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PORT HILLS ROCKFALLS

Rockfall mitigation – design strategy

INTRODUCTION

1. This note is a follow up to the writer's earlier Project Memo #1 (13 June 2012) on protection structure effectiveness sent to CCC on 13 June 2012. It is based on discussions with Dr Chris Massey (GNS) during meetings and email communications between 11 and 18 June 2012. The purpose of this present note is to suggest design guidelines for rockfall mitigation in the Port Hills. Examples from two of the slope areas (Avoca 1 and Heathcote/Morgans Valley) have been used to illustrate the general design principles.

2. The review was carried out in South Australia in a very limited timeframe using information from the GNS report on rockfalls[1], information from Dr Massey and the writer's own experience in the Port Hills and elsewhere. The writer has not seen any of the design work undertaken for the Port Hills rockfalls or had the opportunity for discussions with others working on this project. The report has been prepared for CCC for discussion purposes only and is not intended for general release.

DESIGN EVENT

Return frequencies for design PGA

3. The 22 February 2011 earthquake generated the largest number of mapped rockfalls in the Port Hills Subsequent aftershocks have also generated many rockfalls, most notably the 13 June 2011 earthquake.

4. The horizontal Peak Ground Accelerations (PGAs) recorded in the Port Hills by the GeoNet strong motion network from the 22 February earthquake range between 0.5g to 2.1g[2], with a mean of about 1.3g; for the 13 June earthquake the range is between 0.3g and 2.2g, with a mean of about 1.0g.

5. The return periods of the horizontal PGAs of 1.0 to 1.4g are listed in *Table 1*[3]. These data are derived using the current Composite Seismic Hazard Model (CSHM) for the Canterbury region, and the PGA hazard curves derived from it for locations in the Port Hills.

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[1] Geological and Nuclear Sciences. Canterbury Earthquakes 2010/2011 *Port Hills Slope Stability: Pilot study for assessing life-safety risk from rockfalls (boulder rolls).* GNS Science Report 2011/311, March 2012.

[2] Geological and Nuclear Sciences. *The Canterbury earthquake sequence and implications for seismic design levels*. GNS Science Report 2011/183.

[3] Postscript note 19 December 2013: These data have since been revised and current values are given in Massey, C. I.; Yetton, M. J.; Carey, J.; Lukovic, B.; Litchfield, N.; Ries, W., McVerry, G. 2013. *Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Stage 1 report on the findings from investigations into areas of significant ground damage (mass movements)*. GNS Science Consultancy Report 2012/317.

Table 1. Return periods of a given PGA in the Port Hills.

Year (from January 2012)	*Approx. return periods (years) of 22nd February and 13th June, 2011, earthquake-ground motions in the Port Hills*		
	PGA 1g	*PGA 1.4g*	*PGA 1.6g*
1	49	165	288
2	72	243	423
5	139	465	808
10	264	878	1520
15	405	1339	2315
20	484	1592	2740
30	531	1742	3003
50	549	1805	3115

PGAs were derived using the Composite Seismic Hazard Model for year 1 to year 50, from January 2012. Derived using a minimum earthquake magnitude (M_{min}) of M_W 5.25, for site class C (NZS 1170). These do not include amplification effects induced in the rockfall source areas or any magnitude weighting. Highlighted PGAs have return periods of less than 500 years.

6. The return periods of the range of PGAs recorded during the 22 February and 13 June earthquakes are between about 50 to 165 years (for PGAs of 1 and 1.4g respectively) in year 1, decreasing to about 140 to 470 years in year 5.

7. AS/NZS 1170[4] defines "design events" in terms of the Ultimate Limit State (the design event where a structure will fail), and the Serviceability Limit State (where the structure can continue to be used following the event). For rockfalls, the structure (in this case a home) would fail if it were penetrated by a boulder, therefore posing a life risk to the occupants.

8. According to AS/NZS 1170, a building with a design life of 50 years should be constructed to withstand a 1 in 500 year event (Annual Exceedence Probability, approximating to a 500 year return period), assuming Ultimate Limit State, for Building Importance Category 2 (residential homes).

9. Currently, and for approximately the next five years, the 22 February and 13 June earthquakes and the rockfalls triggered by them have return periods of less than 500 years. Therefore the 22 February earthquake-induced rockfalls can be used as the "design event" for the Ultimate Limit State of a residential home.

ROCKFALL NET FENCES

Rockfall design codes

10. The two European design codes for rockfall are ETAG 027[5] and ONR 24810[6]. ETAG 027 merely defines Maximum Energy Levels (MEL) and Service Energy Levels (SEL) but does not give guidance on how these are determined.

11. Under ETAG 027, the maximum kinetic energy that a rockfall fence can withstand in a single impact is the MEL. The SEL has a safety factor of three with respect to the MEL. The fence must be able to withstand two impacts at SEL level without maintenance between the first and second hit. After the first hit, the residual height of the fence should be at least 70% of the nominal height.

12. Peila & Ronco[7] have provided some useful commentary on ETAG 027. They note that the first design step is to choose whether to design using a MEL or SEL approach:

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[4] Australia New Zealand Standard (AS/NZS) 1170.

[5] European Organisation for Technical Approvals. *ETAG 27. Guideline for European Technical Approval of Falling Rock Protection Kits.* Edition 2008-02-01

[6] Austrian Standards Institute. *ONR 24810. Technical protection against rockfalls - Terms and definitions, effects of actions, design, monitoring and maintenance.* Draft: 21 February 2012

[7] Peila D, Ronco C. *Design of rockfall net fences and the new ETAG 027 European guidelines.* Nat Hazards Earth Syst Sci, 9, 2009

- In the case of a forecast of **low frequency rockfall events and with different fall directions**, in other words, not involving the same module (fence panel), it is possible to adopt the MEL approach;
- If the barrier has to be installed in positions in which it is difficult to carry out maintenance work and it is therefore preferable not to repair it after each block impact, the SEL design approach should be chosen (considering that the design safety factor is three);
- Where the same module could be impacted several times, that is, in the same direction, the designer's choice could be: installation of two net fences with the alignment defined at a MEL level or one net fence with the alignment designed at a SEL level.

On the basis of the above, MEL is not appropriate for the Port Hills design because of the probability of multiple strikes on a module during single earthquake events.

13. In their commentary on ETAG 027, Peila and Ronco note that the design speed and the bounce height of the block are obtained from the calculated 95th percentile values. These values are then scaled by partial safety factors (which have relatively minor effect in the present case as they are generally less than to 1.10. These recommendations are evidently derived from Eurocode 7 (point 2.4.7.3.3 – not checked by the writer).

14. ONR 24810 notes that the design block size should be dependent on the event frequency as follows:

Table 2. Return frequencies and allocated design boulder fractiles (taken from ONR 24810, Table 4)

Event frequency class	*Event frequency n p.a.*	*Design block size fractile*
EF4 (extremely high)	N ≥ 10 (> 10 events/year)	V_{98}
EF3 (high)	1 ≤ n < 10 (1 to 10 events/year	V_{97}
EF2 (low)	0.03 ≤ n < 1 1 event/1 to 30 years)	V_{96}
EF1 (rare)	N < 0.03 < 1 event/30 years	V_{95}

15. If the design is based on the 22 February 2011 event (which has a return period of less than 500 years), the appropriate percentile for the block size would be 95% for "rare" events, (less than 1 event in 30 years, as in *Table 2* above).

16. Both the European guideline ETAG 027 and the Austrian code ONR 24810 state that the kinetic energy (as in the MEL or SEL) is given by the expression $E_{kin} = mv^2/2$ (where E_{kin} is kinetic energy, m = mass of impacting block and v = the speed of the block at impact). This is the kinetic energy due only to translational velocity. ETAG 027 does not allow for the rotational energy of the block. Rotational energy of flat or tabular blocks can have a destructive effect on rock fences. The writer considers that the total energy (translational plus rotational) should be used for design.

