REPORT

Tonkin+Taylor

Redcliffs Park

Rockfall Risk Assessment

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Prepared by
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Executive summary

This document describes the rockfall-related risk assessment undertaken by Tonkin & Taylor Ltd (T+T) for the Ministry of Education (MoE) as part of their due diligence process prior to any potential site acquisition and designation for a proposed primary school in Redcliffs, Christchurch.

This assessment considers the annualised individual risk to life (AIFR) associated with users of a primary school that may be located on the Redcliffs Park site. The AIFR might arise due to rockfall hazard originating from the rock slope above the Moa Bone Cave, which is located to the west of the western boundary of the site.

The proposed site is separated from the adjacent rock slope by Main Road and associated footpath. The site boundary adjacent to the rock slope is approximately 73 m long. Only the southern portion of the site boundary over a length of 30 m is exposed to potential rockfall, with the remaining 44 m of the site adjacent to Main Road not affected by rockfall hazards. The overall length of the potential rockfall hazard zone extends approximately 100 m, which is well beyond the portion that intersects the site.

Analysis of the potential rockfall hazard demonstrates that under conservative conditions rolling boulders could reach the southern 30 m portion of the property boundary. This would require a medium to large future earthquake or extreme rainfall event to trigger a boulder release from the rock slope, which has recently been subject to rock scaling and slope stabilisation works. The boulder would then have to be of suitable dimension to enable it to bounce or roll across Main Road and the adjacent footpath to get to the property boundary. The boulder roll would then need to occur at a point along the site boundary where a person may be located, at the same time that the person is occupying that specific space (and this ignores the potential for the person to identify the danger and escape the hazardous space).

In the context of the site being developed as a primary school with a student Pick Up/Drop Off (PUDO) along the Main Road boundary, the annualised individual lives risk associated with rockfall from the slope above the Moa Bone Cave is of the order of 1.6×10^{-8} (approximately 1 in 67,000,000). This also assumes that there are no school buildings located within 6 m of the site boundary. The level of exposure assumed for a person using the PUDO is considered to represent the upper bound, or greatest potential exposure, of any likely school user.

Uncertainties in the assessment have been considered using sensitivity analysis. Increasing various input parameters by 1 to 2 orders of magnitude does not increase the calculated annualised individual risk level above 1×10^{-6} (1 in 1,000,000), which is widely considered to be an acceptable level of individual risk for land use planning purposes.

The level of individual risk is sufficiently low that specific engineering works to reduce the hazard and/or the consequences further are not believed to be warranted. However, there are options that could be considered to reduce the level of risk even further, should this be contemplated.

1 Introduction

1.1 General

The Ministry of Education (MoE) has engaged Tonkin & Taylor Ltd (T+T) to carry out an assessment of the risks due to rockfall from the Moa Bone Cave slope opposite Redcliffs Park, which is located between Main Road, Beachville Road and Celia Street in Redcliffs (refer Figure 1, Appendix A).

The work described in this report has been carried out in accordance with the terms and conditions outlined in the Short Form Agreement for Consultant Engagement between the MoE and T+T.

The MoE is currently undertaking a range of studies to evaluate the potential for relocating Redcliffs Primary School to Redcliffs Park (the site). Part of the site adjacent to Main Road is within Cliff Collapse Hazard Management Area 2 (CCHMA 2) shown on Christchurch District Plan Map 48. Figure 1 (refer Appendix A) shows the approximate property boundaries of the Lots that make up the site and the approximate location of the eastern limit (boundary) of the CCHMA 2 where it encroaches onto the site by about 5 m.

The purpose of this report is to provide an assessment of the current rockfall hazards from the Moa Bone Cave slope and the risk to life of an individual associated with using a school that may be located on the site. This is expected to form part of the Ministry's due diligence process prior to considering site acquisition and designation.

1.2 Scope of work

The scope of work for the purposes of this report comprised the following activities:

- Site visit by a T+T engineering geologist to investigate the range of rockfall and land instability hazards present following the recent slope stabilisation works undertaken across the rock slope.
- Liaison with the New Zealand Transport Authority (NZTA) and Christchurch City Council (CCC) to understand the slope stabilisation work that has been done regarding the removal of rock material along Main Road and its impact on the rockfall hazard.
- Rockfall and land instability hazard analysis following the GNS methodology for cliff collapse and rockfall scenarios.
- Consequence analysis applying the GNS methodology, suitably amended and supplemented to account for the expected site use.
- Risk analysis and identification of risk treatment strategies.
- Preparation of a rockfall risk assessment report describing the findings of the above work.

1.3 Report layout

This risk assessment report is set out in the following format:

Section 1 **Introduction**

Section 2 **Background -** provides information on the background to this report and provides some discussion on the more important references cited herein.

Section 3 **Methodology -** provides an explanation of the methodology used for this risk assessment

Section 4 **Hazard analysis -** this section discusses the analysis and assumptions of the hazard which in this case is rockfall/boulder roll.

Section 5 **Consequence analysis –** looks at the factors that influence where and how often people could be within the path of the hazard.

Section 6 **Risk assessment results -** provides the results of this risk assessment and the evaluation of the results against commonly used risk criteria.

Section 7 **Conclusions -** summarises the outcomes from this risk assessment.

2 Background

2.1 Site description

The site comprises three parcels of land with legal titles of *Res 4601, Lot 2 DP 47479* and *Lot 3 DP 47479.* The total land area of these three parcels is approximately 1.9 ha (refer Figure 1, Appendix A).

The majority of the site is essentially flat and lies at an elevation of approximately 1.7 m relative to the 1937 Lyttelton vertical datum (LVD). The portion of the site closest to Main Road slopes up towards the road, where it reaches an elevation of approximately 5.0 mLVD. The lower lying flat area of the site comprises grassed areas (sports fields) and two children's playgrounds. There are three buildings on the raised portion of the site; an Orion substation (still in use), a small community hall/clubroom (no longer in use) and a public toilet block (still in use). There are also paved areas and paths in this raised area adjacent to Main Road.

The footpath and road pavement associated with Main Road is approximately 15 m wide in the portion opposite Moa Bone Cave, which is to the west of the site. The base of the Moa Bone Cave slope is another 4 m to the west, i.e. about 19 to 20 m from the western boundary of the site. The Moa Bone Cave slope is approximately 25 m high above the cave entrance and reduces to about 20 m high further to the north.

