5.0 RISK ASSESSMENT RESULTS

5.1 TRIGGERING EVENT FREQUENCIES

Failure of the assessed sources could be triggered by earthquakes (dynamic conditions) or by water ingress (static conditions).

5.1.1 Frequency of earthquake triggers

For earthquake triggers, the frequency of a given free-field peak ground acceleration (A_{FF}) occurring is obtained from the New Zealand National Seismic Hazard Model (Table 25) (Stirling et al., 2012). The increased level of seismicity in the Christchurch region is incorporated in a modified form of the 2010 version of the National Seismic Hazard Model (Gerstenberger et al., 2011).

For these assessments, peak ground acceleration is used to represent earthquake-shaking intensity, as peak ground acceleration is the ground-motion parameter considered to be most directly related to coseismic landslide initiation (Wartman et al., 2013).

Table 25 The annual frequency of a given peak ground acceleration (PGA) band occurring on rock (Site Class B) for different years from the 2012 seismic hazard model for Christchurch (G. McVerry, personal communication 2014). Note: these are free field rock outcrop peak ground accelerations.

PGA Band (g)	**0.1–0.3**	**0.3–0.5**	**0.5–0.8**	**0.8–1.2**	**1.2–1.6**	**1.6–2.0**	**2.0–3**
Year 2012 annual frequency	0.3405	0.0874	0.0329	0.0084	0.0016	0.0004	0.0001
Year 2016 annual frequency	0.1381	0.0322	0.0119	0.0030	0.0006	0.0001	0.00005
Next 50-year average annual frequency	0.0729	0.0148	0.0054	0.0014	0.0003	0.0001	0.00002

To take into account the possibility of larger local failures of the slope the total volume of debris generated in each band was partitioned between: 1) random uniformly distributed failures of the cliff face comprising 40% of the total volume, that may fall from anywhere on the slope; and 2) local (non-random) larger failures comprising 60% of the total volume, corresponding to assessed source areas 1–3 (Table 26). Volumes were estimated based on the upper, middle and lower total volume estimates of debris generated in each band.

Table 26 Proportion of the total debris volume per peak ground acceleration band allocated to distributed and local failures, for upper, central and lower estimates of volume (rounded to the nearest 100 m^3).

Estimated debris avalanche volumes[1] (m^3)	Peak ground acceleration band (g)						
	0.1–0.3	0.3–0.5	0.5–0.8	0.8–1.2	1.2–1.6	1.6–2.0	2.0–3
Distributed debris: Upper volume	8,700	7,700	13,500	22,200	32,600	49,000	98,800
Localised debris: Upper volume	0	11,600	20,300	33,200	48,900	59,700	59,700
Distributed debris: Middle volume	3,900	3,500	6,000	9,900	14,500	19,400	36,300
Localised debris: Middle volume	0	5,200	9,000	14,800	21,800	29,100	34,300
Distributed debris: Lower volume	1,800	1,500	2,700	4,400	6,500	8,600	12,600
Localised debris: Lower volume	0	2,300	4,00	6,600	9,700	13,000	18,900

1 Only the first digit in the number is significant.

5.1.1.1 Peak ground acceleration and permanent slope displacement

The probability of each local source area (1–3) being triggered in a given earthquake was based on the calculated permanent displacement, estimated from the decoupled results.

It is difficult to estimate the probability of triggering failure, leading to catastrophic slope collapse, where the debris runs out down slope forming a debris avalanche. It is also possible that permanent slope displacements could cause catastrophic damage to dwellings located at the cliff crest, even if the debris does not leave the source. The level of displacement chosen to differentiate between safe and unsafe behaviour (Abramson et al., 2002) differs between authors. Some examples are:

a. Hynes-Griffin and Franklin (1984) suggest that up to 0.1 m displacements may be acceptable for well-constructed earth dams.

b. Wieczorek et al. (1985) used 0.05 m as the critical parameter for a landslide hazard map of San Mateo County, California.

c. Keefer and Wilson (1989) used 0.1 m for coherent slides in southern California

d. Jibson and Keefer (1993) used a 0.05–0.1 m range for landslides in the Mississippi Valley.

e. The State of California (1997) finds slopes acceptable if the Newmark displacement is less than 0.15 m. A slope with a Newmark displacement greater than 0.3 m is considered unsafe. For displacements in the "grey" area between 0.15 and 0.3 m, engineering judgement is required for assessment.

The estimated magnitude of permanent slope displacement of the assessed sources in a future earthquake was based on the decoupled assessment results. The permanent displacement of each source at a given level of free-field peak ground acceleration (A_{FF}) was estimated from the relationship between the yield acceleration (Ky) and the maximum average acceleration of the mass (K_{MAX}) (Figure 27). Different levels of peak ground acceleration were adopted based on the seven earthquake event bands, and each multiplied by the site-specific ratio of K_{MAX} to A_{FF} (assuming the mean plus one standard deviation) to estimate the equivalent maximum average acceleration of the mass (K_{MAX}) for the given value of A_{FF}. For example, an A_{FF} of 0.4 g would have an equivalent K_{MAX} of 0.9 g, assuming a ratio of 2.5 (Table 27).

