Appendix B Assessment of a revised operational school boundary

Performance objectives

Our assessment of a revised operational school boundary to (i) maintain safety to a high level, and (ii) minimise disruption to as low as practically possible, is based on GNS's slope stability modelling and runout modelling (GNS 2014/78; Sections 4.1 & 4.2, respectively).

To achieve the aims to minimise disruption, maintain safety and minimise uncertainty we set the following performance objectives:

- Risk of fatality within the school grounds shall be nil
- Establish a revised operational school boundary at a conservatively located set-back[30]
- No rock shall cross the revised boundary
- Minimise risk of rock impacting or damaging the bund
- Minimise risk of rock requiring clearance from behind the bund (in the catch area)
- Minimise monitoring requirements to those to be agreed with the CCC as part of the Building Consent *compliance monitoring* programme
- Provide conservatively established ample storage capacity such that in the event of multiple large volume rockfall events, the rock is well contained in the catch area, and there be little need for detailed reassessment of the slope stability.

Assessment process

GNS modelled randomly distributed cliff collapses as well as three local sources. The local sources represent GNS' estimation of the most likely locations of specific rockfall sources that could generate large rockfall volumes (refer to GNS 2014/78; Section 1.2.2, page 6 and Figure 2, page 7 – reproduced below).

Local source 1 is in the area of Glendevere Terrace (at the cliff top to the west of the site) and Local source 2 is to the north of the site. These two sites are relevant to the risk assessment at the school site so it is of benefit that GNS included these in their assessment. Local source 3 affects Main Road away from the school site.

---

[30] The legal boundaries do not change. It is the operational area that is changed being defined by revised operational school boundaries.

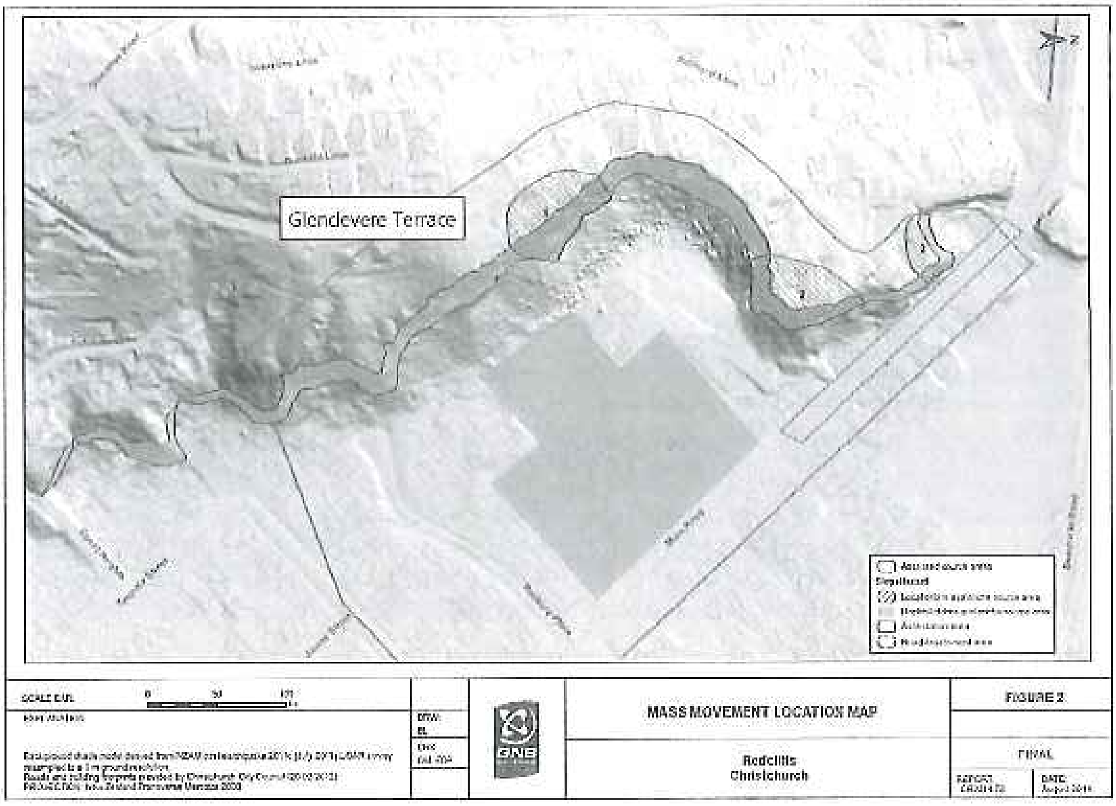


Figure B1: GNS 2014/78 Figure 2 showing local source areas 1, 2 & 3 and school plan area (shaded green) added.

To explore the sensitivity to uncertainty in the modelling GNS estimated potential future source volumes using a range of rock material properties, instability models and earthquake demand (refer to GNS 2014/78, Section 1.6.3.2, page 18 – *Scenarios adopted for modelling*, and Section 4.1, page 61).

Their assessment of runout included an empirical procedure and numerical (RAMMS[31]) modelling. The empirical procedure followed for estimating the empirical run-out distance, in terms of the fahrboeschung angle, is detailed in GNS 2014/78 Appendix 1.

GNS states (page 84) that a total of 45 sections through specific debris avalanches triggered by the 22 February and 13 June 2011 earthquakes have been assessed. For each section the fahrboeschung for "talus" (where the ground surface is obscured by many boulders) and "boulder roll" (individual boulders) have been defined based on field mapping. The results are shown in Figure 32 (reproduced below) as ratios of H/L where H is the height of fall and L is the length, or runout distance, of the mapped rockfalls and debris avalanche deposits (talus).

---

[31] RAMMS rapid mass movement simulation software: http://ramms.slf.ch/ramms/index.php

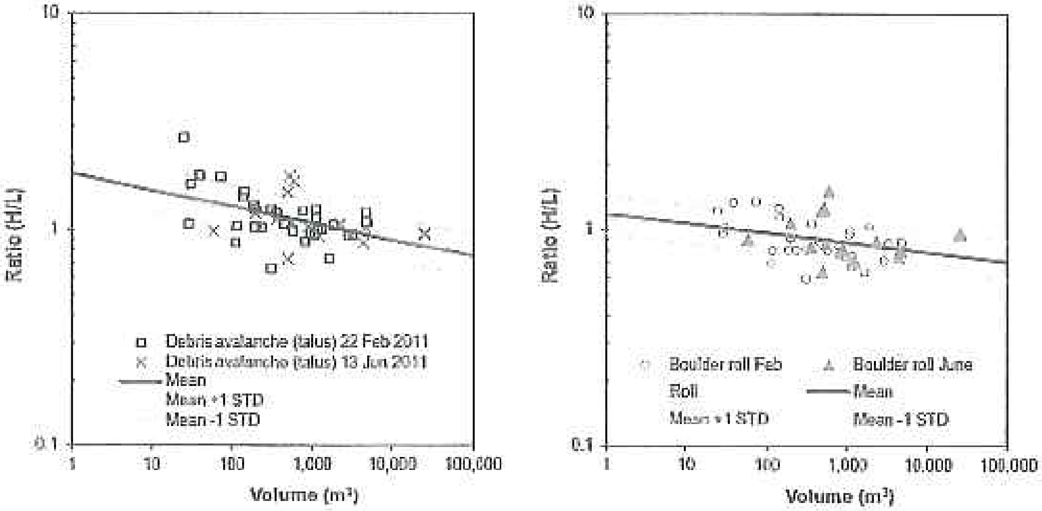


Figure 32 The empirical fahrboeschung relationships, expressed as the ratio of height (H) to length (L) for debris avalanche talus and boulder roll (rockfalls), recorded in the Port Hills. N = 45 sections. Errors are expressed as the mean ± one standard deviation (STD).

GNS states (page 84) that these fahrboeschung relationships are based on debris avalanches that fell from cliffs in the wider Port Hills area during the earthquakes, and not just from the Redcliffs site. They therefore reflect all of the different types of slope shape that could affect the debris avalanche runout. (Our emphasis added in underline).

From this statement we have confidence that the dataset is statistically robust enough on which to base an assessment of a set-back that would be far enough removed from the cliff to safeguard against rockfall hazard and provide assurance against disruption at the school site.

Referring to Figure 32 GNS states (page 84):

1. The results show that for very large failure volumes, the fahrboeschung angles – and therefore runout distances – are the same for talus and boulder rolls. However, for smaller failure volumes (typically less than 100 m^3) the boulders runout significantly further than the talus.

2. The main problem with using the fahrboeschung method to predict runout is that it does not take into account the ramping effect*caused by the shape of the slope below the source area, which can have a significant effect on debris runout. However, they are useful as comparison tools to compare how credible the RAMMS runout modelling results are.

3. From the assessment of the debris that fell from the three main cliffs (Redcliffs, Shag Rock Reserve and Wakefield Avenue/Richmond Hill), during the 2010/11 Canterbury

earthquakes, no debris passed the 31° fahrboeschung angle line (Massey et al., 2012a: GNS 2012/57).

For reference we include below GNS's estimated volumes lost from the various Port Hills cliffs (GNS 2012/57; Section 4.3.4, Table 11, p.38 & 39).

(*the ramping effect was assessed using the numerical RAMMS software that takes into account the site slope geometry when modelling debris runout; GNS 2014/78, page 85).

With respect to forecasting runout modelling GNS states (GNS 2014/78, Section 4.2.2.3, page 88): In general, there is a good correlation between the fahrboeschung angles and RAMMS runout limits for the assessed (high volume) source areas. (Our text added in brackets).

Within the empirical dataset of multiple rockfall events, the 31° fahrboeschung angle is the runout limit of rocks from debris avalanches triggered by the 2010/11 earthquakes from the assessed cliffs (with estimated rockfall volumes up to 35,000m^3 – excluding Whitewash Head). GNS notes that due to fracturing of the rockmass future rockfall volumes could be larger so we have taken this in account in our assessment.

Table 11 Estimated volumes lost from the cliffs calculated from the terrestrial laser scan and LiDAR surveys.

