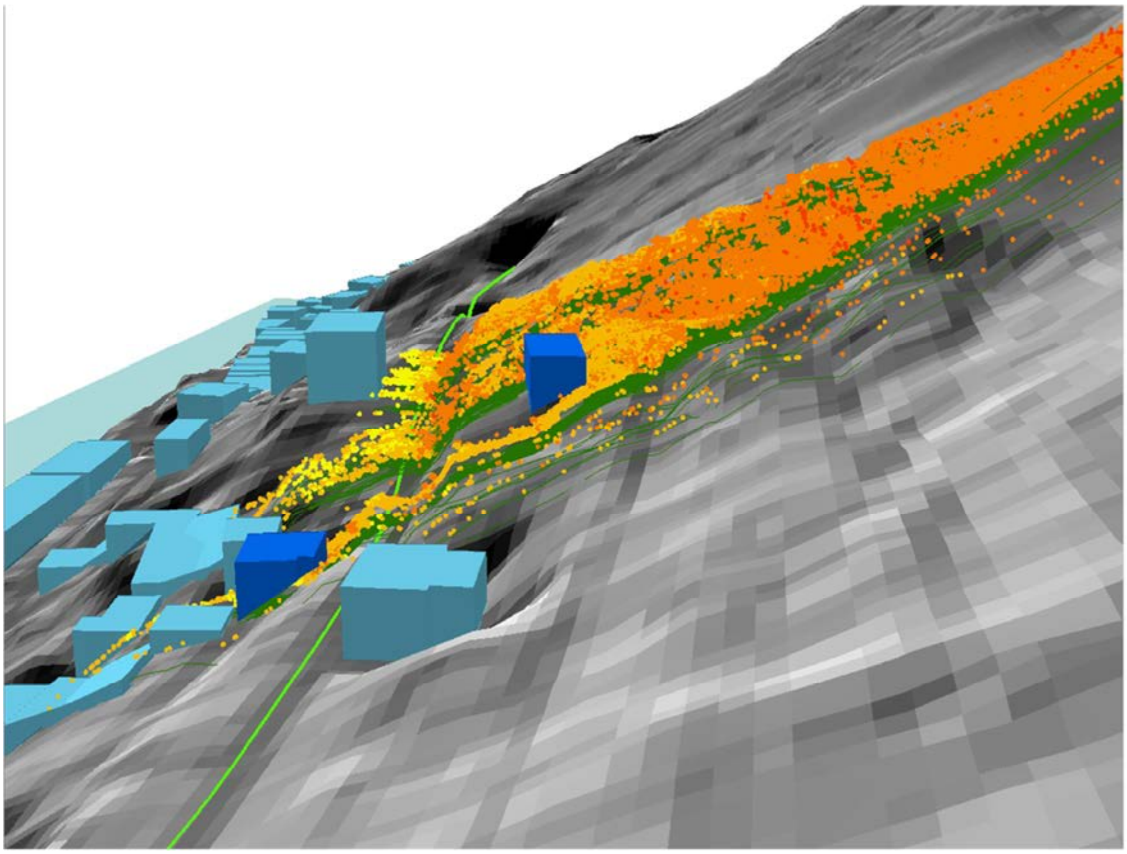

GEOVERT

Port Hills 3D Rockfall Modelling
Christchurch, New Zealand

25 October 2012

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Revisions

Date	Revision	Prepared	Reviewed	Approved
April-2012	Rev 0 - Draft	M. Avery	H Salzmann	A. Teen
May-2012	Rev 1 - Revised maximum boulder size	M. Avery	H Salzmann	A. Teen
Oct-2012	Rev 2 - Incorporating client comments	M. Avery	H Salzmann	A. Teen

CONTENTS

1. Introduction

This report outlines detailed 3D rockfall modelling of multiple areas within the Canterbury Port Hills near Christchurch, New Zealand. It includes a rockfall hazard assessment for the area. This analysis will provide Canterbury Earthquake Recovery Authority (CERA) with an overview of the hazard levels in the affected areas providing supplementary information to the current Christchurch City Council (CCC) commissioned Geological and Nuclear Sciences (GNS) reports.

The aim of this report is to provide outcomes to assist CERA to make critical decisions relating to areas where rockfall hazard exists and where protective works may effectively reduce the this hazard. CERA may use the results in this report to identify properties assessed as having a very low or low hazard from rock fall. This may be followed, with the assistance of CCC, by a cost benefit study for different protective works options for those properties identified as being at medium and high risk from rockfall. This work also enables prioritisation of work and budget forecasting. This work does not consider annual individual fatality hazard (AIFR) from rockfall as presented in the GNS reports.

This report presents 3D modeling results and rockfall prevention and protection options suitable for each respective Sector. Sectors are work areas defined by the Port Hills Geotechnical Group (PHGG), a group of geotechnical consultants working for CCC. The options presented are based on data provided by the Christchurch City Council, the Port Hills Geotechnical Group (PHGG), Geological & Nuclear Sciences (GNS) and CERA, and on field observations made by Geovert and other subcontracted specialists experienced in this matter. The data includes LiDAR survey which has been used to build a 3D model of the greater site to assist with rockfall analysis, including trajectories, bounce heights and velocities.

The 3D modelling was carried out in Italy by a sub consultant to Geovert. All data for the modelling was supplied by CERA, CCC and GNS and is the same data used by other consultants commissioned by CERA and CCC in an attempt to better understand the issues affecting the Port Hills. The 3D modelling forms only part of the bigger picture in this process. Results of the modelling were interpreted by Geovert engineering geologists and also by further sub consultants to Geovert Ltd and discussed at length with the Client during numerous meetings and workshops.

The analysis and mitigation solutions provided in this report are based on the following inputs and information;

- Images as taken on site,
- Site visits from our Geotech team as mentioned above,
- LiDAR 3D data as received from CCC in February 2012,
- Inventory of boulders as received from PHGG in February 2012,
- Geomorphology as received from GNS in March 2012,
- Orthophoto aerial images as provided by CCC in February 2012.