5.1.1.2 Permanent slope displacement and likelihood of catastrophic slope failure

The probability of occurrence of each local source area (1–3) was based on the estimated permanent displacement, estimated from the decoupled results (Figure 27), as follows:

- If the estimated displacement of the source area is ≤0.1 m then the probability of catastrophic failure = 0.
- If the estimated permanent displacement of the source area is ≥1.0 m then the probability of catastrophic failure = 1.
- If the estimated permanent displacements are between 0.1 m and 1 m then the probability of failure (P) is calculated based on a linear interpolation between P=0 at displacements of 0.1 m, and $P = 1$, at displacements of 1 m.

It should be noted that the displacements at different ratios of Ky/K_{MAX}, were calculated using the synthetic earthquake acceleration time histories for the 22 February and 13 June 2011 earthquakes. Both of these events were near-field earthquakes of short duration, but had high amplitude. The calculated displacements in Figure 27 represent displacements in response to these earthquakes (adopting material parameters for model 3). Earthquakes of longer duration may affect the site in different ways. For example, the response of the loess and volcanic colluvium (at higher water contents representative of winter conditions) may be non-linear, and could lead to larger permanent displacements. Conversely, the peak amplitudes relating to longer duration earthquakes from more distant sources are likely to be lower and may not trigger displacement of the slope.

Table 27 Forecast modelling results from the dynamic slope stability assessment for cross-sections 2, 4 and 6, adopting model 3 material parameters, and no water in tension cracks. Estimated displacements are rounded to the nearest 0.1 m.

		Earthquake event band	**1**	**2**	**3**	**4**	**5**	**6**	**7**
		Peak ground acceleration range of band (g)	0.1–0.3	0.3–0.5	0.5–0.8	0.8–1.2	1.2–1.6	1.6–2.0	2.0–3
		Free field peak ground acceleration (A_{FF}) for representative event in band (g)	0.2	0.4	0.65	1.0	1.4	1.8	2.5
		Year 2016 annual frequency of representative event in band	0.1381	0.0322	0.0119	0.0030	0.0006	0.0001	0.00005
		Adopted K_{MAX} to A_{FF}[1] ratio	2.5 (mean plus 1 standard deviation)						
Cross-section	**Adopted yield[2] acceleration (*Ky*) (g)**	**Representative equivalent maximum average acceleration (K_{MAX}) of each band (g)[3]**	0.4	0.9	1.4	2.2	3.1	4.0	5.5
2 (source area 2)	(0.3)	**Estimated permanent displacement (m)**	0.0	0.2	0.8	1.7	2.7	3.5	4.5
		Probability of failure	**0.0**	**0.1**	**0.7**	**1.0**	**1.0**	**1.0**	**1.0**
4 (source area 1)	0.2	**Estimated permanent displacement (m)**	0.0	0.3	1.2	2.3	3.3	4.1	5.0
		Probability of failure	**0.0**	**0.3**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
6 (source area 3)	(0.5)	**Estimated permanent displacement (m)**	0.0	0.0	0.1	0.6	1.2	1.9	2.9
		Probability of failure	**0.0**	**0.0**	**0.0**	**0.5**	**1.0**	**1.0**	**1.0**

1 A_{FF} represents the peak horizontal ground acceleration of the free field input motion, rounded to the nearest 0.1 g.

2 Where shown in brackets, the yield acceleration was calculated using the pseduostatic slope stability method.

3 Rounded to the nearest 0.1 g.

5.1.1.3 Deaggregation of the National Seismic Hazard Model

The seismic performance of the slope in future earthquakes was inferred from assessing its performance in past earthquakes, mainly the 22 February, 16 April, 13 June and 23 December 2011 earthquakes, using the relationship established between peak ground acceleration and the amount of permanent slope displacement. These earthquakes varied in magnitude between M5.2 and M6.3, and were "near-field" i.e., their epicentres were very close, within 10 km, of the Redcliffs site.

The annual frequencies of a given level of peak ground acceleration occurring in the area are given by the National Seismic Hazard Model of New Zealand (Stirling et al., 2012). The National Seismic Hazard Model combines all of the various earthquake sources that could contribute to the seismic hazard at a given location. The National Seismic Hazard Model estimates for the Port Hills are based on a combination of different earthquake sources: 1) subduction zone; 2) mapped active faults; and 3) unknown or "background" earthquakes. For the risk assessment it is important to deaggregate the National Seismic Hazard Model to assess which earthquake sources contribute the most to it.

Buxton and McVerry (personal communications, 2014) suggest that it is magnitude M5.3–6.3 earthquakes on unknown active faults, within 20 km of the site that contribute most to the National Seismic Hazard Model. These earthquakes are similar to the 22 February, 16 April 13 June and 23 December 2011 earthquakes.

