taig, TTAC Limited.

CONTENTS

FIGURES

TABLES

APPENDICES

EXECUTIVE SUMMARY

ES.1 SCOPE AND PURPOSE

GNS Science was commissioned by Christchurch City Council in June 2011 to assess the risk to people living in the Port Hills of Christchurch from rockfall (boulder roll). In the period leading up to June 2012, GNS Science produced two reports (Massey et al., 2012a,b) containing the results from the rockfall risk assessment.

In May and July 2012, the Canterbury Earthquake Recovery Authority (CERA) and Christchurch City Council requested that GNS Science provide additional assessment of the rockfall risk model presented in the two GNS Science reports by further assessing the underpinning assumptions.

In particular CERA and Christchurch City Council asked GNS Science to provide their "best advice" that is neither too conservative nor too optimistic taking into account a range of factors (refer to their letters dated 31st May 2012 and 20th July 2012 in Appendix A).

The aim of this work is to provide technical advice on the assumptions and evolution of rockfall risks in the Port Hills of Christchurch to CERA and Christchurch City Council for their policy development process. This report summarises this work.

The objectives of this work are to:

1. Update the rockfall risk with additional data and further assess the appropriateness of certain input parameters, as requested by CERA and Christchurch City Council;
2. Quantify and discuss the decreasing nature of the risk with time; and
3. Provide additional assessment and maps having taken into account the additional factors.

The report covers all of the suburban areas previously assessed in Massey et al. (2012a,b).

ES.2 CONCLUSIONS

1. Part 1 of the additional assessment tested the sensitivity of the rockfall risk model to a range of factors: i) rockfall scale factors (increasing the number of rockfalls produced by a given event, taking into account earlier under-reporting of boulder numbers and testing the sensitivity to the use of alternative scale factors); ii) the probability of a person being present in a home at the time of an event; and iii) the probability of the person being killed if hit by a boulder.
2. The assessments show that changing the rockfall scale factors had little influence on the risk - about 6 to 14% reduction in risk for the range of scale factors tested, which is relatively small given other uncertainties in the model.
3. The largest change in risk (about a 33% reduction) arises from reducing the probability of a person being present at the time of future rockfall from 1.0 (100% occupancy), that was used in the original assessment, to 0.67 (67% occupancy).
    a. The original assessment adopted occupancy of 100% in order to take into account the most highly-exposed-to-risk people. In the updated assessment an average occupancy rate of 67% has been used for estimating the average risk.

While this assessment is suitable for determining the average risk to the average person, if it is used for planning and regulatory purposes, it may result in some small but clearly identifiable groups in the population living with higher levels of risk.

4. The probability of a person being killed (or receiving injuries which prove fatal in the near aftermath of the event) if present on the slope and in the path of a boulder is expressed as vulnerability. A vulnerability of 50% was used in the original risk assessment contained in Massey et al. (2012a). GNS Science does not recommend using lower values. This parameter has not been changed in this assessment.

5. Part 2 of the assessment specifically addressed: 1) the time-varying nature of the rockfall risk caused by decreasing seismicity over time; 2) the reduction in rockfall risk that could be achieved by removing the contribution to the seismic hazard model from aftershocks; and 3) the probability of the geographical location of future earthquakes.

6. The earthquake hazard model indicates that the most rapid decrease occurs within the first five years from 2012 to 2016, which results in a decrease in rockfall risk of about 51% at an average rate of about 10% per year. The rate of decrease from year 5 to year 10 (2016 to 2021) is about 14% at an average rate of about 3% per year.
    a. As the contribution to the rockfall risk from seismic events decreases over time, the proportional contribution to the rockfall risks from non-seismic events becomes greater. The combined result is that the rate of reduction in rockfall risk becomes smaller over time, until it is almost flat (constant risk) after year 2021.

7. Following the 22nd February 2011 earthquakes, people in rockfall hazard zones were evacuated from their homes and therefore were not present during the 13th June 2011 earthquake when further significant rockfalls occurred. Similarly, following a future major earthquake, it is very possible that people will also be evacuated and therefore would not be exposed to rockfalls triggered by aftershocks.
    a. By excluding exposure to risk arising from aftershocks following a future major earthquake the overall seismic hazard reduces by approximately 30%. The associated decrease in rockfall risk is less than 30%. This seismic model is called the “no-aftershock exposure” model.
    b. This reduction is based on removing the proportion of shallow earthquakes with magnitude $M \geq 5.3$ that are preceded within a time period of 100 to 200 days and distance of 10 km by another earthquake of magnitude $M \geq 5.3$ from the seismic hazard model.
    c. By adopting the rockfall risk estimates assuming the no-aftershock exposure model, we are explicitly assuming civil defence action and/or local government action under the Building Act (as occurred in 2011) would result in residents being evacuated for a length of time that is consistent with the time period used in the no-aftershock exposure model (100–200 days). In order to use the no-aftershock model, policy makers should be satisfied that such an evacuation is likely in the event that there is a major earthquake in the future.

8. It is possible that the forecast earthquake hazard model concentrates too much earthquake activity on Christchurch. However, there is little scope for any better simulation of the geographical location of future earthquakes in that GNS Science are appropriately modelling concentrated seismicity in the short-term and spatially diffuse activity in the long-term. On this basis GNS Science has not included any such reduction in the model update.

    a. For the mid-term (a 10–20 year period) it is possible that the seismic hazard models concentrate too much activity on Christchurch, but if this was the case, any modelled decrease in the seismic hazard could only be by a maximum of 20% over that period.
    b. In this case the corresponding reduction in rockfall risk would be less than 20%, although the exact reduction has not been calculated.
    c. To the extent that this is a genuine effect, it is a longer-term effect. In the short term, the effect of uncertainties on the geographic concentration of future earthquakes is small in the context of the model.
9. Seven new maps (A to G) have been produced using 67% occupancy, the “no aftershocks” model and scale factors of 1.2. The results from the model used to produce these maps represent GNS Science’s “best opinion” of the average risk to the average person from rockfall in the given areas of the Port Hills over the next 10 years, and are thought to be neither too conservative nor too optimistic.
10. The results from the ground truthing of the original risk maps (contained in Massey et al., 2012a) were applied to all of the new risk maps. Additional checking of maps A and C was carried out by appropriately qualified members of the Port Hills Geotechnical Group of consultants.

ES.3 UNCERTAINTIES

The major uncertainties in the rockfall risk model inputs (Massey et al. 2012a) are: 1) the expected time-varying frequency of a given earthquake ground acceleration; 2) the proportion of boulders that will travel given distances downslope; and 3) the assumption that on a given hillside the number of falling rocks, and thus the risk of being hit by one, is uniform along the slope.

The expected confidence limits on the assessed risk levels presented in Massey et al. (2012a,b), are estimated to be marginally greater than an order of magnitude (higher or lower), in terms of the absolute risk levels presented in this report. That is, an assessed risk of 10^{-4} per year could reasonably range from 10^{-3} per year to 10^{-5} per year.

When faced with uncertainties in assessing life safety risk, it is standard practice to take a precautionary view. That is, to base decisions on a risk value towards the upper, rather than the central or lower, end of the range emerging from the risk assessment. Typically (e.g. in the Building Code) an 84th percentile value is used, rather than the 50th percentile (or “best” estimate). However, when risk is decreasing in time the options are more complex. For example, if we were to assess the risk to an individual over a 50-year period, it would be very conservative to use risk estimates at the beginning of the time period based on the 84th percentile values. Similarly, it would be un-conservative to use (lower) risk estimates from later in the time period based on 50th percentile values.