This report assumes that the rockfall hazard from the slopes from various sectors has been deemed as unacceptable by the Client, and presents remediation alternatives as options to consider that may reduce this hazard to acceptable levels.

NOTE: This report outlines the results of a high level first pass analysis only. The information provided is for the purpose of CERA use only and is not to be used for detailed design or assessment purposes. This study also does not specifically consider the issue of boulder flux

(i.e. multiple earthquake generated boulders) that did occur in some places in the Port Hills. This issue would normally be addressed at the detailed design stage using specially developed finite element software which would allow this scenario to be modeled on a case by case basis.

2. Rockfall Hazards

Rockfall is the only hazard considered in this present study. Cliff collapse, debris inundation and land movement has not been considered. Detailed investigation of the basalt cliffs and steep slope areas may expose the need for additional scaling and further active stabilisation measures than those considered in this report.

Rockfalls in the investigated area comprised of different and numerous sized boulders as well as rock and debris avalanches. These were documented in the boulder inventory prepared by PHGG and GNS. The rockfall hazards in the different Sectors originate from a variety of source areas including bluffs, steep slopes and manmade features (i.e. road cuttings and quarries) to name a few, which are located at varying elevations on the slopes.

In some areas there is evidence of limited rockfall originating from small outcrops located sporadically over the slopes, but predominantly they originate from the larger bluff features. It should be noted that for the purpose of this report we considered all source areas contributing to the hazard, directly by releasing material immediately from the rock face and also indirectly in the form of blocks from past rock releases that have been arrested mid slope. Bearing in mind the large geographic areas being considered, to simplify the analysis any slope steeper than 45 degrees was assumed to be a potential rockfall source.

3. Failure Mechanisms

3.1 Toppling Failures

Toppling mechanisms describe movement due to forces that cause an overturning moment about a pivot point below the centre of gravity of the block. Toppling failures most commonly occur in rock masses that are subdivided into a series of slabs or columns.

3.2 Planar/Wedge Failures

Planer/wedge failures occur along one/two joints from different families whose joint face/intersections dips towards the slope respectively. The stability of a wedge depends on the geometry as controlled by the joint spacing, orientation, and shear strength. This mode of failure depends on joint attitude and state, and is more frequent than plane failures; however, many apparent wedge failures are plane failures when studied in detail. The size of wedge failures depends on the joint spacing, as the frequency is usually more minor than in plane failures.

3.3 Rockfall

Rockfall occurs where one or more rocks fall freely from a cliff face or rock slope. A rockfall is a fragment of rock detached by sliding, toppling, or falling, that falls along a vertical or sub-vertical cliff, proceeds down slope by bouncing or by rolling on slopes. Alternatively, a rockfall is the natural downward motion of a detached block or series of blocks with a small volume involving free falling, bouncing, rolling, and sliding.

3.4 Rockslides

A rockslide is a type of landslide caused by rock failure in which part of the plane of failure passes through intact rock and where material collapses en masse and not in individual blocks. The mode of failure is different from that of a rockfall.

4. Rockfall Triggering mechanisms

There are a number of triggering mechanisms for rockfalls including ground shaking from seismic events, high intensity rainfall and weathering. The following mechanisms are possible past and future triggers that can lead to rockfall events.

Note that the 3D model does not assume any particular failure mechanism.

4.1 Triggering by natural weathering and/or rainfall.

Weathering processes reduce the strength of the rock mass especially in the uppermost exposed layer and therefore lead mainly to slope/surface parallel fracturing and jointing. Since this process is ongoing long term the accurate prediction of rockfall is not possible. There are several rockfall records that have documented the activity of the basalt slopes that may be used as a general guide.

Rainfall or precipitation affects mainly the strength of the joints, between the sound rock and the fractured, jointed and weathered surface layer. The increase in pore and joint water pressure leads to a reduction of cohesion and friction between sound and weathered rock and is often a triggering mechanism for rockfall events or small debris flows. The influence of this mechanism depends mainly on two aspects; first on the permeability of the rock mass, and second on the yearly distribution of precipitation, whereas the highest rockfall potential is directly correlated to the amount of precipitation.

Freezing processes taking into account the increase of pore and joint pressures caused by hydraulic expansion due to freezing water located in joints and fissures may have only minor influence for this specific project due its climatic setting.

4.2 Triggering by earthquakes

Boulders and rock sections which are already dilated, disturbed and located in a precarious state on elevated slope surfaces or disintegrated rock masses may start to move when triggered by ground acceleration caused through earthquake activity. Furthermore boulders which are embedded in natural talus lying at its friction angle may start to roll or move down slope caused by a decrease of cohesion and friction angle due to ground acceleration. NB High horizontal or vertical acceleration as experienced in Christchurch has no notable effect on the terminal final energies. i.e. after the rocks have rolled down the slopes the energies will be in the same range regardless of the triggering mechanism at source.

4.3 Triggering by animals

Animals may be present along a certain area of the natural slopes, they are able to trigger smaller boulders which themselves can set off bigger portions of rock that may lead to substantial rockfall events.

5. 3D Rockfall Modelling Input Parameters

5.1 Slope Geometry

Profiles are digitized from the Digital Elevation Model (DEM) as distinct points. The slope surface between the single points is assumed to be linear.