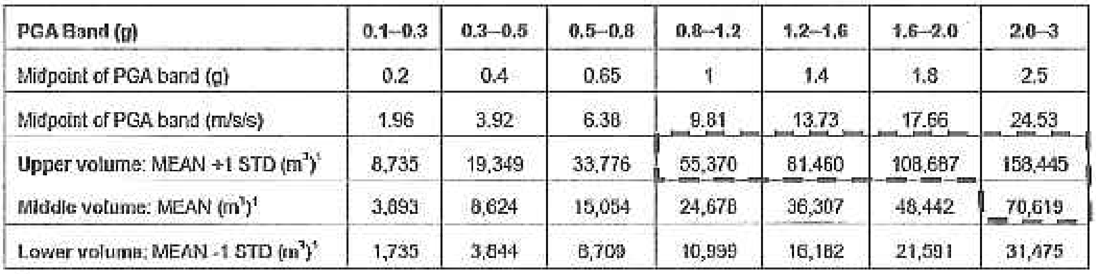
Site	Change model	Volume leaving slope (m^3)*	Area of slope face (m^2)	Volume per unit area (m^3/m^2)	Probable trigger (all earthquakes were in 2011)
Redcliffs	2003 to 2011a	15,065 (±22%)	25,094	0.60	22nd February earthquake
	TLSa to TLSc	2,181 (±3%)	20,506	0.11	16th April earthquake
	TLSc to TLSd	10,336 (±3%)	20,506	0.50	13th June earthquake
	2011a to 2011c	10,182 (±14%)	25,094	0.41	13th June earthquake
Shag Rock Reserve	2003 to 2011a	27,983 (±22%)	20,212	1.39	22nd February earthquake
	TLSa to TLSb	589 (±3%)	15,782	0.04	No obvious trigger
	TLSb to TLSd	35,034 (±3%)	15,782	2.22	13th June earthquake
	2011a to 2011c	34,282 (±14%)	20,212	1.70	13th June earthquake
Nayland Street	2003 to 2011a	1,660 (±22%)	2,881	0.58	22nd February earthquake
	TLSa to TLSc	71 (±3%)	2,413	0.03	16th April earthquake
	TLSc to TLSd	601 (±3%)	2,413	0.25	13th June earthquake
	2011a to 2011c	910 (±14%)	2,881	0.32	13th June earthquake
Wakefield Avenue	2003 to 2011a	7,734	28,192	0.27	22nd February earthquake
	TLSa to TLSc	4,125 (±3%)	22,137	0.19	16th April earthquake
	TLSc to TLSd	11,162 (±3%)	22,137	0.50	13th June earthquake
	2011a to 2011c	6,164 (±14%)	26,192	0.22	13th June earthquake
Whitewash Head	2003 to 2011a	42,279 (±14%)	124,484	0.34	22nd February earthquake
	2011a to 2011c	151,379 (±22%)	124,484	1.22	13th June earthquake

*errors expressed as one standard deviation

We sought to establish a set-back distance that provides assurance that multiple large rockfall events would be very unlikely to reach a revised school boundary. With reference to GNS 2014/78 Table 22 (page 79; reproduced below) we took an upper-bound volume of 50,000m^3 taking into account the uncertainty modelling GNS had undertaken. The dashed outline box we have added to Table 22 shows the scenarios where it is estimated a rockfall event could exceed 50,000m^3. Events of this size are estimated for combinations of (i) very high earthquake demand (very high PGA – significantly larger than ULS IL3 demand for the site) and (ii) upper-bound volumes are assumed i.e. upper-bound conservative scenarios.

Thus, for the purposes of our assessment 50,000m^3 represents a "large rockfall" and a conservative threshold as a reference around which to explore suitable set-back distances (based on fahrboeschung angles).

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.

In Figure B2 we have added a vertical dashed line indicating the 50,000m^3 volume. By inspection the H/L values for the mean and mean -1STD are found, and hence the fahrboeschung angles (F) are simply calculated, as follows:

For the mean relationship line the H/L is greater than 0.7 (we rounded down to 0.7), giving F = tan^{-1} (0.7) = 35°.

For the mean -1 STD relationship line the H/L is greater than 0.6 (we rounded down to 0.6), giving F = tan^{-1} (0.6) = 31°.

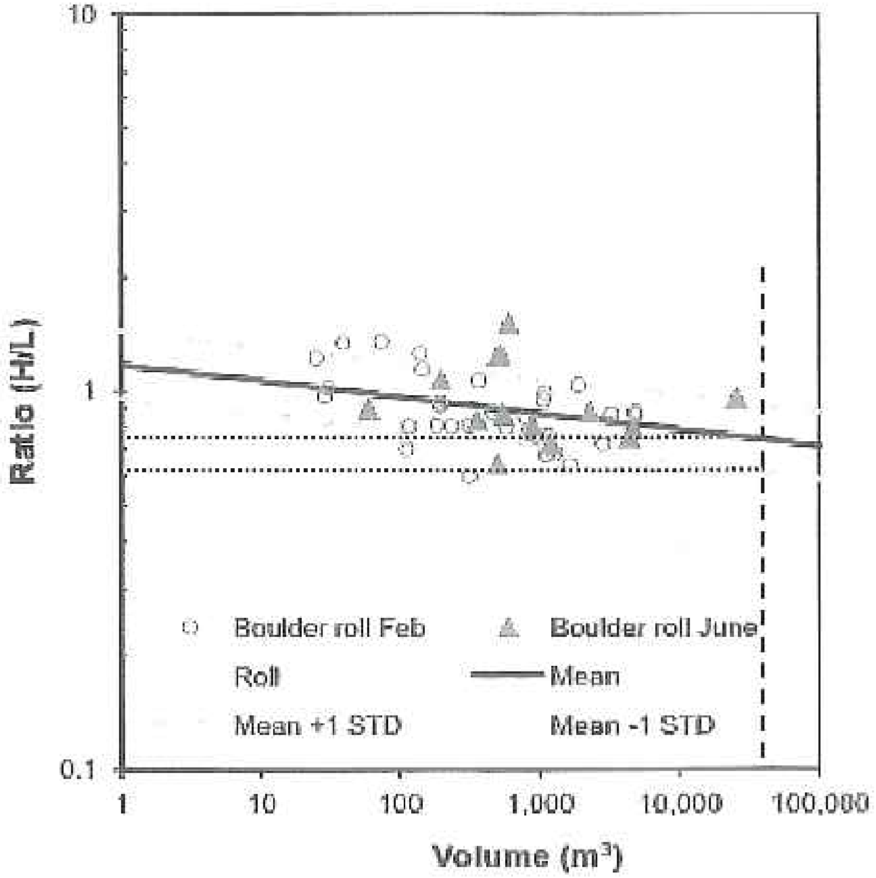


Figure B2: extract from GNS 2014/78 Figure 32 (enlargement of the boulder roll figure)

A single large rockfall event or a series of 50,000m^3 volume rockfalls are expected to runout to a limit indicated by the lower-bound (conservative) F = 31° contour. This is important to establish in terms of understanding the significance for the long-term stability of the cliff. With reference to Table 22 (reproduced above) it is possible (though unlikely) that a series of very large earthquakes could occur during the design life of the school. However, we have avoided the need to introduce uncertainty associated with estimating earthquake return periods, and opted to accept that multiple large volume rockfalls are *possible* (though unlikely) therefore we should ensure that the set-back amply accommodates these in terms of both run-out distance and storage capacity in the catch area.

To explore conservatism further we extended the assessment by:

- Using a relationship line that passes through the lower-bound (conservative) extremities of the dataset (beyond the -1 STD line); and
- Looking at the H/L for an extreme event for which we adopted a 100,000m^3 rockfall volume. The relationship lines indicate that the larger the rockfall volume the further the potential runout distance (i.e. a conservative distance). Also, with reference to GNS 2014/78 Table 22 (reproduced above) events on the order of 100,000m^3 are estimated at very large PGA (>1.6g) and are also the upper-bound (conservative) volume estimates. So, in our assessment we have forced the relationship line to be lower-bound and forced the estimated volume to the upper-bound.

In Figure B3 we have added the dashed lower-bound relationship line and derived the associated H/L value for the extreme rockfall volume. For a 100,000m^3 rockfall and a lower-bound relationship line the H/L ratio is approx. 0.5, giving F = tan^{-1} (0.5) = 26.6°. We have rounded this down to 26°.

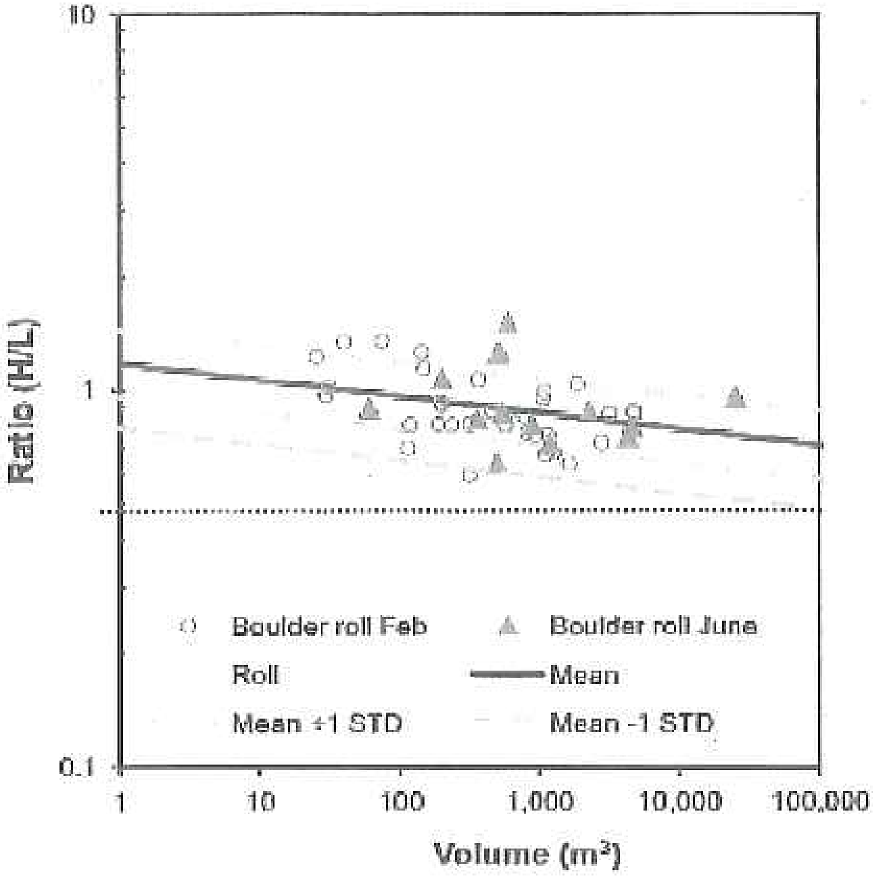


Figure B3: extract from GNS 2014/78 Figure 32 (enlargement of the boulder roll figure)

We recognise that the derivation given above uses extrapolated relationships beyond the empirical dataset. Using this approach uncertainty and conservatism is accounted for by using an additional relationship line that passes through the lower-bound data points (beyond -1 STD). Using the mean and mean -1STD lines the H/L values (and F angles) at 100,000m^3 are 0.7 (35°) and 0.6 (31°), respectively. Using the lower-bound line the F angle is 26°, which is a worse case estimated runout distance (i.e. to the outer limit) of an extreme rockfall event.