17. For the Port Hills situation of multiple impacts during a single earthquake event, it will be necessary to get the fence manufacturers/suppliers to define the energy level that fences can accommodate with multiple hits and within the elastic limits of the fence structure. For the purposes of the present exercise, this Functional Energy Level (FEL) has been estimated to have a safety factor of 6 to 9 with respect to MEL. (*Note this is comparable with the daily event (evenements journaliers) in the previous Geobrugg Optus dimensioning system where the fence remained entirely within the elastic range and needed no maintenance other than inspection*). Even under elastic FEL conditions, there will be some loss of effective fence height due to the loading imposed by boulders retained in the nets.

18. ETAG 027 uses 8 energy level classes for rock fences. Classes 6 to 8 (the highest levels) are shown below in relation to the MEL, SEL and FEL boulder energy that they can withstand (see *Table 3* below).

Table 3: ETAG 027 fence capacity (kJ) related to design boulder energies

		ETAG rock fence energy level classification				
	Safety Factor	*6*	*7*	*8*	*No. hits allowed*	*Comment*
Maximum Energy Level	1	3000	4500	>4500	1	Not suitable for earthquake-induced rockfalls
Service Energy Level	3	1000	1500	>1500	2	Limited application for earthquake-induced rockfalls
Functional Energy Level	6	500	750	>750	Multiple	Most suitable basis for earthquake-induced rockfall design
Functional Energy Level	9	333	500	>500		

19. For Port Hills design, the total kinetic energy (translational plus rotational) of the 95th percentile boulder size should be used as the design basis for rock fences. This required fence energy level class required for a particular Boulder Energy Level (BEL) depends on the number of times that a typical panel is hit by rockfalls during the design event (see *Table 4* below).

Table 4: Required fence capacity for given boulder energy level (BEL) for different design options

Design Option	*Fence capacity*	*No hits*
Maximum Energy Level SF=1	1xBEL	1
Service Energy Level SF=3	3xBEL	2
Functional Energy Level SF = 6	6xBEL	Multiple
Functional Energy Level SF = 9	9xBEL	Multiple

20. Only one and two strikes per panel width are permitted for MEL and SEL events respectively. During the design earthquake event of 22 February 2011, virtually all relevant areas of the Port Hills will have hits in excess of this. *Table 5* shows calculated boulder hits for the Avoca and Morgans Valley areas.

Table 5: No of boulder hits per panel in two areas of Port Hills for 22 February earthquake

	Avoca Valley	*Morgans Valley - all*	*Morgans Valley – random length*
Length of fence	130m	350m	50m
N boulders passing	40	59	15
Panel width	10m	10	10m
N boulders per panel	3.1	1.7	3.0

It is likely that most areas of the Port Hills will have more than two design boulder strikes per panel in the design earthquake event. Therefore it is not possible to design on the basis of MEL or SEL and the rockfall fence must be designed for FEL conditions with a Safety Factor as provided by the manufacturers and verified by field testing.

21. *Figure 1* shows the boulder Particle Size Distributions (PSDs) for all areas in the Port Hills and site specific data for Avoca 1 and Heathcote/Morgans Valley. Typically there is a more or less constant boulder size over a large range of percentile values. During an earthquake event, the fence will suffer multiple hits from the "typical" boulder size. For this reason, it is preferable to adopt FEL on the basis of a safety factor on MEL rather than calculating FEL for a lower percentile size boulder. For example, in the case of Avoca, the boulder size is more or less constant in the range from about 25 to 95 percentile

22. These suggestions do not comply exactly with the codes and do not include partial safety factors as envisaged in Eurocode 7 (which are in any event quite small). However, the recommendations make allowance for the rotational energy of the boulder (which can be a significant component of the total energy – about 20% or more) and are considered to be preferable to using translational energy only.

Rock fence maintenance

23. Maintenance of rock catch fences could pose various difficulties. Firstly it would be unlikely that the maintenance team could immediately start on repair work after a significant seismic as they would need to wait until they were given safety approval to proceed. If a significant number of panels had entrapped

boulders, this work may have to be delayed while the houses below are evacuated. If the anchorages, posts or foundations of the fence structures are damaged, this would require drilling for new anchorages or new excavations for foundations. Transport of materials to the affected area would probably require helicopters and would be dependent on weather conditions at the time. Availability of repair crews and materials at all times (including public holidays) would require the availability of a rapid response team stationed in the area. Once the fences retain material, their effective height is reduced which also need to be taken into account even if the nets are not damaged.

24. The requirements for maintenance and the associated costs of this are likely to be a significant cost in the overall scheme. Even if there are no further rockfall events, the cost of having these resources available at short notice would be significant.

Design life

25. According to ETAG 027 δ1.3, the assumed working life for a falling rock protection kit without any rock impact and under normal environmental conditions is 25 years. In aggressive environmental conditions (e.g., coastal), the assumed working life is at least 10 years with appropriate maintenance.

26. Paragraph δ9 above notes that, for approximately the next five years, the major 2011 earthquakes (22 February and 13 June, 2011) and the rockfalls triggered by them have return periods of less than 500 years, which then reduces to greater than 500 years after about five years. Rockfall protection is therefore required primarily for the next approximately five years, provided no other large earthquakes (typically greater than magnitude M6) occur in this time period.

27. In the longer term, permanent ongoing rockfall protection could be maintained above pre-earthquake levels by means of a protective forest[8] uphill of the fence structures. Investigation of this option by appropriate specialists should be carried out in parallel with the engineering design of the rock fence structures.

PROTECTIVE BUNDS

28. Passive rockfall protection structures can include concrete walls or reinforced ground embankments[9]. Bunds are robust structures which can withstand higher loads than dynamic rock fences at a significantly lower cost. Where ground conditions (typically slope < 20°) and space permit, these would generally be the preferred method of mitigation.

29. Ronco et al give recommendations for design, analysis and testing of bunds. Numerical analyses of their behaviour would give valuable information – however these may need to be supplemented with full scale tests to account for shortfalls in parameter data for loess and colluvium.

SOURCE AREA TREATMENT

30. Treatment of source area instability can be implemented by bolting potentially unstable blocks. This is requires detailed geological assessments and design, involves difficult access and is generally fairly expensive. An alternative approach is draped rockfall containment mesh as used on large rockfall stabilisation projects at Reunion and St Helena Islands (see Memo #1). The weight of mesh on the slope provides a restraint to potentially unstable blocks, and the proximity of the mesh to the slope surface means that falling blocks are not able to gain significant kinetic energy before they impact the net. *Figure 2* shows examples of rock catch fences and containment netting.

31. A further type of source area treatment involves the hybrid barrier[10]. This type of barrier is a passive rockfall protection system consisting of a flexible fabric suspended from a top horizontal cable raised off the ground by posts or by anchoring across a chute; it includes no internal, side or bottom anchoring of

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[8] Berger F. *Rockfall - Forest interrelation. Efficiency of the protective function of mountain forest against rockfalls.* Cemagref, Grenoble, Final Report 2004

[9] Ronco C, Oggeri C, Peila D. *Design of reinforced ground embankments used for rockfall protection.* Nat Hazards Earth Syst Sci, 9, 2009

[10] Badger TC et al. *Hybrid barrier systems for rock fall protection.* Interdisciplinary Workshop on Rockfall Protection, Morschach, 2008

the fabric. They address rockfalls occurring both underneath the fabric and upslope of the installation, controlling their descent under the fabric and into a containment area at the base of the system.

32. The writer has not seen any of the proposals for source area stabilisation. However, draped netting systems may often be a complement or alternative to rock catch fences since they have advantages with respect to lower boulder energy for entrapment, simpler installation and lower maintenance.

ROCKFALL ANALYSES

33. Several software packages exist for modelling rockfalls, which range from two-dimensional to three-dimensional. The most widely used modelling package is Rocscience's RocFall program, which is a two-dimensional lumped-mass model. This software package is well calibrated and has been independently verified by the Hong Kong Geotechnical Engineering Office. In most situations this software is assumed to be adequate for design of protection structures, however, in areas where the slope geometry is more complex e.g Lyttelton and parts of the Inner crater such as Governors Bay, three dimensional rockfall modelling may be appropriate.