5.2 Slope surface parameters

To calculate the interaction between the boulder and the slope surface the following slope surface parameters have to be specified for each area:

- Dynamic friction angle, **Rg** in degrees – governs the friction between boulder and surface in case of sliding; range of accepted input values: 0° to 89°.
- Static friction angle, **Rh** in degrees –governs the friction between boulder and surface in case of a static contact; range of accepted input values: 0° to 89°.The static friction angle has to be greater than or at least equal to the dynamic friction angle
- Normal damping **Dn** – governs the damping of the velocity component normal to the slope surface during collision; range of accepted input values: 0 (fully plastic impact) to 1 (fully elastic impact).
- Tangential damping **Dt** – governs the damping of the velocity component parallel to the slope surface during collision; range of accepted input values: 0 (fully plastic impact) to 1 (fully elastic impact).
- Rolling resistance **Rw** – governs the energy loss of the rolling boulder; range of accepted input values: 0 (no rolling resistance) to 0.35 (extreme rolling resistance).
- Amplitude of surface roughness **Oa** – in meters; defines the vertical distance of the peaks of undulations below and above the connecting line of two neighboring coordinates; ranges of accepted input values 0 – 5 m. With a value of zero for the amplitude, the calculation would consider no roughness.
- Frequency of surface roughness **Of** – in meters; defines the horizontal distance between the peaks of undulations; range of accepted input values 0 – 20 m.

5.3 Rockfall Theory

A two-dimensional profile is determined for the simulation which is represented in single area (slice). The number and extent of slices is determined according to the form of the slope. The surface properties are assigned to individual slices and are at first constant over the slices. The simulation calculates the track data of a block according to the laws of motion and impact theory and taking into account the angular momentum.

The following types of motion are possible as initial motion of the rockfall:

- Free-fall
- Sliding
- Rolling

- Toppling

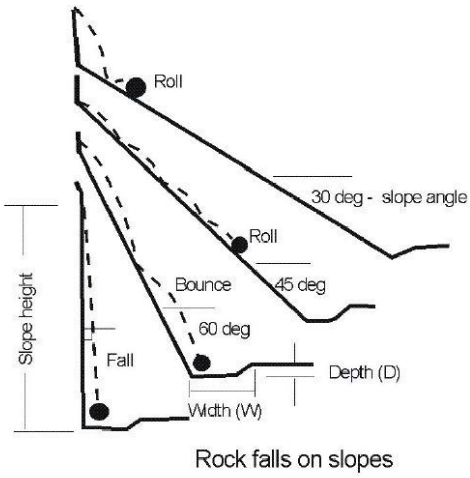


Image taken from FHWA Manual 'Rock Slopes'.

In the course of the motion, the following resulting motions are added according to the slope gradient and geometry.

- Sliding
- Rolling
- Toppling
- Inclined throw

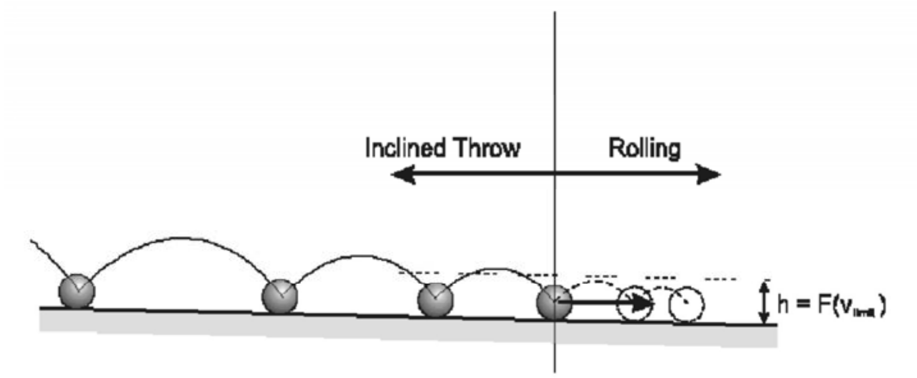
After each impact with the ground and at each change of slice, the motion situation is evaluated and the resulting motion initialised with the suitable type of motion in each case.

The calculation is continued until one of the following events (stop criteria) occurs:

- A structure is impacted
- Rolling to a stop on flatter ground
- Impact with the ground which throws the block back
- The block leaves the profile.

The stopping of motion and the decision whether a block continues its motion in inclined throw or rolling after an impact is controlled in the algorithm according to the criterion of falling below the limiting velocities. Both limiting velocities, the tangential and the normal limiting velocities, were chosen based on past experience and field observations.

When the normal and tangential velocities both fall under the limiting values, the motion stops. If the normal velocity falls below the limiting velocity after an impact, the motion is continued as rolling.



Images taken from Dr Spang 2003

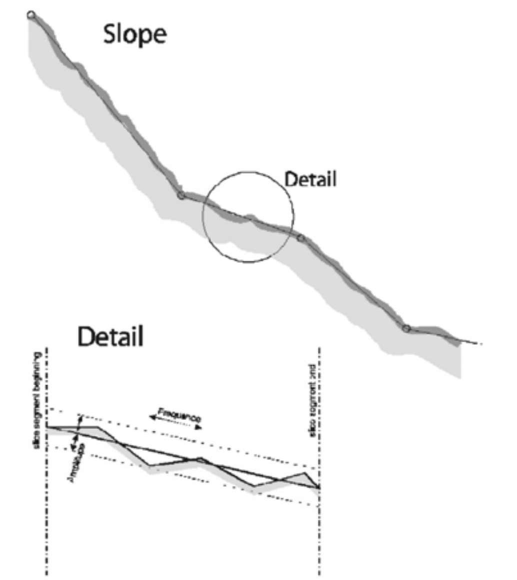
For various reasons, the problem of rockfall simulation cannot be solved deterministically:

- Effect of scale of roughness: slope surfaces are macroscopically rough. Rolling or sliding occur in nature mostly over short sections of slope, inclined throws following one another normally have varying jump distances, even on an even gradient. Blocks contact on different surfaces, edges and corners.
- Parameter variation: The properties of the slope surface vary, even within sections of slopes having principally similar characteristics of soil properties and soil layers.

To model these influences, two different methods are used and the relevant starting values determined. The two methods are:

- Introduction of a roughness concept for the surface of the slope.
- Stochastic determination of the starting values to be used at each changeover, for example for the restitution coefficient using a random generator.