ES.4 RECOMMENDATIONS

1. CERA and Christchurch City Council use the results from this assessment (maps A to G), in conjunction with the results from the original assessment (in Massey et al., 2012a, b) for their policy development process.
    a. For example, it may be appropriate to use the risk maps in the original reports (Massey et al., 2012a,b) for "greenfield" planning purposes. However, when developing policy for existing homes, it may be more appropriate to use those maps produced for this report, that are based on GNS Sciences "best opinion" of the average risk to the average person, in the short term (5 years or so) future.
    b. By adopting the risk maps presented in this report, policy makers would be accepting that small but clearly identifiable population groups would be living with higher levels of risk.
    c. By adopting the "no-aftershock" seismic hazard model, policy makers should be convinced that an evacuation is likely after a major earthquake in the future.
2. CERA and Christchurch City Council take into account the uncertain nature of the position of risk contours on the ground. Whilst these contours may be presented as narrow lines on a map, in reality they are estimates with a degree of uncertainty about them.

ES.5 ACKNOWLEDGMENT

This report was prepared by GNS Science, assisted by the Port Hills Geotechnical Group of Consultants comprising URS, OPUS, Aurecon and GHD. The rockfall risk maps were created by Bilijana Lukovic of GNS Science. The advice given by Kelvin Berryman (GNS Science) throughout this work is greatly appreciated. This report was reviewed by Terry Webb and David Rhoades (GNS Science), and previous drafts were independently reviewed by Tony Taig (TTAC Ltd).

1.0 INTRODUCTION

GNS Science was commissioned by Christchurch City Council in June 2011 to assess the risk to people living in the Port Hills of Christchurch from rockfall (boulder roll). In the period leading up to June 2012, GNS Science produced two reports (Massey et al., 2012a,b) containing the results from the rockfall risk assessment.

In May and July 2012, the Canterbury Earthquake Recovery Authority (CERA) and Christchurch City Council requested that GNS Science assess the sensitivity of the rockfall risk model presented in the two GNS Science reports, to changes in the underpinning assumptions.

In particular CERA and Christchurch City Council asked GNS Science to provide their "best advice" that is neither too conservative nor too optimistic taking into account a range of factors (refer to their letters dated 31st May 2012 and 20th July 2012 in Appendix A).

The main requests are summarised below:

1. The extent to which the GNS Science reports (Massey et al., 2012a,b) may be slightly conservative;
2. The extent to which the risk might decrease over time given expected decreases in the underpinning seismicity;
3. The extent to which risk would be reduced if occupants were to move out of their house for a period of time if there were to be another significant earthquake, thereby removing themselves from the risk associated with aftershocks arising from that event; and
4. The extent to which the GNS Science seismicity models are able to simulate the probability of the geographical location of future earthquakes.

On the 8th June 2012 GNS Science provided CERA and Christchurch City Council with two reports addressing these issues. The first report CR2012-150LR (Massey, 2012) responded to points 1 and 2, and the second report R2012-152LR (Rhoades et al., 2012) to points 3 and 4.

This report summarises the results and conclusions from the work carried out by GNS Science for CERA and Christchurch City Council as result of the requests made in their two letters (Appendix A). This report includes the results already contained in Massey (2012) and Rhoades et al. (2012).

1.1 AIM AND OBJECTIVES

The aim of this work is to provide technical advice on the assumptions and evolution of rockfall risks in the Port Hills of Christchurch to CERA and Christchurch City Council for their policy development process.

The objectives of this work are to:

1. Update the rockfall risk with additional data and provide further assessment of certain input parameters, as requested by CERA and Christchurch City Council;
2. Quantify and discuss the decreasing nature of the risk with time; and
3. Provide additional analyses and maps having taken into account the additional factors.

The report covers all of the suburban areas previously assessed in Massey et al. (2012a,b).

This work has been undertaken in conjunction with checking of selected maps by the Port Hills Geotechnical Group. The Port Hills Geotechnical Group is a consortium of geotechnical engineers contracted by Christchurch City Council to assess slope instability in the Port Hills.

2.0 ASSUMPTIONS AND INPUT PARAMETERS

The sensitivity of the rockfall risk model has been assessed in relation to changes in the following underpinning assumptions:

- Rockfall scale factors;
- Probability a person is present in a home at the time of an event;
- Probability of the person being killed if hit by a boulder;
- Decreasing rockfall risk with time caused by the time-varying seismic hazard
- Removing aftershocks from the seismic hazard model; and
- Probability of the geographical location of future earthquakes.

2.1 ROCKFALL SCALE FACTORS

These are factors by which the numbers of boulders generated per representative event in each band have been increased.

1. For seismically-generated rockfall, the scale factor takes into account a small number of unmapped boulders (triggered by the 2010-2011 Canterbury earthquakes but not mapped and therefore not included in the initial risk assessment).
2. For non-seismically generated rockfalls (e.g. those triggered by rainfall), the estimated numbers of boulders generated over time are based on pre-earthquake data. However, the frequency of non-seismic rockfalls is likely to increase because the rock masses have now been broken and disturbed by the earthquakes.

Scale factors used in the original maps (contained in Massey et al., 2012a) were 1.5 for seismically-generated boulders (1.5 times the actual number of mapped boulders – therefore if 100 boulders were mapped the actual number of boulders used in the analyses would be 1.5 x 100 = 150), and 2.0 for non-seismically generated boulders.

During the ground truthing carried out for the risk maps contained in Massey et al. (2012a) the field teams identified some additional boulders that were assumed to have been triggered by the 2010-2011 Canterbury earthquake sequence that had not been originally mapped, and therefore not included in the risk assessment. However, no systematic re-mapping of the boulder distributions were carried out during the ground truthing, and therefore it is not possible to quantify what seismic scale factor should be used, other than it has to be greater than one. It is likely that the scale factor for seismically generated rockfalls is within the range of >1 to ≤1.5 in residential areas where much time has been taken to carefully map fallen boulders. However, in rural areas and areas with sparse residential housing the scale factor may be as high as 2.

It is also not possible to accurately quantify what the scale factor for non-seismically generated rockfalls should be, as there is a large uncertainty on their production rates, both historically and what they are likely to be in the future. Historical and pre-historical non-seismic boulder production rates used in the risk assessment (Massey et al., 2012a) were based on limited historical records and the geomorphological expression of past rockfall events. These data sets are inherently uncertain. The 2010-2011 Canterbury earthquakes have caused the rock masses forming the rockfall source areas to become more broken, open and dilated and therefore more susceptible to both earthquake and non-earthquake triggering events. It is therefore highly likely that rates of rockfall production from non-seismic events are currently significantly elevated and that the scale factor is likely to be within the range of 1 to 2. However, it should be noted that the future performance of the disturbed rockfall source areas under non-seismic conditions is unknown and therefore in some areas may be greater than 2.

For this assessment we have adopted scale factors of 1.2 for both seismic and non-seismic generated boulders. These parameters are considered to represent the “average” of a range considered to be reasonable.

2.2 PROBABILITY A PERSON IS PRESENT IN A HOME AT THE TIME OF AN EVENT

This is the probability an individual is present in the portion of the slope when a boulder moves through it. It is a function of the proportion of time spent by a person at a particular location each day and can range from 0% if the person is not present, to 100% if the person is present all of the time.

For planning and regulatory purposes it is established practice to to consider individual risk to a “critical group” of more highly-exposed-to-risk people. For example, there are clearly identifiable groups of people (with significant numbers in the groups) who do spend the vast majority of their time in their homes – the very old, the very young, the disabled and the sick.

The assumption used in the risk assessment (contained in Massey et al., 2012a) for judging whether risk controls should be applied to individual homes was thus that more-exposed individuals at risk would be those who spend 100% of their time at home.

For the purpose of this assessment, GNS Science has adopted average occupancy rates to assess the average annual individual fatality risk from rockfall across the exposed population in order to estimate the average risk to the average person.