34. A three dimensional rockfall model (commissioned by CERA) has been used to analyse much of the Port Hills area, using various input boulder sizes, typically ranging from the 95% to 97% percentiles. These data would be a valuable tool for the rockfall mitigation designer, provided that the three dimensional models adopt the same input parameters as those used in any two-dimensional analysis.

Boulder sizes & source areas

35. The 22 February 2011 event is near the extreme end of the spectrum for rockfall phenomena as far as boulder numbers are concerned. The Port Hills group has an extensive database on boulder sizes and runout distributions which can be used as the basis for mitigation design on a sector by sector and slope to slope basis (rather than using a global PSD of all the Port Hills data).

36. The boulder size used in the rockfall analyses should be based on the PSD for each reasonably uniform slope area. PSDs for three areas (all Port Hills, Avoca 1 and Heathcote/Morgans Valley) have been shown on *Figure 1* with the 95th percentile values summarised below:

Table 6: Examples of 95th percentile particle size distributions at different slope regions

	All data		*Below fence location*	
	Boulder volume (m^3)	*Boulder weight (kg)*	*Boulder volume (m^3)*	*Boulder weight (kg)*
Port Hills global	3.5	9450		
Avoca 1	1	2700	0.7	1890
Heathcote/Morgans Valley	1.1	2970	2.7	7290

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37. For Avoca 1, the 95th percentile boulders downhill of the proposed fence location are smaller than those on all of the slope. At Morgans Valley, the 95th percentile downhill is significantly larger than that for all the slope. Both Avoca and Morgans Valley show a similar pattern with a large percentile range of the blocks having a similar size (see paragraphs δ19 to 21 above).

38. The boulder distribution statistics should be taken from areas where the fall paths have not been modified by vegetation or structures. In areas where there are insufficient data (less than say 100), adjacent slopes of similar characteristics should be used to improve the statistical reliability.

39. GNS has provided a summary for all the Port Hills data in terms of boulders passing each shadow angle (*Figure 3*). This shows that there is a definite trend towards gravity sorting (below shadow angles of about 27° to 25°) with larger blocks reaching the more distal areas. Boulder fragmentation does not seem to be a major factor possibly because of the high boulder strength relative to the relatively soft loess/colluvium impact sites. This gravity sorting is notably different to experience elsewhere[11].

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[11] Corominas J, Copons R, Moya J, Vilaplana·JM, Amigo J. *Quantitative assessment of the residual risk in a rockfall protected area.* Landslides (2005) 2: 343–357.

40. The seeders used for the RocFall trajectory analyses should be checked against the geological data on the GIS maps. Some of the sections checked have seeders extending well below the base of source material (toe of source) as interpreted by GNS and shown on the PHGG mitigation options maps.

41. Source areas should be rechecked during design to assess whether there are any areas where boulders greater than the design size may be released. If this is the case, source stabilisation or containment may be required. Note the requirements of ONR 24810 for suitably experienced personnel to undertake such inspections.

Bounce heights

42. The design interception height (h_i) of a rockfall fence or bund should be greater than the modelled interception height (h_p) determined from rockfall trajectory modelling. According to Eurocode 7[7], the interception height used for design (h_i) should be the 95th percentile of h_p plus a clearance (f) that is not less than half the average size of the design boulder, i.e.,:

$$h_i \geq h_p + f$$

43. Calibration of the rockfall modelling results with on-site observations of rockfall impacts on trees, houses, fences etc. indicates that in the Port Hills the observed bounce heights are greater than those derived from the modelling. This is mainly the case in the more distal rockfall runout zones, where the rockfall models show the boulders to be rolling, but in reality site observations indicate they were actually rolling and bouncing. This experience is consistent with recent experiments reported by Buzzi (see δ18 of Memo #1). In these more distal runout zones, field observations of impact marks from boulders should be used to validate the rockfall modelling results. As a general guide, protection structure heights for rolling boulders should be at least 3m in height.

44. Comparisons of actual versus modelled bounce heights in the central and upper runout zones appear to correlate more accurately, although field observations should also be used to validate the modelling. If design is on the basis of FEL conditions, the weight of boulders trapped in the panel(s) will lower the effective fence height and this must be allowed for in design.

Indicative RocFall analyses

45. *Figures 4* to *6* show some rockfall trajectory analyses carried out for Sections 41 and 43 at Avoca 1 and Section 10 at Heathcote/Morgans Valley. These use PHGG's RocFall modelling data prepared for the GNS report (CR2011-311) and have not been modified other than to include a barrier and to change the boulder dimensions – they are included here only for illustrative purposes. The results and conclusions are as follows:

Table 7: Results of some RocFall analyses and implications for protective works (locations of protective works as proposed by PHGG)

Boulder Size (m^3)	*Total KE kJ Max/95th*	*Bounce height (m) Max/95th*	*Ground slope*
Section 41 Avoca 1			
3.5 (Port Hills wide 95th percentile)	440/210	0/0	≈20°
1 (Site specific, 95th percentile all data)	260/160	0/0	
0.7 (Site specific, 95th percentile downslope of fence)	260/160	0/0	
Mitigation measures for 95th percentile boulder passing protection location: ***Bund** OK* ***Fence*** *MEL: No, multiple boulder strikes* *SEL: No, >>2 strikes* *FEL: OK, would require 960-1440 kJ fence (6-9 x 160) – Class 3 to 4* *Height: 3m height at least* ***Probable measure**: Bund always likely to be preferred option if site conditions permit.*			

Section 43 Avoca 1			
3.5	4725/3845	7.1/4.4	>20°
1	1350/1100	7.1/4.4	
0.7	945/770	7.1/4.4	
Mitigation measures for 95th percentile boulder passing protection location: ***Bund**: No, ground too steep* ***Fence*** *MEL: No, multiple boulder strikes* *SEL: No, >>2 strikes* *FEL: OK but would require about 4620-6930 kJ fence (6-9 x 770 (Geobrugg max is 8000 without ETAG certification)* *Height: Requires 8m height at least (GBE-8000A is 9m max)* *At upper limit for fence capacity; consider containment mesh over source area.* ***Probable measure:** Containment mesh or move fence downhill*			

Section 10 Morgans Valley			
2.7 *(Site specific, 95th percentile downslope of fence)*	40/30	0/0	≈20°
1.1 *(Site specific, 95th percentile all data)*	15/12	0/0	
Mitigation measures for 95th percentile boulder passing protection location: ***Bund** OK*			

Fence location with respect to modelling output

46. GNS has produced plots of total kinetic energy predictions for each slope area (see *Figure 7* for example from Heathcote Valley). These plots can be characterised as follows:
    - Falling zone Relatively short length of trajectory with moderate energy levels
    - Bouncing zone: Length of trajectory with moderate to high energies and significant bounce heights
    - Rolling zone: Relatively long zone of predominantly rolling and bouncing behaviour with moderate to low energies.

47. Rock catch fences need to be located in the more distal areas of the rock trajectory where energies and bounce heights have been reduced to levels that can be accommodated by the fence. The boulder energy and bounce heights in the middle bouncing zone will often exceed available fence capacities. If boulders cannot be arrested by fences (or bunds), containment of the source area or source material stabilisation are the next options to be considered.

48. *Figure 7* shows how the RocFall output data can be used to locate rockfall protective structures. (The example given on *Figure 7* is based on the 95th percentile boulder from all the Port Hills data – 3.5m^3 or 9450 kg which is not dissimilar to the site specific value of 2.7m^3 below the fence location (*Table 6*)). As noted in an earlier part of this report, rock fences must be designed on a functional basis whereby they are not loaded beyond their elastic limits during multiple boulder impacts. The likely Safety Factor required for FEL with respect to fence capacity has been assumed to be in the range from 6 to 9 (but this must be validated by actual field testing for any given product).