2.2 Development

We understand that the MoE are looking to relocate Redcliffs School to a site at Redcliffs Park and are currently undertaking their due diligence process for this new location. Although no specific development plans or building locations have yet been identified on the site, we understand that the proposed school will likely include typical educational facilities such as single and two storey lightweight timber-framed buildings, outdoor paved areas and car parks.

One of the higher use elements of the school would most likely be a student pick-up/drop-off area (PUDO), which could be located on the site adjacent to Main Road. Alternatively, this could be located along Beachville Road with a pedestrian entry gateway to the site on the Main Road frontage. A minimum setback of 6 m from the site boundary to any new building is expected to apply to this development. These aspects are expected to influence the level of risk to site users associated with the rock slope to the west and have been considered in the risk assessment.

2.3 Geology and risk background

Redcliffs Park is located along the foot of the Port Hills. In the general vicinity of the site the natural soil and rock slopes have been undercut by wave action in the past several thousand years to produce over steepened soil slopes and rock cliffs up to 70 m high. The slopes and cliffs have been protected from ongoing wave action and removal of debris from the toe in relatively recent times (approximately 1,000 to 3,000 years) by the build-up of the New Brighton Spit and development of the present day estuary.

The seismic shaking experienced during the 2010/2011 Canterbury Earthquake Sequence (CES) has resulted in several areas of major cliff collapse and rockfall associated with over steepened slopes at the foot of the Port Hills. The scale of the cliff collapse and rockfall highlights the existence of such hazards and the potential consequences of occupying sites close to the foot of these steep slopes. These events have also provided a unique opportunity to map and analyse the hazard, and to quantify the future risk to life. GNS Science has carried out a large body of work investigating and analysing the future risk of the Port Hills slope hazards, which has been used by CERA in the establishment of the Port Hills red zones, based on life risk criteria.

The relevant reports by GNS Science relating to rockfall[1] (GNS, 2012 and 2013) and cliff collapse[2] (GNS, 2014) have been reviewed and the information used in the preparation of this report, along with our direct observations of the local slope conditions.

The GNS report on cliff collapse (GNS, 2014) includes maps[3] showing bands (or contours) of annualised individual life risk (AIFR) for residential occupation. The risk bands for cliff collapse are limited by a 31^{o} fly rock line (fahrboeschung angle), which is similar to 10^{-6} AIFR lines shown on rockfall/boulder roll risk maps in other GNS reports.

The hazard management line shown on Figure 1 (refer Appendix A) is coincident with the eastern limit of the Cliff Collapse Hazard Management Area (CCHMA 2) shown on Christchurch District Plan Map 48. The hazard management area reflects the location of the change of risk to life (AIFR) from 10^{-4} to 10^{-6}, as calculated by GNS. District Plan rules (District Plan Section 5.5) for this management area list new development as a non-complying activity. A site specific risk assessment report must be submitted to CCC to accompany an application for an AIFR Certificate[4], which then allows 2 years to apply for a restricted discretionary consent for site development. Quantitatively estimating the slope instability-related individual lives risk to school users is necessary so that the potential development can be evaluated in terms of the Christchurch District Plan Map 48.

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[1] Canterbury Earthquakes 2010/2011 Port Hills Slope Stability: Pilot study for assessing life safety risk from rock falls (boulder rolls). GNS Science Consultancy Report 2012/123, March 2012 Final Issue 2.

[2] Canterbury Earthquakes 2010/2011 Port Hills Slope Stability: Risk Assessment for Redcliffs. GNS Science Consultancy Report 2014/78, August 2014 Final

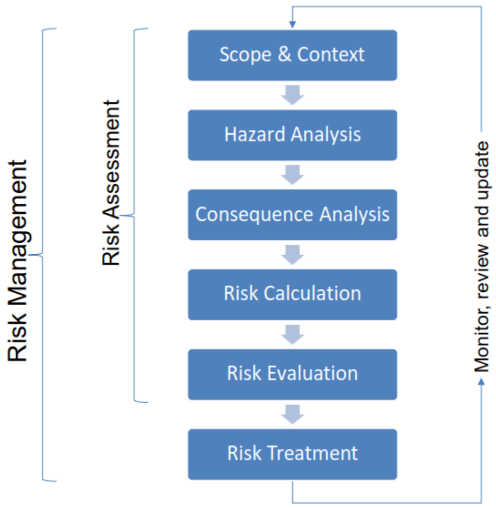
[3] Canterbury Earthquakes 2010/2011 Port Hills Slope Stability: Life safety risk from rock falls (boulder rolls) in the Port Hills. GNS Science Consultancy Report 2012/123, May 2013 Final Issue 2. Map C: Risk Model year 5 2016.

[4] An AIFR Certificate is that instrument used by CCC to control potential development within an area that is assessed as having a less than unacceptable individual life risk due to natural cliff hazards such as rockfall and cliff collapse.

3 Methodology

3.1 Risk assessment overview

The overall risk assessment methodology, which is part of a more general risk management process, comprises of several steps shown diagrammatically below:



This risk management process is based on the appropriate parts of AS/NZS ISO 31000:2009 and the Australian Geomechanics Society framework for landslide risk management[5]. The scope, context and methodology for this risk assessment are provided in Sections 1, 2 and 3 of this report. The hazard and consequence analysis are discussed in Sections 4 and 5. Section 6 provides the results of the risk calculation along with the evaluation of the calculated risks.