For example, in other international rockfall risk assessments (e.g., Corominas et al., 2005), values ranging from 58% (for a person spending 14 hours a day at home) to 83% (for a person spending 20 hours a day at home), have been used to represent the “average” person and the “most exposed” person, respectively. However, in reality the most exposed person is still likely to be present 100% of their time.

For this assessment, GNS Science has assumed that an average person spends on average 16 hours a day at home (16/24 = 0.67 or 67%).

2.3 PROBABILITY OF THE PERSON BEING KILLED IF HIT

This is the probability of a person being killed (or receiving injuries which prove fatal in the near aftermath of the event) if present on the slope and in the path of a boulder.

This probability is expressed as vulnerability, the term used to describe the amount of damage that results from a particular degree of hazard. Vulnerability ranges between 0 and 1 and for fatality risk represents the likelihood of an injury sustained by the individual being fatal (1). Vulnerability may also take into account the possibility of getting out of the way to avoid being struck although this logically is an influence on the probability of being struck.

Studies from Hong Kong (e.g. Finlay et al., 1999) summarised the vulnerability ranges and recommended values for death “if struck by rockfall”. The vulnerability of an individual in open space if struck by a rockfall is given as 0.1 – 0.7, with a recommended value of 0.5, assuming that it may be possible to get out of the way. For people in homes, it would be unlikely that a person would be able to take evasive action as they would not see the boulder coming. However, this argument is counterbalanced by the level of protection a house may provide by stopping a boulder from entering it. Using the recorded 22nd February 2011 rockfall consequences, out of about 65 houses hit by rocks, about 29 (about 45%) had boulders enter them (Massey et al., 2012a).

Based on these discussions, a vulnerability of 50% was used in the original risk assessment contained in Massey et al. (2012a). GNS Science does not recommend using lower values and so this parameter has not been changed in this assessment.

2.4 DECREASING ROCKFALL RISK WITH TIME

The earthquake models used to estimate the seismic hazard through time are based on GNS Science’s “best knowledge” of the cluster-like behaviour of earthquakes. The estimated hazard is highest in the first years, followed by a rapid fall off as the region moves from what can be considered traditional aftershock clustering. The total number of anticipated earthquakes drops by roughly one order of magnitude within the first 5-10 years (Figure 1).

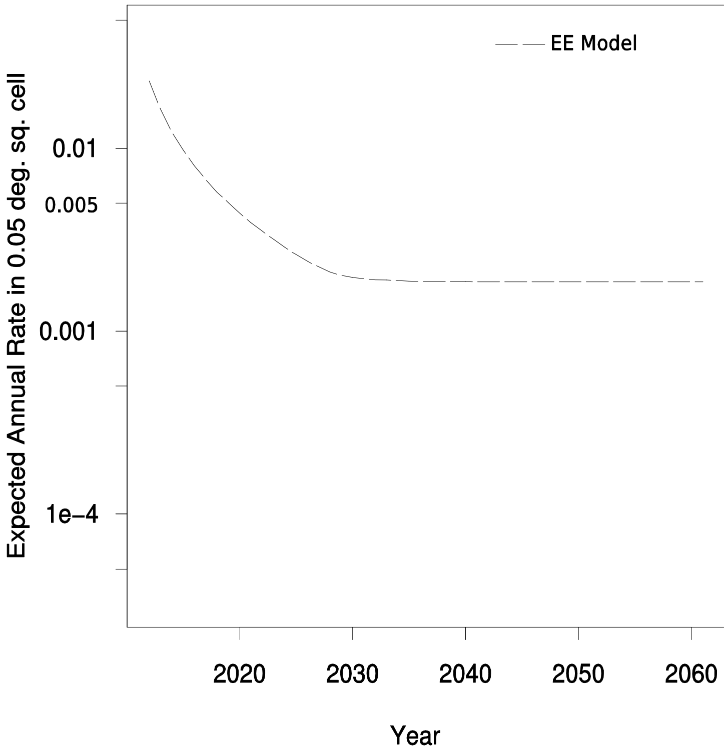

Figure 1 Estimated annual rate of occurrence of earthquakes of M ≥ 5.0 in a 0.05 degree square cell in central Christchurch. The estimates are based on a composite model arising from an Expert Elicitation (EE Model) Workshop held at GNS Science in November 2011.

The rockfall risk sensitivity analyses takes this decay into account by using seismic hazard estimates for different years over the next 50-year period, starting in 2012, which is year 1. The sensitivity of the seismic hazard model results have also been assessed with regards to:

1. The contribution to the seismic hazard model from aftershocks, which are earthquakes that follow a larger earthquake; and
2. How the probability of the geographical location of future earthquakes has been modelled.

2.5 THE NO-AFTERSHOCK EXPOSURE SEISMIC HAZARD MODEL

Following the 22nd February 2011 earthquakes, people in rockfall hazard zones were evacuated from their homes and therefore were not present during the 13th June 2011 earthquake when further significant rockfalls occurred. Similarly, following a future major earthquake, it is very possible that people will also be evacuated and therefore would not be exposed to rockfalls triggered by aftershocks.

CERA and Christchurch City Council asked GNS Science to quantify the extent to which rockfall risk would be reduced if occupants of affected areas were to move out of their homes for a period of time following a significant earthquake, thereby removing themselves from the risk associated with aftershocks arising from that event.

To do this requires quantifying the contribution to the risk from aftershocks following a previous earthquake event of a given magnitude, within a given distance/radius, and within a given time period.

Work by Rhoades et al. (2012) since the issue of GNS Science's earlier reports (Massey 2012a,b) has quantified the probability that strongly shaking earthquakes could occur relatively close together in space and time. To quantify this, GNS Science examined the entire New Zealand earthquake record and found that for earthquakes with magnitude M≥5.3, using a 100-200 day evacuation window, and a radial distance of 10 km, the seismic hazard can be reduced by approximately 30%.

This is referred to as the "no-aftershock exposure" seismic hazard model. For more detail refer to Rhoades et al. (2012). The magnitude threshold of M5.3 was based on the median near-source peak ground acceleration estimates in the McVerry et al. (2006) ground-motion model. For magnitude M>5.25, the median peak ground acceleration at distances less than 2 km from the earthquake source is in excess of 0.4 g. Therefore, there is a significant chance that such earthquakes could induce rockfalls (Massey et al., 2012a).

2.5.1 Incorporating the no-aftershock exposure assumption in the current assessment

For the current assessment, a new set of peak ground acceleration hazard curves were produced based on the "no-aftershock exposure" assumption. This assumption was implemented by multiplying the rate of magnitude M≥5.3 earthquakes by a factor of 0.7 to take into account the estimated 30% reduction in seismic hazard.

The original risk assessments (Massey et al., 2012a, b) were based on peak ground acceleration hazard curves that included 100% of the seismic hazard, rather than 70% as used in the no-aftershock exposure model.

As per the original assessments, peak ground acceleration hazard curves were produced for different stages in time from 1st January 2012 to take into account the seismic decay over time. The annual frequencies of the representative earthquake in each peak ground acceleration band, derived from the no-aftershock exposure peak ground acceleration hazard curves (Figure 2) and used in the rockfall model, are shown in Table 1. The values from the given years have been used as these years best represent the general shape of the seismic hazard decay curve.