49. For a Class 7 fence (capacity = 4500kJ) and FEL design with Safety Factor = 9, the maximum BEL is 500 kJ (*Tables 3* and *4*). Using *Figure 7* data, the fence should therefore be located between the energy level markers for 0-500 and 501-1000 kJ. The red fence position plotted on *Figure 7* is substantially lower than the green line labelled as Geovert Barriers – the basis for this location is not known. The location for a Class 7 fence with a Safety Factor = 6 would be slightly higher in the middle of the 501-1000 kJ markers on the plot. This assessment suggests that it is unlikely that a rock catch fence could provide the required safety or risk reduction) between Sections BPR 02 and BPR 22 along Bridle Path Road.

RISK REDUCTION

50. The effectiveness of a barrier in reducing the analysed risk has been quantified using the method described in a GNS Science working note provided by Dr Massey.

51. In general barriers (both bunds and fences) can be rendered ineffective if:
    1. boulders have larger impact energies than the design energy,
    2. boulders bounce over the fence,

3. the fence is damaged (deforms plastically) by multiple hits from boulders less than the design energy level, and
4. is being repaired following a significant hit.

52. Using the example from Avoca Valley (*Table 7*), the fence proposed by PHGG is located along the 27° shadow angle line, and it is designed to stop the energy from the 95th percentile boulder size.

53. If designing for the 95th percentile boulder volume and associated energy, 5% of the boulders are going to be larger and therefore have higher energies than the fence can handle and as a result will pass through the fence. Also if designing for the 95th percentile bounce height, 5% of the boulders will overtop the fence and continue down slope rendering the fence ineffective.

54. Even if designed for the 95th percentile boulder volume, there is a chance that, if the fence is hit by multiple boulders ≤ the 95th percentile, one of these could damage the fence. Using the site specific data for Avoca Valley the probability (P) of each boulder hitting a 10m wide fence panel can be expressed as:

$$P = \frac{10}{L}$$

Where 10 is the fence-panel width in metres and L is the cross slope length e.g. the shadow angle line. The next boulder reaching the fence panel has the same chance (P) of hitting the panel, but there is a chance that the panel has already been hit and damaged by a previous boulder ≤ e.g. ($P_{HIT} = 1\text{-}(1\text{-}P)$). The Nth boulder still has a chance (P) of hitting the same fence panel and finding the fence already hit ($P^{N}{}_{hit}$) therefore:

$$P^{N}{}_{HIT} = 1 - (1 - P)^{(N-1)}$$

Where N is the number of boulders that would have reached and passed through the location of the fence from each considered event (prior to installation of the fence).

55. By combining all of the ways a fence could be rendered ineffective it is possible to estimate the total ineffectiveness of the fence (*Table 8*)

Table 8: Estimated ineffectiveness of a fence located on the 27° shadow angle in Avoca valley (excluding PGA events >> 2g)

Mechanism 1: % boulders that are bigger than the protection structure can stop	12%
Mechanism 2: % boulders that bounce over the protection structure	5%
Mechanism 3: % boulders that find the protection structure already damaged in event	10%
Mechanism 4: % of time for which protection structure is unavailable due to repair or maintenance (assumed to be about 1 month in 10 years)	1%
Overall ineffectiveness	**25%**

56. The annual individual fatality risk (AIFR) immediately downslope of the barrier, prior to installation of the barrier, was estimated to be about $2\text{x}10^{-3}$ (CERA risk model assuming year 1 seismicity), the barrier is about 75% effective thus reducing the AIFR to $5\text{x}10^{-4}$. However, there is about one order of magnitude uncertainty in either direction on the estimated risk, therefore the designer should not be placing high confidence on having reduced the AIFR below 10-3 per year if the estimated risk with the fence is just below this.

57. The CERA Year 1 risk model has been used as the basis to assess what level of risk reduction is achievable through mitigation. This is because, in our opinion, once mitigation measures are in place they will be expected to take rockfalls triggered by all of the considered events both seismic (earthquakes of varying PGA's including aftershocks) and non-seismic. However, it is understood that this decision is ultimately a policy one.

58. Regardless of the risk profile used, fences and barriers in the Port Hills are being designed for seismic conditions. Earthquakes with PGAs lower than those recorded on 22 February will still induce swarms of rockfalls and so the mitigation measures must be designed for multiple hits.

59. In general bunds offer levels of protection that would reduce the annual individual fatality risk by about an order of magnitude or greater (typically 90 to 95% effective). This is because bunds have the capacity to handle larger impact energies (>5,000 kJ) and greater number of hits than fences without being damaged (Ronco et al., 2009), therefore reducing the numbers of boulders that could breach the barrier.

CONCLUDING COMMENTS & SUGGESTIONS

60. The 22 February 2011 earthquake and the rockfall data from this earthquake should be used as the design event as the average PGAs recorded during this event currently have return periods of less than 500 years.

61. Protective bunds are likely to be the preferred method of mitigation wherever slope topography is suitable. These are robust structures which can withstand higher loads than dynamic rock fences at a significantly lower cost with lower ongoing maintenance requirements (subject to detailed design and cost estimates).

62. Rock catch fence design should take the following factors into account:

- Fence design should be for total kinetic energy (translational plus rotational)
- MEL and SEL are not suitable options for design of earthquake-induced rockfalls since they allow for only 1 and 2 impacts per panel respectively during the event
- FEL design is a more appropriate option for design of earthquake-induced rockfalls since it allows for multiple strikes per event. The required Safety Factor for this level of design is likely to be in the range from 6 to 9. This has to be confirmed by the fence manufacturers and validated by field testing.
- FEL design involves the nets being loaded with multiple boulders during the earthquake event and leads to a reduction in the effective fence height which must be taken into account in design

63. Fence designs should be based on site specific PSDs since these will reflect local geological conditions in the source area and the runout characteristics on the given slope. On the basis of the data provided by GNS over the last few days, there is a definite trend towards gravity sorting (larger boulders travelling the furthest) rather than fragmentation with travel.

64. The choice of boulder size is directly related to the kinetic energy that will be produced. It is not practical to design rock catch fences to accommodate the largest boulders observed in the Port Hills rockfalls. The probability of rocks higher than the design values (based on site specific data) being released in future earthquakes cannot be well quantified based on present data.

65. The bounce height of boulders in the distal part of the runout will be greater than indicated by the current rockfall models. Bounce heights need to be checked against local evidence. As a general rule, protection structure heights for rolling boulders should be no less than 3m.

66. The location of rockfall fences can be determined from kinetic energy plots as shown in *Figure 7.* For typical boulder sizes and FEL designs with SF = 9, fences must be located at the distal ends of the trajectory where boulders are rolling and kinetic energy values have been reduced. Retention of boulders in the midslope zone of bouncing rocks is likely to be impractical.

67. In the Port Hills coastal situation, rock fences have a relatively short life (10 years minimum, 25 years maximum) even without rock impacts. Longer term protection beyond this period could be provided with a purpose designed protective forest.