3.2 Risk definition

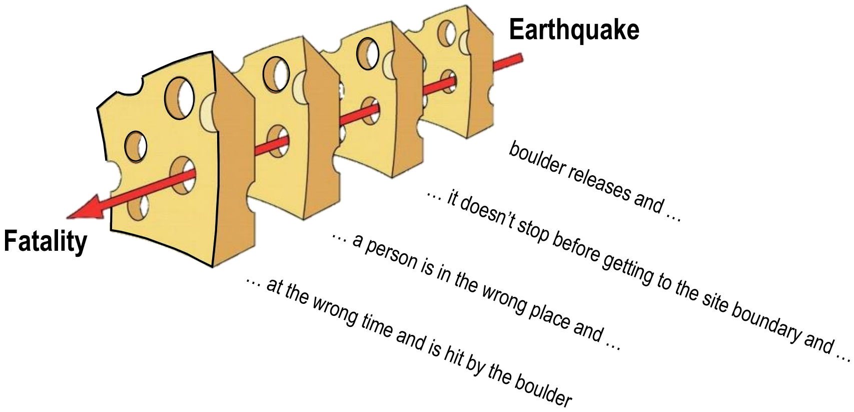
Some important terminology that is used within this report is presented below and explained to help understand the following parts of the document. Key to this is the word "Risk". Risk is defined in general terms as the product of the frequency (or probability) of a particular event and the consequence of that event, which for this assessment is potential loss of life due to impact from a rock or land instability debris for an individual that spends the most time in the hazard zone during a 12 month period (Annualised Individual Life Risk, AIFR).

We note that the AIFR is defined (GNS, 2012) as "*the probability (likelihood) that a particular individual will be killed by a rockfall in any year at their place of residence*." The AIFR is not an appropriate measure of life risk for a school site since the length of time that school users might be exposed to the rockfall hazard is typically much less than residents living in a dwelling. Therefore, the calculation used in this risk assessment to estimate the individual lives risk for a school user is necessarily different to that used by GNS, although the overall methodology is based closely on the GNS approach.

For this assessment the risk is calculated quantitatively by multiplying the probability of the event occurring by the probability of the consequence, which itself is the product of the probabilities of several factors (conditional probabilities) that combine to result in the final outcome of the event.

[5] Australian Geomechanics Society 2007. Practice note guidelines for landslide risk management. Journal and news of the Australian Geomechanics Society 42(1), March.

The imagery associated with the "Swiss cheese model" can help communicate the risk concept, which is illustrated in the diagram below. In this model, a number of factors that would not ordinarily be expected to occur need to happen concurrently (or sequentially) for the threat to be realised (in this case the end result would be a fatality due to a rockfall impacting someone that happened to be in the path of the boulder, at the time of the earthquake or extreme rainfall event that triggered the rockfall). This is illustrated in the following pictogram.



Symbolically the general expression for calculating the risk is:

$$\mathbf{R} = \mathbf{P_{(H)}} \times \mathbf{P_{(S:H)}} \times \mathbf{P_{(T:S)}} \times \mathbf{V} \times \mathbf{E}$$

Where:

R = annualised risk (which may be thought of as the annual probability of fatality or property damage in financial terms)

$P_{(H)}$ = annual probability of the hazardous event (in this case rockfall)

$P_{(S:H)}$ = probability of spatial impact (or accident) given the hazardous event (this is typically the product of a number of conditional probabilities of contributing events that all have to occur to end up with the element at risk being physically exposed to the hazard)

$P_{(T:S)}$ = temporal probability of the consequence occurring i.e. probability of the element at risk being present within the impact zone at the time that the hazard occurs (often this is a function of the length of time that the element at risk is exposed to the hazard)

V = vulnerability of the element at risk given the presence of the element at risk within the impact space or zone, due to the hazardous event, at the time the event occurs

E = the element at risk i.e. an individual, a group or community, or property (in this case the key element is an individual school user at risk due to the hazard)

3.3 Uncertainty

Risk assessment is not an exact science. There is insufficient, and often no actuarial data on which to make statistically valid estimates on the inputs into the risk assessment, such as the frequency of slope instability and the estimates of the consequences of the instability. Therefore, data are developed through the collaborative efforts of experienced practitioners best qualified to make such assessments. To this end, much work has already been undertaken since the Darfield earthquake in late 2010 to understand the risks associated with slope instability in the Port Hills area, and in particular rock fall. That body of work has been used, as appropriate, for this risk assessment. However, while producing the best available information, the inputs for this risk assessment still contain uncertainty.

The uncertainties associated with this type of assessment may be described in three broad categories:

- uncertainty associated with the probability of an occurrence of slope instability;
- uncertainty associated with predicting the scale of consequences if a failure occurs; and
- uncertainty associated with determining the likelihood of an interaction between people and the outcome of slope instability, and the result of any interaction.

The approach taken in this risk assessment to consider uncertainty is to look at the sensitivity of the outputs to various input parameters. This results in the estimate of the fatality risk being presented as a range, albeit with a "best estimate" value to provide guidance on the expected level of life risk.

3.4 Risk evaluation criteria

For this risk assessment the lives risk has been quantified for the individual most at risk while attending at the proposed Redcliffs School site. The assessment represents an identifiable individual that is expected to be exposed to the highest risk of fatality associated with the Moa Bone Cave slope. This is more or less the element at risk used in the GNS reports, although not exactly the same, since the level of exposure is different for the proposed school site compared with that used for the GNS reports (which assumes residential property occupancy).

For individual risk, guidance on acceptable and/or tolerable risk levels is available from a range of sources, including:

- Australian Geomechanics Society (AGS, 2007)
- UK Health and Safety Executive (UK HSE, 2001)[6]
- NSW Department of Planning (NSW DP, 2011)[7]
- Australian National Committee On Large Dams (ANCOLD)

These sources commonly use a value for annualised individual risk of 1×10^{-6} as a threshold below which the risk is usually considered to be acceptable i.e. the level of risk due to the assessed hazard(s) is sufficiently below other commonly tolerated or accepted risks in society. Other sources of guidance relevant to this assessment includes the pilot study on risk assessment in the Port Hills (GNS, 2012) that recommended:

- *"… a suitable starting point for Christchurch City Council's deliberation as to where within this range to set their threshold would be a level of 1×10^{-4} (1/10,000 per year) annual individual fatality risk."*

[6] UK Health and Safety Executive (2001). Reducing Risk, Protecting People.

[7] NSW Department of Planning (2011). Hazardous Industry Planning Advisory Paper No. 4: Risk Criteria for Land Use Safety Planning. ISBN 978-0-73475-923-8.

