DESIGN AND CONSTRUCTION OF ROCK FALL PROTECTION EMBANKMENTS

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Abstract
Following the 2010/2011 earthquake sequence numerous properties in the Port Hills of Christchurch were red-zoned because of the assessed elevated risk to residents from rockfall. Arup have completed detailed geoseismic risk assessments of the outcrops on the slope above numerous properties to assess the risk of loss of life and property damage. Following this, the construction of reinforced earth rockfall protection embankments was considered to be the most suitable option to reduce the risk to an acceptable level at several sites.

This paper includes a review of the recommendations in current academic literature, the embankment design process and construction considerations for rockfall protection embankments at sites currently under construction. The paper will discuss sensitivities with fill material and geometry of embankments.

This type of rockfall protection structure could be adopted in Victoria as a cost effective method to reduce the risk of rockfall to infrastructure and property.

Introduction and Background

The Port Hills are located south of Christchurch, New Zealand between the city and its Port of Lyttleton. The valley areas around the Port Hills contain areas of residential development including the suburbs including Heathcote Valley, Avoca Valley and are remnants of the Lyttleton volcano crater. Rock outcrops are common up slope from residential developments in the area.

The geology of the area is characterised by the rock of the Lyttleton Volcanic group. The basaltic to trachytic lava flows are interbedded with brecchia and tuff. Quaternary sediments, including Loess deposits have been encountered at the Port Hills (Forsyth, 2008).

As a result of the 2010/2011 Canterbury earthquake sequence, significant rockfall occurred in the Port Hills area as rock outcrops on the hill faces were dislodged and rolled down the hills, resulting in significant damage to properties downslope of rockfall areas and causing fatalities.

Zoning of properties

Following the magnitude 6.3 Canterbury earthquake of 2011, caused by the rupture of a fault along the southern edge of Christchurch, studies were commissioned to analyse the risk to residents in the area from rockfall. Following the analysis, properties were categorised as 'red zoned' or 'green zoned'. Canterbury Earthquake Recovery Authority (CERA) defines properties that are 'red zoned' as *"Properties affected by rock roll have been zoned red where they face an unacceptable risk to life (greater than 1 in 10,000 at 2016 risk levels), and an area wide engineering solution to remediate them has been determined not to be practicable for a number of reasons including uncertainty around timeliness and costs."* A

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total of 714 properties were classified as within the ‘red zone’ (CERA website, accessed October 2015).

Where a property was classified as in a ‘red zone’, property owners were required to vacate the property and were compensated with a payout, typically at the 2007 rated property value. However, the Christchurch City Council (CCC) will allow re-zoning of properties if the level of risk can be reduced to the threshold level, including a requirement for an independent review (Skinner, 2015).

Considering the above, some property owners in the Port Hills area had elected to install Rock Protection Structures (RPS) to mitigate the risks associated with rockfall events on their property. Arup was commissioned to provide recommendations and design appropriate RPS to reduce the risk from rockfall to within the threshold level for property owners. It should be noted that the Crown would provide funding to property owners electing to install RPS.

Rockfall events at the Port Hills

Site specific assessments and rockfall analysis were carried out by Arup at several properties in the Port Hills area. The assessments included mapping of slope faces investigating rock outcrop size, location and the size and trajectory of boulders displaced as a result of recent earthquake events. The visual survey, along with terrain survey were input into Arup modelling software in order to determine rockfall pathways, trajectories and the risk of damage to properties, excluding the installation of RPS. Based on the conditions observed, energy levels of the 95^{th} percentile were often in excess of 6000kJ, boulder size in the order of $1.2m^3$, and velocities in excess of 25m/s. These varied depending on observation location, however gives an idea of the order of magnitude of potential consequence of a rockfall event.

Alternative Rockfall Protection Structures (RPS) for consideration

Several rockfall protection systems are available to the market, each serving specific needs of the end user. These systems include prevention of rockfall via treatment at the source (primary measures), or creating barriers/attenuation systems (secondary measures).

Prevention of rockfall

Preventative systems to rockfall work to reduce the likelihood of rockfall occurring, or reducing the boulder size on the slope. Preventative measures may include rock anchors, rock breaking, or installation of mesh over rocks at risk of being dislodged (see Figure 1 below). These measures can be costly, and involve high risk construction and maintenance when required. This method is also heavily dependent on the identification of rock masses likely to be dislodged.

Arup site specific assessments identified isolated, accessible rock sources which could be cost effectively removed. The first of these sites has been remediated.