In addition to establishing a conservative revised school boundary location we recommend the addition of a bund, the design principle being having established a suitably conservative set-back distance the risk of rock rolling across the boundary should be nil for the school site.

Storage capacity

The revised boundary location at the F = 26° contour retreats the revised operational school boundary in the order of 25m (max.) into the school site. Even for large rockfall events (e.g. Local Source 1 at 25,000m^3) empirical data and modelling estimate the runout to be within the F=31° contour (i.e. at the legal school boundary).

Refer to Sheets 1 & 2 in Appendix A. The bund would be located on the cliff side of the contour over most of its length with the northern end running parallel to the school boundary with a 4m wide service road behind (see extract in Figure B4).

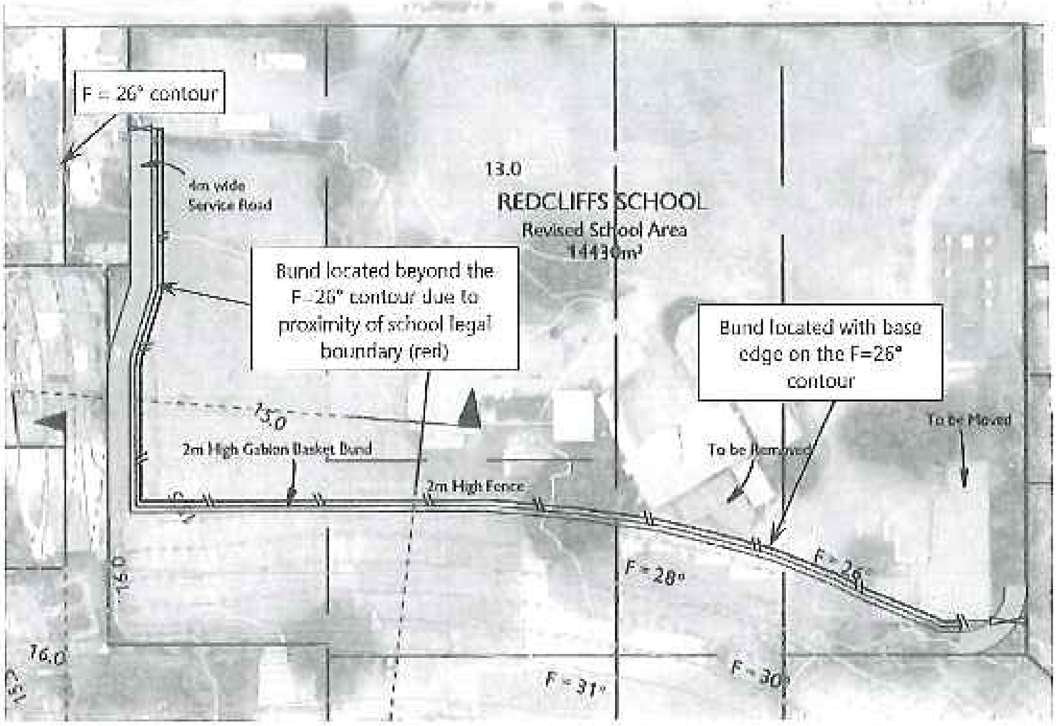


Figure B4 (extract from Sheet 1, Appendix A of this report)

For a series of large volume events the source volume becomes depleted, the fall height reduces as the talus accumulates and the source crest retreats away from the school land as does the F=31° contour (the limit contour establish from GNS's review of rockfalls over 30,000m^3 – refer to Table 11, above). Even for a series of large volume events empirical evidence and modelling validates that the F=31° contour as a reliable maximum fly-rock limit, with runout being within this contour.

As discussed above, for an extreme event (e.g. 100,000m^3) the runout distance could extend to the F = 26° contour, but this is the runout limit, not the body of displaced rock. GNS assessed the proportion of debris volume passing a given F angle (GNS 2014/78, page 83), and their Figure 31 is reproduced below.

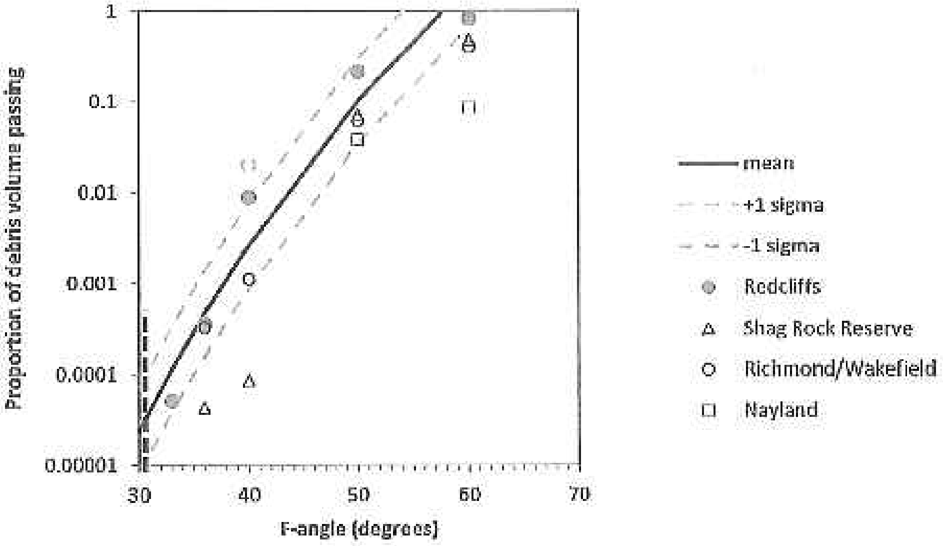


Figure 31 Proportion of debris volume passing a given fahrboeschung angle (F-angle) line, from debris avalanches triggered during the 22 February and 13 June 2011 earthquakes at Redcliffs. Trend lines are fitted to Redcliffs data only. Data from Shag Rock Reserve, Richmond Hill/Wakefield Avenue and Nayland Street are also shown for comparison.

Although the runout distance may extend with increasing event volume the Port Hills cliff data indicates that at F = 31° contour volumes are in the order of 0.0001 of the total rockfall event volume or 0.01%.

For example, 100,000m^3 of solid volume bulking by a factor of 1.25 (GNS 2012/57, Section 4.3.5, page 42) gives 100,000m^3 x 1.25 x 0.0001 (upper bound) = 12.5m^3 at the F = 31° contour. This is a very manageable volume of rock.

There would need to be an adjustment to Figure 31 relationship for larger volumes than have been experienced to date, but taking the upper bound 0.0001 proportion at F=31° and using bulking factor as high as 2.0 gives 100,000m^3 x 2.0 x 0.0001 = 20m^3 at the F = 31° contour.

From Figure 31, following the +1 STD line down to the x-axis it is seen that the volume at the F=26° contour could be an order of magnitude less i.e. in the order of 2m^3.

These numbers are estimates but we are interested in the order of volumes that might travel to the outer limits of the where we are recommending the revised school boundary. Even for such an extreme event (e.g. 100,000m^3 triggered by a greater than 1.6g earthquake, or perhaps greater than 2g – refer to Table 22, above) it is evident that such small volumes of rock are of little consequence for a protection bund's integrity or storage capacity.

Similarly, a series of large rockfall events are also of little consequence for a bund located at the revised school boundary defined by the F=26° contour, as each event would likely shed relatively little rock across the existing school boundary.

Appendix C Rockfall hazard analysis

Contents

Appendices

Appendix A : Rockfall modelling results (GNS slope parameters)

Appendix B : Rockfall modelling results (intermediate slope profiles XS160small and XS160big, GNS slope parameters)

Appendix C : Rockfall modelling results (XS160big, 5m^3 and 30m^3 boulder, with scaling by mass and velocity)

Appendix D : Typical barrier design at F=26° line

Executive Summary

Eliot Sinclair has modelled the individual rockfall hazard for Redcliffs School, Christchurch.

The rockfall modelling has been undertaken in accordance with the requirements set out in the Christchurch City Council's "Technical Guidelines for Rockfall Protection Structures" and uses standard slope parameters that have been determined for the Port Hills by GNS. The standard slope parameters have been developed by GNS after back-analysis of a variety of rock fall records from the Canterbury earthquakes, and represents the best available data for rockfall modelling in Christchurch.

Redcliffs School is located on an area of level ground, however a large cliff that is around 40 to 70m high is located to the southwest and northwest of the school. Cliff collapse and rockfall occurred from this area in the Canterbury earthquakes, and resulted in some rockroll onto the southwestern part of the school grounds in the area of the school hall. The main cluster of school buildings to the east of the school hall were not impacted.

