4.2 RUNOUT DISTANCE

4.2.1 Potential future source volume estimation

4.2.1.1 Earthquake volumes

The total volumes of cliff-collapse debris likely to be generated in an earthquake representative of each peak ground acceleration band was determined from the relationship between the volumes of material leaving the cliffs during the 2010/11 Canterbury earthquakes (per square metre of cliff face), and the calculated free field rock outcrop peak ground acceleration at the Redcliffs site (Holden et al., 2014) (Table 21 and Figure 28).

Table 21 The volumes of debris leaving the slope during each of the 2010/11 Canterbury earthquakes and the earthquake's estimated peak ground acceleration, at the Redcliffs site – horizontal (H) and vertical (V) peak ground acceleration (PGA) components are listed separately.

Earthquake	PGA H (m/s/s)	PGA V (m/s/s)	Origin[1]	Volume leaving slope (m^3)	Source slope surface area (m^2)	Volume/slope area (m^3/m^2)
4 September 2010	3.3	1.5	GeoNet LPCC	60 (±10)	22,000	0.003
22 February 2011	8.6	6.4	Synthetic	23,800 (±6,600)	22,000	1.08
16 April 2011	0.5	0.2	Synthetic	1,170 (±110)	22,970	0.05
13 June 2011	3.7	2.7	Synthetic	11,800 (±3,500)	22,970	0.51
23 December 2011	1.6	1.2	Synthetic	1,180 (±130)	22,870	0.05

[1] With the exception of the 4 September 2010 earthquake, peak ground accelerations were taken from the synthetic time acceleration histories (free field rock outcrop motions) derived from earthquake source modelling for the Redcliffs site (Holden et al., 2014). For the 4 September 2010 earthquake the instrumental record (maximum single component) from the GeoNet station LPCC was used.

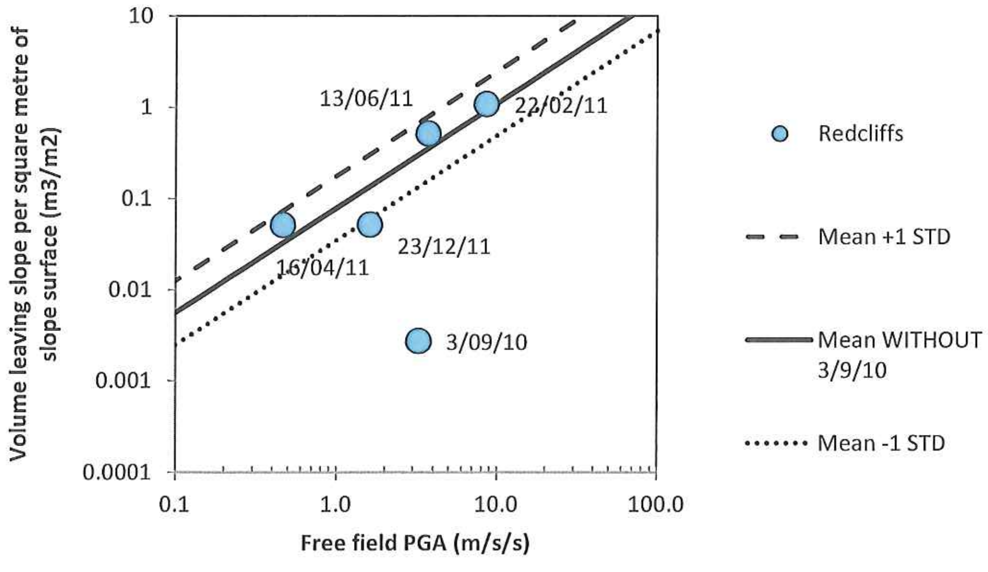

Figure 28 Relationship between free field peak ground accelerations at Redcliffs and the volume of debris leaving the Redcliffs slope.

The observed rockfall volumes correlate well with horizontal peak ground accelerations, with the exception of the 4 September 2010 earthquake. The data are well fitted by a power law, with a coefficient of determination (R^2) of 0.8, if the 4 September 2010 earthquake data is removed, and an R^2 of 0.2 if left in, indicating a poor correlation. In the 4 September 2010 earthquake much smaller volumes were generated (at all Port Hills sites) than for the other, later earthquakes. This difference is presumed to be because of the more fractured nature of the rock slopes following the 22 February 2011 earthquake (consistent with ground observations and measured cracks).

The ground conditions are likely to have weakened further after the 22 February 2011 earthquake. Earthquake induced fracturing and strength degradation of the rock during each subsequent earthquake will have caused further deterioration to rock-mass quality, but the amount of degradation likely in each earthquake is not known.

