A1.1.2.4 Impact from debris avalanches

$P_{F(S:H)}$ is the probability of the debris reaching or passing a portion of slope as it travels downhill from the source area. The probability of one boulder hitting an object when passing through a particular portion of the slope, perpendicular to the boulder path, is expressed as:

$$P_{F1(S:H)} = \frac{(D+d)}{L}$$ **Equation 3A**

where D is the diameter of the design boulder (assumed to be 0.5 m) that travels along a path either side of d, within which the boulder cannot miss, d is the diameter of an object such as a person or width of a building, and L is the unit length of slope perpendicular to the runout path, in this case L is 2 m which corresponds to the 2 m by 2 m grid-cell width adopted for the risk assessment.

However, the debris leaving the cliffs during the 2010/11 Canterbury earthquakes predominantly consisted of a mass of boulder- and cobble-sized blocks that were not all equal in volume. The distribution of block sizes within the debris has been simply quantified by counting and measuring boulders within the debris at the toe of the cliff. Based on this assessment a volume of 0.07 m^3 has been adopted, which is based on a 50th percentile boulder width of 0.5 m and assuming that boulders are spherical. This means that each cubic metre of debris comprises about eight boulders (taking into account the space between the boulders). For the assessment, a conservative estimate of 15 boulders per cubic metre of debris has been adopted If it is assumed that each cubic metre of debris comprises about 15 boulders of 0.07 m^3 in volume, then the probability of one cubic metre of debris hitting an object when passing through a particular portion of the slope is expressed as.

$$P_{F15(S:H)} = 1 - \left(1 - \frac{(D+d)}{L}\right)^{15}$$ **Equation 3B**

The probability of one cubic metre of debris formed of 15 boulders reaching/passing the same portion of slope increases as a function of the volume of debris travelling down the slope. The probability of one cubic metre of N cubic metres of debris hitting an object when passing through that same portion of slope is then given, by:

$$P_{FN(S:H)} = 1 - (1 - P_{F15(S:H)})^{N}$$ **Equation 3C**

For the purposes of risk estimation, it is necessary to have a quantitative measure of the size of a person. In this report, a "person" is assumed to be a cylinder of 1 m diameter and unspecified height (no specification of height was required in the model). The assumed value covers the order-of-magnitude range from about 0.3 m (vertical e.g., the person is standing) to about 3 m (horizontal, e.g., the person is lying down).

For randomly distributed sources, the volume of debris passing a given distance down the slope is taken from the empirical relationship. For the local assessed source areas 1–3 the debris is distributed using the numerical RAMMS model (refer to Section A1.1.2.5).

A1.1.2.5 Cliff-top recession

For cliff-top recession, the recession of the cliff edge is approximately proportional to the cube root of the volume lost from the cliff face. The relationship between the volume lost from the cliff face and the corresponding area of cliff top lost during the 2010/11 Canterbury earthquakes is reported in Massey et al. (2012a) for Richmond Hill/Wakefield Avenue, Shag Rock Reserve and Redcliffs. From these data the ratio of area lost per unit of volume leaving the cliff face is about of 0.016 ± 0.001m^2 per m^3 (at one standard deviation). That is, for every 100 m^3 of cliff face lost, about 1.6 m^2 (±6%) of cliff top area is expected to be lost. For this assessment, however, a ratio of 0.019 was adopted, which is the ratio plus two standard deviations (95% error limit).

A1.1.2.6 Falling due to cliff-top recession

$P_{R(S:H)}$ is the probability of a particular location at the cliff top falling and a person falling with it should they be present in that location when the cliff top falls. The probability of a person if present at the cliff top falling, given one metre of cliff top recessing, perpendicular to cliff edge, is expressed as.

$$P_{R1(S:H)} = \frac{(2D)}{L}$$

Equation 4A

where D is the approximate area occupied by a person at the cliff edge, assumed to be 1 m^2, and L is the unit length of cliff parallel to the cliff edge.