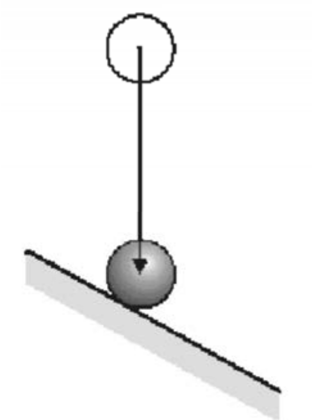
So a complete statistical study (stochastic simulation) can be carried out in a single simulation.



On the surface of natural scree slopes, there is a grading according to block size. Accordingly, the largest blocks mostly lie at the base of the slope (gravity sorting – the biggest boulder is most likely to roll furthest). As can be shown with the program ROCKFALL and the roughness concept described above, the blocks, whose size lies below or in the range of the roughness size, remain stationary, because they give up their energy through impacts to the sharp points; the relatively large blocks roll over their sharp edges, their loss of energy is correspondingly less and their range therefore correspondingly further.

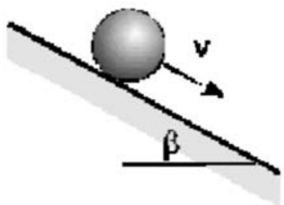
1. Free Fall

Free fall is a uniformly accelerated motion in the direction of the center of the earth.



acceleration	g
fall velocity	$v = g\, t$ [m/s]
fall distance	$s = 0.5\, g\, t^2$ [m]
with	$g = 9{,}81\ m/s^2$ acceleration due to gravity
	t = time from start of fall

2. Sliding



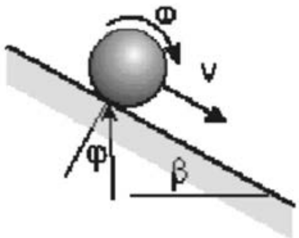
Sliding is an accelerated motion parallel to the ground surface.

acceleration	$a = g * \sin ß - g * Rg * \cos ß$
velocity	$v = a * t + v0$
travel distance	$s = 0.5\, a * t^2 + v0 * t + x0$
Angular velocity	(not affected)
with	

ß slope angle of track

g	acceleration due to gravity
t	time from start of motion
v0	velocity at time t=0
x0	position at time t=0
Rg	tangent of the angle of friction under sliding

3. Rolling



Rolling is an accelerated motion parallel to the ground surface.

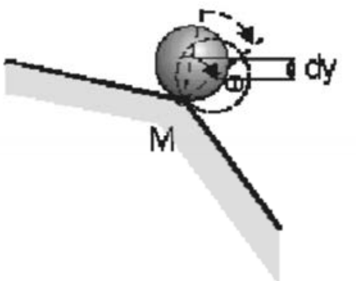
acceleration	a = g sin ß / (1+c) - g Rw cos ß / (1+c)
velocity	v = a t + v0
travel distance	s = 0.5 a t^2 + v0 t + x0
angular velocity	omega = v / radius

with,

ß	slope angle of the track
g	acceleration due to gravity
c	factor for calculation of moment of inertia (sphere c=0.4; cylinder c=0.5
t	time from start of motion
v0	velocity at time t=0
x0	position at time t=0
Rw	rolling resistance

4. Toppling

Toppling is a circular motion, with a non-sliding condition at the contact point between an edge of the surface and the toppling body. The equation of motion is derived from energy conservation.



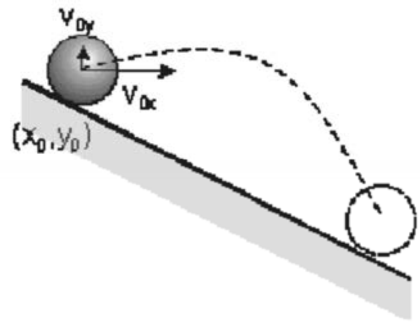
angular velocity	omega = (E0 - g yi) 2 / (radius ^{2} (1 + c))

track velocity v = omega radius
with

$E0 = 0.5\ (1 + c)\ v0^2$	kinetic energy at the start of motion
r	radius [m]
M	moment at pole
g	acceleration due to gravity
c	factor for calculation of moment of inertia (ball c=0.4; cylinder c=0.5)
t	time from start of motion
v0	velocity at time t=0

5. Inclined Throw

The inclined throw is an accelerated motion on a parallel track. The body does not rotate, or the rotation is not influenced by the motion.



acceleration	ax = 0
	ay = g
velocity	vx = vx0
	vy = - g * t + vy0
travel distance	x = vx0* t + x0
(parallel track)	$y = -0.5\ g\ t^2 + vy0^*\ t + y0$

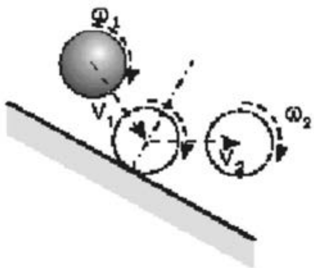
with

g	acceleration due to gravity
t	time from start of motion
vx0	velocity at time t=0 in x-direction
vy0	velocity at time t=0 in y-direction
x0, y0	position at time t=0

6. Impact Calculation

A rock hitting the surface is modeled as an elastic plastic impact, with restitution (damping) normal and tangential to the impact plane. Additionally the angular momentum of the rock is taken into consideration in the impact analysis. The tangential force during impact is either governed by dynamic friction or for a harder impact by static friction. Thus we solve the problem of the impact of a sphere or cylindrical shaped mass on rigid surfaces.

Applying momentum conservation normal and tangential to the surface as well as the conservation of angular momentum leads to the translation velocities and the angular velocity after impact.



6. Rockfall Modelling

6.1 HyStone

The information provided herein is the result of a high level 3D simulation of rockfall using Hy-Stone software. HyStone is a rockfall modelling software utilizing numerical code to analyze rock falls, the related hazard and the associated risk. The software is the result of collaboration between FEAT (Finite Element Application Technology, NL) and the University of Milano (Bicocca, Dipartimento di Scienze Geologiche e Geotecnologie).

