1.3 PREVIOUS WORK AT THE REDCLIFFS SITE

During the 22 February 2011 earthquakes, within the Redcliffs mass movement area, significant volumes of debris fell from the steep rock slope (debris avalanches), inundating dwellings at the cliff bottom, along with localised recession and cracking of the cliff crest. These have been collectively termed cliff-collapse hazards (Figure 3–Figure 9). Previous investigations of the site comprised:

1. The risk to life of people in dwellings at the cliff top and bottom from cliff top recession and debris avalanche hazards has already been estimated by Massey et al. (2012a);
2. Field mapping of the crack distributions at the cliff crest was carried out by GNS Science and Geotech Ltd., and the results are contained in the Stage 1 report (Massey et al., 2013);
3. Ground investigation of the site has involved drilling of two fully cored drillholes and a third open hole (with no core recovery), and inclinometer monitoring, carried out by Aurecon NZ Ltd, under contract to Christchurch City Council. The results of the drilling are reported by Pletz and Revell (2013); and
4. Ground investigation and field mapping of the site was also carried out by Tonkin and Taylor Ltd, (Tonkin and Taylor, 2012a) under contract to the Earthquake Commission. The ground investigations comprised the drilling of three drillholes (one cored, one open hole and one open barrel), 11 test pits to depths between 2 and 3.5 m below ground level, two cone penetrometer tests and two Scala penetrometers. Three standpipes were installed to measure groundwater levels and one drillhole inclinometer tube was installed.

Figure 3 Aerial view of the Redcliffs mass movement area after the 4 September 2010 (Darfield) earthquake and before the 22 February 2011 earthquakes. Photograph taken by M. Yetton.