The probability of a person falling is dependent upon the total area of cliff edge that collapses during a given event, and how close the person is to the outer edge, as the proportion of cliff top that collapses in any event decreases away from the cliff edge. Therefore the probability of a person falling if one square metre of N square metres of cliff top were to fall is given by:

$$P_{RN(S:H)} = 1 - (1 - P_{R1(S:H)})^N$$

Equation 4B

For randomly distributed failures triggered by earthquakes and for non-seismic failures (both are assumed to be randomly distributed along the cliff), the proportion of cliff top lost per metre back from the cliff edge is based on what happened to the cliff edge at Redcliffs during the 2010/11 Canterbury earthquakes (Massey et al., 2012a). For assessed source areas 1–3 the proportion of cliff top lost per metre back from the cliff edge is calculated from the geometry of the source areas, adopting the lower, middle and upper area estimates.

Although the most likely locations of source areas 1–3 have been determined, it is possible that such failures could occur from elsewhere along the steep cliff face, especially as the rock mass, forming the slope, is now open and dilated. Therefore the risk estimates including the local source areas 1–3 have been distributed across the cliff top in the assessment area and not just in the locations of the assessed source areas 1–3.

A1.1.2.7 Probability of a person being present

$P_{(T:S)}$ 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 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 most-exposed individuals at risk would be those who spend 100% of their time at home.

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 the land zoning assessments carried out by the Canterbury Earthquake Recovery Authority – with regards to rockfall and debris avalanche risk – their policy adopted an "average" occupancy rate, to assess the average annual individual fatality risk from rockfall across the exposed population in order to estimate the risk to the average person.

For this assessment, GNS Science has assessed the sensitivity of the risk assessment results to a range of values representing the most exposed and average person. It has been assumed that the most exposed person spends 100% of their time at home, and that an average person spends on average 16 hours a day at home (16/24 = 0.67 or 67%).

When a person is at home they tend to spend more time in their home than in their garden. Whilst in their home they cannot occupy every part of it at the same time. To proportion the person across their home, GNS Science has assumed that Port Hills homes have a footprint area (assuming a single story dwelling) of A_F = 100 m^2. The probability that a person will be occupying a given area within their home at any one time can be expressed as:

$$P_{(T;S)} = \frac{(0.67)}{(A_F / P_A)}$$ **Equation 5**

Where 0.67 (67%) is the proportion of time an average person spends in their home and P_A is the area of home occupied by a person at any one time. For this assessment, GNS Science has adopted the area of the grid used for the risk assessment, in this case a 2 m by 2 m (4 m^2) grid-cell to represent P_A. Therefore the probability of person being present in a given grid cell within their home is assumed to be 0.03 (3%) for the average person.

A1.1.2.8 Probability of the person being killed if hit or falling

This is the probability of a person being killed if present and either in the path of one or more boulders or on an area of cliff top that falls. Vulnerability (*V*) depends on the landslide intensity, the characteristics of the elements at risk, and the impact of the landslide (Du et al., 2013).

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) and the possibility of getting out of the way to avoid being struck.

Studies from Hong Kong (e.g., Finlay et al., 1999) summarised the vulnerability ranges and recommended likelihood of 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, but conversely, flying debris (shrapnel) inside a house may contribute to injury.

Data on homes damaged in the cliff-collapse areas of the Port Hills indicate they were struck by many boulders, and in some cases the building collapsed. Finlay et al. (1999) recommend using a vulnerability of 1.0 if a person is in a building and if the building is hit by debris and collapses, or is inundated with debris. However, Du et al. (2013) propose vulnerability ranges from 0.24 for timber buildings to 0.45 for masonry buildings indicating that somebody is more likely to survive in a timber building that has collapsed.

At Redcliffs one person was killed in their home when it was struck by many hundreds of boulders, which caused it to collapse and another person was hit by boulders and killed whilst in their garden. In other parts of the Port Hills, a further three people died when they were buried by many boulders while outside.

The "landslide intensity" related to a debris avalanche is a function of the numbers of boulders passing through a given location and their velocity. In this risk assessment the probability of being in the path of one or more of N boulders within the debris (should a person be present) has been calculated separately as $P_{(S:H)}$.

Debris velocities derived from RAMMS model outputs are typically >5 m/s for most of the runout areas assessed. However, the velocity rapidly drops to <0.05 m/s in the distal limits of runout over a relatively short distance of several metres. These calculations are similar to field observations made from video footage although, some boulders within the distal debris fringe (mainly individual boulders) travelled at higher velocities, i.e., "fly rock". Fly-rock may occur when moving blocks impact and fracture resulting in high velocity rock fragments being released.