Figure 1: Rockfall anchors and mesh (http://www.abseilaccess.co.nz/)

Barriers or attenuation fences

Rockfall chain linked barrier fences (See Figure 2) have been used to mitigate the risk of rockfall as secondary mitigation measures. Several proprietary products exist in the market. These systems can be installed typically with a smaller footprint than a reinforced earthworks embankment however the mesh may deform several meters under large impacts. Additionally fences are not considered appropriate protection measure against falling rock masses with very high energy levels, >1500kJ (CCC, 2013), therefore do not meet requirements to resist rockfall events with energy levels in the order of 6000kJ as noted above. Attenuation fencing requires regular maintenance and repair following rockfall events, making these less attractive for use in domestic applications compared with earthworks embankments.

Figure 2: Chain link rockfall barrier (http://www.geofabrics.co.nz)

Rockfall Protection Embankments (RPE)

Rockfall protection embankments are used as secondary mitigation measures to rockfall events. They can be used to resist high kinetic energy rockfall events and to protect dwellings and elements of infrastructure (Ronco, 2009). Reinforced ground structures have been constructed to resist up to 10000kJ of energy (Lambert, 2013).

Rockfall protection embankments have been constructed using a variety of materials and geometric arrangements. Materials include natural compacted soils, reinforced natural compacted soils, natural rocks or gabion baskets. Embankment facings vary also, and may include natural soil, tyres or concrete blocks.

A ditch is commonly constructed with the embankment, which acts as catchment for rocks. The excavated material can be used as embankment fill, and reduce the cost of construction.

A typical rockfall embankment cross section is shown below in Figure 3.

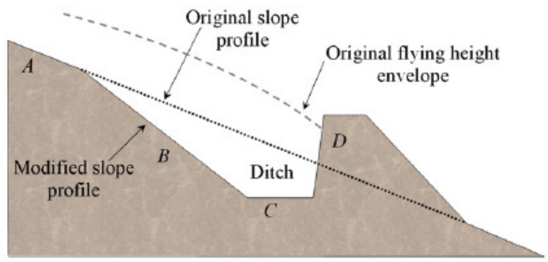

Figure 3: Typical cross section of embankment (Lambert, 2013)

<u>*Design Approaches*</u>

A summary of different approaches and levels of detail for the design of an RPE is included in Lambert, 2013. A summary is provided below.

1. Design based on an embankments mass, the embankment is considered to be able to stop the block and withstand the impact;
2. Design based on the penetration of a block in the embankment, which is multiplied by a factor of safety (typically 2–3) to obtain the minimum embankment thickness;
3. Pseudo-static approaches which consider a load that is statically equivalent to the dynamic impact load for designing the embankment. The structure's static stability is checked considering this load in combination with gravity loads;
4. Energy balance approaches which use analytical methods to compare the incident translational kinetic energy of the block with the energy dissipated within the embankment during the impact. The design consists of assessing that the structure deformation required to dissipate the block's kinetic energy is consistent with the embankment dimensions. For this purpose, the deformation due to the block penetration may be deduced from the impact force; or
5. Design approaches based on numerical modelling using specific numerical tools to model the impact and evaluate the deformation of the embankment, using either finite or discrete element methods (FEM or DEM).

Academics and engineers have attempted modelled the behaviour of RPEs in order to provide design guidance, however due to the variability of geometry, fill material, embankment construction, various reinforcement options, interactions between soil and reinforcement, and the dynamic behaviour of the soil, a consistent design procedure has not been developed in Australia/NZ for rockfall protection embankments.

Adopted design procedure

For the purposes of efficient design and construction, the rockfall embankment design methodology adopted by Arup for various projects in the Port Hills was method 4 above, energy balance equations. This design procedure is best set out in Ronco (2009) and was modified to meet the requirements of the Christchurch City Council (CCC) Technical Guideline for Rockfall Protection, March 2013. The design procedure involves two stages:

1. Assessment of rockfall energy levels

Rockfall embankments are designed theoretically based on energy balance of a 95% confidence interval event occurring. The nominal design energy level (DEL) and associated, velocity, bounce height and design boulder radius are determined from the rockfall analysis as described above.

2. Design the RPE

The DEL parameters obtained are factored based on ETAG 27 requirements. These factored energy levels are used to design the embankment. The factors applied include:

- Maximum Energy Level, MEL (in the order or 1.3 times DEL; for assessing low frequency rockfall events)
- Service Energy Level, SEL (in the order of 0.3 times DEL; for assessing multiple impacts)

The MEL and SEL energy levels were used to determine the most appropriate rockfall protection structure, and the energy levels are inputs to the design of the RPE.