- *"Christchurch City Council should adopt a lower threshold of annual individual fatality risk above which development is be controlled to prevent accumulation of people in areas of substantial risk below the sustainable threshold of tolerability. Such a threshold could be set 10x below the tolerability threshold for general property uses involving significant occupancy by people, and 100x below the tolerability threshold for particularly sensitive property uses (e.g. schools, care homes, hospitals)."*

4 Hazard analysis

Geological and engineering geological assessment of the rock slope associated with the Moa Bone Cave area identifies the potential sources and modes of failure (referred to as failure scenarios) that could result in debris originating on the current slope crossing the Main Road and reaching the site, along with an estimate of the likelihood of the failure scenarios occurring. This work looks at the nature and characteristics of the current landform along with the historical performance of the slope that is discernible from available records. The results of our investigations are provided below, but in general terms the hazards include individual or multiple boulders rolling across the road due to individual rockfall events or debris from larger-scale slope instability. These hazards may be triggered by earthquakes or instances of intensive or prolonged rainfall. We note that the terms rockfall and boulder roll are used in this report. For this risk assessment these terms essentially mean the same thing and refer to the hazard posed by boulders dislodging from the subject slope face and making their way across Main Road to reach, or pass beyond, the site boundary.

4.1 Moa Bone Cave prior to the Canterbury Earthquake Sequence

The rock above Moa Bone Cave comprises a lower sub-vertical section of volcanic breccia capped by ash layers and columnar jointed lava flows. The ash layers are the downslope continuation of the Redcliff ash layer seen half way up the high cliff behind the existing Redcliffs School site. They are the basal layers of the Mt Pleasant Formation eruption which flowed down the northern flank of the Lyttelton volcano about 10 million years ago.

Rockfall has occurred from the arch of the Moa Bone Cave and the entrance was barricaded in the mid-2000s. Figure 2 (refer Appendix A) shows a street view image of the cave in 2008 with temporary barricades in place and the kerb of the north bound traffic lane moved out eastwards (into the roadway) from its original location.

4.2 Rockfall and earthquake damage from the CES

Rock fall occurred during the 22 February 2011 Christchurch earthquake. Figure 2 (street view 2008) (refer Appendix A) is annotated to show the locations of rock fall from the columnar jointed lava flow above the cave entrance and the immediate area to the north. Figure 3 (refer Appendix A) shows an aerial image from 24 February 2011, annotated to show the extent of debris on the road from rock fall and locations of individual boulder impact out to the centre of the road. Between 2011 and 2016 the road was protected by a row of double stacked containers, which sustained several hits from falling rocks, although nothing ended up on the road.

4.3 Slope modification works in 2016

Works have been carried out on the rock face associated with the Moa Bone Cave area by CCC and NZTA as part of the Sumner to Lyttelton road corridor risk mitigation works, which has included:

- Light scaling over 450 m^2 of rock face above Moa Bone Cave.
- Installation of two 3 m long rock bolts into 1 potentially unstable block of rock on the face above Moa Bone Cave.
- Mechanical scaling of blocks from around the entrance of Moa Bone Cave.
- Excavation of the face to the north of Moa Bone Cave to create a benched slope that trends away from the road in a north westerly direction.
- Scaling of large up to 24 m^3 rock slabs from the face to the south of Moa Bone Cave.
- Construction of an earth bund in front of the face to the south of Moa Bone Cave.

The key slope works relevant to this MoE hazard assessment involve the light scaling above Moa Bone Cave and the benched slope to the north. The areas of scaling and benching are shown on Figure 4 (refer Appendix A) overlaying an oblique Google Earth view of the face in 2012.

4.4 Current Moa Bone Cave face and assessed failure scenarios

The two main types of slope instability hazards are discussed below, which comprise:

- Cliff collapse type failure scenario; and
- Rockfall type scenario.

This section also discusses the evaluation that was carried out to understand the credible rockfall scenarios that could present a hazard to school users. This evaluation was informed by computer analysis of rocks detaching from the slope and bouncing/rolling onto or across Main Road, using the RocFall computer simulation program. Ground slope profiles were developed for the rockfall scenarios that are considered to present credible hazards to school site users. These ground slope profiles are referred to as RocFall profiles (refer Appendix B).

4.4.1 Cliff collapse type failure scenario

The potentially larger-scale cliff collapse instability mechanism as defined and assessed in the relevant GNS reports (e.g. GNS 2014) is not considered credible on the Moa Bone Cave rock face and therefore does not need to be included in our assessment of hazards. This cliff collapse scenario is not considered to present a credible risk to the proposed MoE site at this location because of:

- The lack of systematic earthquake cracking and deformation behind the crest of the slope above the Moa Bone Cave compared to other cliff faces in the Redcliffs and Sumner areas where cliff collapse occurred during the CES.
- The area at the north end of Moa Bone Cave rock face where cracking and potential overall cliff movement was observed has now been benched down such that the cliff collapse mechanism has been removed from that particular rock face (see Figure 4, Appendix A).
- After scaling of the rock face above Moa Bone Cave there are no through-going or sufficiently continuous defects in exposed rock units that form credible cliff collapse-scale volumes of rock mass.

4.4.2 Rockfall type failure scenarios

Figure 5 (refer Appendix A) shows the areas assessed as the source of potential rockfall (and potentially resulting boulder roll) from the columnar jointed lava that occurs upon the slope above the Moa Bone Cave. The potential face areas where rockfall may occur in the future are relatively limited since scaling was carried out by NZTA and the remaining potential blocks are at least partly attached to the slope, further reducing the likelihood of failure in future triggering events.

The observed boulder size likely to be derived from the columnar jointed lava and released on existing joints in the volcanic breccia is assessed as 1 m^3. In addition to 1 m^3 boulders we have considered 3 m^3 boulders in the RocFall analysis (Section 3.3.3) to account for some uncertainty in the rock jointing and orientation. The likelihood of a 3 m^3 boulder being released is considered to be less likely than a 1 m^3 boulder. Our assessment is that for every 10 to 20 instances of a 1 m^3 boulder being released perhaps one 3 m^3 boulder release may occur.

Arch collapse above the entrance to Moa Bone Cave has been identified as a potential slope instability mechanism and this is shown on Figure 5 (refer Appendix A). However, the likelihood is relatively low given the observed lack of sub-vertical defects to break up the arch. The cave face is about 5 m back from the general line of the rock face (i.e. approximately 25 m away from the site boundary) so debris from a collapse is extremely unlikely to extend significantly onto the road, let alone cross the road and adjacent footpath and onto the MoE site. Figure 6 (refer Appendix A) shows the assessed extent of a potential debris zone from arch collapse. The talus slope formed by debris from a potential arch collapse could exacerbate the boulder roll hazard due to release of rocks from the slope above or adjacent to the arch. This particular scenario has been modelled using the RocFall profile 1 with a talus slope added to the profile extending out from the toe of the slope.