The two-dimensional rockfall modelling (Appendix 9) suggests that boulder velocities in the distal runout zone are still in the range of about 3 to 5 m/s and not < 0.5 m/s as suggested by RAMMS. Such velocities are more consistent with field observations. At these boulder velocities, of about 5 m/s (18 km/hr), it is unlikely that a person could get out of the way of a boulder (Australian Geomechanics Society, 2007).

Based on these results, a constant vulnerability factor of 70% has been adopted for this risk assessment as it was the factor adopted by the Canterbury Earthquake Recovery Authority for the previous risk assessments. A constant vulnerability value is thought reasonable as the velocity of the boulders, even in the distal runout zone are still relatively high with people unlikely to be able to get out of the way. The protective effects of buildings have not been taken into account, this is because most people killed by falling boulders during the 22 February 2011 earthquake were outside and therefore not protected by buildings. However, it is noted that buildings do have a sheltering effect as only 45% of buildings hit by boulders were penetrated (Massey et al., 2012b).

For a person falling from a cliff, the severity of injury increases with the height of fall, but it also depends on the age of the person, nature of the impact surface and how the body hits the surface. The chance of surviving increases if landing on a surface that can deform, such as snow or water. In a study by Barlow et al. (1983), the height at which 50% of children die from a fall is between 12 and 15 m. The cliffs in this study range from 40 to 70 m in height and the nature of the surface onto which a person would fall is boulder size debris formed of rock. Taking all these considerations into account, for this study, $V_{(D:T)}$, the probability of being killed if a person is on an area of cliff that falls, is assumed to be 0.7 as there might be a chance that a person could get away from the edge of the cliff before it falls.

A1.2 ROAD-USER RISK ASSESSMENT

This assessment uses a simplified version of the method used for Deans Head (Massey et al., 2014). This appendix describes:

- The background and context in terms of the road, its users and the slope collapse hazards they face (A1.1.1);
- The general modelling approach adopted (A1.1.2);
- Main Road traffic parameters for this road section, including the effect of the road being blocked at the time of a slope collapse event (A1.1.3);
- The estimation of individual road user risk per journey due to impact or inundation by slope collapse debris (A1.1.4); and
- Calculation of aggregate risk per journey and other risk metrics derived from it (A1.1.5).

It should be emphasised from the outset that the risk estimates for road users throughout this report use simple models which in many cases cannot be and have not been directly validated against hard evidence. There is a good deal of approximation, informed by the authors' knowledge of the area and of transport accidents more generally. Risk estimates per journey are presented as approximate ranges of possible values; presenting "point values" might provide a spurious sense of the accuracy of the assessment results.

A1.2.1 Background and Context

The section of Main Road modelled is shown in Figure A1.2 (and Figure 2 of the main report), and a Google Street View image, looking northwest along the road section modelled is shown in Figure A1.3.

Figure A1.2 Main Road section modelled (opposite Redcliffs Park).

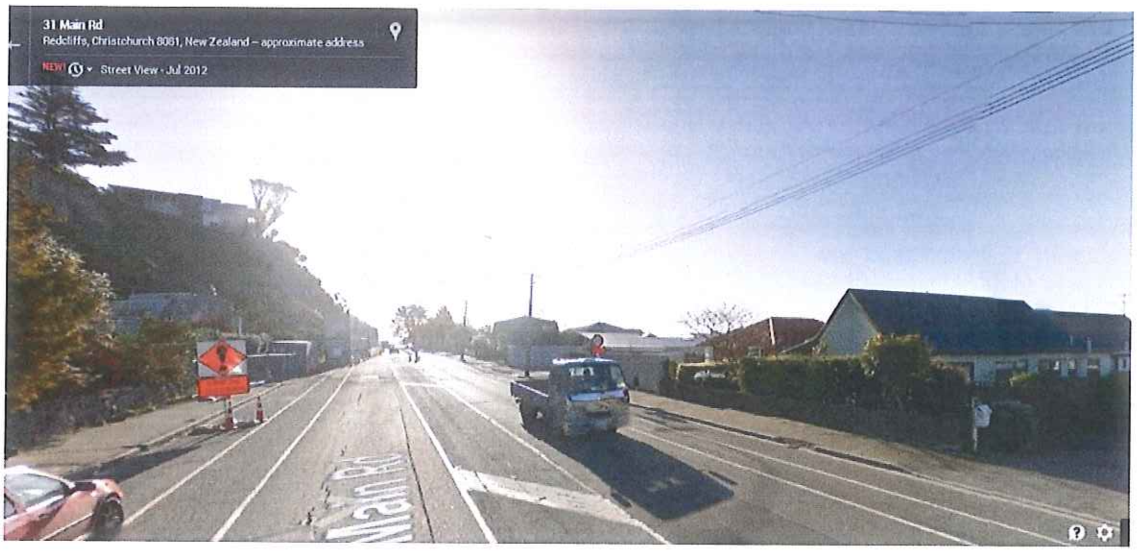

Figure A1.3 View northwest along the Main Road section assessed for Redcliffs (image taken from Google Earth).