The geometry of the RPE is determined by multiple elements, including:

1. Impact bounce height;
2. Tolerable deformation from boulder impact and construction requirements;
3. Global slope stability;
4. Global embankment stability due to accelerations from earthquakes; and
5. Effects of the embankment acting as a dam should also be considered.

Based on the calculated MEL and SEL energy levels, a stability analysis was carried out on the embankment. The procedure used to determine the stability of the embankment post rockfall event is outlined in Ronco (2009) where the deformation on the up slope side (the side of the embankment facing rock impact) and the down slope side (side of the embankment facing away from the rock impact) of the embankment are calculated separately. A deeper/thicker embankment results in a larger capacity.

Embankment size is assessed for both the up-slope and down-slope deformation, see Figures 4 & 5.

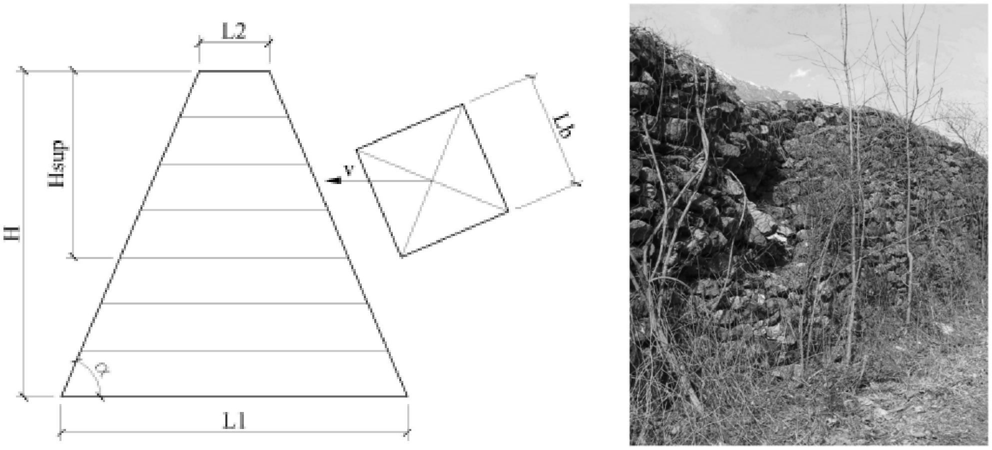

Figure 4: Left Hand Side - Embankment height (H), impact boulder diameter (Lb), Height from bottom of boulder impact including freeboard (Hsup) (Ronco 2009) Right Hand Side – Embankment with insufficient freeboard height, rock was able to roll over (Lambert 2013)

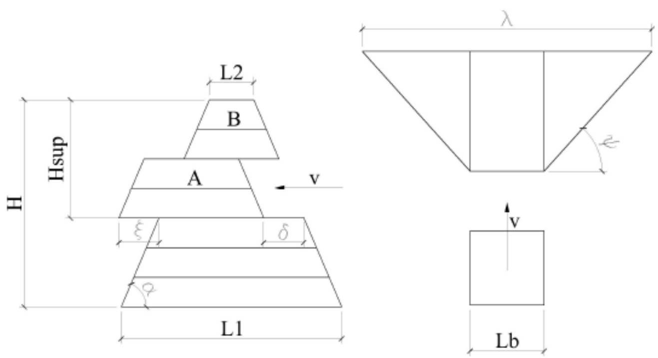

Figure 5: Up-slope (δ) and down-slope (ξ) deformation depicted (Ronco 2009)

Up Slope deformation is made up of two components:

- The penetration due to plasticisation/compression: This typically accounts for 80-85% of impact energy
- Maximum sliding of the soil layers: This typically accounts for 15-20% of the impact energy by the lateral sliding frictional resistance between blocks.

Down slope deformation is made up of only the ‘maximum sliding of soil layers’ outlined above.

Global Stability Checks

Once the geometry of the embankment had been calculated based on the above criteria, global stability checks based on classic geotechnical theory were undertaken:

- Overturning check post MEL deformation;
- Overturning check post design earthquake event;
- Sliding check post design earthquake event;
- Bearing capacity check; and
- Global slope stability check.