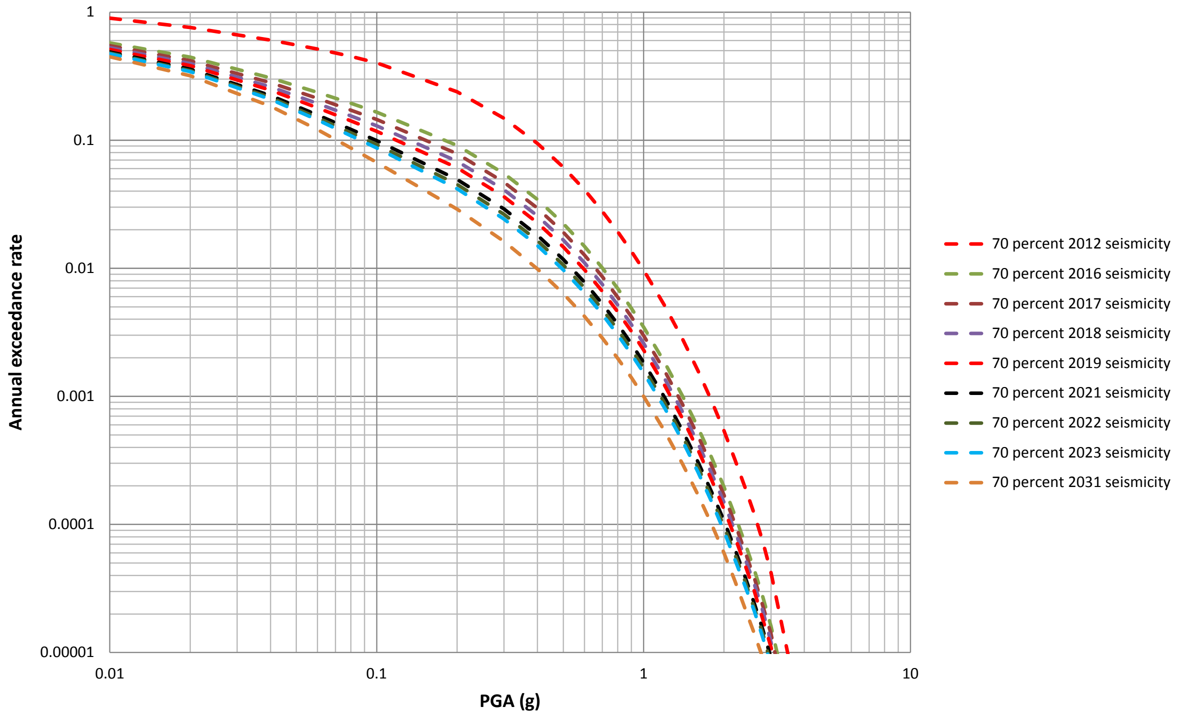

Figure 2 Selected peak ground acceleration hazard curves (annual rate (annual frequency) of a given peak ground acceleration being exceeded) for shallow soil site conditions for a selection of years between 2012 and 2031 based on the “no aftershock exposure” assumption.

Table 1 Annual frequency of the representative event in each peak ground acceleration band occurring per given year, assuming the no-aftershocks exposure model results.

Seismic hazard NO aftershocks (Year)	**Years from 2012**	**Annual frequency of the representative event (earthquake) in each peak ground acceleration band (g)**				**Average reduction in seismic hazard (ALL bands) from year 1**
		0.1 – 0.4	0.4 – 1.0	1.0 – 2.0	2.0 – 5.0	
2012	1	0.3067	0.0847	0.0091	0.0005	-
2014	3	0.1815	0.0456	0.0048	0.0003	45%
2016	5	0.1312	0.0310	0.0033	0.0002	62%
2018	7	0.1040	0.0231	0.0024	0.0001	71%
2019	8	0.0947	0.0204	0.0022	0.0001	74%
2020	9	0.0871	0.0181	0.0019	0.0001	77%
2021	10	0.0810	0.0163	0.0017	0.0001	79%

In the rockfall risk assessment by Massey et al. (2012a), the relationship between the numbers of boulders produced, and peak ground acceleration, was derived from the actual peak ground acceleration measurements. These measurements were from all of the stations in the Port Hills regardless of site class, recorded during the 2010-2011 Canterbury earthquakes. The stations used are typically sited on classes B (rock) and C (shallow soil)

(NZS1170.5:2004) and the recorded values do not represent the actual peak ground accelerations recorded at the rockfall source areas, which are likely to have been higher as a result of localised site effects.

The recorded peak ground accelerations have not been normalised to one particular site class and so the measured peak ground accelerations are being used as an index of what the range of peak ground accelerations were that triggered a particular number of recorded boulders. There is a large uncertainty on this relationship, which has been quantified (Massey et al., 2012a), and which reflects the large variations in the recorded peak ground accelerations and site conditions of the rockfall source areas.

The peak ground acceleration hazard curves have been estimated using the McVerry et al. (2006) ground-motion prediction equations. These equations are used in the New Zealand National Seismic Hazard Model (Stirling et al., 2012) that underlies the hazard section of the structural design standard NZS1170.5:2004. The ground motions recorded in the near-source region in the M_w6.2 earthquake of 22nd February 2011 and many aftershocks were considerably higher than anticipated from the McVerry et al. (2006) ground-motion prediction equations. Many of the 2010-2011 Canterbury earthquakes have exhibited high apparent stresses (Fry & Gerstenberger, 2011), which are likely to produce the higher than expected ground motions. The peak ground acceleration hazard calculations allow for enhanced motions by applying Atkinson & Boore (2006) multiplicative factors for stress-drop effects, assuming stress-drops increased by 50% above normal (150 bars versus 100 bars), which produce a smaller percentage increase in the ground motions. The stress-drop factor was a convenient readily available tool to produce enhanced motions, rather than representing a belief that high stress-drops were the only contributor to the stronger than expected motions.

Recent estimation of spectra and peak ground accelerations for liquefaction assessments for deep or soft soil conditions in Christchurch have been based on a weighted combination of the Bradley (2010) and McVerry et al. (2006) equations. The Bradley (2010) equations provide a better match to the recorded near-source motions on deep soil conditions in several of the 2010-2011 Canterbury earthquakes, including the 22nd February 2011 Christchurch earthquake. The Bradley (2010) model has not been used for the peak ground acceleration estimates for rockfall, largely because GNS Science has not as yet evaluated its suitability for shallow soil conditions. Also, its site-effect term depends on V_s30, the shear-wave velocity to 30 m depth, and Z 1.0 km/s, the depth to a shear-wave velocity of 1 km/s. These have not been assessed for the locations that are the sources of potential rockfalls.

2.6 PROBABILITY OF THE GEOGRAPHICAL LOCATION OF FUTURE EARTHQUAKES

The seismic hazard model GNS Science uses to estimate the numbers and locations of earthquakes is a composite model resulting from an Expert Elicitation Workshop held at GNS Science in November 2011. This model is currently considered to represent “best available science”. It combines the time-varying seismicity estimates from short-term clustering (aftershock) models and medium-term clustering models, and the time-invariant estimates of long-term seismicity models. In the short-term the highest occurrence rates are concentrated at locations where earthquakes have already occurred. As time goes on, the level of knowledge about the likely locations of future earthquakes becomes poorer, and the high rates are smoothed out over a much larger spatial area.

Currently there is little scope for any better simulation of the geographical location of future earthquakes in that GNS Science are correctly modelling concentrated seismicity in the short-term (1–10 year period) and more spatially diffuse activity in the long-term (beyond 20 years).

For the intervening 10–20 year period it is possible that the seismic hazard models concentrate too much activity on Christchurch, but if this was the case, any correction to the seismic hazard model could only be at most 20% over that 10-year period, as the model involved carries only this amount of weight in the calculations (so to achieve 20% one would need to move all future seismicity well away from Christchurch for this particular component model).

This 20% figure is not one that can currently be derived from modelling; instead it illustrates the extent to which one uncertainty in the model can affect the result, noting that there are many other uncertainties in the model (Rhoades et al., 2012). On this basis GNS Science has not included the 20% reduction in this assessment.