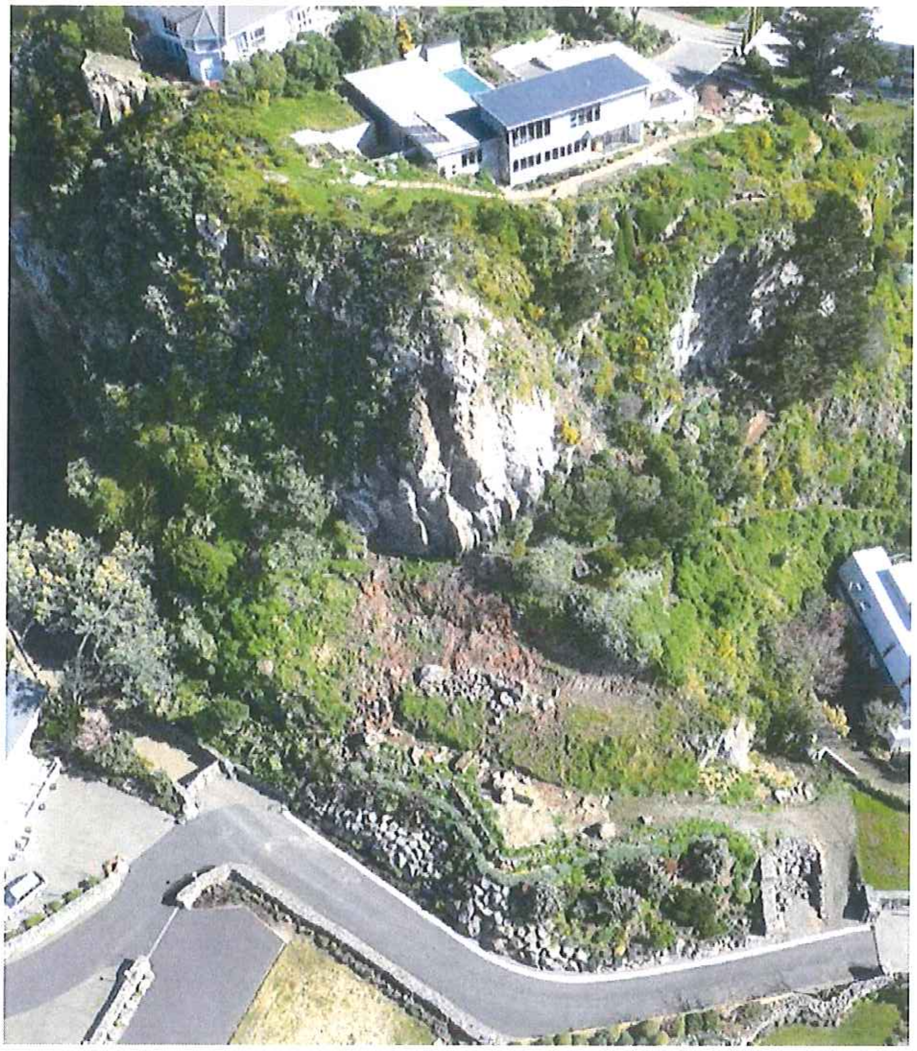

Figure 4 Aerial view of the Redcliffs mass movement area after the 4 September 2010 (Darfield) earthquake and before the 22 February 2011 earthquakes. Photograph taken by M. Yetton.

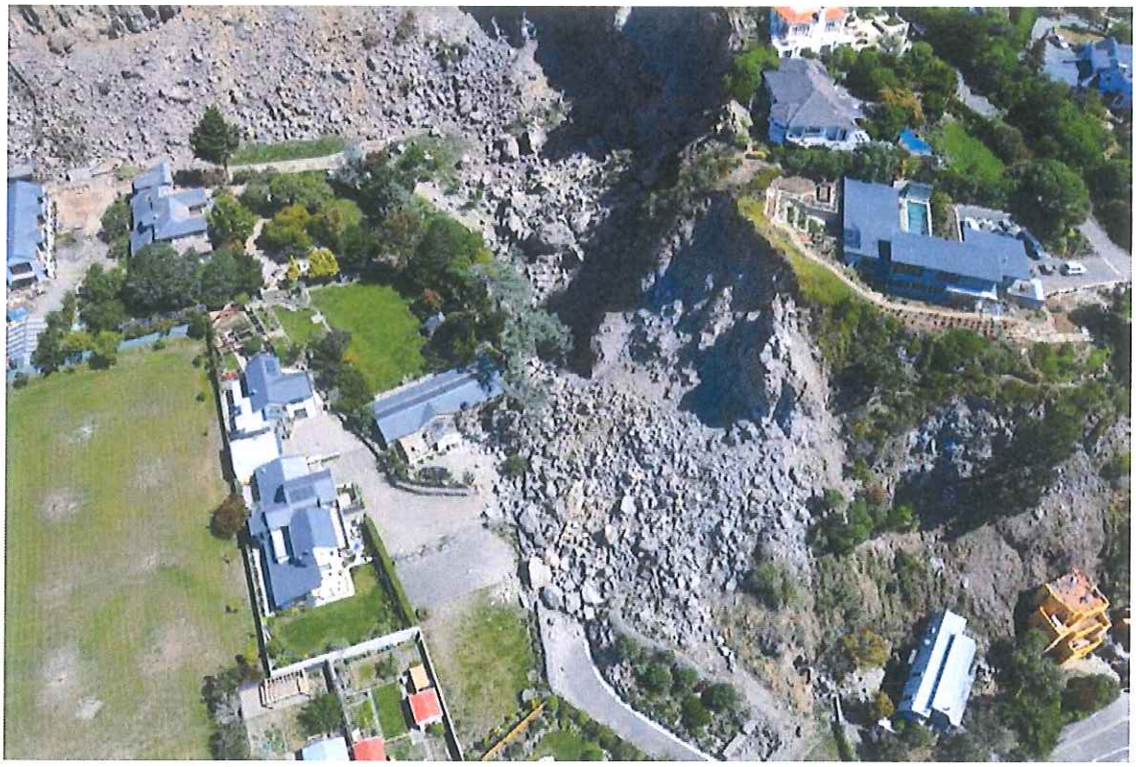

Figure 5 Aerial view of the Redcliffs mass movement area after the 22 February 2011 earthquakes and before the 13 June 2011 earthquakes. Photograph taken by G. Hancox.

Figure 6 Aerial view of the Redcliffs mass movement area after the 22 February 2011 earthquakes and before the 13 June 2011 earthquakes. Photograph taken by G. Hancox.

Figure 7 Aerial view of the Redcliffs mass movement area after the 22 February 2011 earthquakes and before the 13 June 2011 earthquakes. Photograph taken by G. Hancox.