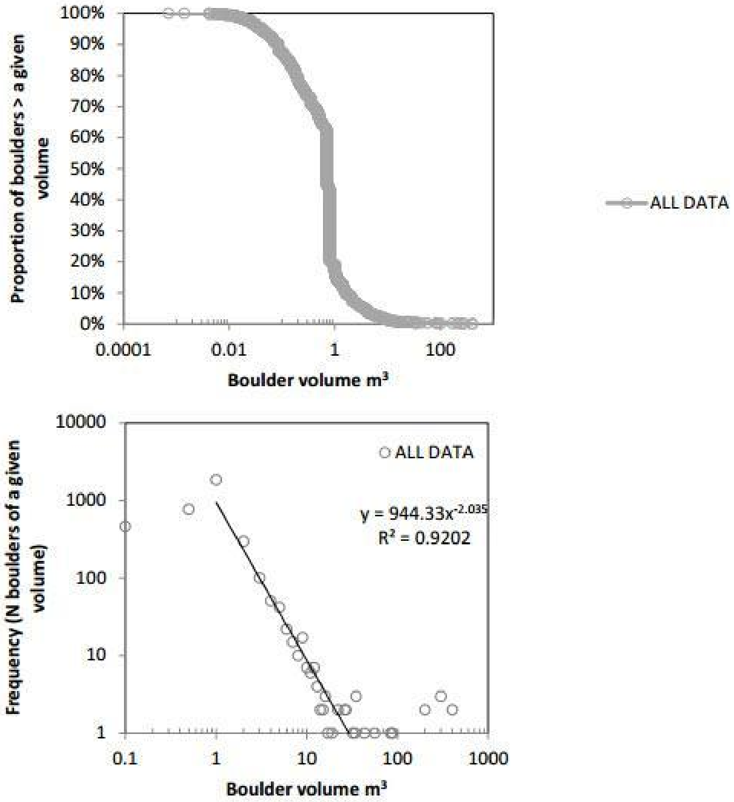
68. Maintenance costs for rock catch fences could be significant mainly because of the need to provide a rapid response to any incident. These will need to be estimated in detail to ensure that lifetime maintenance costs are not prohibitive.

69. There is little, if any, precedent (at least known to the writer) for the use of rock catch fences to protect residential housing under the prevailing earthquake conditions where swarms of boulders are released in a single event. Similarly, there seems to be little experience that can be used as guidance for the behaviour of rock catch fences under multiple strikes and with retention of multiple boulders in single panels. (Note that even for the ETAG 027 SEL test, the first boulder is removed from the net before the second boulder is dropped). The fence capacity requirements for the Port Hills are at or beyond the sizes presently available with ETAG certification from manufacturers such as Geobrugg.

70. CCC requested the writer to provide an opinion as to *whether fences are viable or not for the Port Hills rockfall boulder roll conditions taking into account the Protection Structure Effectiveness Calculator (*discussed in Memo #1*) and drawing on your (and others') wide knowledge of boulder roll fence protection design.* The writer's opinion is that rock catch fences will not provide a global fix for the Port Hills rockfall problems. There may be some localised sections of slope, which are not suitable for bunds and where the boulder energies are relatively low, where fences might be suitable.

71. Use of containment netting systems on the source areas may provide a complement or alternative to rock catch fences since they have advantages with respect to lower boulder energy for entrapment, simpler installation and lower maintenance. Within the time available, the writer has not had the opportunity to carry out any assessment of this option.

Laurie Richards

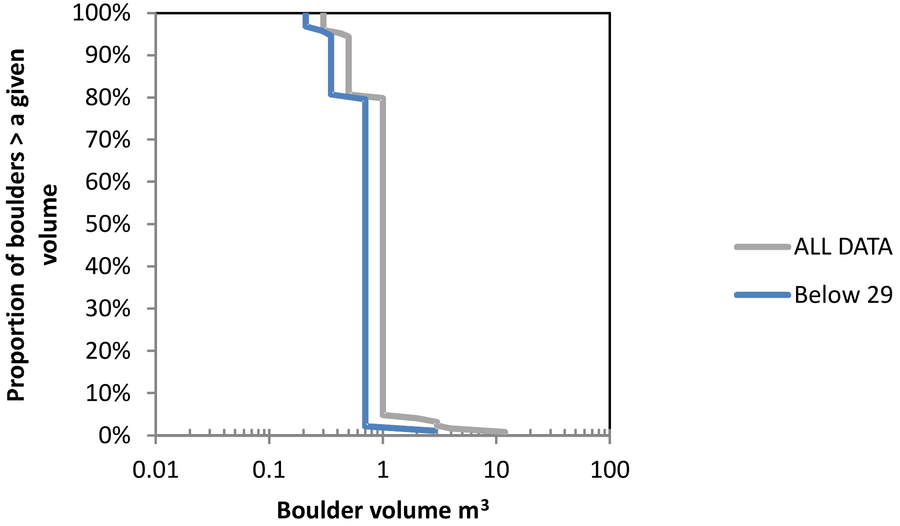


Percentile

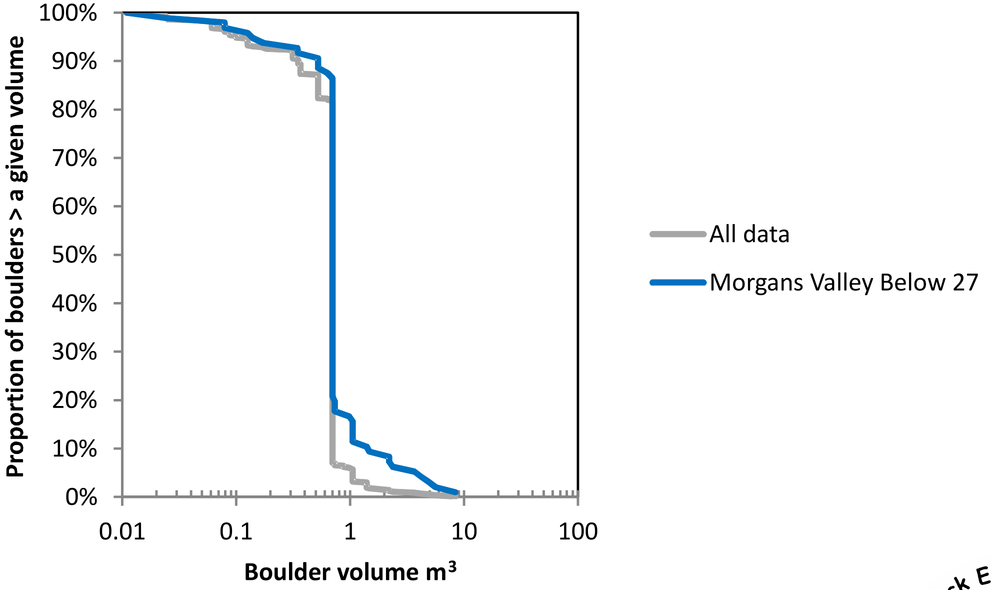
Percentile

SECTOR	**0.95**	**0.96**	**0.97**	**0.98**	**N records**
1	1.7	2.1	3.3	5.1	518
2	2.4	2.5	3.1	4.3	358
3	0.8	0.8	0.8	1.6	39
4	2.5	3.2	4.2	4.4	561
5	2.1	2.4	2.8	3.4	748
6	9.5	10.3	10.8	14.2	261
7	1.4	1.4	1.5	2.1	796
8	11.2	16.3	25.2	35.0	321
9	1.9	2.2	3.0	4.5	85
ALL	**3.5**	**4.2**	**5.3**	**8.0**	**3687**