The reduction in rockfall risk assuming future events are overly clustered in the city area, would be less than 20% as any reduction in seismic hazard would only affect the contribution to the risk from seismically triggered boulders and not the contribution from non-seismically triggered boulders. The exact reduction has not been calculated.

3.0 ASSESSMENT METHOD

3.1 ROCKFALL RISK PARAMETERS MODELLED

This assessment comprised two parts:

Part 1: varied assumptions of the rockfall risk model, with changes in: a) rockfall scale factors; b) probability a person is present in a home at the time of an event; and c) probability of the person being killed if hit by a boulder. These were assessed by keeping all other input parameters fixed, including the underpinning seismic hazard model results. The parameters used in that assessment are shown in Table 2, along with the original parameters used for risk Scenario C, contained in Massey et al. (2012a).

The sensitivity of the rockfall risk model to changes in the parameters listed in Table 2 has been assessed by inputting them into the model and comparing the risk estimates with those estimated using the original parameters (risk Scenario C, contained in Massey et al., 2012a). The underpinning seismic hazard model results used in this assessment are the Year 1 (2012) median results described in Massey et al. (2012a).

Table 2 Parameters used in the current assessment.

	Non-seismic rockfall scale factor	**Seismic rockfall scale factor**	**Probability person present**	**Vulnerability of a person if hit**
This assessment	1.2	1.2	67%	0.5
Scenario C (original)	2	1.5	100%	0.5

Part 2: sensitivity of the rockfall risk model to the time-varying seismic hazard. The annual frequencies of the representative event in each peak ground acceleration band for the given years are derived from the no-aftershock exposure peak ground acceleration hazard curves (Figure 2). These values are shown in Table 1 for each event band per year from 2012. The values from the given years have been used as these years best represent the general shape of the seismic hazard decay curve. All other parameters used in this assessment have been kept constant, as per those listed in Table 2. The sensitivity assessments are listed in Table 3.

Table 3 Sensitivity assessments for Part 2.

Map	Seismic hazard No-aftershock exposure model results (Year)	Years from 2012
A	2012	1
B	2014	3
C	2016	5
D	2018	7
E	2019	8
F	2020	9
G	2021	10

The average reduction in seismic hazard has been estimated for each year as the average reduction in the annual frequencies of the representative event for all peak ground acceleration bands.

The annual individual fatality risk from rockfall was calculated for each shadow angle within each suburb (as per the method contained in Massey et al., 2012a) using the peak ground acceleration values estimated for the years given in Table 1. All other parameters remained constant and are listed in Table 4.

These risk estimates were then modelled using ArcGIS® to interpolate between the risks calculated at given shadow angles so as to produce contours of equal risk, presented in risk maps A to G. Contours were developed for logarithmic classes, e.g. $10^{-2} – 10^{-3}$, $10^{-3} – 10^{-4}$, of individual risk values.

3.2 APPLYING THE GROUND TRUTHING

The risk maps contained in Massey et al. (2012a), produced using Risk Scenario C input parameters, were ground truthed by the Port Hills Geotechnical Group of consultants using the procedure contained in Massey et al. (2012a,b). The results from the original ground truthing were also applied to risk maps A to G, generated using the parameters listed in Table 2. This was possible because the ground truthing relied upon defining particular local features that would affect the risk, irrespective of the different parameters used in the rockfall risk model. The original ground truthing defined:

1. A line where the assumed annual individual fatality risk was about 10^{-6} per year, which was based on two-dimensional numerical modelling, geomorphological mapping and 2010-2012 rockfall distributions, which did not change; and

2. Local variations from the suburb-average risk where:
    a. The risk was field-assessed as greater than the suburb average, e.g. where the property is within a depression that directs boulders onto it, or where the source area (where the boulders originate) is larger or more disturbed than the suburb average; or
    b. The risk was field-assessed as less than the suburb average, e.g. the property is sheltered by a local permanent topographic feature or where boulder runout is stopped by, for example, extensive natural or prepared flat ground (such as roads, tennis courts and large swimming pools). The presence of other buildings, fences (whether designed to stop boulders or not), and trees were not classed as sheltering features that would limit the runout of boulders as these are ephemeral features.

Maps A and C (derived from the parameters in Table 4) were then given to the relevant Port Hills Geotechnical Group consultants for checking. The consultants made changes to these risk maps by moving the different risk contours based on their local knowledge of the areas. The maps were then revised to reflect these changes.

4.0 CURRENT ASSESSMENT RESULTS

4.1 PART 1

The rockfall model input parameters used for the current assessment are shown in Table 4. For each test, the average reduction in risk is calculated for all areas and for all shadow angles. The average reduction in risk per sensitivity test is calculated from comparison with the reference test (1), which are the original parameters used. For sensitivity Tests 2 to 5 only one parameter per test was changed.

For the purpose of these analyses all other parameters (i.e., any parameters not listed in Table 4), are consistent with those used in the original assessment.

Table 4 Input parameters used in the rockfall model for each assessment.

Sensitivity Test Number	Non-seismic rockfall scale factor	Seismic rockfall scale factor	Probability person present	Vulnerability of a person if hit	Reduction in rockfall risk (ALL areas) from Test 1	Factor by which the average risk reduces from Test 1**
1*	2	1.5	100%	0.5	-	
2	**1.2**	1.5	100%	0.5	6%	1.1
3	2	**1.2**	100%	0.5	14%	1.2
4	2	1.5	**67%**	0.5	33%	1.5
5	**1.2**	**1.2**	**67%**	0.5	47%	1.9

* Sensitivity test No. 1 represents the original parameters used for rockfall risk Scenario C in Massey et al. (2012a).

** A factor of 10 is one order of magnitude change.

The reduction in the rockfall risk is calculated by first averaging the risk estimated for all given shadow angles within a given suburb, then dividing the average risk per given suburb using the results from Tests Nos. 2 – 5 by the results from Test No. 1 of the same suburb.

Then the average reduction across all of the suburbs is calculated as a percentage per Test Nos. 2 – 5. The locations are listed in Massey et al. (2012a). The results are shown graphically in Figure 3.

The reduction of rockfall risk from the rockfall model (part 1) sensitivity tests is shown in the last two columns of Table 4. These results show that there is a maximum reduction in risk between the original risk estimates and those used in this assessment of about a factor of two (the difference between Test No. 1 and Test No. 5). A factor of 10 would equate to one order of magnitude change in the risk for example from 10^{-3} to 10^{-4}. The largest change in risk is between Test Nos. 3 and 4, and is caused by the reduction in the probability of a person being present from 100%, used in the original assessment, to 67% used in the current assessment. However, in general the analyses indicate little difference between the original rockfall risk results (Risk Scenario C) and the results using the alternative parameters.