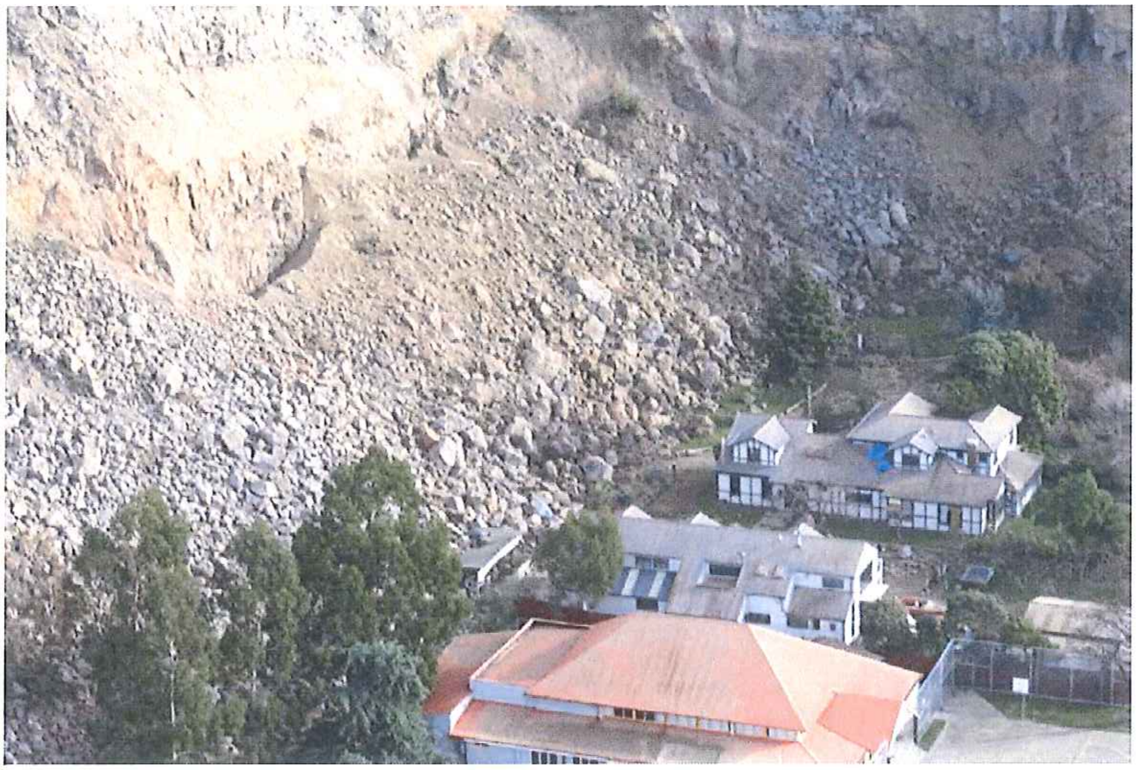

Figure 8 Aerial view of the Redcliffs mass movement area after the 22 February 2011 earthquakes and before the 13 June 2011 earthquakes. Photograph taken by C. Gibbons.

Figure 9 Aerial view of the Redcliffs rock slope after the 13 June 2011 earthquakes. Photograph taken by C. Massey.

1.4 SCOPE OF THIS REPORT

The scope of this report as per Appendix A of contract No. 4600000886 (December 2011) is to:

1. Estimate the annual individual fatality risk for affected dwelling occupants from cliff collapse hazards (debris avalanche and cliff-top recession) in the study area in Figure 2;
2. Estimate the fatality risk for users of Main Road from cliff collapse hazards for the section of Main Road shown in Figure 2; and
3. Provide recommendations to assist Christchurch City Council with considering options to mitigate life risks, associated with the assessed cliff collapse hazards.

For the purpose of this risk assessment, dwellings are defined as timber framed single-storey dwellings, of building importance category 2a (AS/NZS 1170.0.2002). The consequences of the hazards discussed in this report on other building types, such as commercial buildings, Redcliffs School and the retirement home (30 Raekura Place), fall outside the terms of reference for this report and have not been assessed.

The risk results contained in this report supersede the preliminary results contained in Working Note CR2013/304LR (Massey and Della Pasqua, 2013).