The 4 September 2010 datapoint is treated as anomalous and was not included in the correlations used to estimate rockfall production as a function of peak ground acceleration.

Seven peak ground acceleration bands are chosen for the assessment and the volumes generated in each band have been estimated from the relationship shown in Figure 29, adopting the mean, the mean minus one standard deviation and the mean plus one standard deviation, as the middle, lower and upper volume estimates respectively (Table 22).

Table 22 The estimated volumes of debris leaving the slope for different bands of peak ground acceleration (PGA). STD is the standard deviation of the mean based on the correlation in Figure 28.

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**
Midpoint of PGA band (g)	0.2	0.4	0.65	1	1.4	1.8	2.5
Midpoint of PGA band (m/s/s)	1.96	3.92	6.38	9.81	13.73	17.66	24.53
Upper volume: MEAN +1 STD (m^3)[1]	8,735	19,349	33,776	55,370	81,460	108,687	158,445
Middle volume: MEAN (m^3)[1]	3,893	8,624	15,054	24,678	36,307	48,442	70,619
Lower volume: MEAN -1 STD (m^3)[1]	1,735	3,844	6,709	10,999	16,182	21,591	31,475

[1] Only the first digit in the number is significant.

Analysis of the volume and frequency distribution of discrete failures that fell from the cliffs during the 13 June 2011 earthquake shows that the total volume of material leaving the cliff will be dominated by infrequent and local large failures. In the case of the 13 June 2011 landslide volumes, one landslide accounted for about 60% of the total volume of all of the surveyed cliff collapses in the Port Hills. At Redcliffs, there were three discrete local cliff collapses of volumes between 1,000 and 2,000 m^3 per failure (total volume of about 5,000 m^3) which accounted for about 42% of the total volume of debris leaving the slope in response to the 13 June 2011 earthquake.

The 13 June 2011 cliff-collapse data shows that 40% of the total failure volume came from many small randomly distributed failures and 60% from a few very large local failures, with a change in rate at a failure volume of about 2,500–3,000 m^3 (Figure 29).

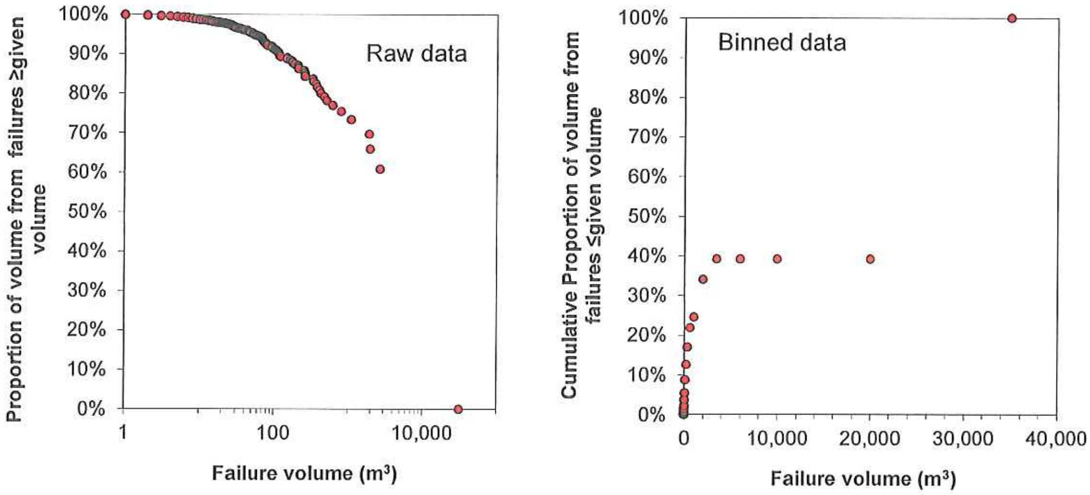

Figure 29 Proportion and cumulative proportion of volume from cliff collapses in the Port Hills greater than or equal to a given volume. Data from the 2011 cliff collapse volumes triggered by the 13 June 2011 earthquakes, derived from terrestrial laser scan change models of Richmond Hill, Shag Rock Reserve and Redcliffs. The different plots represent raw data and binned data.

Local sources (assessed source areas 1–3)

The likely locations and volumes of potential source areas (1–3) have been estimated based on:

1. Numerical stability analysis results;
2. Mapped crack distributions relating to the 2010/11 Canterbury earthquakes; and
3. Engineering geology and morphology of the slope.