It is now proposed to limit the area occupied by the school by locating a nominal rockfall protection structure at the distal limit of potential rock roll and cliff-collapse debris runout. This location is referred to by Eliot Sinclair's review as the F=26° contour line. This assessment considers whether or not a rockfall/roll hazard is likely at the F=26° line.

In order to verify the modelling undertaken by GNS in report CR2014/78 we have independently modelled the extent of rockfall runout using RocFall® software. When standard slope parameters set out in GNS report CR2011/311 and CR2014/78 are adopted, modelling confirms a $1m^3$, $5m^3$ and $30m^3$ boulder would not reach the revised operational school boundary, noted as F=26° on Eliot Sinclair drawing 412368S1, sheet 2 of 2, dated 23.3.2016.

The 95th percentile boulder size for the Port Hills is reported by GNS to be $3m^3$, and therefore the modelled boulder sizes typically exceed the 95th percentile size by a significant amount.

When GNS' slope parameters are adopted for rockfall modelling, all rockfall is calculated to come to rest before the F=26° line, regardless of boulder size. Based on these parameters, cliff collapse and rock roll is *not* a known hazard to the proposed school area (at or beyond the F=26° contour).

Even if the rolling and bouncing characteristics adopted for rockfall modelling were adjusted to artificially increase runout distance, it was only possible to generate boulder roll to the F=26° line if the properties of the talus slope and flat land between the school and the cliff are assumed to comprise a very hard, smooth, rigid surface that would need to be similar to a concrete or asphalt road. Clearly this is not a realistic scenario at this site, and again it can be concluded that rockroll to the proposed F=26° line is not likely.

Despite this, there is always a remote risk that future rock roll runout exceeds known parameters (i.e. does not fit within existing statistical data). We have considered the very unlikely scenario that a boulder travels beyond the distal extent (F=26° line) of known rock roll. In this scenario, any boulder would be decelerating and is likely to be coming to rest. We have, therefore, adopted a nominal boulder velocity of $2ms^{-1}$ for the purpose of designing a barrier. Analysis finds that in order to arrest a 3m^3 boulder travelling at 2ms^{-1}, a gabion basket bund that is 2m high, 1m wide at the top, and 1.5m wide at the base would be needed.

In summary, all reasonable modelling indicates rockfall to the proposed revised operational school boundary, defined by the F=26° line, would not occur. In order to address the remote risk that rockfall could travel beyond known limits, a small rockfall bund should be constructed that is 2m high and at least 1.5m wide at the base, and 1m wide at the top of the bund. This could be achieved using a simple gabion basket wall. We have adopted a 2m wide base for the purpose of the design at this stage (refer to Rockfall Hazard Mitigation report).

1 Introduction and Scope of Work

Eliot Sinclair was engaged to review the existing rockfall hazard assessment undertaken previously by other consultants for the Redcliffs School.

This report outlines the results of rockfall modelling to verify if a rockfall hazard exists at the F=26° line, and to comment on the extent and type of any measures that could be used to mitigate any uncertainty relating to future rockfall hazard at the proposed school boundary.

2 Site Description

2.1 Topography

The site is located across an area of level ground, northeast and southeast of a large cliff of volcanic bedrock.

The crest of the cliff varies in elevation, but gradually reduces in elevation to the north and south. The cliff face is near-vertical in many places.

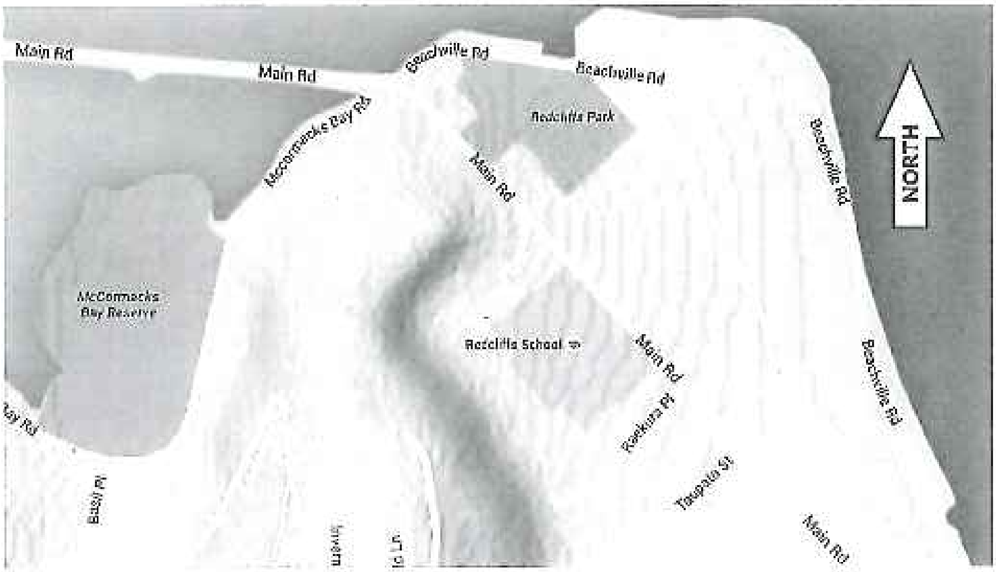


Figure 1: Site location plan. Source: Google Maps, March 2016.

A talus slope is located at the base of the cliff, and comprises volcanic debris from previous cliff collapse and regression. The height of the talus slope varies across the cliff face.

The variation in height of the talus slope results in the height of the near-vertical part of the cliff face varying along its length, and the part of the cliff face which has the largest sub-vertical exposure is located near the western corner of the Redcliff School site.

A number of residential dwellings are located adjacent to and north and southeast of the school site, on relatively level ground.

The area of level ground northwest and northeast of the main cluster of school buildings is largely grassed and is used as the school sports field/playground, with the area immediately adjacent to the buildings surfaced with asphalt and used as either a court surface, or for vehicle parking.

The school hall is located to the west of the main cluster of school buildings, near the toe of the talus slope. Rock roll occurred around the area of the school hall in the Canterbury earthquakes.

Figure 2: Aerial photo of site and surrounding land. (Source: Google Maps, March 2016).

Figure 3: Aerial view of the talus slope below the cliff after the 22 February 2011 earthquake, and before the 13 June 2011 earthquake. Note school hall with reddish roof in foreground. (Source: GNS report 2014/78, Figure 6, August 2014)

2.2 Geology

Our observations are that the nature of the exposed rock outcropping can vary significantly across the Port Hills. The cliff face located to the southwest and northwest of the school site is no exception, and GNS report CR2014/78 [1] identifies the presence of relatively shallow fill, loess silt and silt colluvium across the upper part of the cliff face, over basalt lava breccia, lava, epiclastic materials, basalt lava, and basalt lava breccia.

3 Design Boulder Size

3.1 Background

Boulder size is a key parameter that is needed to assess rockfall/roll runout distance, and is also an important consideration where designing rockfall mitigation measures.

The Christchurch City Council's *Technical Guideline for Rockfall Protection Structures* requires the 95th percentile boulder size be used a *minimum* standard for rockfall mitigation design.

The method of determining the 95th percentile boulder size is not clearly defined by the Council's *Technical Guideline for Rockfall Protection Structures*, however, 'percentile' is a standard statistical term which the Merriam-Webster dictionary defines as *"a value on a scale of 100 that indicates the percent of a distribution that is equal to or below it"*

Therefore, the 95th percentile boulder size is the size that is equal to or larger than 95% of the boulder sizes in the data set, and implies that 5% of the boulder sizes recorded in the data set will exceed the 95th percentile size.

Based on aerial photography and Eliot Sinclair's site inspection, the 95th percentile boulder size that has travelled to the toe of the talus slope is likely to be around 2 m^3 to $3m^3$. This is consistent with the 95th percentile boulder size of $3m^3$ set out in GNS report 2011/311.

The 95th percentile boulder size is NOT the largest possible boulder size than can be found within a rockfall catchment.

GNS [1] advise 'the talus at the toe of the cliff – present before the 2010/11 Canterbury earthquake-induced talus accumulations – comprises several car-sized boulders along with many smaller boulders of volcanic rock that have fallen from the cliff'.

A 'car-sized' boulder that is around 5m long x 3m wide x 2m high has come to rest next to the dwelling that is northwest of the school hall in Figure 2. The boulder has an estimated volume of around $30m^3$.

Whether or not a 95th percentile or the 99th or 100th percentile (i.e. largest credible boulder size) is adopted for assessing rockfall hazard to the school is discussed later in this report.

3.2 Effect of geology

Large boulders were randomly distributed across the talus slope, and are most likely to comprise columnar jointed basalt, or lava breccia. The location and thickness of the source of these materials varies randomly across the cliff face, and is a reflection of the highly variable nature of the Port Hills volcanic deposits. Further, the jointing and any fracturing within the rockmass will predispose the cliff face to failure of various sizes over time, and this is discussed in detail by GNS report 2014/78.

3.3 Design Boulder Size

For the purpose of this assessment, the Council's guidelines require any rockfall protection structure adopt the 95th percentile boulder size as a minimum standard, which is reported by GNS to be at least $3m^3$ for the Port Hills.

GNS assessment of the rockfall hazard to Redcliffs (GNS 2014/78) adopts a $1m^3$ boulder size for Rocfall modelling.

There are also a number of boulders across the site that are clearly around 2m diameter, and are estimated to be around $5m^3$. Further, GNS acknowledge very large boulders can occur infrequently, i.e. the $30m^3$ 'car-sized boulder'

Therefore, for the purpose of our rockfall modelling, a more common boulder size of $1m^3$, a less common boulder size of $5m^3$ and an extremely unlikely boulder size of $30m^3$ have been modelled.

4 Site-Specific Rockfall Modelling

4.1 Cross-Sections

A number of topographical cross-sections have been generated from LiDAR data, and imported into RocFall software (v4.058) as 2-dimensional data.

Cross-sections 02, 80, 120, and 160 were used to assess the rockfall hazard to the Redcliffs School.