1.5 REPORT STRUCTURE

- Section 1.6 of the report details the methodology.
- Section 2 details the data used in the assessments.
- Sections 3–5 contain the results from the engineering geological, hazard and risk assessments respectively.
- Section 6 discusses the results of the risk assessment and explores the uncertainties associated with the estimated risks.
- Section 7 summarises the assessment findings.
- Section 8 presents recommendations for Christchurch City Council to consider.

1.6 METHODS OF ASSESSMENT

The site assessment comprised three stages:

1. Engineering geology assessment;
2. Hazard assessment; and
3. Risk assessment.

The methodology adopted for each stage is described in detail in Appendix 1, and is summarised in the following sections.

1.6.1 Engineering geology assessment

The findings presented in this report are based on engineering geological models of the site developed by GNS Science. The engineering geological assessment comprised:

1. Interpretation of aerial photographs covering the period 1940–2011, to determine the history of the site.
2. Surveying of cadastral survey marks within and around the study area, to determine the magnitudes of displacement of the slope during the 2010/11 Canterbury earthquakes.
3. Assessment of the results from the surveying of monitoring marks installed on the site by Aurecon NZ Ltd. (under contract to Christchurch City Council), following the 22 February 2011 earthquake. This was undertaken to assess the amount of slope displacement relating to the 22 February, 16 April, 13 June and 23 December 2011 earthquakes.
4. Geological and geomorphological field mapping to identify the materials and processes that have been active within the study area.
5. Construction of an engineering geological map and six cross-sections, based on the results from the aerial photograph interpretation, surveying, field mapping, and the ground investigations carried out by Aurecon NZ Ltd. (Pletz and Revell, 2013), and Tonkin and Taylor Ltd. (Tonkin and Taylor, 2012a). These were used as the basis for the hazard and risk assessments.

1.6.2 Hazard assessment

The hazard assessment method followed three main steps:

Step 1 comprises assessment of the static stability of the slope under non-earthquake (static) conditions, and an assessment of the dynamic (earthquake) stability of the slope, adopting selected slope cross-sections, to determine the likelihood of large-scale cliff collapse, and whether these can/cannot be triggered under static and/or dynamic conditions.

Step 2 uses the results from step 1 to define the likely failure geometries (source areas) of potential failures, which are combined with the crack patterns and slope morphology and engineering geology mapping to estimate their likely volume. Three volumes are defined for each source area (upper, middle and lower volumes), which represent the probable range of potential source areas that could occur within the assessment area.

Step 3 models: 1) the distance the debris travels down the slope (runout); and 2) the volume of debris passing a given location, should the failure occur. Modelling is done for each representative source area, and for the upper, middle and lower volume estimates.

The results from this characterisation are then used in the risk assessment.

1.6.2.1 Estimation of Slope Failure volumes

The original cliff-collapse risk assessment by Massey et al. (2012a) was based on the simulation of potential future cliff collapses that were all randomly distributed across the slope face. The results of the engineering geological assessments identified that during the 2010/11 Canterbury earthquakes, many cliff collapses were randomly distributed across the slopes, however, these only accounted for a relatively small proportion of the total volume of debris leaving the cliff. Much of the debris leaving the Redcliffs cliff (and other similar cliffs in the Port Hills), derived from a few discrete (local) failures that involved larger volumes of rock, particularly in areas where the rock mass strength had been weakened as a result of earthquake-induced cracking.

This assessment improves on the original work by Massey et al. (2012a), by:

1. Taking into account the potential for large local cliff collapses from three assessed source areas;
2. Revising the risk estimates from other cliff collapses that are randomly distributed across the cliff; and
3. Including an assessment of the risk from cliff collapses on users of Main Road.

The volumes of debris that could fall from the cliff under dynamic (earthquake) and static (non-earthquake, e.g., rain) conditions have been assessed.

- Earthquake generated failure volumes:
    - The volumes of material lost from cliffs during the 2010/11 Canterbury earthquakes were estimated using change models generated from airborne LiDAR and terrestrial laser scan surveys. The volumes lost in each earthquake were graphed against the corresponding synthetic free-field rock-outcrop peak horizontal ground accelerations relating to the earthquake (calculated specifically for Redcliffs; Holden et al., 2014). The synthetic free-field rock-outcrop motions

were used because there are no instrumental records at the site, and the existing instrumental records from nearby sites each contain site effects that relate to the instrument site.