HyStone is a 3D rock fall simulation program designed to take advantage of a high-resolution description of 3D slope geometry and perform accurate and easy-to-calibrate multi-scale stochastic modeling. The main features of the code are,

- use of Digital Elevation Model (DEM) to describe topography with no restriction on resolution,
- definition of rock fall sources as point, polygons or lines,
- modeling parameters (topography, sources, energy restitution and rolling friction coefficients) are spatially distributed,
- kinematic (lumped mass) and hybrid (mixed kinematic-dynamic) algorithms to simulate free fall, impact and rolling motions, with different damping relationship available to simulate energy loss at impact or by rolling,
- stochastic modeling to include the variability parameters,
- elasto-visco-plastic model to simulate impact on soft ground,
- simulation of passive countermeasures with specific geometry and energy absorption capability,
- raster and vectors output, including rock fall frequency, minimum, mean and maximum values of velocity, fly height and energy, as well as information about the type of motion, the location of impacts, etc., and,
- simulation of the possible presence of vegetation and the occurrence of fragmentation of main blocks into small flying rocks.

6.2 3D Modelling

A number of rockfall source areas were identified by PHGG and GNS in the Sectors shown in

Figure 1. Similar to a more traditional 2D analysis the 3D modelling takes into account a number of site specific parameters including source area size and height, slope angle, surface material properties (soil, rock etc.), surface roughness and conditions of the run out zones. Additional information critical to an accurate model includes source area characteristics such as block size and shape, density and strength. Similarly within the run out zone a number of factors can be considered including existing structures and infrastructure.

The data is inputted into a very powerful computer based at the University of Milan. A team of up to five highly trained technical staff is required to input, check and run the program. The computer requires many hours to fully run one Sector (normally between 8 - 12 hours) such are the scale of the Sectors but also the complexity of the algorithms. The data is then checked for errors then cross checked with other Sector results to assure consistency.

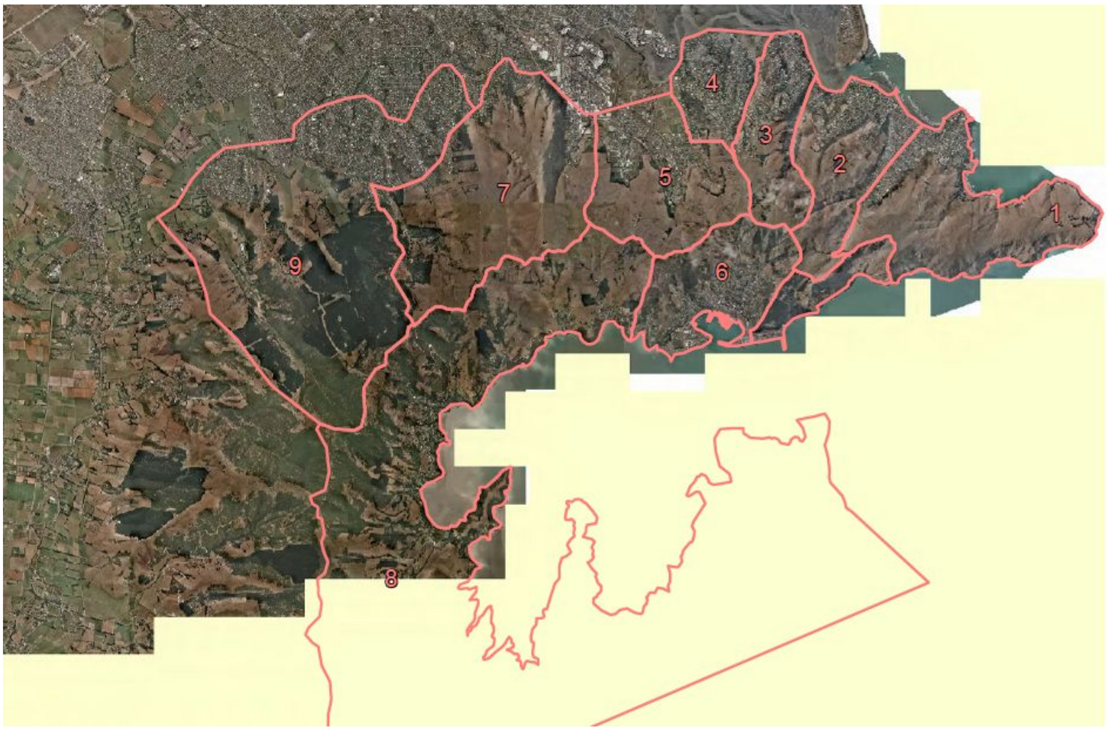
6.3 Input parameters

For this modelling we have treated the site as 'green field' and as such have not included for any trees or vegetation on the slopes or runout zones (other than minor tussock), and have not included any houses, buildings, roads or structures anywhere in the model. These parameters can be considered at a later date if required or appropriate.

The data for the modelling has predominantly been supplied by the Client including,

- LiDAR data to build the DEM,
- Catalogue of mapped boulder locations and boulder parameters as a result of the February and June earthquakes,
- Rockfall source area shape files for source area locations,
- Typical block characteristics including rock type and properties including size and shape, and
- Geological and geomorphological maps of the majority of the considered area,
- Some surface characteristic information has also been provided by GNS to assist with model calibration.

Figure 1 - Port Hills Sector Map (from PHGG)



Additionally high resolution aerial photographs were supplied by CCC showing images from before and after the February 2011 earthquake – these were used to assist in source area location and identification. All slopes that are steeper than 45 degrees assumed to be sources.

The shape of the boulder used in the 3D simulations was spherical – this was mainly to do with calculation time, as spherical shapes are the easiest to handle in this respect. Boulder size was set according to the data supplied by GNS (based on the PHGG database) using the 95th percentile boulder as a fixed boulder size. For some sectors different scenarios were run including some with a boulder size distribution – in such a case an exponential distribution was used. This process was carried out as part of the checking procedure and also to observe how sensitive the model was to different inputs.