5.1.2 Frequency of rainfall triggers

As discussed in Section 4.1, it is possible that local source areas (1–3) could be triggered under non-seismic (static or natural) conditions, as strength degradation caused by future earthquakes and/or periodic wetting and drying of the slope face could lead to larger static failures in the future.

However, it is unlikely that a rainstorm will trigger a comparable number and volume of cliff collapses over an area similar to a large magnitude earthquake (typically $>M_W$ 6). This is because earthquake loading can greatly exceed the rock mass strength resulting in slope factors of safety of <<1.0, while intense rain can only reduce rock mass strength until it becomes unstable (factor of safety = 1.0).

Debris avalanche rates triggered by non-seismic events were taken from Massey et al. (2012a). The results from Massey et al. (2012a) for Redcliffs are shown in Table 28.

Table 28 Representative annual event frequency of debris avalanches occurring, and the representative volume of the avalanche, for each time-period band. These represent the estimated volumes of the material leaving the cliffs per site with a given frequency, for non-seismic triggers. Taken from Massey et al. (2012a) for Redcliffs, using historical data.

Location	Return period (years)	Number of events in band	Annual frequency of events	Mean event volume (m^3)	Annual accumulation rate (m^3/year)
Redcliffs	1–15	5.5	0.37	5	1.8
	15–100	1.3	0.0133	170	2.3
	100–1,000	0.7	0.0007	1,500	1.0
	1,000–10,000	0.3	0.00003	10,000	0.3

Given the historical rates of rainfall triggered rockfall for the slope of about 5–6 m^3/year (estimated from historical data in Massey et al., 2012a), the current rates of rockfall triggered by rainfall are considerably higher (480 m^3 per year for 2012 and 90 m^3/year for 2013). To take the increased non-seismic rockfall rates into account a factor of two has been applied to the annual rate in Table 28, based on the measured rates of rockfall from the terrestrial laser scan surveys.

At present the non-seismic rockfall rates derived from terrestrial laser scan surveys are considerably higher than 10–12 m^3/year (historical rate multiplied by a factor of two), but these rates are expected to reduce with time as the more unstable boulders are removed from the slope. The rates recorded from the terrestrial laser scan surveys represent cumulative volumes of debris for a single year. Historically, a maximum yearly rate of up to 50 m^3 has been recorded, but this reduces once divided over a longer time period.

If the site were to be affected in the near future by another large earthquake, it is probable that these currently high rates would continue to persist for much longer.

5.2 DWELLING OCCUPANT RISK

The results from the risk assessment are shown in Figure 38 (Maps 1–3) as the annual individual fatality risk for scenarios A, B and C (Table 2), adopting the input parameters as shown in Table 2. Map 1 shows the annual individual fatality risk estimated for cliff collapses (debris avalanches and cliff-top recession) adopting the upper debris volume and runout estimates. Map 2 shows the estimated annual individual fatality risk for cliff collapses adopting the middle debris volume and runout estimates. Map 3 shows the annual individual fatality risk adopting the lower debris volume and runout estimates.

5.2.1 Variables adopted for the risk assessment

Other variables used in the risk assessment were discussed at a workshop with Christchurch City Council on 18 March 2014. Based on the results from the workshop the risk estimates presented in Figure 38 adopt the following main variables:

- $P_{(H)}$ for earthquake triggers the annual frequency of the triggering event adopt the 2016 seismic hazard model results, which include aftershocks.
- $P_{(S:H)}$ the probability that a person, if present, is in the path of the debris is based on variable (lower, middle and upper) estimates of the debris volume that could be triggered in an event.
- $P_{(T:S)}$ the probability that a person is present at a particular location, as the debris moves thought it, of 67%. Assuming an "average" person spends 16 hours a day at home. For this assessment, GNS Science has assumed the same "average" occupancy rate value adopted by the Canterbury Earthquake Recovery Authority.
- $V_{(D:T)}$ the vulnerability of a person, if present and inundated by debris, is 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 (CERA) for the previous risk assessments.

5.2.2 Debris avalanche

For comparison purposes only, the effect of including the three assessed source areas in the risk assessment are shown by including an estimation of the risk without these three source areas, where all of the debris generated in the peak ground acceleration bands is uniformly distributed across the slope (Figure 39). There is little difference between the two maps, indicating that for scenario B (Figure 38, Map 2) the presence of localised sources has little impact on the risk.

Other parameters such as the probability of a person being present ($P_{(T:S)}$) and the vulnerability of a person if present and hit are held constant across all scenarios where $P_{(T:S)}$ = 0.67 and $V_{(D:T)}$ = 0.7.

Graphs showing the results for each scenario with/without local seismic sources are shown in Figure 40 and 41. The number of 2 m by 2 m cells shown in the graphs indicates the spread of the risk at different levels of annual individual fatality risk between the scenarios.