- Assessment of the many failures that occurred from the steep rock slopes in the Port Hills during the 2010/11 earthquakes indicates that about 60% of the total volume of debris leaving the cliffs during the 13 June 2011 earthquakes is attributable to a small number of specific local failures of greater than 2,500 m^3 in volume.
- The most likely locations and volumes of three potential large localised failures were estimated based on the assessment of crack distributions, inferred displacements, slope morphology and geology and numerical analyses. The purpose of this exercise was to constrain the likely depth, width and length of the three assessed source areas.
- Three possible failure volumes were estimated for each assessed source area; a low, middle and upper estimate. This variation in failure volume is intended to reflect the range of uncertainty from the results of the modelling and mapping, e.g., the depth, width and length dimensions.
- The credibility of these potential failure volumes was evaluated by comparing them against: 1) the volumes of relict failures recognised in the geomorphology near the site and elsewhere in the Port Hills; and 2) the volume frequency distribution of debris that fell from this site and other similar sites in the Port Hills during the 2010/11 earthquakes.

- Non-earthquake generated failure volumes:
  - There are four main sources of information on historical non-earthquake failures for the Port Hills: 1) archived newspaper reports from 1870 to 1945; 2) the GNS Science landslide database, which is "complete" only since 1996; 3) insurance claims made to the Earthquake Commission for landslips which are "complete" only since 1996; and 4) information from local consultants (M. Yetton, Geotechnical Consulting Ltd. and D. Bell, University of Canterbury) which incompletely covers the period 1968 to present. These have been used to estimate the likely process rate of non-seismic rockfalls from the slope. These data are detailed in Massey et al. (2012a).
  - These failure volumes were assumed to be randomly distributed across the slope as per those recorded from sequential terrestrial laser scan surveys of the slope carried out after the 2010/11 earthquakes, during a period when no strong earthquakes occurred.

1.6.2.2 Estimation of debris runout

The distance that debris from debris avalanches travels down a slope is called the runout. The runout distance of debris falling from Redcliffs has been assessed both empirically and numerically. The methods adopted are described in Appendix 1.

For large local failures from the three assessed source areas, the volume of debris passing a given distance down the slope was assessed numerically, using the RAMMS software (RAMMS, 2011). These calculated runout distances were calibrated using data from debris avalanches that occurred from Redcliffs and other similar slopes in the Port Hills, during the 2010/11 Canterbury earthquakes.

For the randomly distributed failures, empirical models were used to estimate the debris runout down the slope. These models were based on the volumes of debris that fell and travelled given distances downslope at Redcliffs during the 2010/11 earthquakes.

1.6.3 Risk assessment

The risk metric assessed in this report is the annual individual fatality risk. The risk is assessed for dwelling occupants and regular road users from the cliff-collapse hazards assessed in this report. The cliff collapse hazards are:

1. Debris avalanches – a type of landside comprising many boulders falling simultaneously from a slope. The rocks start by sliding, toppling or falling before descending the slope rapidly (typically at greater than five metres a second) by any combination of falling, bouncing and rolling; and
2. Cliff-top recession – the result of parts of the cliff top collapsing, causing the cliff edge to move back up the slope.

The quantitative risk assessment uses risk-estimation methods that follow appropriate parts of the Australian Geomechanics Society framework for landslide risk management (Australian Geomechanics Society, 2007). It provides risk estimates suitable for use under SA/SNZ ISO1000: 2009.

Using the Australian Geomechanics Society (2007) guidelines for landslide risk management, the annual fatality risk to an individual is calculated from:

$$R_{(LOL)} = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(D:T)} \qquad \textbf{Equation 1}$$

where:

$R_{(LoL)}$ is the risk (annual probability of loss of life (death) of a person) from debris/earth flows/avalanches;

$P_{(H)}$ is the annual probability of the initiating event;

$P_{(S:H)}$ is the probability that a person, if present, is in the path of the debris at a given location;

$P_{(T:S)}$ is the probability that a person is present at that location; and

$V_{(D:T)}$ is the vulnerability, or probability that a person is killed if present and hit by debris.

The details relating to each of the above input parameters used in the risk assessments are discussed in Appendix 1.