Figure 4: Location of cross-sections used for rockfall modelling. (Source: Eliot Sinclair, 2016).

4.2 2D rockfall analysis using standard GNS parameters

The method of analysing the rockfall hazard used standard GNS slope parameters, and is consistent with the recommendations of GNS Science Report CR2011-311 (Massey, et al., 2012).

As a conservative approach, three separate calculations were performed to model the effect of 2000 boulders of either $1m^3$, $5m^3$ or $30m^3$ released from the cliff crest, cliff face, and the talus slope areas.

Boulders were modelled with an initial horizontal velocity of $+1.5ms^{-1}$ (i.e. movement from left to right out of the cliff face), and an initial vertical velocity of +1.0m/s (i.e. uplift).

A boulder density of 2700kg/m^3 was assumed for rockfall modelling, as set-out in GNS Science Report CR2011-311 (Massey, et al., 2012).

The cliff face and any other obvious sub-vertical exposures of bedrock were modelled using GNS parameters for '*bedrock*', the steep slope below the cliff modelled using GNS parameters for '*talus*', and the flat land between the toe of the slope and the proposed school boundary was modelled as '*colluvial loess with vegetation, smooth*'. Refer to Table 1.

The modelling indicates rockfall from XS02, 80, and 120 would not reach the F=31 degree line, but at XS160 a very small proportion of fallen boulders may reach the F=31 degree line but would not reach the F=26° line. This is consistent with the conclusions of GNS report 2014/78.

Refer to summary charts in Appendix A that identify the modelled locations at which 1m^3, 5m^3 and 30m^3 boulders would come to rest at cross sections 02, 80, 120, and 160.

Table 1: GNS [2] slope parameters.

Slope parameters, GNS [2]	Clean, hard bedrock and rock at surface (e.g. basalt, trachyte rockfall sources)	Rock at/near surface, when rock is covered in parts by talus, etc.	Colluvial loess with vegetation (smooth)
Coefficient of normal restitution (Rn)	0.53	0.50	0.3
Standard deviation	0.04	0.04	0.03
Coefficient of tangential restitution (Rt)	0.99	0.85	0.85
Standard deviation	0.04	0.04	0.03
Friction angle (degree)	40	20	4
Standard deviation	2	2	2
Slope roughness (degree)	-	-	-
Standard deviation	5	5	0

Table 2: Rockfall properties at proposed revised operational boundary (F=26°) using standard GNS slope parameters.

Boulder Size	1m^3	5m^3	30m^3
Kinetic Energy, kJ	0	0	0
Bounce Height, m	0	0	0
Velocity, ms^{-1}	0	0	0

4.3 Clifftop regression

The height of the exposed vertical to sub-vertical cliff face, and the length of the talus slope vary along the extent of the proposed school boundary. Based on the modelling of the four cross-sections it is the vertical cliff height that has the greatest effect on the distal extent of any rockfall.

Of the cross-sections modelled, XS160 produces the greatest runout distance from the cliff face.

Consideration was then given to the effect of clifftop regression at XS160 in order to assess if this could result in an increased hazard, which is not immediately apparent.

There is a theoretical limit to the amount the cliff face could regress back before it stabilises. This point is largely controlled by fallen debris at the base of the cliff accumulating to the point where it self-supports or buttresses the cliff face. This is unlikely to occur as a single mass-failure, and we have therefore considered two intermediate profiles to investigate the risk of rockfall as cliff regression occurs over time.

The effect of progressive cliff regression and accumulation of debris across the talus slope has been modelled at XS160 assuming a 'small' failure and a 'big' failure, with a bulking factor of 1.3 used for the 'small failure' and a bulking factor of 2.0 adopted for the 'big failure'.

The results of this rockfall modelling confirms a 'small' and a 'big' failure would not result in rock roll reaching the F=26° line. Refer to Appendix B.

4.4 Scaling Rn by velocity and mass

GNS report CR2011/311 suggests, as a default, the coefficient of normal restitution be scaled by taking into account the boulder velocity, and this has been followed with the modelling outlined in Appendix A and Appendix B.

However, as a sensitivity check we have also analysed XS160 'big' by scaling the coefficient of normal restitution by taking into account both the boulder velocity and mass. Again, using these parameters, the results of the rockfall modelling confirms boulders would not reach the F=26° line. Refer to Appendix C.

5 Design parameters for a rockfall protection structure

All of the modelling undertaken by both GNS and verified by Eliot Sinclair confirms that based on existing data from across the whole of the Port Hills after the Canterbury earthquakes, even in the worst-case scenario rock roll would not reach the F=26° line.

There is a remote chance that rock runout in the future could occur in a manner that does not fall within the existing statistical bounds. While this risk of this occurring is exceptionally small and in our opinion the risk of this occurring is virtually nil, the school may want to address this small uncertainty by construction of a physical barrier at/close to the F=26° line.

For the purpose of this report, we have assumed a Reinforced Earth Embankment Barrier (REEB) could be constructed near the F=26° line.

Despite the apparent zero risk beyond the F=26° line, the REEB would still be designed and constructed in accordance with the Council's '*Technical Guideline for Rockfall Protection Structures*'.

The philosophy of any REEB at the F=26° line would be arrest any boulder that will at the distal limit of possible rockroll, and would therefore be rolling very slowly and would require only minor energy dissipation to bring it to rest.

A REEB with a vertical face that extends 2m above surrounding ground level on the uphill face would be capable of arresting a $3m^3$ boulder travelling at 2 metres per second. Refer to Appendix D.

6 Conclusion

GNS has assessed numerous rockfall and rockroll events across the Port Hills which resulted from the Canterbury earthquakes. This data was then used by GNS to develop a range of slope parameters to be used for rockfall modelling.

These parameters have been adopted by Eliot Sinclair's rockfall modelling to verify the nature of any rockfall hazard to the Redcliffs School, including assessment of the potential effects of cliff-top regression.

Our rockfall modelling indicates that based on known data, there is a very, very small proportion of rockfall that could reach the F=31 degree line at the western corner of the site (XS160) where the cliff face is the highest, but rock roll would come to rest just beyond this point and would not travel to the F=26° line.

In order to mitigate any uncertainty in rock runout, a small gabion basket wall could be constructed that we recommend be 2m high, 1m wide at the top, and at least 1.5m wide at its base.

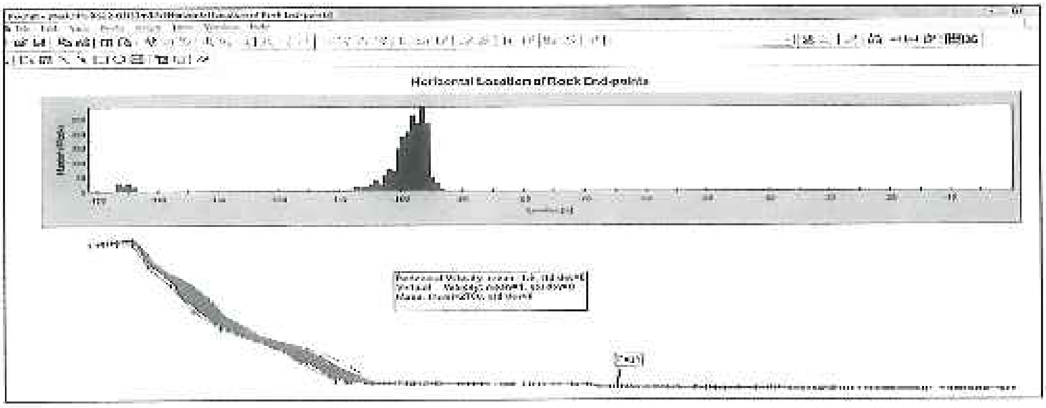
7 References

[1] GNS, "Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Risk assessment for Redcliffs," GNS Science Consultancy Report 2014/78, 2014.

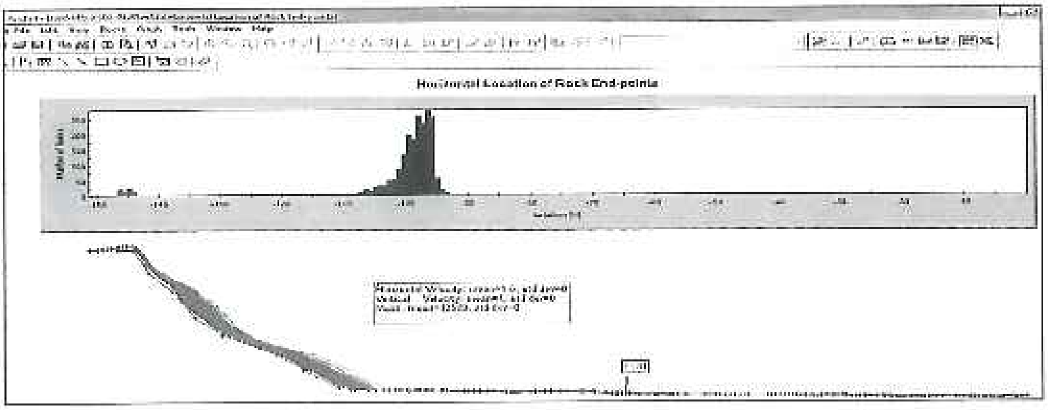
[2] GNS, "Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Pilot study for assessing life-safety risk from rockfalls (boulders rolls)," GNS Science Consultancy Report 2011/311, 2012.

[3] Christchurch City Council, "Technical Guidelines for Rockfall Protection Structures," Christchurch City Council, Christchurch, 2013.