4.4.3 RocFall analysis

Boulder rolling analysis was undertaken using the RocFall computer program, as used for analysis by GNS and CCC since the 2011 earthquake events. The parameters used in the analysis are listed in printouts attached in Appendix B. Where possible parameters are similar to the GNS/CCC work, modified by back analysis to provide relatively realistic bounce paths across the Main Road. Each case was run several times with 10,000 boulders per run until stable results were achieved. The results of the analysis are presented in Appendix B and summarised in Table 4.1 (below).

Table 4.1 RocFall analysis results

RocFall Cases	**Boulders passing a specified point on the ground profile, based on RocFall analysis using 10,000 boulder rolls**			**At site boundary**		**Maximum boulder reach**
	Main Road centre line	**Kerb nearest the site**	**Site boundary (ψ)**	**Bounce height (m)**	**Total kinetic energy (kJ)**	**Distance past site boundary (m)**
RocFall profile 1						
3 m^3 existing slope	0.59 %	0.08 %	0 %	0	0	0
3 m^3 with talus at base	0.55 %	0.10 %	0.01 % (i.e. 1 in 10,000 boulder roll events made it to, or past, the site boundary)	1.2	210	6.1
1 m^3 existing slope	0.44 %	0.13 %	0.02 % (i.e. 2 in 10,000 boulder roll events made it to, or past, the site boundary)	1	140	3.5
1 m^3 with talus at base	1.0 %	0.15 %	0.02 % (i.e. 2 in 10,000 boulder roll events made it to, or past, the site boundary)	1	35	1.7
RocFall profile 2 (all cases)						
	0	0	0	0	0	0

The RocFall analysis along with observations from February 2011 also indicate that rockfall/boulder roll from the low slope north of Moa Bone Cave cannot reach the site boundary and do not present a hazard within the site.

The above outputs from the RocFall analysis inform the assessment of the likelihood of a rock/boulder presenting a hazard to a site user, given a triggering event, as discussed in the next section.

4.5 Likelihood of failure scenarios occurring

4.5.1 GNS assessments

Our hazard assessment for the site has produced a limited number of slope failure scenarios where rockfall/boulder roll, either directly from the Moa Bone Cave rock face, or associated with the talus slope resulting from arch collapse above the cave entrance, presents a potential hazard to site users.

Another aspect of the hazard analysis, which is the likelihood of a trigger event occurring, is discussed in this section and is based on an earthquake event and rainfall-related trigger event. GNS have assessed rockfall triggers following the CES. Based on our review of GNS 2012[8], the rockfall triggers considered relevant to the site are provided in Table 4.2 (below).

Table 4.2 Rockfall triggers

Trigger		**Annual likelihood in the next 50 years** (P_L)	**Number of 1 m^3 boulders released from Moa Bone Cave rock face (T+T assessment)** (n)
Earthquake trigger	1g to 2g band (“large” event)	0.003 (GNS 2012, pg 21)	10
	0.4g to 1g band[a] (“medium” event)	0.03 (GNS 2012, pg 21)	1
Non-earthquake trigger (rainfall)	100 year to 1,000 year return period	0.01 to 0.001 (GNS 2012 pg 30)	1 to 10

Table notes:

a. This event approximately corresponds to the February 2011 earthquake.

In addition to the likelihood of rockfall triggering events, GNS also discuss the number of boulders that might fall across all of the areas studied across the Port Hills. The cumulative width/distance of slopes in the study areas is approximately 14.2 km. The total annual rockfall rate from earthquake events is about 31 boulders per year (GNS 2012, pg 27). The total from non-earthquake events is about 15 boulders per year (GNS 2012, pg 32). These estimates provide a characteristic assessment of the number of boulders that might fall from any segment of rock slope. For the Moa Bone Cave slope, which has a total length of approximately 40 m, this approach could be used to provide an indicative number of potential boulders that could release from the slope. This has been used as a check on the engineering geological assessment of the slope and the RocFall analysis discussed in Section 4.4.3 (refer to Section 4.6 for further explanation).

[8] Canterbury Earthquakes 2010/2011 Port Hills Slope Stability: Pilot study for assessing life safety risk from rock falls (boulder rolls). GNS Science Consultancy Report 2012/123, March 2012 Final Issue 2.

4.5.2 Likelihood of boulders reaching the property boundary

Combining the triggering event likelihoods with estimated number of boulders released from the slope and the likely proportion of boulders that may reach the site boundary (from RocFall analysis) provides an estimate of the overall likelihood of a boulder reaching the property and effecting school users i.e. $P_{(H)}$ (the probability of the hazardous event). These values are presented in Table 4.3 (below).

Table 4.3 Likelihood of the hazard

Trigger	Annual likelihood (P_L from Table 4.2)	Number of 1 m³ boulders released (n_1 from Table 4.2)	Number of 3 m³ boulders released (n_3)	Proportion reaching the property boundary [a] (Ψ from Table 4.1)	Calculated likelihood of boulders reaching the property boundary [a] ($P_H = P_L \times n_{(x)} \times \Psi$)
"Medium" earthquake, 0.4 to 1g band [b]	0.03	1	0.1	0.0002 to 0.0001	6×10^{-6} to 3×10^{-7}
"Large" earthquake, 1 to 2g band	0.003	10	1	0.0002 to 0.0001	6×10^{-6} to 3×10^{-7}
100 year return period rainfall event	0.01	1	0.1	0.0002 to 0.0001	2×10^{-6} to 1×10^{-7}
1000 year return period rainfall event	0.001	10	1	0.0002 to 0.0001	2×10^{-6} to 1×10^{-7}

Table notes:

b. A proportion of 0.0002 and likelihood of 6×10^{-6} and 2×10^{-6} applies to 1 m³ boulders travelling up to 3.5 m on to the property. A proportion of 0.0001 and likelihood of 3×10^{-7} and 1×10^{-7} applies to 3 m³ boulders travelling up to 6.1 m on to the property.

c. This event approximately corresponds to the February 2011 earthquake, with the estimated probability that it occurs again as provided in the table.