(a) All areas in Port Hills



(b) Avoca: Data for entire slope and below proposed location of rockfall fence



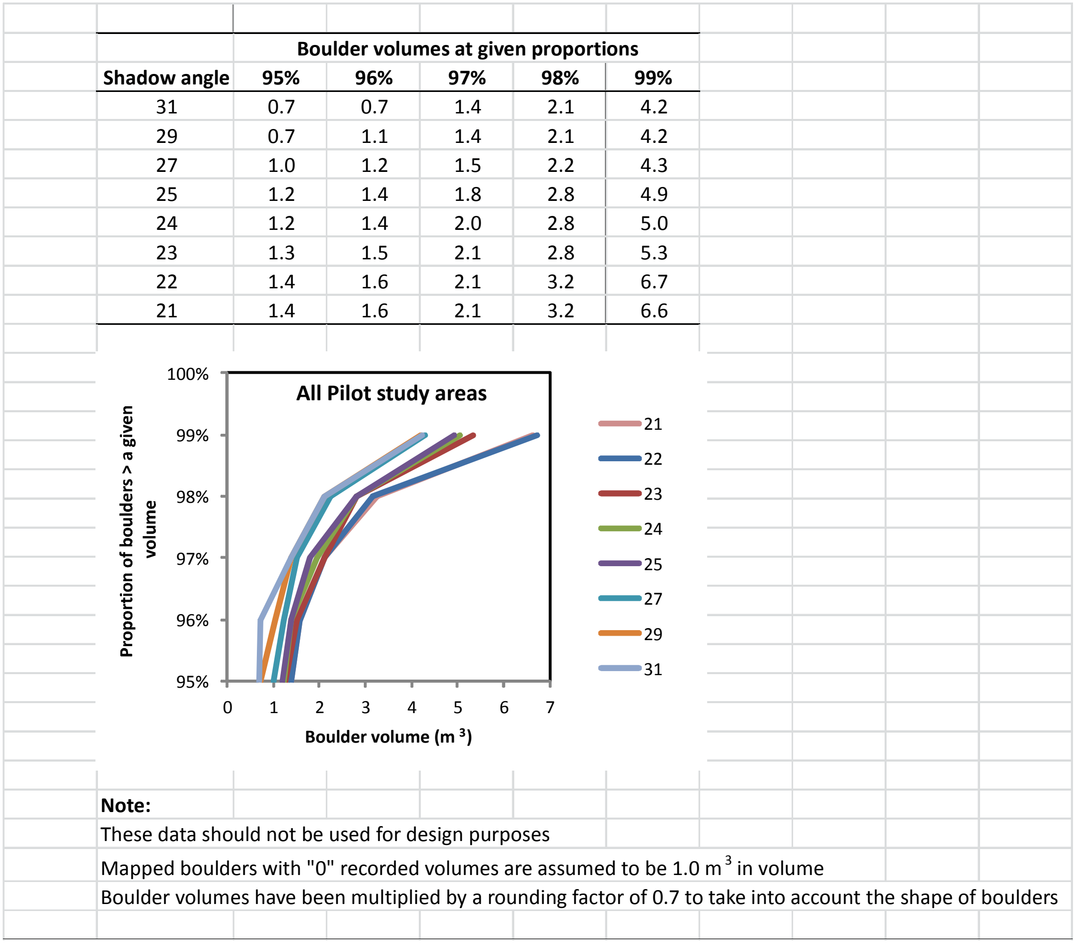
(b) Heathcote/Morgans Valley: Data for entire slope and below proposed location of rockfall fence

Figure 1: Rock boulder particle size distributions

Rock catch fences

Containment netting

Figure 2: Catch fences and containment netting: St Helena



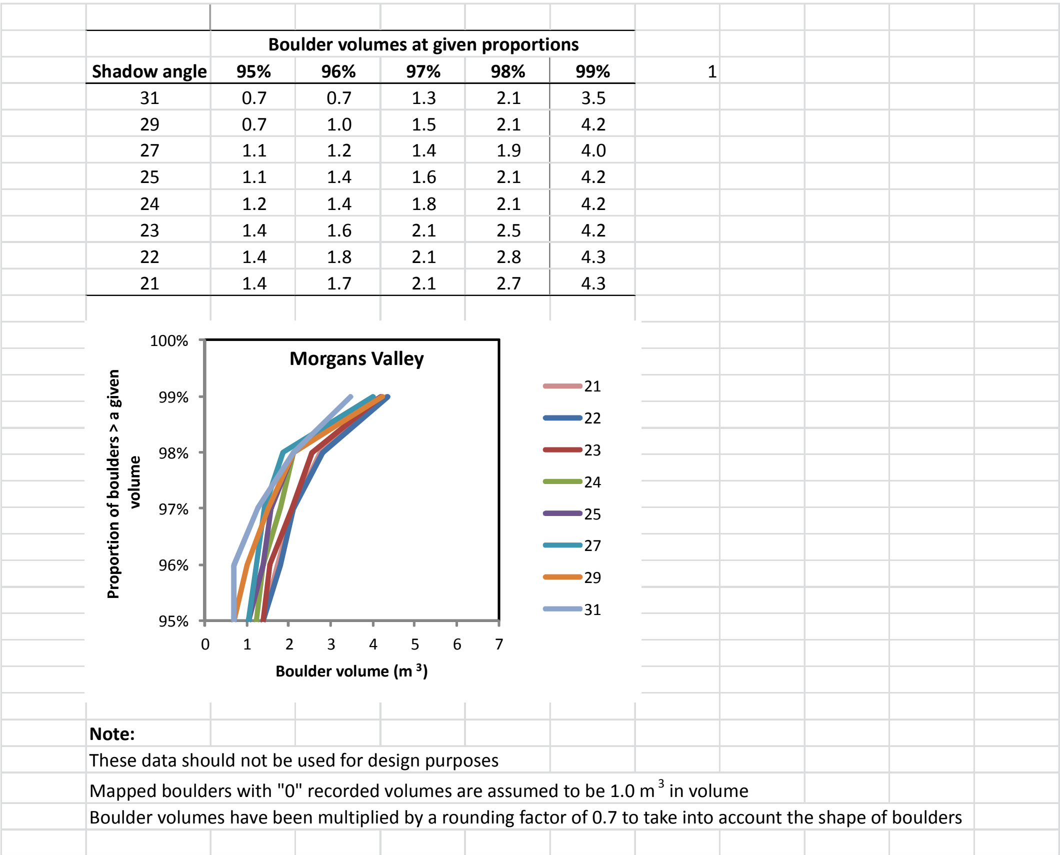
	Boulder volumes at given proportions				
Shadow angle	95%	96%	97%	98%	99%
31	0.7	0.7	1.4	2.1	4.2
29	0.7	1.1	1.4	2.1	4.2
27	1.0	1.2	1.5	2.2	4.3
25	1.2	1.4	1.8	2.8	4.9
24	1.2	1.4	2.0	2.8	5.0
23	1.3	1.5	2.1	2.8	5.3
22	1.4	1.6	2.1	3.2	6.7
21	1.4	1.6	2.1	3.2	6.6

Note:

These data should not be used for design purposes

Mapped boulders with "0" recorded volumes are assumed to be 1.0 m^3 in volume

Boulder volumes have been multiplied by a rounding factor of 0.7 to take into account the shape of boulders



	Boulder volumes at given proportions				
Shadow angle	95%	96%	97%	98%	99%
31	0.7	0.7	1.3	2.1	3.5
29	0.7	1.0	1.5	2.1	4.2
27	1.1	1.2	1.4	1.9	4.0
25	1.1	1.4	1.6	2.1	4.2
24	1.2	1.4	1.8	2.1	4.2
23	1.4	1.6	2.1	2.5	4.2
22	1.4	1.8	2.1	2.8	4.3
21	1.4	1.7	2.1	2.7	4.3

1

Note:

These data should not be used for design purposes

Mapped boulders with "0" recorded volumes are assumed to be 1.0 m^3 in volume

Boulder volumes have been multiplied by a rounding factor of 0.7 to take into account the shape of boulders

Figure 3: Rock boulder particle size distributions related to shadow angle (GNS analysis)