Design Considerations

From our experiences with rockfall protection embankments, the following considerations specific to each individual site may govern design of the embankment including construction sequencing, product limitations and contractor requirements.

Natural Terrain

- The existing steep, undulating slopes can dictate the footprint of the embankment, it is prudent to obtain feature survey data early in the design stage to aid in finalising the embankment layout.

Geometry of the embankment

- Batter angle of the rockfall protection embankment has been taken as 70° from the horizontal due to the commercial product adopted for construction and the alignment with calculations presented by Ronco (2009).
- Angles in the order of 70° when compared to more shallow angles lower the risk of rock passing over the embankment due to a reduction in rotational energy (Ronco, 2009).

Embankment fill

- Placing granular rock material in the lower layers of the embankment aid with drainage through the embankment;
- Sourcing local excavated fill may reduce the cost of construction when compared to importing fill;
- Where local excavated material is considered erosive, containment or soil improvement methods may be considered when placing embankment fill (such as geofabric wraps or lime stabilisation); and
- Cost savings may also be realised due to minimsing offsite classification and disposal and importing fill when using excavated material for embankment fill.

Minimum depth/thickness of the embankment.

- Embankment width must be sufficient to allow compaction machinery to operate (Lambert (2013) recommends a minimum width of 2m at the top of the embankment, Ronco (2009) analyse embankments as narrow as 0.9m at the top of the embankment);
- It is prudent to discuss this dimension with the contractor during the design phase; and
- Care was taken not to jeopardise embankment mass in order to achieve construction efficiency.

Access Tracks

- An access track on the up slope side of the embankment is required for maintenance;
- Typical width in the order of 2.0m has been adopted on projects.

Drainage

- The use of granular rock fill allows overland flows to pass through the embankment, minimising changes to existing overland flow paths;
- Concentrated overland flow should be avoided to minimise erosion;
- The potential for the embankment to silt up act as a dam during heavy rainfall events should be considered; and

- Overflow pipes with rock beaching and subsurface drainage systems may be adopted for embankments to minimise the risk of damming.

Consideration for differing geometry, backfill and reinforcement

Significant research and understanding of trapezoidal embankments has been undertaken in the past. Several papers have completed finite element (FE) modelling to assess RPE performance and their design. Due to the variables discussed above, it is difficult to accurately predict embankment behaviour with finite element modelling without back analysis through field testing.

Case Studies

Arup have been engaged for the design of a number of RPEs in the Port Hills area. Each of varying size and with their own site constraints. Site A is an example of a RPE being utilised to reduce the risk of rockfall for a single property, where Case B demonstrates effectiveness of a RPE to reduce the risk of rockfall over several properties. The applications demonstrated can be adopted in Victoria.

Site A – Ferrymead

At Site A pictured below, the rockfall MEL was in the order of 7000kJ at the proposed location of the rockfall protection embankment. Due to the large predicted energy levels of rock impact, rockfall fences were not considered appropriate. Removal of the rockfall hazard was not a feasible option due to the steep slope and size of cliffs, the location of outcrops are outside of the property which was being considered which would require additional consent and approval. A rockfall protection embankment was considered to be the most feasible option.

Visual surveys conducted by Arup revealed large rock outcrops, and evidence of rockfall damage in the past, see Figure 6.

Figure 6: Example of rock outcrop (left) and evidence of rockfall damage through roof of dwelling (right)

Optioneering of the RPE position was carried out by Arup. Two locations were considered. The first, directly upslope of the dwelling, and another midway between the dwelling and the extent of the property. It was found that, due to the extent of the property boundaries, locating the RPE midway up the slope was not a feasible option as it would not provide the same level of protection as when the RPE was located directly above the dwelling. Two options are depicted in Figure 7 below.

Geotechnical investigations were commissioned at the site, which revealed shallow depths of Loess overlying volcanic bedrock.