Three possible failure volume estimates – lower, middle and upper range estimates – have been calculated for each potential source area. The variation in failure volumes reflects the uncertainty in the source shape (depth, width and length dimensions) estimated from site conditions and the modelling.

Volumes were calculated by estimating the shape of any future failures as quarter-ellipsoids (half-spoon shaped) (following the method of Cruden and Varnes, 1996) (Figure 30). Estimated volumes are shown in Table 23.

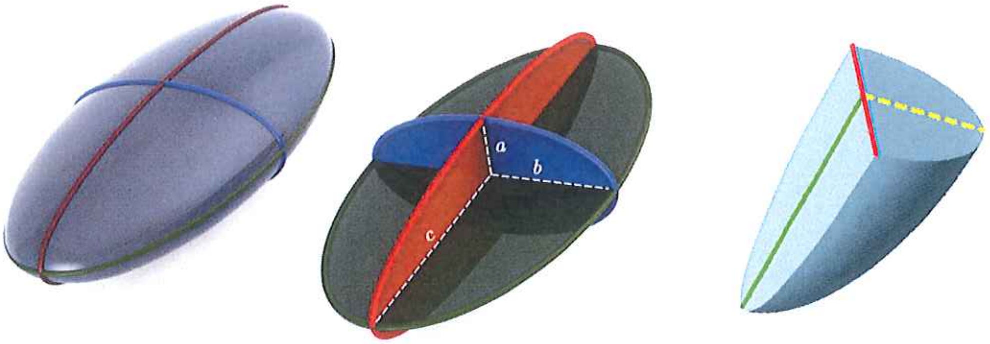

Figure 30 Estimation of landslide volume assuming a quarter-ellipsoid shape.

Table 23 Example of estimated source volumes (the first digit in the number is significant) and fahrboeschung angles.

Assessed source area	Source volume estimate	Volume (m^3)	Fahrboeschung[1] angle – talus (°)		Fahrboeschung angle – boulder roll (°)	
			Mean	Mean – 1 STD	Mean	Mean – 1 STD
1	LOWER	7,700	38.6	33.0	38.6	33.0
	MID	12,800	38.0	32.4	38.0	32.4
	UPPER[1]	25,000	36.9	31.4	36.9	31.4
2	LOWER	3,700	39.5	33.9	39.5	33.9
	MID	9,400	38.4	32.8	38.4	32.8
	UPPER	18,300	37.6	32.0	37.6	32.0
3	LOWER	1,800	40.4	34.7	40.4	34.7
	MID	2,500	40.0	34.3	39.3	34.3
	UPPER	4,300	39.3	33.7	39.3	33.7

[1] For descriptions of the fahrboeschung angles used in the report refer to Section 4.5.

The credibility of these potential failure volumes has been evaluated by comparing them with estimated volumes of individual debris avalanches that fell from the slopes at Richmond Hill Road, Shag Rock Reserve and Redcliffs (Massey et al., 2012a) during the 13 June 2011 earthquakes (Figure 31). These volumes were derived from the terrestrial laser scan change models.

The estimated potential failure volumes of assessed source areas 1–3 are within the upper volume range of data from relict failures and those that fell in the 13 June 2011 earthquakes. This suggests that such failure volumes could occur, but they are likely to be very infrequent and few in number during a single strong earthquake.

4.2.1.2 Non-earthquake volumes

Non-earthquake volumes and rates of cliff collapse were taken from Massey et al. (2012a) and are based on historical data. The historical data used to infer these rates is summarised in Table 24.

Table 24 Information used to estimate event volumes contributing to the total risk from non-seismic rockfall triggering events, all sites.

Time period (years)	Type of events	Description
<1–15	Rainstorms/frosts that occur frequently.	Cliff collapses tend to be small and localised from events with this high frequency of occurrence. Estimated volumes of events derived using Earthquake Commission claims, local consultant files and the GNS Science database.
15–100	Rainstorms with larger intensities and durations that occur once every 15 – 100 years on average.	Cliff collapses occur but their volumes tend to be limited and localised. Estimated volumes of events derived using historical newspapers and consultant reports.
100–1,000	Rainstorms with very large intensities and durations that occur once every 100 – 1,000 years on average.	Cliff collapses will be widespread. Estimated volumes of events derived using old newspaper reports.
1,000– 10,000	Rainstorms with extreme intensities and durations exceeding Cyclone Bola (1988) and the Manawatu storm (2004) that occur once every >1,000 years on average.	These events might trigger a large number of cliff collapses over a wide area and may be large in volume. However, cliff collapse risk would be low compared with risk from flooding or debris flows.