4.6 Characteristic boulder roll frequency

Following on from the discussion in the last part of Section 4.5.1, above, the GNS estimates of characteristic boulders falling per year for all slopes in the Port Hills study area can be estimated for the Moa Bone Cave slope, as follows:

- 31 plus 15 boulders equals 46 boulders in total per year (Section 4.5.1).
- 46 boulders divided by 14,200 linear metres of face for all areas across the Port Hills equals 0.003 boulders per metre run of slope face, per year, on average for all areas.
- Moa Bone Cave rock face is 40 m long and thus 40 m x 0.003 boulders/m equals 0.12 boulders per year that could, on average, fall/roll from the face.

- 0.12 boulders per year multiplied by the percent of boulders that might reach the property boundary (from the RocFall analysis) equals 2.4 x 10^{-5} (characteristic probability of a boulder reaching the property boundary).

4.7 Summary of boulder roll hazard assessment

Figure 6 (refer Appendix A) shows the assessed limits of slope instability debris (arch collapse talus zone) and individual rockfall/boulder roll that may occur from the failure scenarios considered. In summary, the rockfall/boulder roll hazards presented to school users are:

- The typical 1 m^3 boulder has an annualised likelihood of about 6 x 10^{-6} of rolling up to 3.5 m onto the property. Boulder bounce heights at the property boundary are generally less than 0.5 m, with the maximum height of approximately 1 m achieved during the computer simulations. The energy at the property boundary was a maximum of 140 kJ. In the computer simulations only 2 out of 10,000 rockfall trials reached, or passed, the site boundary.
- Rolling 3 m^3 boulders may travel as far as approximately 6 m onto the property, which is about 2 m past the CCHMA 2 line. Based on our assessment the annualised likelihood of this occurrence is in the order of 3 x 10^{-7}. Boulder bounce heights at the property boundary are generally less than 0.5 m, with the maximum height of approximately 1.2 m achieved during the computer simulations. The energy at the property boundary was a maximum of 210 kJ. In the computer simulations only 1 out of 10,000 rockfall trials reached, or passed, the site boundary.
- Using information reported by GNS for characteristic boulder roll, an “average” annualised likelihood of a boulder releasing from the slope and reaching the site boundary is 2.4 x 10^{-5}, which is considered to be the upper bound likelihood for rockfall impacting the property, since it does not take into consideration the specific geological attributes of the subject slope nor the remedial works that have been carried out. The boulder size associated with this estimate is of the order of 1 m^3.

The area subject to rockfall hazard is limited to a portion of about 29 m length extending along the boundary with Lot 3 DP47479 and a small portion of Lot 2 (refer Figure 1, Appendix A for Lot locations).

5 Consequence analysis

5.1 General

The consequence analysis part of the risk assessment estimates the potential consequences and the likelihood of the consequences due to the identified hazards, and comprises the following typical steps:

1 Identification of the elements at risk (E). In this case the elements at risk are the people within the site that may be affected as a result of a failure, such as students attending the school, parents dropping off and picking up students or visitors to the school. The possible layout of the school has not yet been defined and therefore it is unknown at this stage where key facilities such as buildings, parking areas and school access points are expected. However, for the purposes of this assessment we have made the following assumptions regarding site layout and therefore where people may be located:

- Buildings will be at least 6 m away from the Main Road site boundary.
- There will be a school entrance/exit located somewhere along the Main Road portion of the Site boundary.
- A student pick up/drop off (PUDO) may be located along the boundary of the Main Road portion of the Site.

Therefore, the potential elements at risk include students, parents and visitors accessing the school site from the Main Road boundary. Based on our assessment of the extent of potential boulder roll and the likely building setback from the school boundary, people within any buildings will not be exposed to the hazard. Similarly, no student play areas are expected to be developed on the school site in this vicinity.

2 Assessment of spatial variability [$P_{(S:H)}$] and temporal probability [$P_{(T:S)}$] of the elements at risk. When the element at risk involves life, the temporal probability needs to take account of the likelihood of the person being in the place impacted by the hazard given the time of year or the reason why the person may be in the potential impact zone (e.g. study, work or recreation). We note that the various GNS rockfall/cliff collapse reports assume that the elements at risk (in their case the property residents) are at home and exposed to the risk either 67% or 100% of the time. Further discussion on the temporal probability and spatial variability is provided in the following subsections.

3 Estimation of the vulnerability of the elements at risk (V). The vulnerability may be thought of as the probability of a loss of life given the impact of an event. This may be affected by the size and type of failure, whether the element at risk is out in the open and struck by a moving object or buried by debris, is in a vehicle or building that collapses or is damaged but stays essentially intact, etc. In some cases the possibility of warning and the potential for escape should also be considered and allowed for in the risk calculation, which may inform the vulnerability aspect or possibly the spatial variability element.

We note that the various GNS rockfall/cliff collapse reports assume that the elements at risk (in their case the property residents) have a 50% vulnerability if hit by a rockfall. For this assessment, we assume a vulnerability of 1 for the individual most at risk i.e. if the person is hit by a rolling boulder they will be killed by the impact. This is irrespective of whether there is a full and direct impact on a person, or whether it might be more of a glancing impact that would otherwise be expected to have a lower likelihood of resulting in a fatality.

5.2 Spatial variability

The spatial variability [$P_{(S:H)}$] is the probability of a rolling boulder entering the area where people could be exposed to the hazard (referred to as the vulnerable space) and impacting a person occupying the physical pathway of the boulder. This requires consideration of the following aspects:

4 The location of the space relative to the location of the hazard source area.
5 The size of the potential rolling boulder that can enter the space.
6 The size of the space in which the element is vulnerable to the hazard.
7 The size of an individual vulnerable element.

5.2.1 Location of the vulnerable space

The vulnerable space can be defined as an area of the site that borders Main Road adjacent to the portion of the Moa Bone Cave rock slope that has the potential to provide a rockfall source.

The potential rockfall sources from the Moa Bone Cave rock slope extend over a length of approximately 40 m. However, due to the slope modification works (described in Section 3 of this document) that have been completed, there is no credible remaining hazard source from the north western end of the slope. Therefore, the length of site boundary over which a boulder could present a hazard to school users is limited to approximately 30 m.