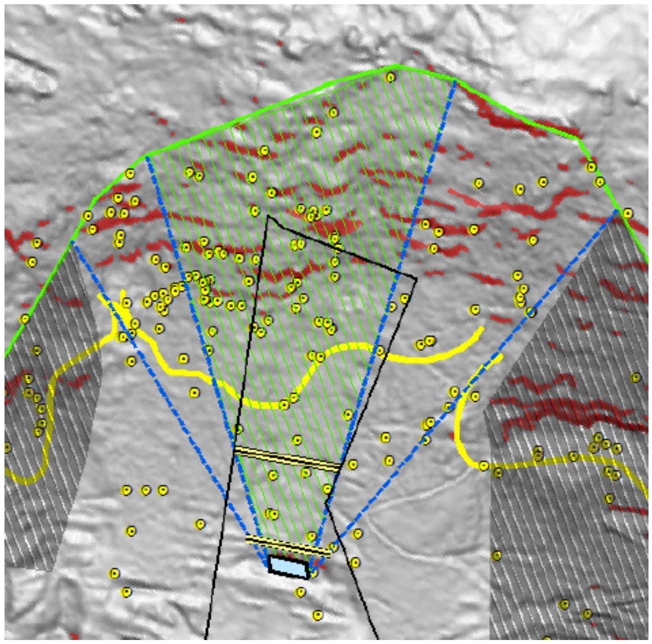

Figure 7: Options for the location of RPE at Site A showing mapped historic boulder locations (yellow dots) zones of rockfall pathways

In order to produce an efficient design, the aim was to balance cut to fill across the embankment area. The design allowed for excavation for the 'ditch' terrace, however due to the natural slope in the order of 26°, a retaining wall was designed in order to prevent the cut 'chasing' up slope and potential erosion in the dispersive loess soils.

Due to the steep slope, and the upslope embankment height governing design based on 95th percentile design boulder bounce height and diameter, the maximum downslope embankment height will be in the order of 7.5m.

Internal and global slope stability was checked, including consideration for seismic events. Due to the presence of underlying high strength rock, the construction of the embankment did not significantly affect the global slope stability.

A commercial product was elected for this rockfall protection embankment. However it is noted that cost efficiencies may be realised through custom geometric setout and material selection which may allow sourcing of local materials for the embankment face (eg. tyres, logs) and steeper batter angles resulting in a smaller net volume of earthworks required.

Backfill material specified for the embankment was granular fill, including excavated rock onsite. The commercial product elected allows for topsoil at the face of the embankment to allow for growth of grass or other flora. Typical geometric setout is shown in Figure 8.

It was recommended that the surface material at the 'ditch' is scarified and loosely compacted to act as a damper to falling rock. The 'ditch' is also proposed to act as an access track for maintenance of the embankment.

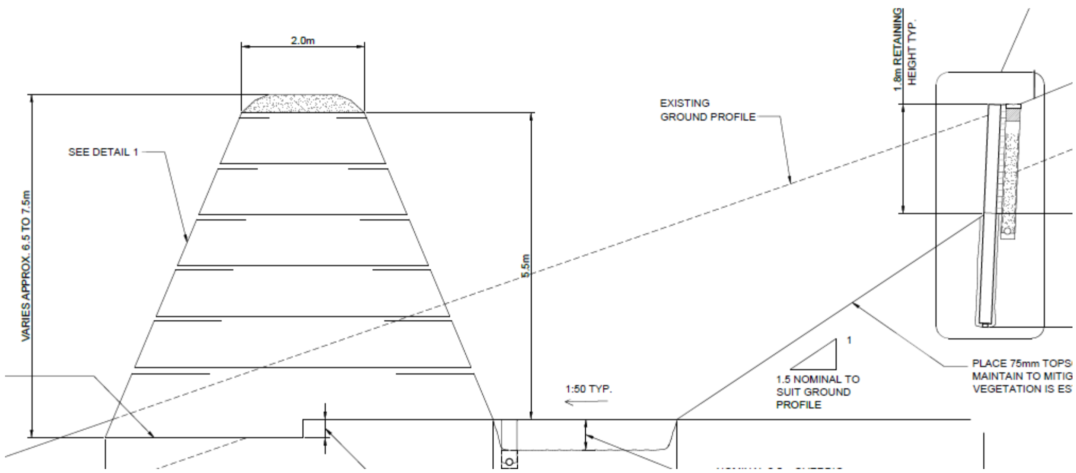

Figure 8: Typical cross section of RPS at Site A

Site B – Heathcote Valley

Site B (pictured below), extends across two property boundaries and when constructed will provide rockfall risk reduction to several dwellings.