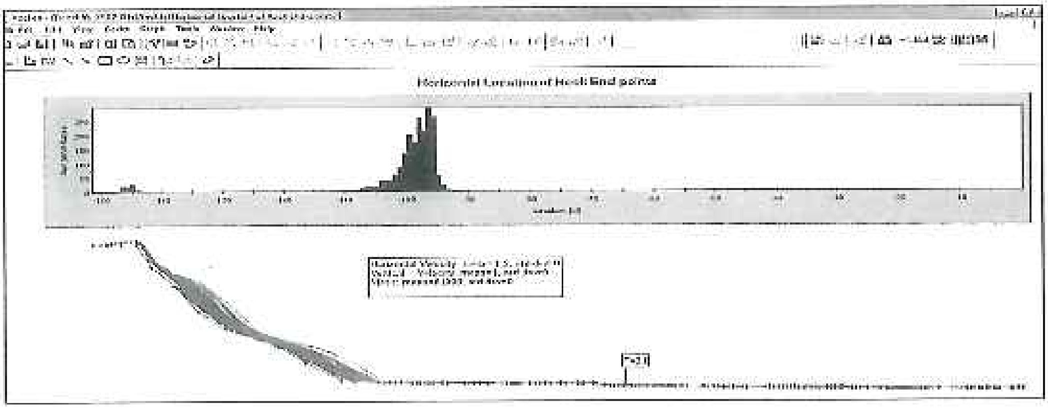
Appendix A: Rockfall modelling results (GNS slope parameters)



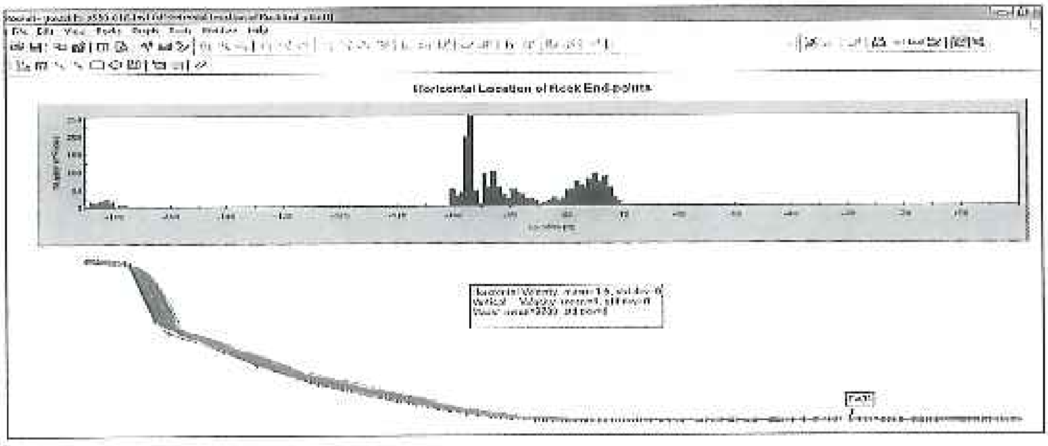
Cross-Section XS02, 1m3 boulder. No boulders reach F=31° or F=26° line.



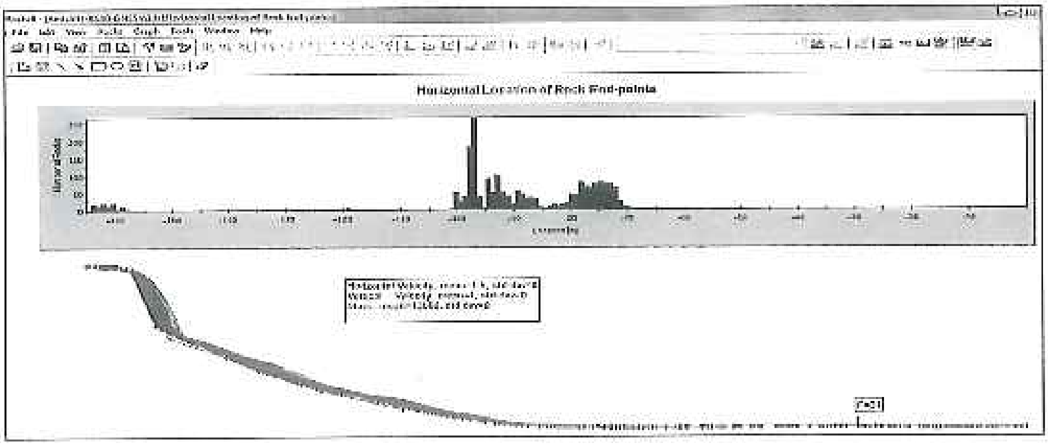
Cross-Section XS02, 5m3 boulder. No boulders reach F=31° or F=26° line.



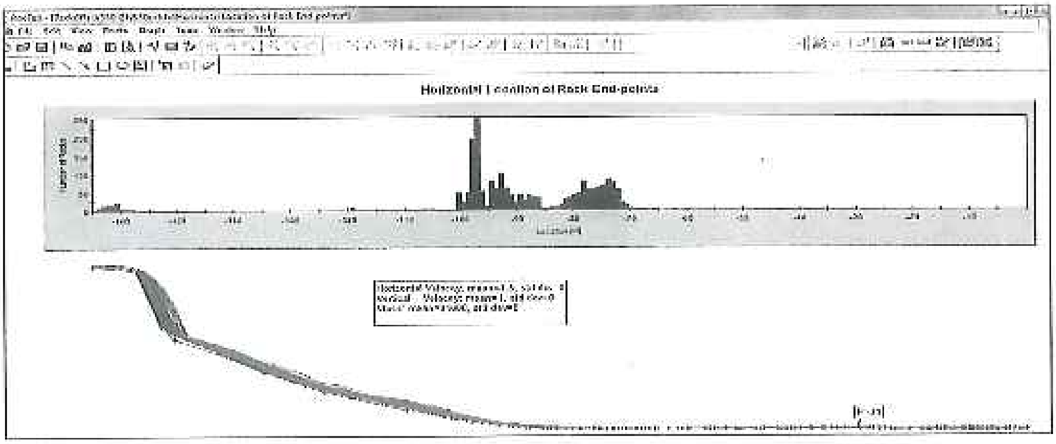
Cross-Section XS02, 30m3 boulder. No boulders reach F=31° or F=26° line.



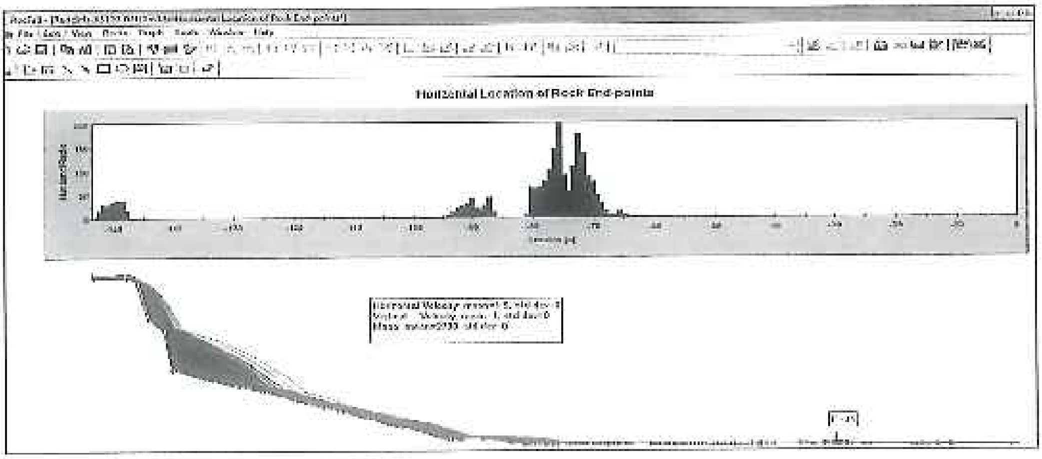
Cross-Section XS80, 5m3 boulder. No boulders reach F=31° or F=26° line.



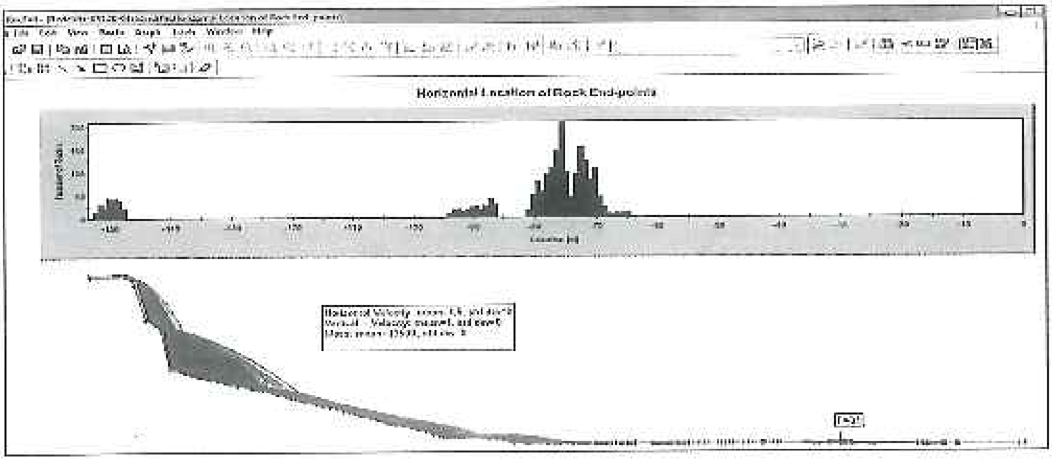
Cross-Section XS80, 5m3 boulder. No boulders reach F=31° or F=26° line.



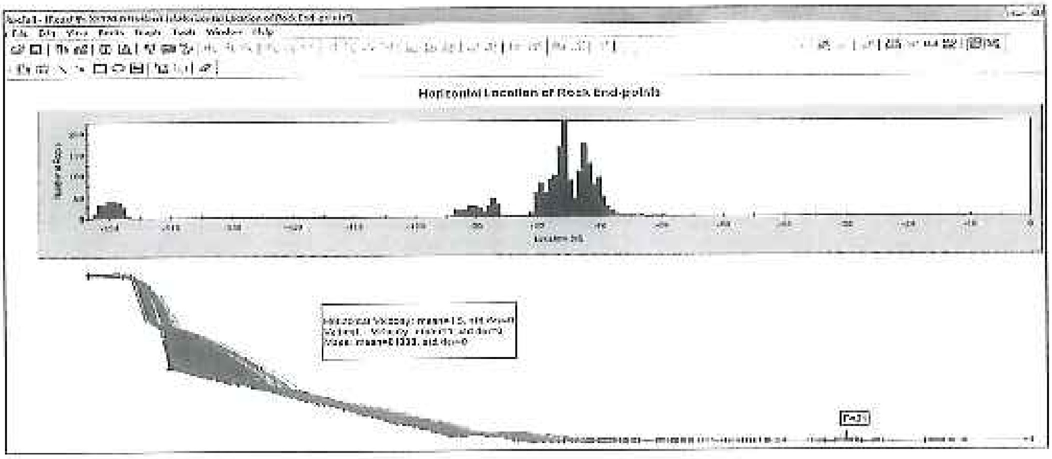
Cross-Section XS80, 30m3 boulder. No boulders reach F=31° or F=26° line.