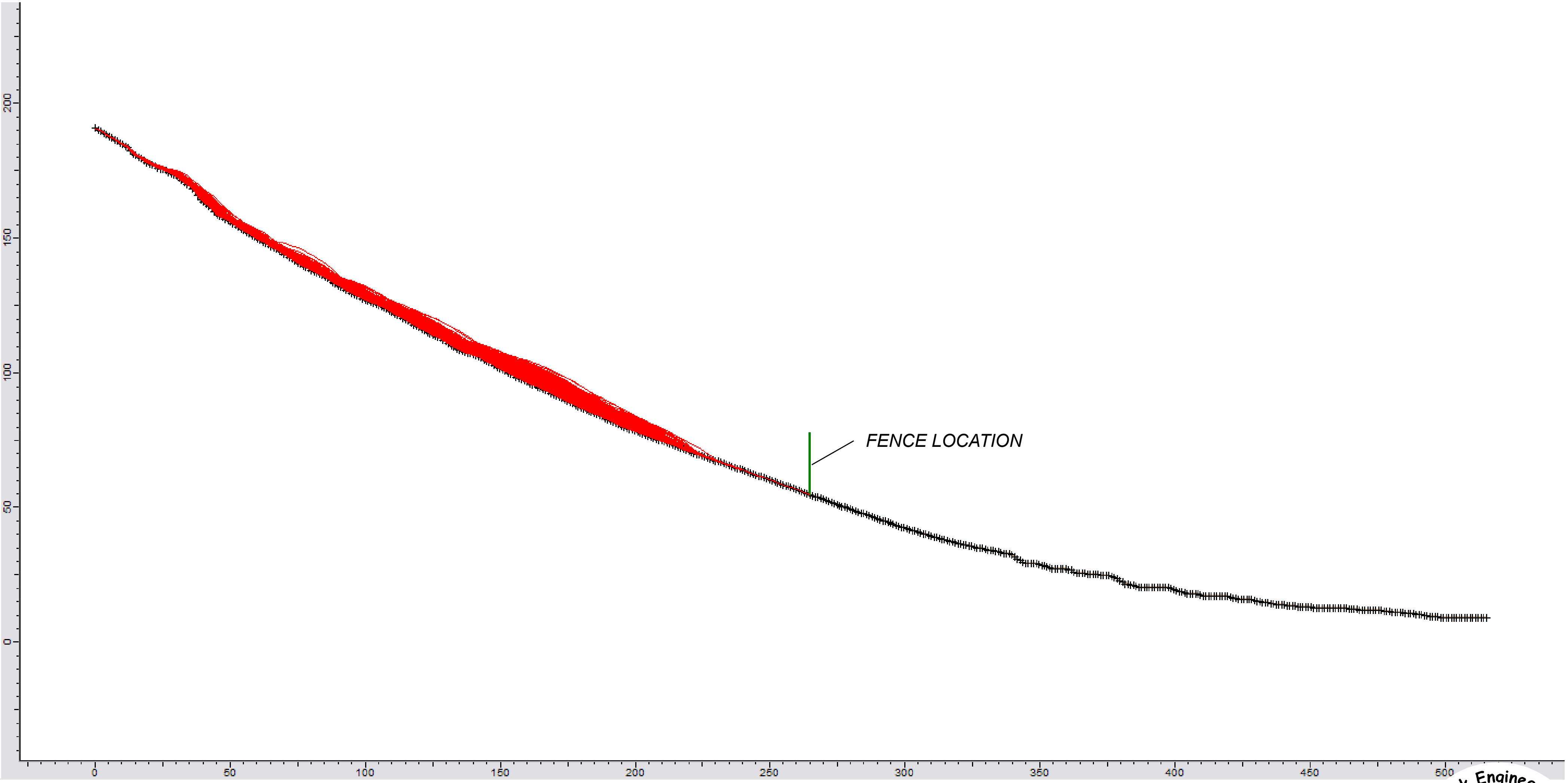


Figure 4: Avoca Valley 1 - Section 41 - 0.7m^3 boulder

PORT HILLS ROCKFALL REVIEW (Memo #2)

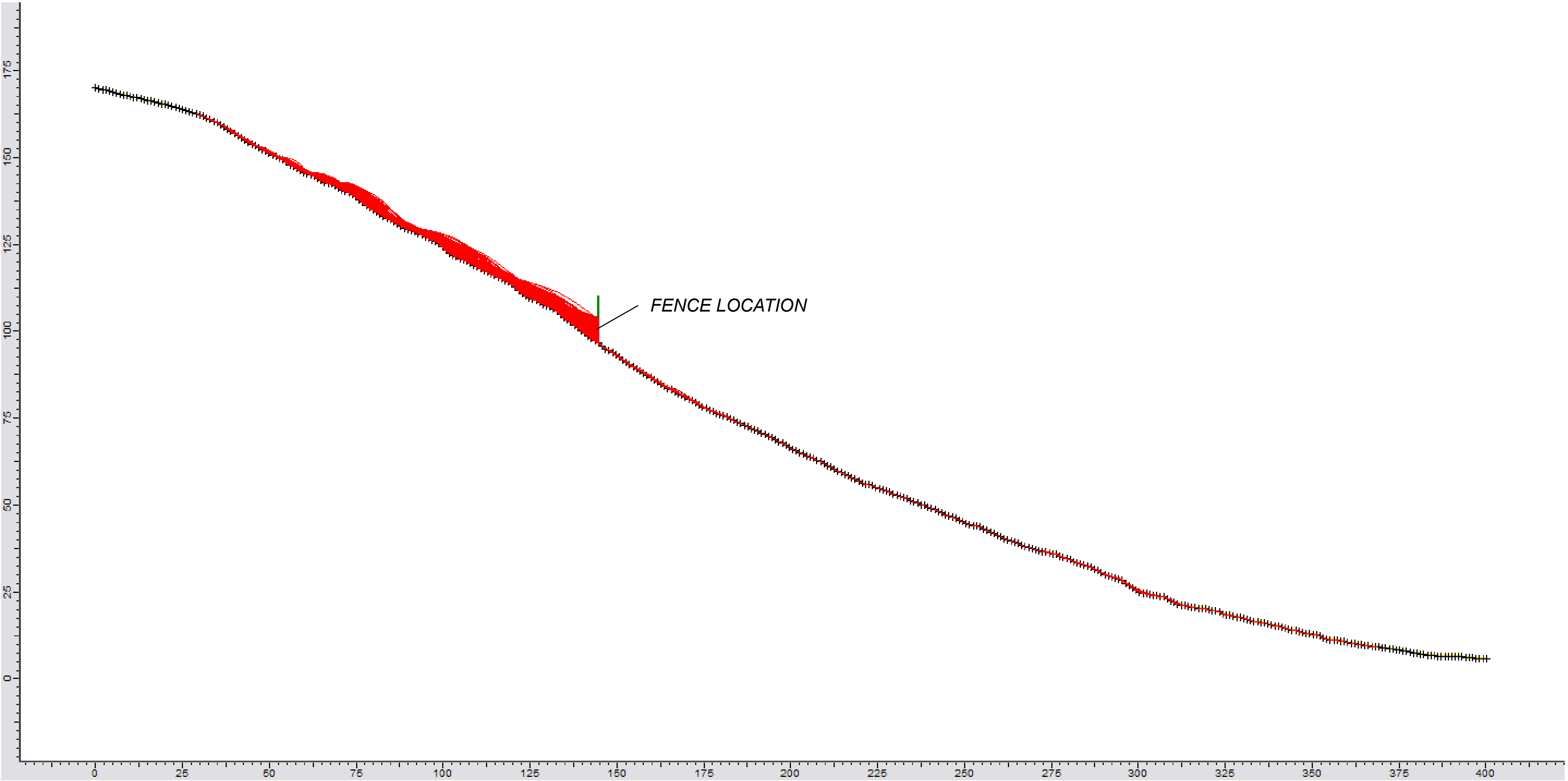


Figure 5: Avoca Valley 1 - Section 43 - 0.7m^3 boulder

PORT HILLS ROCKFALL REVIEW (Memo #2)