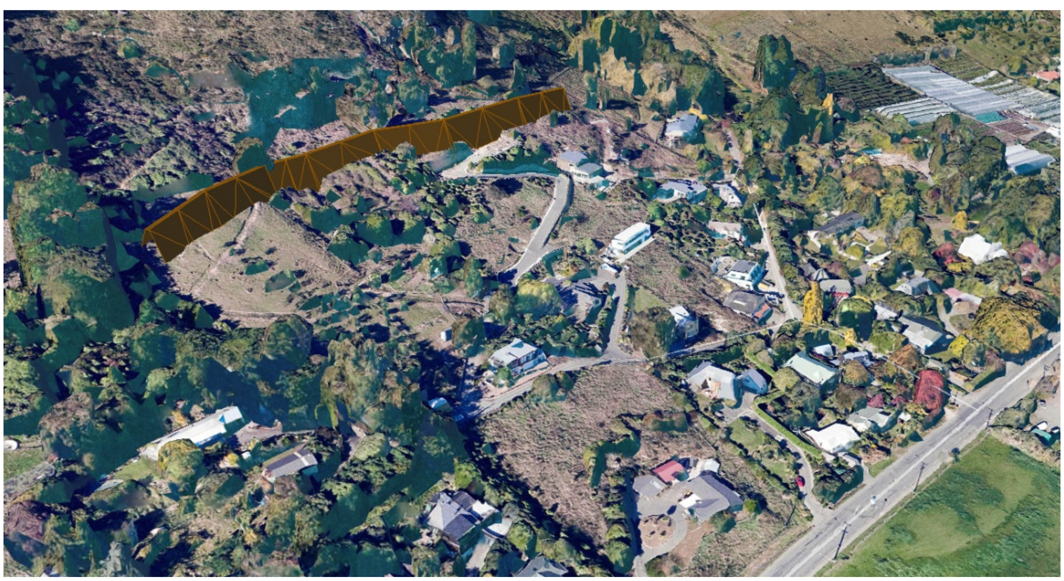

Figure 9: Aerial computer generated image of the 'Heathcote Valley Embankment'

The calculated rockfall MEL energy varies from 2000kJ to 5000kJ at the proposed location of the rockfall protection embankment. Due to the high energy levels, a rockfall embankment was considered the most feasible RPS.

The design methodology adopted in Case B was similar to Case A, with some additional considerations as described in this section.

In order to optimise the design, the embankment was divided into three zones which are dependent on the design rockfall energy at each zone and as a result, the embankment height varies between approximately 3.0m to over 6.0m height. This refinement results in a reduction of fill required for the embankment and a narrower embankment footprint can be achieved.

The potential for the embankment to act as a dam is particularly critical at this site as the length of the embankment will be approximately 200m. Subsurface drainage is proposed at the up slope side of the embankment with overflow culvert through the embankment discharging into an open channel downslope of the embankment to prevent erosion of the loess material.

The key risk in projects spanning several property boundaries is that agreement must be reached between all parties in order to achieve the required effectiveness of the RPE.

Conclusions

The impact of rockfall can be mitigated in a number of ways depending on the anticipated kinetic energy that will be applied to the system. For PRS where high energy absorption and low maintenance is required, rockfall protection embankments are a cost effective structure which can be installed to reduce the risk of rockfall.

While there are no design guidelines in Australia/NZ, a large amount of literature exists exploring embankment behaviour at differing levels of complexity. As such, it is possible to effectively design rockfall embankments to reduce the risk of rockfall to infrastructure and property in Victoria.

Embankment geometry and layout on steep, undulating slopes can dictate design. Site and construction constraints and opportunities should be considered early in the design phase in order to achieve an economic and practical design.

Areas for future development include modelling and scale testing of materials and geometry from locally sourced materials.

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References

Canterbury Earthquake Recovery Authority, http://cera.govt.nz/port-hills accessed October 2015.

CCC (2013). Technical Guideline for Rockfall Protection Structures.

Forsyth, P., Barrell, D., and Jongens, R. (2008). Geology of the Christchurch Area. GNS 1:250,000 Map 16.

Lambert S., & Bourrier F. (2013). Design of rockfall protection embankments: A review, Engineering Geology 154 77-88

Ministry of Business, innovation & employment (2014, November), Guidance on the seismic design of retaining structures for residential sites in Greater Christchurch, Version 2 . In Build it right, Canterbury

Peila D. (2011). Ground reinforced embankments for rockfall protection: from real scale tests to numerical modelling, Rockfall Engineering Chapter 12.

Ronco C., Oggeri C., & Peila D. (2009). Design of reinforced ground embankments used for rockfall protection, Natural Hazards and Earth System Sciences 9 1189-1199.

Skinner M., Mote T.I., & Cox J. (2015). Risk and rockfall: Observations on the implementation of rockfall mitigation at residential properties in the Port Hills, 6th International Conference on Earthquake Geotechnical Engineering.