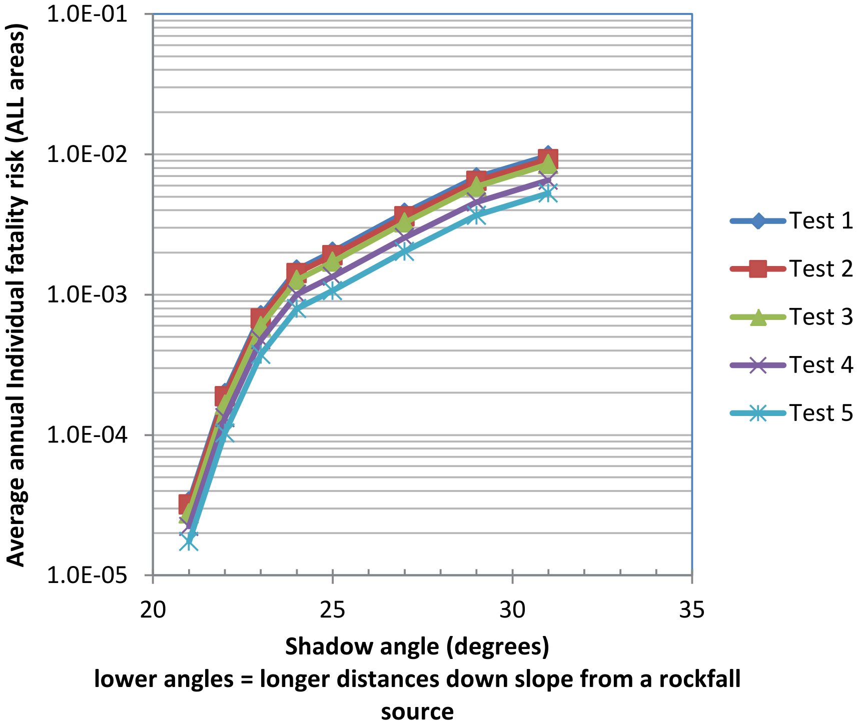

Figure 3 Average rockfall risk in 2012 estimated at a given shadow angle for all areas (listed in Massey et al., 2012a) per sensitivity tests Nos. 1 – 5, using the input parameters as listed in Table 4. All other input parameters, not listed in Table 4, remain consistent with those used in rockfall risk Scenario C contained in Massey et al. (2012a). Note that the underpinning seismic hazard model results used in these analyses are for year 2012 only.

4.2 PART 2

Results from the seismic hazard (part 2) assessment are summarised in Table 5. These results show that the rockfall risks decrease with time as the seismic hazard decreases. The most rapid decrease occurs within the first five years from 2012 to 2016, representing a decrease in risk of about 51% at an average rate of about 10% per year. The rate of decrease from year 5 to year 10 (2016 to 2021) is about 14% at an average rate of about 3% per year.

Table 5 Results from the assessments.

Map	Seismic hazard NO aftershocks (Year)	Years from 2012	Average reduction in seismic hazard from year 1	Average reduction in rockfall risk (ALL areas) from year 1			Contribution of Non-seismic events to the risk
				From/to	%	Factor	
A	2012	1	-	-	-	-	19%
B	2014	3	45%	1 to 3	38%	1.6	31%
C	2016	5	62%	1 to 5	51%	2.0	39%
D	2018	7	71%	1 to 7	59%	2.4	46%
E	2019	8	74%	1 to 8	61%	2.6	49%
F	2020	9	77%	1 to 9	63%	2.7	52%
G	2021	10	79%	1 to 10	65%	2.9	54%

It should be noted that the decreasing risk does not follow a linear pattern; instead, the decrease is more rapid in the first few years becoming less rapid with time. However, as the contribution to the rockfall risk from seismic events decreases over time, the relative contribution to the rockfall risks from non-seismic events becomes greater. As a result the rate of reduction in rockfall risk becomes smaller over time, to almost constant risk after year 2021.

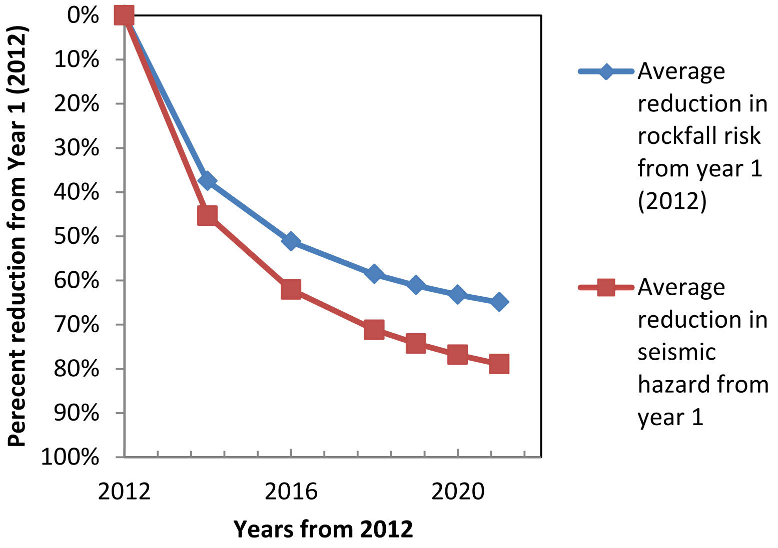

Figure 4 Average reduction in rockfall risk (all areas contained in Massey et al., 2012a) from year 1 using the input parameters contained in Table 2, and the average reduction in seismic hazard from year 1 using those values in Table 1.

On the ground, the decreasing rockfall risk with time is represented by the up-slope migration of the risk contours towards the rockfall source areas. For example, the annual individual fatality risk contour of 10^{-4} in 2012 (equivalent to about the 22° shadow angle) would in 2016 be equivalent to the 2012 risk contour of about 2.3×10^{-4}, (shadow angle of about 23°) and in 2021 would be equivalent to the 2012 risk contour of 3×10^{-4} (a shadow angle of about 23.5°) (Figure 5). These “equivalency values” are based on the average rockfall risks per shadow angle calculated using all areas listed in Massey et al. (2012a), using the input parameters in Table 2. It should be noted that these equivalency values and corresponding shadow angles will vary between the different areas.

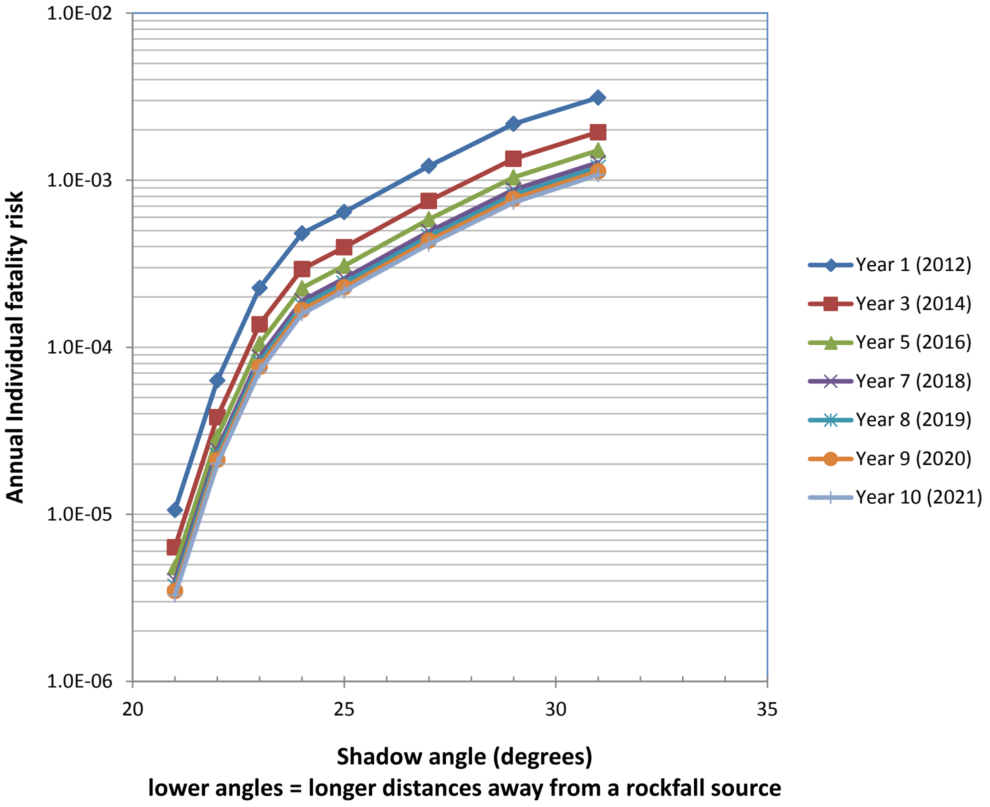

Figure 5 Average reduction in rockfall risk (average of all areas contained in Massey et. al., 2010a) from year 1 to year 10 assuming the input parameters contained in Table 1 and Table 2.