There are no turnings along this short (81 m) section of road except for Puriwheriro Lane which has been closed since the 22 February 2011 earthquakes. There are no particular hazards such as steep drops or water into which a road user might fall when swerving from the road in the event of an accident.

Therefore, the hazard assessed for this section of Main Road is the direct impact of debris from cliff collapses (debris avalanches) falling onto road users or their vehicles.

Road user risk is assessed for:

a. Car occupants;

b. Bus occupants;

c. Truck occupants;

d. Motorcyclists;

e. Pedal Cyclists; and

f. Pedestrians.

The modelling approach is explained in Section A1.2.2.

A1.2.2 Risk Modelling Approach

Risk is assessed in terms of the risk per journey to the assessed road users. The risk per journey is calculated for each grid adopting the same grid used in the dwelling risk assessment. To streamline the calculation, risk is calculated for cells running along the near (slope side) and far (seaward) sides of the road, rather than for all cells within the road area. The basic equation used to estimate risk per journey (with dimensions of each term in brackets) is given as:

$$\text{Risk (probability of death per journey)} = SC_{event} \times P_{death} \times T_{journey} \quad \textbf{Equation 6}$$

Where: SC_{event} is the debris avalanche event frequency (in units of events/yr), P_{death} is the probability of death per event, if present and $T_{journey}$ is the time a road user is present per journey (in units of years per journey).

Risk contributions are calculated for each cell, each road user and each representative event per earthquake and non-earthquake band (adopting the inputs parameters for scenarios A–C), which are then summed to provide overall estimates of risk per journey for each side of the road.

The risk per journey outputs are then used to estimate risk per year to heavy users of this section of road, and to estimate the average expected total annual fatalities due to cliff collapse. The risks per journey are compared with the background motor vehicle crash risk that would be expected for this length of an average New Zealand urban road.

There is limited potential for multiple vehicles/road users to be involved in a single cliff collapse event at this site (the modelled road section is only 81 m long), so no "societal risk" calculation has been carried out.

The risk calculations rely on being able to estimate how many road users travel over the road section in question and how fast they travel. These issues are discussed in Section A1.2.3.

A1.2.3 Traffic Parameters on Main Road at Redcliffs

For an individual road user's trip, their travel speed determines the time they are at risk. Traffic does generally keep moving along this stretch of road, but at peak times becomes congested meaning vehicles are closer together (hence more are at risk) and travelling somewhat more slowly (hence at risk for longer periods) than at other times.

Average speeds and traffic densities (in terms of spacing between vehicles) taking into account periods of slow or static traffic are worked out using the traffic count data collected by Christchurch City Council on an hour-by-hour basis. There are no direct data available in recent years any closer to Redcliffs than the Sumner West Surf Club site to the east and the Causeway to the west. Traffic counts have therefore been taken as the averages of those used for Dean's Head to the east and Quarry Road to the west of the Redcliffs road section modelled. The resulting most recent available traffic counts for each hour of the week are shown in Table A1.1. Note that these are counts of motor vehicle traffic; "vulnerable road users" (motorcyclists, pedal cyclists and pedestrians) are not included.

While there is considerable use of this road section by pedal cyclists and a moderate level of motorcycle traffic, there is relatively light pedestrian usage as the footpath along the slope side of the road is currently closed, and blocked by containers, while pedestrians have been rerouted to the seaward side of the road adjacent to Redcliffs Park. More comprehensive counts of different road users are available for Main Road considerably further to the west (at the junction with Ferrymead Terrace), and these have been used to inform rough estimates of the split of motor vehicles between cars and trucks. Rough estimates based on the authors' own observations are made of cyclist, motorcyclist and pedestrian numbers of road users. Buses are considered separately (see below).