The number of boulders used in the modelling was set at twenty boulders per source cell with the cell size set at 1m x 1m. Some minor variations occurred. The total number of boulders used in each simulation (each Sector) varied depending on the size of the source area(s) in that Sector. For instance in Sector 2 there are a total of 10,640 cells which totaled to 212,800 boulders modeled.

All vegetation has been completely removed from the ground model. While larger vegetation can sometimes have a positive effect on reducing the hazard for the sake of this report any vegetation cannot be considered effective in the long term (i.e. there is a real risk of fire removing the vegetation).

The input parameters for the rock properties, including starting velocity and rotational velocity, are outlined here. For all modelling we used a specific weight of 2.7t/m3.

Table 1 - 3D Modelling Input Parameters

Parameter	Value	Unit
Starting velocity	1	m/s
Starting rotational velocity	0.5	rad/s
Damping coefficients for bouncing, A	6.096	m/s
Damping coefficients for bouncing, B	1.2	m/s
Damping coefficients for bouncing, C	76.2	m/s
Damping coefficients for bouncing, D	9.144	m/s
Specific weight of rock	2700	kg/m3

The input parameters used regarding slope condition varied from sector to sector, however the predominant inputs were as follows (refer

below).

6.4 Field Observations

In addition to the computer modelling and in order to aid calibration of the model a number of full scale boulder rolling exercises were carried out on the Port Hills. These were digitally recorded by Geovert engineers for back analysis to observe the behavior of falling and rolling blocks in the actual environment where the rockfall hazard exists. This proved invaluable as the boulders showed unique behavior not often seen elsewhere, including particularly high (and variable) bounce heights and a wide variable in the number of blocks that either stayed intact or fell apart mid slope.

As a result of this exercise we reran the model and adjusted a number of parameters to better represent actual rockfall on the Port Hills.

Table 2 - Restitution Coefficients

Class	Normal Restitution Dn (%)	Tangential Restitution Dt (%)	Rolling Friction Coeff Rw (tan)
alluvial deposit, bare	25	73	0.38
alluvial deposit, bush covered	25	73	0.38
alluvial deposit, forest covered	25	65	0.4
alluvial deposit, grass covered	25	73	0.38
colluvial deposit, bare	27	84	0.33
colluvial deposit, bush covered	27	84	0.33
colluvial deposit, forest covered	27	75	0.38
colluvial deposit, grass covered	27	84	0.33
loess deposit, bare	27	84	0.31
loess deposit, bush covered	27	84	0.31
loess deposit, forest covered	27	75	0.34
loess deposit, grass covered	27	84	0.31
outcropping rock, bare	35	85	0.3
outcropping rock, bush covered	35	85	0.3
outcropping rock, forest covered	35	85	0.3
outcropping rock, grass covered	35	85	0.3
subcropping rock, bare	30	85	0.31
subcropping rock, bush covered	30	80	0.31
subcropping rock, forest covered	30	75	0.34
subcropping rock, grass covered	30	85	0.31
debris deposit, bare	30	75	0.4
debris deposit, bush covered	30	70	0.4
debris deposit, forest covered	30	65	0.45
debris deposit, grass covered	30	75	0.4
dune, bare	20	50	0.4
road	35	80	0.3
building	10	20	1
Stoch distribution (all classes)	*Normal distribution*	*Normal distribution*	*Normal distribution*
Minimum value (all classes)	*10*	*20*	*0.3*
Maximum value (all classes)	*50*	*95*	*1*
CoV (all classes)	*20*	*20*	*20*

7. Rockfall Mitigation and Protection Options

There are various options for treating rockfall and the decision to use one method over another is controlled by a number of factors, including access, cost, time and physical constraints. The main treatment options are as follows:

1. Remove the human aspect (house, road etc.) that is being impacted
2. Remove the hazard source area
3. Treat the hazard source area
4. Provide protection from falling rocks/boulders. This can be achieved by,
    a. Mass earth rockfall bunds
    b. Flexible rockfall barriers
    c. Natural protection including trees (limited ability)

When considering the best solution for any particular area all the above options were assessed on their individual merits. They were either discounted or taken further based on the site specific requirements.

7.1 Presenting options based on a Hierarchy of Controls

When the risk (likelihood and probability of the consequence) of a rockfall event occurring is considered unacceptable in its natural state, remediation measures must be considered to reduce the likelihood, probability, and consequence of the event occurring. The selection of a remediation method from the list of possible options is dependent on a range of factors including, effectiveness, economical, and administrative (aesthetics and legislative) considerations. The last two of these factors are subjective assessments based on external constraints placed on a particular project, and are usually decided by a client and driven by policy decisions that are outside the scope of this report.

The effectiveness, however, of a method is objectively measurable across all projects according to a hierarchy of controls overarching hazard management.

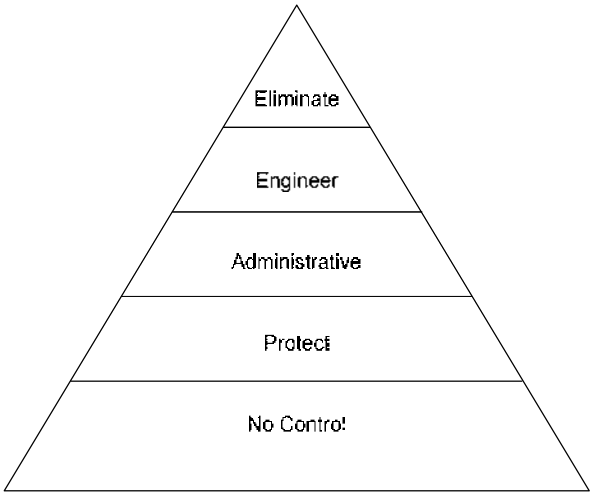


Figure 2 - Hierarchy of Controls

A number of different practically achievable remediation options are presented in the following sections. For each of these, the effectiveness is described according to this hierarchy of controls.

7.2 Option 1 - Do Nothing

This option is always available however for the purpose of this study it was not deemed appropriate to include.