5.0 DISCUSSION

Seven new maps (A to G) have been produced using 67% occupancy, the “no aftershocks” model and scale factors of 1.2. The results from the model used to produce these maps represent GNS Science’s “best opinion” of the average risk to the average person from rockfall in the given areas of the Port Hills over the next 10 years, and are thought to be neither too conservative nor too optimistic.

When using these maps for policy development some considerations need to be taken into account, these are discussed in turn.

5.1 CONSIDERATION OF THE RESULTS – PART 1

Part 1 of this assessment tested the sensitivity of the risk model to changes in: a) rockfall scale factors; and b) the probability of a person being present in a home at the time of an event and c) probability of the person being killed if hit by a boulder.

Rockfall scale factors that represent the average of a range of values considered to be reasonable were adopted. The sensitivity tests showed that changing these values had little influence on the risk, especially given the uncertainties involved.

The largest change in risk is caused by the reduction in the probability of a person being present from 1.0 (100% occupancy), used in the original assessment, to 0.67 (67% occupancy).

The original assessment adopted occupancy rate of 100% in order to take into account the more highly-exposed-to-risk people. For this assessment an average occupancy rate of 67% has been used for making a “best opinion of the average risk to the average person”. While this assessment may provide the best assessment of the current average risk to members of the population concerned, using an occupancy rate of 100% would be consistent with a precautionary approach for new consents or for long term landuse planning.

5.2 CONSIDERATION OF THE RESULTS – PART 2

Part 2 of the assessment specifically addressed: 1) the reduction in rockfall risk that could be achieved by removing the contribution to the seismic hazard model from aftershocks; and 2) the time-varying nature of the rockfall risk caused by decreasing seismicity over time.

Rockfall risks decrease with time as the seismic hazard decreases. The most rapid decrease occurs within the first five years from 2012 to 2016, after which the rate of decrease reduces. However, as the contribution to the rockfall risk from seismic events decreases over time, the relative contribution to the rockfall risks from non-seismic events (e.g. rainfall) becomes greater. Although the results presented in Figure 5 are based on the no-aftershock exposure seismic hazard model results, the shape of the curves would not change if the “with-aftershock” seismic hazard model results were to be used. Instead, the risk in any one year would be about 30% higher.

The overall seismic hazard (in this case the annual frequency of a given peak ground acceleration being exceeded) reduces by approximately 30% by adopting the “no-aftershock exposure” seismic hazard model results. This reduction is based on removing the proportion of shallow earthquakes with magnitude $M \geq 5.3$ that are preceded within a time period of 100 – 200 days and distance of 10 km by another earthquake of magnitude $M \geq 5.3$ from the seismic hazard model. The results used in the sensitivity assessment are all median values.

By adopting the rockfall risk estimates from the no-aftershock exposure model, we are explicitly assuming civil defence action and/or local government action under the Building Act (as occurred in 2011) would result in residents being evacuated for a length of time that is consistent with the time period used in the no-aftershock exposure risk model (100–200 days). To use the no aftershocks model, policy makers should be satisfied that such an evacuation is likely in the event that there is a major earthquake in the future.

6.0 UNCERTAINTIES

The major uncertainties in the rockfall risk model inputs are discussed in Massey et al. (2012a). The most important uncertainties are: 1) the expected time-varying frequency of a given earthquake ground acceleration; 2) the proportion of boulders that will travel given distances downslope; and 3) the assumption that on a given hillside the number of falling rocks, and thus the risk of being hit by one, is uniform along the slope. It is likely that the frequency of rockfalls triggered by events other than earthquakes, such as long-duration or high intensity rainstorms, has been increased because the shaking has made the rockfall source areas more unstable. Such an increase will only become apparent through continued monitoring of rockfalls as they occur.

The expected confidence limits on the assessed risk levels presented in Massey et al. (2012a,b), are estimated to be marginally greater than an order of magnitude (higher or lower), in terms of the absolute risk levels presented in this report. That is, an assessed risk of 10^{-4} per year could reasonably range from 10^{-3} per year to 10^{-5} per year.

When faced with uncertainties in assessing life safety risk, it is standard practice to take a precautionary view. That is, to base decisions on a risk value towards the upper, rather than the central or lower, end of the range emerging from the risk assessment. Typically (e.g. in the Building Code) an 84th percentile value is used, rather than the 50th percentile (or “best estimate”). However, when risk is decreasing in time the options are more complex. For example, if we were to assess the risk to an individual over a 50-year period, it would be very conservative to use risk estimates at the beginning of the time period based on the 84th percentile values. Similarly, it would be un-conservative to use (lower) risk estimates from later in the time period based on 50th percentile values.

7.0 CONCLUSIONS

1. Part 1 of the additional assessment tested the sensitivity of the rockfall risk model to a range of factors: i) rockfall scale factors (increasing the number of rockfalls produced by a given event, taking into account earlier under-reporting of boulder numbers and testing the sensitivity to the use of alternative scale factors); ii) the probability of a person being present in a home at the time of an event; and iii) the probability of the person being killed if hit by a boulder.
2. The assessments show that changing the rockfall scale factors had little influence on the risk - about 6 to 14% reduction in risk for the range of scale factors tested, which is relatively small given other uncertainties in the model.
3. The largest change in risk (about a 33% reduction) arises from reducing the probability of a person being present at the time of future rockfall from 1.0 (100% occupancy), that was used in the original assessment, to 0.67 (67% occupancy).
    a. The original assessment adopted occupancy of 100% in order to take into account the most highly-exposed-to-risk people. In the updated assessment an average occupancy rate of 67% has been used for estimating the average risk. While this assessment is suitable for determining the average risk to the average person, if it is used for planning and regulatory purposes, it may result in some small but clearly identifiable groups in the population living with higher levels of risk.
4. The probability of a person being killed (or receiving injuries which prove fatal in the near aftermath of the event) if present on the slope and in the path of a boulder is expressed as vulnerability. A vulnerability of 50% was used in the original risk assessment contained in Massey et al. (2012a). GNS Science does not recommend using lower values. This parameter has not been changed in this assessment.
5. Part 2 of the assessment specifically addressed: 1) the time-varying nature of the rockfall risk caused by decreasing seismicity over time; 2) the reduction in rockfall risk that could be achieved by removing the contribution to the seismic hazard model from aftershocks; and 3) the probability of the geographical location of future earthquakes.
6. The earthquake hazard model indicates that the most rapid decrease occurs within the first five years from 2012 to 2016, which results in a decrease in rockfall risk of about 51% at an average rate of about 10% per year. The rate of decrease from year 5 to year 10 (2016 to 2021) is about 14% at an average rate of about 3% per year.

   a. As the contribution to the rockfall risk from seismic events decreases over time, the proportional contribution to the rockfall risks from non-seismic events becomes greater. The combined result is that the rate of reduction in rockfall risk becomes smaller over time, until it is almost flat (constant risk) after year 2021.

7. Following the 22nd February 2011 earthquakes, people in rockfall hazard zones were evacuated from their homes and therefore were not present during the 13th June 2011 earthquake when further significant rockfalls occurred. Similarly, following a future major earthquake, it is very possible that people will also be evacuated and therefore would not be exposed to rockfalls triggered by aftershocks.

   a. By excluding exposure to risk arising from aftershocks following a future major earthquake the overall seismic hazard reduces by approximately 30%. The associated decrease in rockfall risk is less than 30%. This seismic model is called the “no-aftershock exposure” model.

   b. This reduction is based on removing the proportion of shallow earthquakes with magnitude M≥5.3 that are preceded within a time period of 100 to 200 days and distance of 10 km by another earthquake of magnitude M≥5.3 from the seismic hazard model.

   c. By adopting the rockfall risk estimates assuming the no-aftershock exposure model, we are explicitly assuming civil defence action and/or local government action under the Building Act (as occurred in 2011) would result in residents being evacuated for a length of time that is consistent with the time period used in the no-aftershock exposure model (100–200 days). In order to use the no-aftershock model, policy makers should be satisfied that such an evacuation is likely in the event that there is a major earthquake in the future.