5.2.2 Size of boulders

We consider that a ‘typical’ boulder that could be released from the slope is approximately 1 m^3, given our geological assessment of the apparent frequency of jointing within likely boulder roll source areas. We have also considered a 3 m^3 boulder to account for some uncertainty associated with identifying rock joint planes, and the like. This size of boulder has been included in the RocFall analysis, although the likelihood of this rock size being released is significantly less than for a 1 m^3 rock, as discussed in Section 3.

5.2.3 Size of the space exposed to the hazard

The RocFall analysis indicates that boulders could potentially roll across the boundary and onto the site at most by a few metres. However, it is not envisaged that boulders could threaten buildings on the site. Nor would any land be occupied other than that associated with getting to or from the school. Therefore, the area of the site that is exposed to the rockfall hazard is effectively a 30 m long portion at the Main Road boundary of the site.

5.2.4 Size of an individual vulnerable element

A quantitative measure of the size of a person is needed to enable the estimation of an individual’s annual exposure risk to the hazard. GNS[9] adopted a “person unit” assumed to be a cylinder of 1 m diameter with an unspecified height for use in their rockfall risk models. This has been adopted for our assessment.

5.2.5 Likelihood of a boulder impact

Based on the above discussion of the aspects influencing the spatial variability, the probability that a person is in the same physical space as a boulder that reaches the site boundary is calculated using

[9] Slope Stability: Life safety risk from rock falls (boulder rolls) in the Port Hills. GNS Science Consultancy Report 2012/123, May 2013 Final Issue 2. Paragraph 3, Page 14.

the methodology as set out in Section 6.1 in the GNS report[10] and considering the following (noting that the factors influencing the time that a person is likely to be in the path of a boulder is described by a separate parameter):

- Given the relatively low potential bounce height for boulders that could reach the space we have not considered the potential for boulders to bounce over a person without causing injury.
- The passage of a rolling boulder is assumed to be a straight line.
- A person is assumed to be fixed at their location at the time of triggering of the hazard and no account is taken of the potential for the person to detect that there is any threat and escape from the boulder roll pathway.
- An individual person may occupy any 1 m segment of the part of the site exposed to a boulder roll hazard, which in this case is approximately one third of the boulder roll hazard zone that has a length of approximately 100 m (refer Figure 6, Appendix A).
- A rolling boulder may impact an individual person squarely, so that the boulder coincides with and removes the individual from a 1 m segment of the space. However, if the rolling boulder passes into the segment to the left or to the right of the one occupied by the individual there is a likelihood that the individual will be 'winged' by the boulder, which still has the potential to result in fatality. Therefore, the effective width of the hazardous zone is 2 x the diameter of the boulder (D) plus the notional width of a person (taken as 1 m).

Therefore, Table 5.1 (below) provides the probabilities of a rolling boulder encountering an individual at the site boundary, either by direct impact or partial contact, for the various hazard scenarios. Note that the value in Column C of Table 5.1 is used in calculating the scenario risks as set out in Table 6.1 (refer Section 6).

Table 5.1 Spatial variability

Boulder size	Number of rolling boulders reaching or passing the site boundary	Probability of a boulder passing through a portion of the runout zone as it travels along its trajectory	Probability of *N* boulders hitting a person occupying the same portion of the boulder runout zone	Probability of a rolling boulder encountering a person on site ($P_{S:H}$)
	N	*[Column A]*	*[Column B]*	*[Column C]*
		= ((2 x D) + 1)/100	*= 1 - (1-[Col A])^N*	*= [Col B]/3*
1 m^3	1	0.034	0.034	0.011
1.2 m dia (D) [a]	2	0.034	0.07	0.023
3 m^3 1.8 m dia (D) [a]	1	0.046	0.046	0.015

Table notes:

a. The boulder roll hazard is conceptualised as a certain boulder volume (i.e. 1 m^3 or 3 m^3). Only generally spherical-shaped boulders are expected to be able to roll across the road and footpath and then across the site boundary. In consideration of the dimensions of a block that may roll, we have assumed that a 1 m^3 block may have a 1.2 m diameter and a 3 m^3 block may have a 1.8 m diameter, whilst still maintaining an

[10] Canterbury Earthquakes 2010/2011 Port Hills Slope Stability: Pilot study for assessing life-safety risk from rockfalls (boulder rolls). GNS Science Consultancy report 2011/311, March 2012 Final Issue 2.

overall shape that is able to roll (as opposed to more of a flat or tabular shape with larger aspect ratio that would not be able to roll and would be expected to land on the road and stop).

5.3 Temporal probability

The temporal probability [$P_{(T:S)}$] considers the exposure time of a given individual to the rockfall hazard i.e. the probability that a person will occupy the space where a boulder roll occurs, at the same time as the event happens. To calculate this we need to consider:

- The use of the space and why an individual will be within it.
- The range of individuals who are likely to occupy the space for a period of time, including an estimation of the highest individual exposure time per annum to the hazard.
- The length of time the most at risk individual is likely to occupy the space as a proportion of a year, being the sum of an individual's annual exposure to the hazard.

We have assumed that school buildings will be located at least 6 m from the site boundary. Since the maximum estimated boulder roll scenario suggests that rocks may only reach up to 6 m beyond the boundary, buildings and their occupants are not considered likely to be exposed to the rockfall hazard from the Moa Bone Cave slope. We have assumed that there will be a pedestrian access gate to the school site within the PUDO area.

Within the course of typical school activities the following persons are considered likely to occupy the space:

- Parents dropping off and picking up students. Let us say that the parent spends one hour in the morning and one hour in the afternoon within the PUDO area, which equates to 2 hours per day each school day during the year. Although unlikely, we have also assumed that the parent spends a similar time on the weekend associated with sporting activity. Therefore, the total exposure time includes two hours on a weekend day during term time. Overall, this equals approximately 5.6% of a year (0.056). This is considered to be a very conservative estimate (over estimate) of the exposure time.
- Students – likely to be present when being dropped off or picked up from school (assuming that a PUDO is located along this part of the site boundary). This equates to, say, 15 minutes at the start and end of each school day during the year, which equals approximately 1.17% of a year (0.017) and is less than that of a parent using the PUDO.
- Students not being picked up or dropped off could use the school entrance that is expected to be along the Main Road boundary. These students could be within the space for, say, 5 minutes, twice per day for the school year. This represents approximately 0.37% of a year (0.0037) and is less than that of a parent using the PUDO.
- Teachers – this group of school users are likely to enter and exit the school site from a different location, even if a PUDO is not located here, and so this group of site users is not envisaged to be exposed to the rockfall hazard.