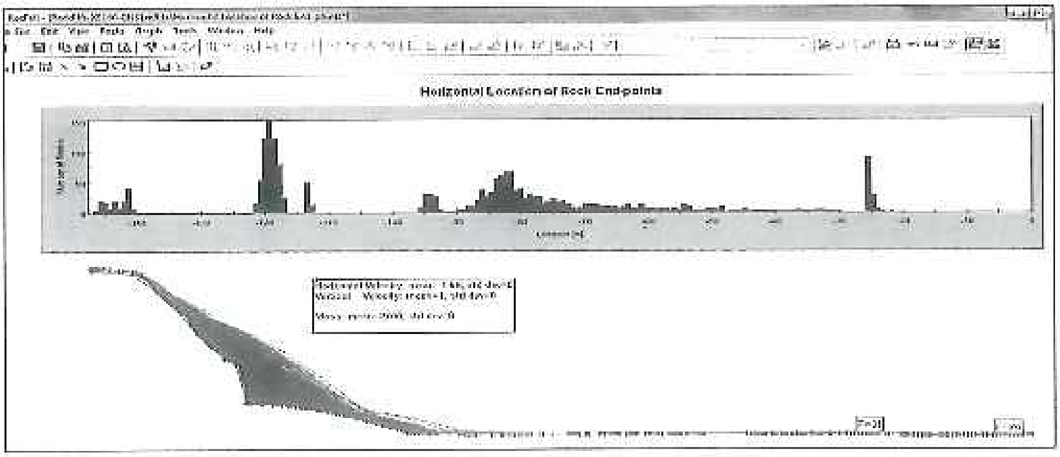
Cross-Section XS120, 1m3 boulder. No boulders reach F=31° or F=26° line.



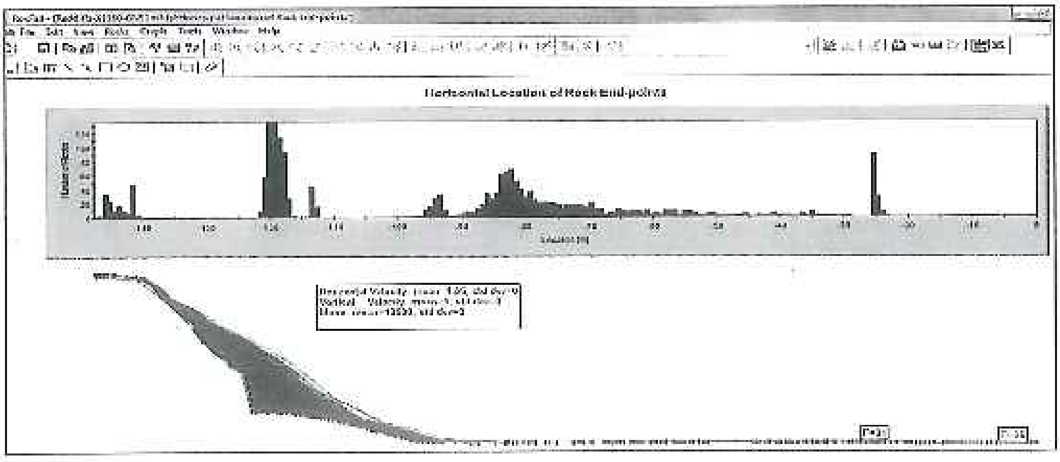
Cross-Section XS120, 5m3 boulder. No boulders reach F=31° or F=26° line.



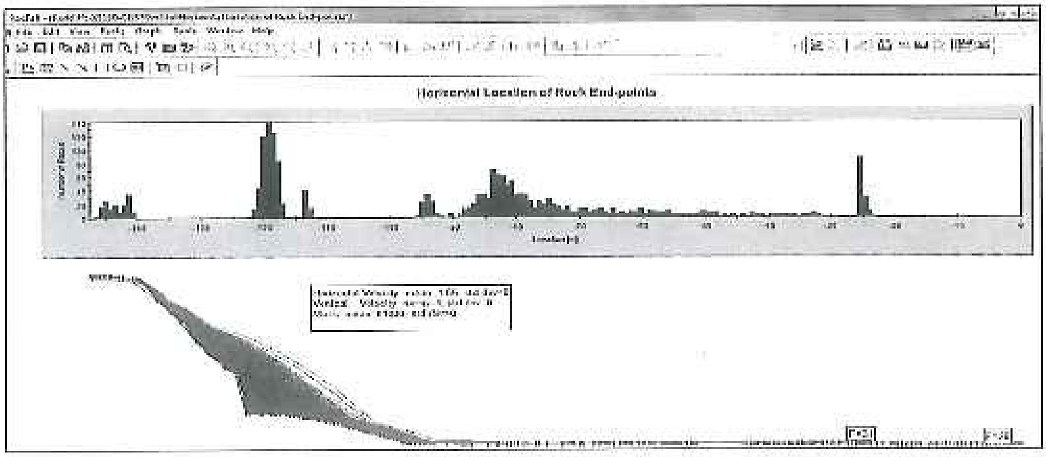
Cross-Section XS120, 30m3 boulder. No boulders reach F=31° or F=26° line.



Cross-Section XS160, 1m3 boulder. No boulders reach F=26° line.

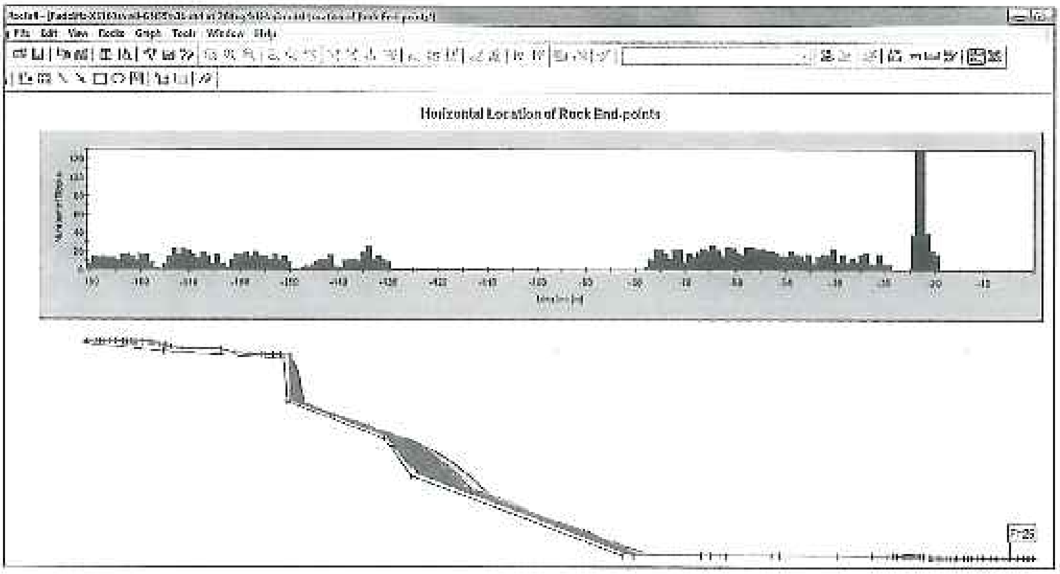


Cross-Section XS160, 5m3 boulder. No boulders reach F=26° line.

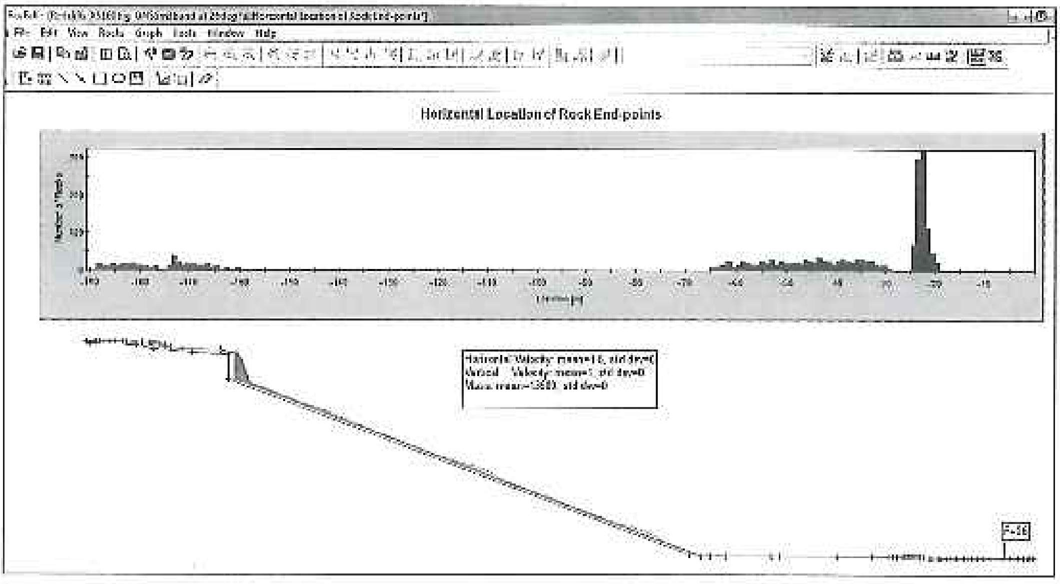


Cross-Section XS160, 30m3 boulder. No boulders reach F=26° line.