1.6.3.1 Event annual frequencies

The frequency of occurrence of the events that could trigger the assessed cliff-collapse failure volumes is unknown. In place of this lack of information, the ranges of frequencies are defined, and the magnitudes of representative triggering events with these frequencies of occurrence are used to estimate the likely volumes of collapses that are triggered when the triggering event occurs.

- For non-earthquake triggers such as rainfall, rates of debris avalanches, rockfalls and cliff top recession triggered without earthquakes were taken from Massey et al. (2012a). These rates were used to estimate the contribution to total risk from non-earthquake triggering events. Four representative event-trigger frequencies were used and the volumes of the debris triggered by events with these frequencies were estimated.

- For earthquake events, rates of debris avalanches and rockfalls and cliff-top recession were estimated using the empirical relationship between the volumes of debris leaving the cliffs, and amounts of cliff-top recession recorded during the 2010/11 Canterbury earthquakes, and the synthetic free-field peak ground acceleration of the event that triggered them. Seven representative event-trigger frequencies were used and the volumes of debris triggered by events with these frequencies were estimated.
- For earthquake triggers, the frequency of a given free-field peak ground acceleration occurring is obtained from the New Zealand National Seismic Hazard Model (Stirling et al., 2012), using a modified form of the 2010 version of the National Seismic Hazard Model (Gerstenberger et al., 2011), which takes into account the increased level of seismicity in the Christchurch region.
- For the three assessed source areas – where larger volumes of rock could potentially fall, leading to larger areas of cliff top to be lost – the probability of failure was estimated based on the amount of permanent slope displacement that could occur in response to each of the seven representative events. This was done, adopting the decoupled method (Makdisi and Seed, 1978), by using:
    a. The relationship between the yield acceleration (Ky) and the maximum average acceleration of the mass (K_{MAX}), derived from back analysing the permanent displacement of the slope during the 2010/11 earthquakes; and
    b. The New Zealand National Seismic Hazard Model to provide the annual frequencies (return periods) of free-field rock outcrop peak horizontal ground accelerations (A_{MAX}) and therefore the annual frequencies of the equivalent maximum average acceleration of the mass (K_{MAX}).

The methods adopted are discussed in detail in Appendix 1.

1.6.3.2 Scenarios adopted for modelling

Three cliff-collapse risk scenarios have been adopted for modelling (Table 2). The three scenarios are chosen to examine the effect on risk of uncertainties in: 1) the assessed total volume that could be generated in a representative event; and 2) the volume of debris that passes a given distance down the slope.

Table 2 Risk scenarios used in the modelling of cliff collapses.

Volume	Source volume scenario	Runout volume scenario
Earthquake induced volumes		
Total volume generated in a representative earthquake event. Based on the empirical relationship between peak ground acceleration and volume leaving the slope, estimated from slope failures at Redcliffs during the 2010/11 earthquakes.	A) The relationship adopted is the mean plus one standard deviation B) The relationship adopted is the mean C) The relationship adopted is the mean minus one standard deviation	
Local earthquake failures. Representing 60% of the total earthquake volume	A) Adopting upper estimates of the source volumes (of assessed source areas 1–3) B) Adopting middle estimates of the source volumes (of assessed source areas 1–3) C) Adopting lower estimates of the source volumes (of assessed source areas 1–3)	A) RAMMS model adopting upper source volume estimates B) RAMMS model adopting mean source volume estimates C) RAMMS model adopting the lower source volume estimates
Randomly distributed earthquake failures. Representing 40% of the total earthquake volume.	A) Adopting 40% of the total volume derived from the mean plus one standard deviation relationship B) Adopting 40% of the total volume derived from the mean relationship C) Adopting 40% of the total volume derived from the mean minus one standard deviation relationship	A) Empirical model adopting the mean plus 1 standard deviation relationship B) Empirical model adopting the mean relationship C) Empirical model adopting the mean minus 1 standard deviation relationship
Non-earthquake induced volumes		
Randomly distributed non-earthquake failures. Volume estimated from historical non-earthquake rockfall production rates	A) Historical rates multiplied by a factor of two to take into account the increased production rates as the rock mass (post 2010/11 earthquake) is now broken. B) Historical rates C) Historical rates divided by two to take into account any potential overestimate of the historical rockfall rates	A) RAMMS model adopting upper source volume estimates B) RAMMS model adopting mean source volume estimates C) RAMMS model adopting the lower source volume estimates