Rock Engineering 43° South

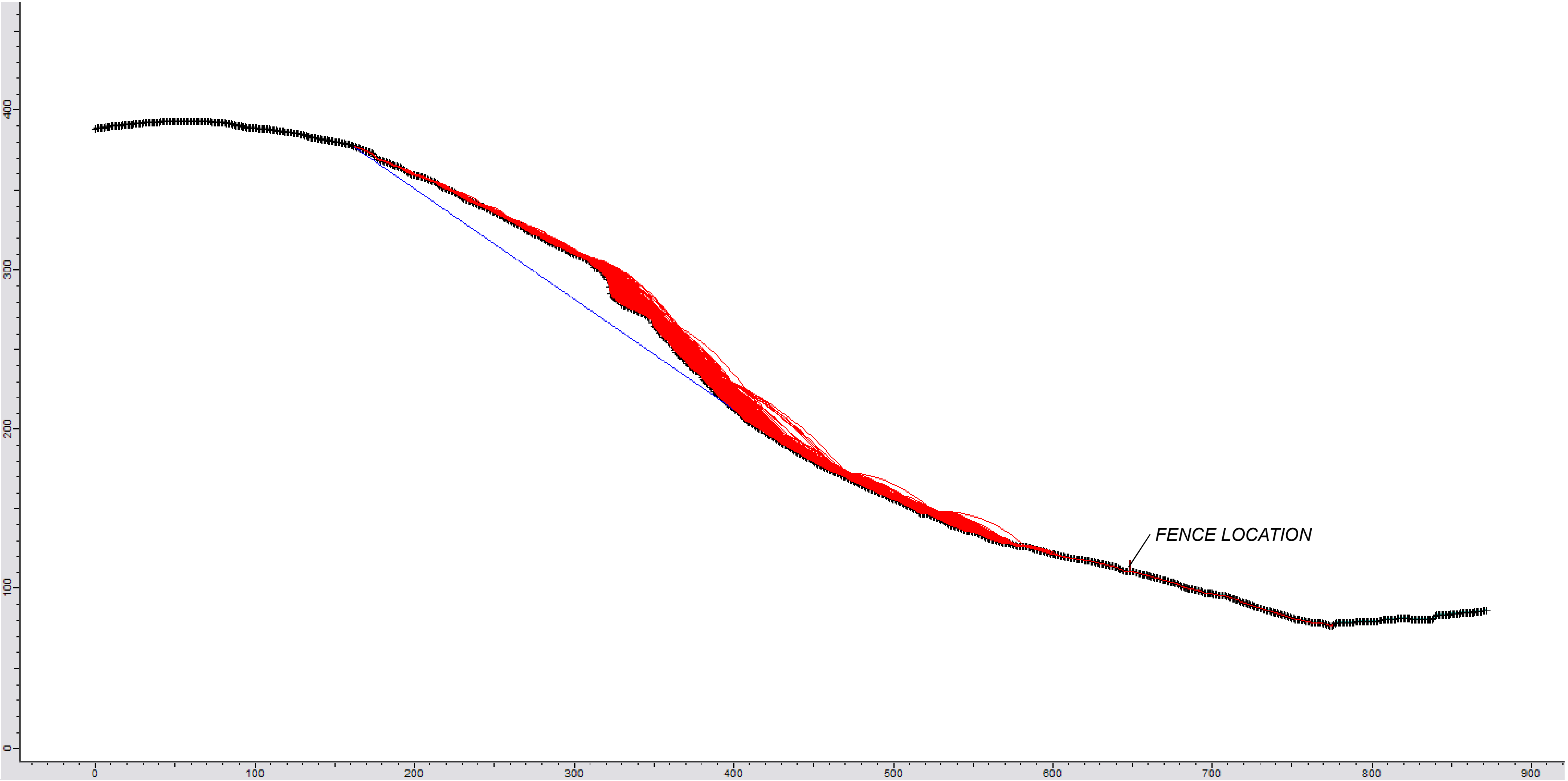
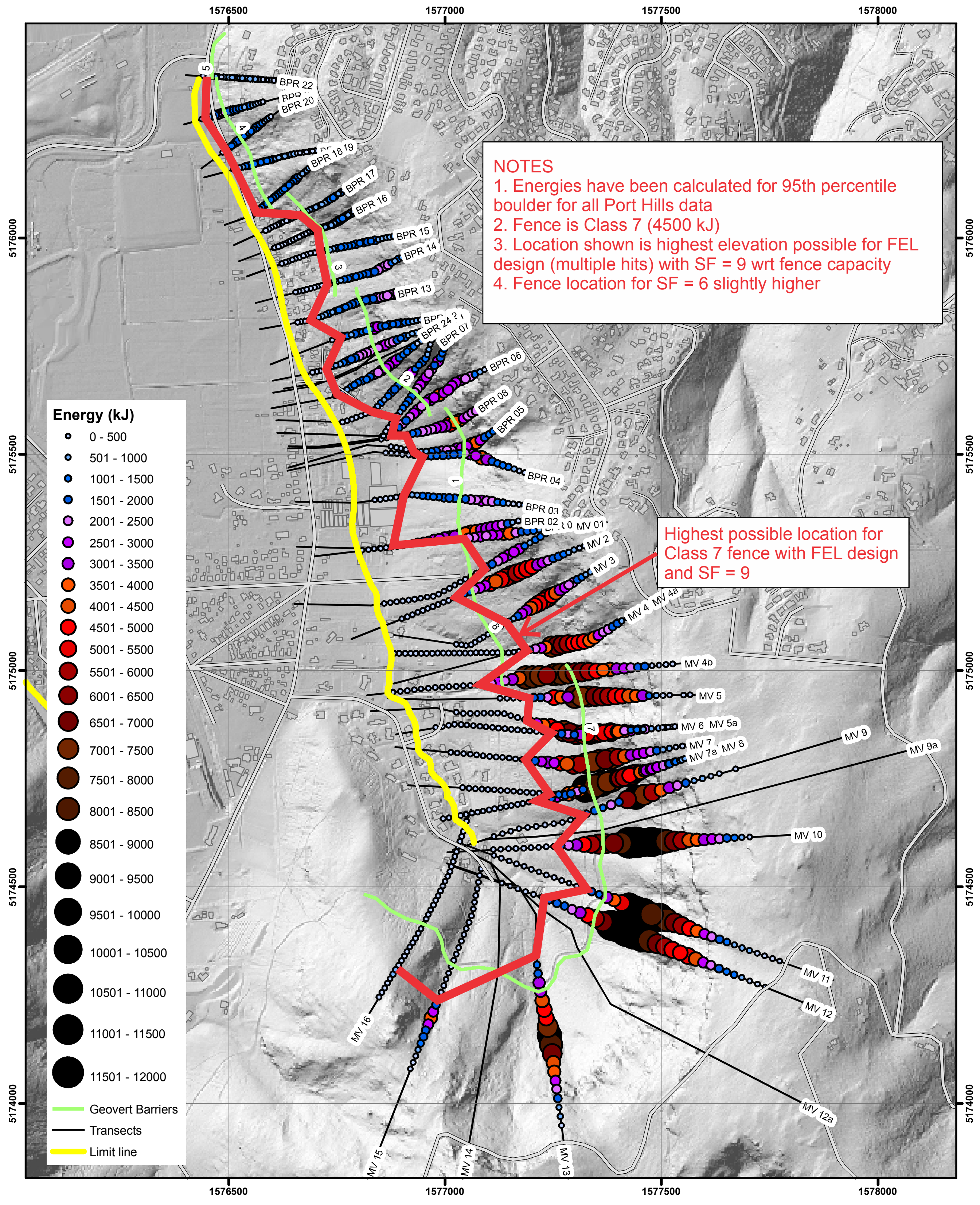


Figure 6: Heathcote/Morgans Valley - Section 10 - 2.7m^3 boulder

PORT HILLS ROCKFALL REVIEW (Memo #2)



NOTES
1. Energies have been calculated for 95th percentile boulder for all Port Hills data
2. Fence is Class 7 (4500 kJ)
3. Location shown is highest elevation possible for FEL design (multiple hits) with SF = 9 wrt fence capacity
4. Fence location for SF = 6 slightly higher

Highest possible location for Class 7 fence with FEL design and SF = 9

SCALE BAR: 0 50 100 150 200 250 m

EXPLANATION:
Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1m ground resolution.

Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

Modelling carried out by PHGG using the RocScience RocFall programme.

DRW: DWH, BL, WR

CHK: CM

GNS SCIENCE

ROCKFALL
TOTAL KINETIC ENERGY PLOTS

Heathcote Valley
Christchurch

PROJECTION:
New Zealand Transverse Mercator 2000

REPORT: CR2012/57

DATE:

Figure 7: Possible Class 7 fence location in relation to kinetic energy plots for Heathcote Valley