7.3 Option 2 - Treat the Source Area

The most comprehensive form of rockfall prevention, or hazard elimination, is to permanently treat the source area by actively removing, stabilizing or retaining the rocks in situ. The down side to this is that it is typically a more expensive option for a number of reasons, namely it often involves very difficult access which requires specialist plant and materials, and as is often the case and especially so in the Port Hills area the size of the source areas can be very extensive.

Typical costs for remediation of source areas ranges from several thousands of dollars per boulder[1] up to hundreds of thousands of dollars for a fully dimensioned active slope stabilization system[2]. As an example of the complexity and extent of work the source areas in Sector 1 (eastern side of Heberden Avenue in Sumner to Godley Head) range significantly in size and shape. Our assessment carried out for this report shows that there is likely to be in the order of well over 15,000m2[3] of source area that would require treatment, in addition to numerous individual boulders that would require treatment. Without fully assessing each individual treatment site detailed costs cannot be ascertained, but could be in the multi-million dollar range.

Another significant factor to consider in treating the source area is the trajectories of the falling boulders; whether they flow into narrow catchment fields or onto wide open slopes, and the resulting bounce heights and energies. If a small source area spreads onto a wide slope then the passive retaining measure will be comparably large. If a wide source area sends the majority of the material into narrow gully features the resulting passive measures will be comparably small and they will possibly need to address the issue of multiple boulder strikes.

For much of the Port Hills the 3D modelling has shown that, taking into account the above factors including the very large source areas and relatively low rockfall energies and bounce heights, passive measures are likely to be significantly more economical than source area treatment. As such based on Geovert's comprehensive experience in this area of construction it has been decided that for the purpose of this study treatment of the source area as a whole will not be considered as an option.

7.4 Option 3 - Rockfall Arrest by Construction of Earth Bunds

Earth bunds can be used as feasible options to control rockfall. Typically they are also able to contain larger volumes of rock than rockfall barriers. Earth bunds are most suited where there is ample flat (or low angle) land available for construction, along with ease of access.

As with all systems there are pros and cons with earth bunds. Some of these are highlighted here:

Pros

- Relatively inexpensive to construct on flat easily accessed areas
- Ease of construction (general earthworks)
- Greenable final surface
- Capable of arresting a large number of boulders

[1] Assumes 2nos rock anchors per boulder to 6m depth at nominal drill and install rate.
[2] Assumes 500m2 source area covered in high tensile steel wire mesh active stabilisation system.
[3] Assumes 1.5km of bluffs average 10m high

Cons

- Requires maintenance following impact from rockfall
- Large area of flat (or gently sloping) land required to allow room for both the bund and an access track for maintenance
- Potentially creates large unusable area behind bund as this is not protected from the rockfall hazard
- Maximum height and width limited by available land
- Susceptible to foundation issues on flat land and shaking damage
- Will fill up over time and require regular cleaning
- Susceptible to erosion/collapse from large volume impacts
- Management of storm water can be problematic
- Relatively expensive to construct on slopes due to increased footprint

7.5 Option 4 - Rockfall Arrest by Installation of Tested Approved Rockfall Barriers

Rockfall protection barriers are typically used where specifics of a site are well understood. They come in a variety of sizes and ratings and are therefore suitable for many different situations, including difficult access and sites with steep terrain. The greatest advantage comes in the tested and approved rating available from some suppliers. With a sound understanding of the processes taking place at any given site the installation of a tested, approved barrier provides the Client with certainty of the benefits provided by the specified protection.

Rockfall protection barriers absorb the energy from a rockfall by virtue of their flexing characteristics without the need for significant maintenance after the impact in the adjacent, non-impacted, fields (i.e. independent from the point of impact). The development of barriers over recent years was using the results of extensive field tests and subsequent analysis. The design, layout and anchoring of a rockfall barrier ensures easy installation, taking into account that such installations mostly have to be realised in difficult, steep and remote terrain. Lightweight parts, a minimum of anchors and quick erection are important aspects.

Pros

- Ease of installation
- Suitable for either flat easy access or difficult access sites or steep terrain
- Minimal maintenance requirements
- Comparatively small footprint
- Variety of impact ratings ensures installation of most suitable barrier
- Tested and certified systems available

Cons

- Requires specialist installers
- Lead time on materials
- Possible requirement for replacement of parts after very large impacts, although assumed as normal maintenance for which stock would be kept.

Basic assumptions for the rockfall barriers are as follows,

1. Locations shown in report indicative only, final locations to be confirmed on site,

2. Location and marking out to be completed by suitably qualified persons,
3. Minimum acceptance criteria - all barriers to be tested and certified to ETAG 27 (minimum Category A) and CE marked, or more stringent Swiss Guideline (BAFU)
4. Barriers specified using maximum energy level,
5. All barriers are minimum 3.0m high, varying lengths, varying impact ratings,
6. Barrier materials to be corrosion protected to allow minimum 30 year design life.

Important Note:

It is critical to note that the rock fall modelling carried out for this report and the subsequent recommendations are based on the specification and installation of barriers that meet as a minimum ETAG27 Category A approval. The 'Category A' approval is a minimum requirement as it ensures that the residual height of the barrier is sufficiently high to sustain two hits of 95th % boulder – critical in an environment prone to ground shaking.

To achieve Category A ETAG 27 approval requires the barrier to have a residual height after an MEL (Maximum Energy Level) impact of ≥ 50% of the design height.

- Category A : Residual Height ≥ 50 % nominal height
- Category B: 30% nominal height < Residual Height < 50 % nominal height
- Category C: Residual Height ≤ 30 % nominal height (this can be – rock stopped but barrier laid flat)

A European Technical Approval (ETA) gives the basis for the certification procedure to award the CE approval marking to the product and its basic tenets are as follows:

- It is not just one full-scale test,
- Manufacturer must submit application to an approval body,
- Full-scale tests by a notified test institute (accredited by European Commission for ETAG 027) must be conducted,
- Individual identification tests of components used in 1:1 test must be performed,
- Factory production control FPC (initial and continuous) must be conducted,
- European Technical Approval ETA (circulated to all approval bodies for review) must be obtained,
- CE Marking is then awarded and applied to the product.