Appendix B: Rockfall modelling results (intermediate slope profiles XS160small and XS160big, GNS slope parameters)

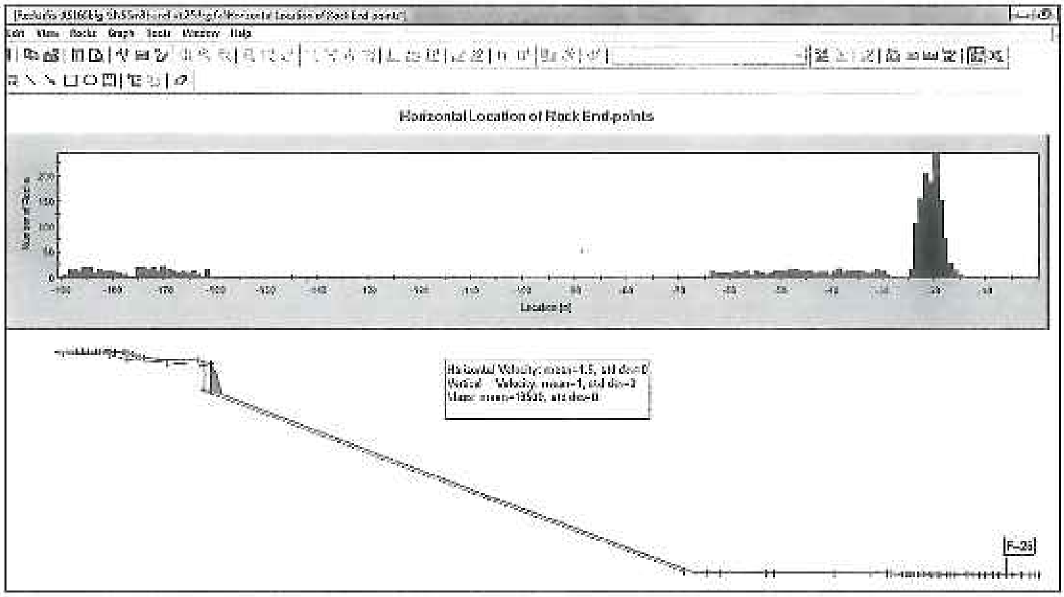


Cross Section XS160 with small failure, 5m^3 boulders. No boulders reach F=26° line.

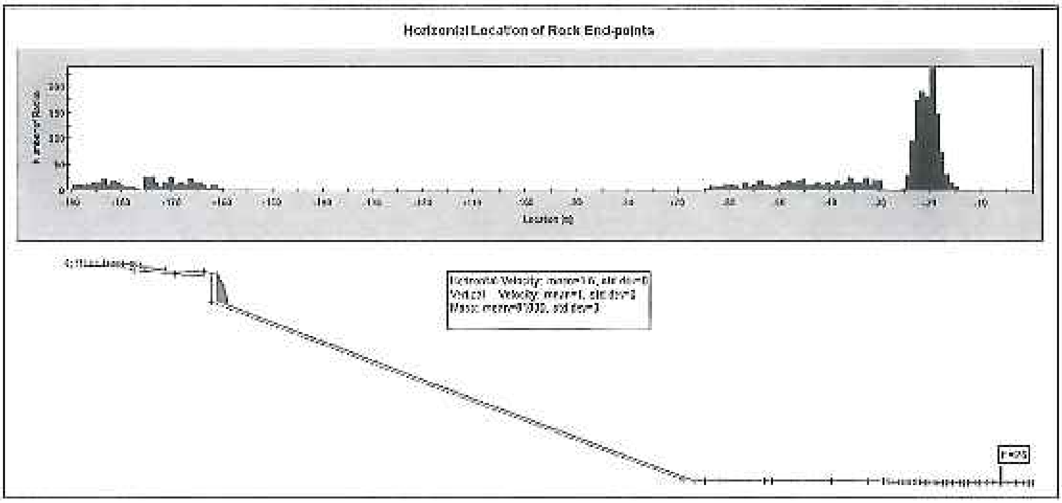


Cross-Section XS160 with big failure, 5m^3 boulders. No boulders reach F=26° line.

Appendix C: Rockfall modelling results (XS160big, 5m^3 and 30m^3 boulder, with scaling by mass and velocity)



Cross-Section XS160'big', 5m^3 boulders. Uses scaling by velocity and mass No boulders reach F=26° line.

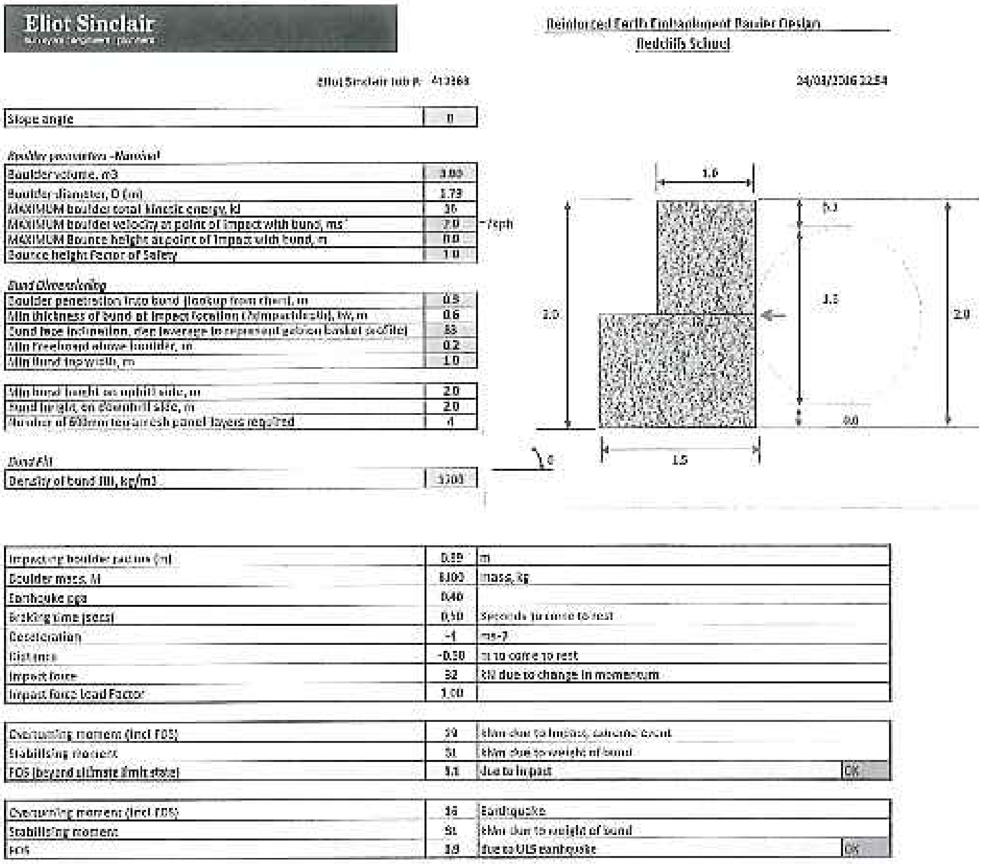


Cross-Section XS160'big', 30m^3 boulders. Uses scaling by velocity and mass No boulders reach F=26° line.

Appendix D: Typical barrier design at F=26° line

Table 3: Nominal design assumptions - Reinforced earth embankment barrier

Intention to bring slow moving boulder to a stop.	
Nominal boulder volume (95th *percentile of Port Hills, GNS 2011/311*)	3m³
Nominal boulder speed *(coming to rest beyond distal limit of all known rockfall data for the Port Hills)*	2ms⁻¹
Nominal boulder diameter (95th *percentile of Port Hills, GNS 2011/311*)	1.8m
Freeboard above top of boulder	0.2m
Boulder bounce height, at F=26deg line	0.0m
Minimum REEB height above ground level	2.0m
Nominal boulder velocity, ms⁻¹ for bund design	2.0
Penetration of 3m³ boulder into gabion bund	0.5m
REEB Fill material (greywacke river cobbles) bulk density, kg/m3	1700
REEB Fill material (greywacke river cobbles), angle of friction	35°-40°
REEB face angle *(average of 83 degrees, represents 1m wide gabion over 1.5m wide gabion)*	83 degrees
Minimum width at top of REEB	1.0m
Minimum width at base of REEB	1.5m



Reinforced Earth Embankment Barrier Design
Redcliffs School

Eliot Sinclair Job #: 412368

24/03/2016 22:54

Slope angle	0

Boulder properties -Nominal

Boulder volume, m3	3.00
Boulder diameter, D (m)	1.79
MAXIMUM boulder total kinetic energy, kJ	16
MAXIMUM boulder velocity at point of impact with bund, ms⁻¹	2.0
MAXIMUM Bounce height at point of impact with bund, m	0.0
Bounce height Factor of Safety	1.0

~7kph

Bund Dimensioning

Boulder penetration into bund (lookup from chart), m	0.5
Min thickness of bund at impact location (2/impact/load), tw, m	0.6
Bund face inclination, deg (average to represent gabion basket profile)	83
Min freeboard above boulder, m	0.2
Min bund top width, m	1.0

Min bund height on uphill side, m	2.0
Bund height, on downhill side, m	2.0
Number of 600mm terramesh panel layers required	4

Bund Fill

Density of bund fill, kg/m3	1700

Impacting boulder radius (m)	0.89	m	
Boulder mass, M	8100	mass, kg	
Earthquake pga	0.40		
Braking time (secs)	0.50	Seconds to come to rest	
Deceleration	-4	ms-2	
Distance	-0.50	m to come to rest	
Impact force	32	kN due to change in momentum	
Impact force Load Factor	1.00		

Overturning moment (incl FOS)	29	kNm due to impact, extreme event	
Stabilising moment	51	kNm due to weight of bund	
FOS (beyond ultimate limit state)	1.8	due to impact	OK

Overturning moment (incl FOS)	26	Earthquake	
Stabilising moment	51	kNm due to weight of bund	
FOS	1.9	due to ULS earthquake	OK