8. It is possible that the forecast earthquake hazard model concentrates too much earthquake activity on Christchurch. However, there is little scope for any better simulation of the geographical location of future earthquakes in that GNS Science are appropriately modelling concentrated seismicity in the short-term and spatially diffuse activity in the long-term. On this basis GNS Science has not included any such reduction in the model update.

   a. For the mid-term (a 10–20 year period) it is possible that the seismic hazard models concentrate too much activity on Christchurch, but if this was the case, any modelled decrease in the seismic hazard could only be by a maximum of 20% over that period.

   b. In this case the corresponding reduction in rockfall risk would be less than 20%, although the exact reduction has not been calculated.

   c. To the extent that this is a genuine effect, it is a longer-term effect. In the short term, the effect of uncertainties on the geographic concentration of future earthquakes is small in the context of the model.

9. Seven new maps (A to G) have been produced using 67% occupancy, the “no aftershocks” model and scale factors of 1.2. The results from the model used to produce these maps represent GNS Science’s “best opinion” of the average risk to the average person from rockfall in the given areas of the Port Hills over the next 10 years, and are thought to be neither too conservative nor too optimistic.

10. The results from the ground truthing of the original risk maps (contained in Massey et al., 2012a) were applied to all of the new risk maps. Additional checking of maps A and C was carried out by appropriately qualified members of the Port Hills Geotechnical Group of consultants.

8.0 RECOMMENDATIONS

1. CERA and Christchurch City Council use the results from this assessment (maps A to G), in conjunction with the results from the original assessment (in Massey et al., 2012a, b) for their policy development process.
    a. For example, it may be appropriate to use the risk maps in the original reports (Massey et al., 2012a,b) for "greenfield" planning purposes. However, when developing policy for existing homes, it may be more appropriate to use those maps produced for this report, that are based on GNS Sciences "best estimate" of the average risk to the average person, in the short term (5 years or so) future.
    b. By adopting the risk maps presented in this report, policy makers would be accepting that small but clearly identifiable population groups would be living with higher levels of risk.
    c. By adopting the "no-aftershock" seismic hazard model, policy makers should be satisfied that an evacuation is likely after a major earthquake in the future.
2. CERA and Christchurch City Council takes into account the uncertain nature of the position of risk contours on the ground. Whilst these contours may be presented as narrow lines on a map, in reality they are estimates with a degree of uncertainty about them.

9.0 ACKNOWLEDGMENTS

This report was prepared by GNS Science, assisted by the Port Hills Geotechnical Group of Consultants comprising URS, OPUS, Aurecon and GHD. The rockfall risk maps were created by Bilijana Lukovic of GNS Science. The advice given by Kelvin Berryman (GNS Science) throughout this work is greatly appreciated. This report was reviewed by Terry Webb and David Rhoades (GNS Science), and previous drafts were independently reviewed by Tony Taig (TTAC Ltd.).

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APPENDICES

APPENDIX 1: LETTERS SENT BY CERA & CHRISTCHURCH CITY COUNCIL TO GNS SCIENCE

CERA
Canterbury Earthquake
Recovery Authority

Christchurch
City Council

31 May 2012 Via Email k.berryman@gns.cri.nz

Kelvin Berryman
Manager, Natural Hazards Research Platform
GNS

Dear Kelvin

Port Hills Rockfall Study – Additional Outputs

In relation to the rockfall report (GNS Science Consultancy Report 2011/311, March 2012) we understand the annual individual fatality risk levels presented are necessarily underpinned by certain assumptions. These include factors such as the number of unmapped boulders, house occupancy, the location of future events, and the seismic model applied.

In discussions since the finalisation of these reports, a range of issues have come to light that have the potential to alter the risk levels presented. These are:

- The extent to which the GNS report may be slightly conservative – the possibility of this was raised in the peer review of the GNS work carried out by Baynes Geologic;
- The extent to which risk might decrease over time given expected decreases in the underpinning seismicity;
- The extent to which risk would be reduced if occupants were to move out of their house for a period of time if there were to be another significant earthquake, thereby removing themselves from the risk associated with aftershocks arising from that event;
- The extent to which the GNS models are able to simulate the probability of the geographical location of future earthquakes.

We are keen to understand how the risk lines would be affected by a re-examination of the assumptions in these areas, and any other areas that you think are relevant. To that end, we would like to commission additional outputs, specifically:

- An updated set of risk contour maps reflecting the best information that is available to you at this point in time; and
- A letter from GNS that discusses these factors and how significant they are, along with a discussion of the likely effect of any factors that you have not been able to quantify in your model.

We understand John Scott had a useful conversation with Chris Massey on Wednesday regarding an alternative scenario, and there has been some recent email correspondence on this theme. We would propose that you talk to John about specifics for modelling – and it may be that modelling more than one scenario is appropriate. The revised maps should cover the same geographic areas as the full report.

Kelvin, this goes without saying but is important to point out that any revised maps must represent GNS's best opinion. Your work should not be overly conservative, nor should it be overly bullish.

In terms of timing, we would need an initial draft of the additional maps by close of play this Friday 1 June 2012, and the final output no later than Friday 8 June.

Please could you confirm your availability to do this work.

Yours sincerely

Diane Turner
General Manager
Strategy, Planning & Policy
Canterbury Earthquake Recovery Authority

Peter Mitchell
General Manager
Regulation and Democracy Services
Christchurch City Council

CERA
Canterbury Earthquake Recovery Authority

Christchurch City Council

20 July 2012

Terry Webb
Director, Natural Hazards Division
GNS Science

(Email Terry.Webb@gns.cri.nz)

Dear Terry

Port Hills Rockfall Study

We would like to thank you and the GNS team for the efforts that you have made with regards to assisting the policy development process in relation to the Port Hills. This work has been invaluable for our policy development process.
Thank you also for your responses of 8 June (CR 2012/150LR and CR 2012/152LR) to the points made in our letter to you dated 7 June.

There is considerable interest in the GNS work that has been undertaken in the Port Hills, and you have done a significant amount of further rock roll modelling since the finalisation of your March reports [GNS Science 2011/311, 2011/319 and 2012/57 refer]. It is our intent to make public as much as possible of your work in the weeks following the planned Port Hills announcement on 17 August. We would also seek to make public the letters referred to above, as well as this letter.

Given the high level of public interest in the GNS work, and the volume of work that has been undertaken since the finalisation of your March report, we ask if you are able to produce one last rock roll report for publication. We do not see any need to seek any revisions to the March reports.

We would see that a final report would describe the additional rock roll model runs that have been produced. As such, one might expect it to cover (inter-alia):

- A description of (and confirmation) that the 2012, 2016, 2018 and 2021 models that have been supplied to us use the same underpinning assumptions, especially as they relate to the so-called "no aftershocks" assumption and occupancy rates of 67% (these are our best assumptions), and

- Discussion and quantification of the decrease in risk over time

- A description of how PHGG ground truthing contributed to GNS's models

We would also like to request that you prepare very brief summary documents for life risk, cliff collapse and rock roll, aimed particularly at the lay person.

We would appreciate it if you can confirm that you are able to prepare the requested reports.
An indication of when we might be able to receive relevant drafts would also be useful.
Thank you again for your help.

Yours sincerely

Yours sincerely

Diane Turner
General Manager
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CERA

Peter Mitchell
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