8. Indicative Construction Program and Costs

Indicative construction periods are in the order of 1-3 days per 10 linear metres of barrier, or between 2-4 days per 1m height gain for bunds. These values are based on 100m long sections but are highly sensitive and depend on a number of variables including access, weather, material deliveries etc.

As an indicative total construction programme for the barriers, based on only one construction team and a consecutive construction programme (i.e. construction of one barrier followed by another), the full 30km of barriers recommended in this report could be constructed within 10 to 30 months (1-2.5 years) based on a construction rate of 1-3 days per 10 linear meters.

Table 3 - Indicative construction programme

Sector (#)	Proposed lemgth of all Barriers in Sector (m)	Construction Period (weeks)
1	2598	26
2	1739	17
3N	1155	12
3S	2137	21
4	1364	14
5	5176	52
6	5103	51
7	3693	37
8N	1219	12
8S	3668	37
9	1416	14
Total	**29268 lm**	**293**

Based on Geovert's extensive experience both locally and international as a specialist in this area of construction we are very confident the program provided is realistic and achievable. This is based on a sum of all rates for all barrier sizes required as per our modeling results. Individual barrier construction rates will vary based on size or energy capacity of the system, access to the construction zone and ground conditions for anchoring.

These rates are provided to give the Client a high level indication of typical construction times. Consideration was given only to the major components of each option. The client should note that additional time requirements may become apparent during detailed design phase.

Pricing for the construction of both bunds and barriers has been provided separately to the Client and has not been included in this report for public release as it is commercially sensitive.

9. Discussion

The study results presented in this report have been presented to, and discussed with, the Client (CERA) on numerous occasions throughout the study period. The inputs, while being extensive in volume, are the direct outputs of a very large earthquake event that was not only unexpected but also far greater in magnitude than anyone anticipated. The collection of data from in the field post-earthquake has resulted in a very detailed and extensive database from which no one can argue the extent of rock fall activity on the Port Hills during and post these series of earthquakes.

As authors of this report we attempted at every point in the study to ensure the outputs of the study matched as close as possible the real outputs of the earthquake as measured in the field. To achieve this numerous discussions, meetings and workshops were held with the Client and other significant stake holders, scientists, engineers and geologists from local and international organisations. As an outcome of these communications it became apparent that the results of the 3D modelling tied in very well with the evidence from the field in 95% of the study area. The 3D modelling also tied in very well with the other modelling being carried out simultaneously by others (i.e. GNS and PHGG).

There remains a further 5% of results that have produced a small number of anomalies leading to inaccurate outputs. The areas where there was poor alignment include Morgans Valley and

Rapaki Valley. Perhaps the reason for inconsistencies here are the results of less data collected from these areas, or the small amount of vegetation present.

The use of 2D modelling contributed to the accuracy and confidence of the outputs presented here in this report. As the graphical outputs of this modelling are replicated in work carried out by others it was deemed unnecessary to present this data here.

The individual Sector results, shown here in the attached appendices, outline the type, location and extent of protection measures required to reduce the hazards associated with rockfall in the Port Hills. While a number of options were considered as part of this study, for good measure, it was immediately evident to Geovert senior management that the most appropriate solution to the hazard was the installation of rockfall barriers.

Treatment of the source area is often a suitable solution, and has not been ruled out for specifically suitable cases, however given the extent of the source areas identified in the Port Hills this solution as a whole was not considered viable, nor was in general the construction of mass earth bunds. The size of their footprint is such that construction requires a relatively gentle slope (or flat ground) and these are not very common on the Port Hills, especially when considering the protection of houses which are predominantly located on the steeper slopes. Perhaps at detailed design stage when site specific details can be considered these options may become more suitable, however at this higher level and without sufficient funds (or time) to carry out more detailed investigations they score low on suitability.

The table below outlines the total extent of barrier construction for all sectors.

Table 4 – Proposed lengths of barriers (per Sector) for all Sectors

Sector (#)	Proposed lemgth of all Barriers in Sector (m)
1	2598
2	1739
3N	1155
3S	2137
4	1364
5	5176
6	5103
7	3693
8N	1219
8S	3668
9	1416
Total	**29268 lm**

Further to the modelling and recommended protection measures outlined in this report there are a number of factors, not necessarily engineering driven, that may also need to be considered. What was considered highest priority at the time of this study may not be so important in 10 years' time for example. As can be seen in the attached appendices such extensive use of barriers may raise questions beyond the financial such as aesthetics and accessibility (i.e. accessing land beyond the barriers). These issues are beyond Geovert's control and have not effected the outputs of this report.

10. Summary

The information in this report has been provided to the Client with the intention of presenting options for potential remedial works on the Port Hills in order to mitigate the effects of rockfall. The mitigation options, whether they are bunds, barriers or other such, have been recommended based on highly detailed 3D modelling of rockfall in combination with Geovert's extensive international and local experience in providing and constructing rockfall solutions.

NOTE: This report outlines the results of a high level first pass analysis only. The information provided is for the purpose of CERA use only and is not to be used for detailed design or assessment purposes.

In summary the modeling has indicated, for the purpose of protecting residential dwellings only, a total of nearly 30,000 linear meters of barriers and very few bunds. This length will protect 95% of the Port Hills properties reducing the hazard significantly. If the criteria for the placement of protection measures are altered from that within Geovert's brief then the extent of bunds recommended may increase simply because of the lower slope angles further away from the source areas (i.e. more suitable land areas).

11. References

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Refer separate files for:

Appendix A Sector 1

Appendix B Sector 2

Appendix C Sector 3

Appendix D Sector 4

Appendix E Sector 5

Appendix F Sector 6

Appendix G Sector 7

Appendix H Sector 8N

Appendix I Sector 8S

Appendix J Sector 9