Additionally, members of the public may occupy the space when using the school facilities for intermittent community activities, however the exposure time associated with this group is much lower than regular school users.

6 Risk assessment results

6.1 Calculated individual risk

The calculated AIFR using the risk methodology described above for a school user at the proposed Redcliffs Park site identified with the highest level of exposure to the rockfall-related risk is of the order of 1.5×10^{-8}.

This compares with an individual risk of the order of 1.3×10^{-8} using an algorithm based on the AIFR calculation methodology used by GNS (for individuals in their place of residence), which does not take account of factors specific to the use of the Redcliffs Park site as a school.

Table 6.1 (refer page 21, below) sets out the risk calculation for the various scenarios considered.

6.2 Sensitivity and uncertainty

The sensitivity of the risk model outputs to the assumptions used to develop the model inputs can be examined to help understand the level of uncertainty associated with the calculated risk. For example, if the frequency of the initiating event, such as an earthquake, is increased by a factor of 10, then the risk increases by the same amount i.e. the calculated risk increases by 10 times. If the length of time that a person is exposed to the hazard doubles, then the calculated risk doubles. The following table illustrates what we believe to be the risk model inputs with the greatest degree of uncertainty, our assessment of the possible upper limit for that parameter (and in some cases beyond the level of credibility) and the risk re-calculated with the modified input.

Table 6.2 Sensitivity analysis

Parameter	Upper bound value	Calculated individual risk	Comment
P_L *[Annual likelihood of imitating event]*	10x value given in Table 6.1	1.47×10^{-7}	This is equivalent to a likelihood of the event trigger between 1 in 10 for a large rainfall event or medium size earthquake, or 1 in 100 for a large earthquake. These trigger likelihoods are considerably higher than the general consensus amongst the experts involved with the Port Hills natural hazards work suggest could give rise to a rockfall release. Using these elevated likelihood estimates gives a level of individual risk that is still much lower than 1×10^{-6}.
ψ *[Proportion of rocks reaching the property boundary]*	0.001	1.47×10^{-7}	Increasing the proportion of boulders that reach the site boundary to this level is at least three times higher than that estimated using the RocFall analysis involving 10,000 trial rock falls. That analysis indicated that of the 10,000 trials examined, only 0.02 % produced instances when rocks reached or crossed the site boundary. Increasing this proportion any further is not considered credible and even with the artificially increased proportion considered here, the level of calculated individual risk is still much lower than 1×10^{-6}.

$P_{S:H}$ *[Spatial variability – i.e. is the person in the same physical space as the boulder along the site boundary]*	0.1	1.0 x 10^{-7}	To achieve this level of spatial variability the individual person would need to take up several metres along the site boundary at any one time (which is not physically possible), or the boulder would need to be around 10 m^3 (and there is no observational evidence to expect boulders this large to be released). Or, there would need to be ten times the number of boulders released at the one time – given the geological evidence observed across the slope and the performance noted during the CES, it is very difficult to conceive that this many rocks could be released from the source areas that have the potential to reach the site.
$P_{T:S}$ *[Temporal probability – i.e. is the person in the same space as the boulder at the time the boulder passes]*	0.18	4.75 x 10^{-8}	The exposure times estimated for this risk assessment, as set out in Section 5.3, are considered to be realistic, albeit at the upper end of what would be expected for a typical primary school situation. For this variable to be equal to 0.18 would require a person to be within the potential hazard space for the equivalent of around 8 hours per day for every day of the school year. Spending this length of time within a PUDO (or other activity associated with this part of the potential school site) is not really that credible. Occupation of a classroom could result in this length of exposure, but no school buildings are envisaged being within the potential rockfall exposure area. Even so, the annualised individual life risk associated with this level of exposure still does not exceed 1 x 10^{-6}.

Based on the above sensitivity analysis, there is not considered to be a credible scenario where the annualised individual life risk due to rockfall could exceed 1 x 10^{-6}.

Table 6.1 Risk calculation

$P_{(H)}$			$P_{(S:H)}$	$P_{(T:S)}$	V	r_i	R
Hazard scenario (i)	**Annual likelihood of trigger** (P_L from Table 4.3)	**Likelihood of boulders reaching property boundary** [a] (ψ from Table 4.3)	**Spatial variability** (from Table 5.1)	**Temporal probability** [b] (from Section 5.3)	**Vulnerability of the element at risk** [c] (V)	**Scenario risk** ($r_i = P_{Hi} \times P_{S:Hi} \times P_{T:Si} \times V \times E$)	**Individual risk** $= \sum r_i$
1 x 1 m^3 boulder triggered by medium earthquake (0.4g – 0.1g bands)	3×10^{-2}	2×10^{-4}	0.011	5.6×10^{-2}	1	3.7×10^{-9}	1.6×10^{-8}
0.1 x 3 m^3 boulder triggered by medium earthquake (0.4g – 0.1g bands)		1×10^{-4}	0.015			2.5×10^{-10}	
10 x 1 m^3 boulder triggered by large earthquake reach the site, 1g to 2g band (2 reach the site)	3×10^{-3}	2×10^{-4}	0.023	5.6×10^{-2}	1	7.7×10^{-9}	
1 x 3 m^3 boulder triggered by large earthquake 1g to 2g band		1×10^{-4}	0.011			1.8×10^{-10}	
1 x 1 m^3 boulder triggered by 100 yr rainfall	1×10^{-2}	2×10^{-4}	0.011	5.6×10^{-2}	1	1.2×10^{-9}	
0.1 x 3 m^3 boulder triggered by 100 yr rainfall		1×10^{-4}	0.015			8.4×10^{-11}	
10 x 1 m^3 boulder triggered by 1,000 yr rainfall (2 potentially reach the site)	1×10^{-3}	2×10^{-4}	0.023	5.6×10^{-2}	1	2.6×10^{-9}	
1 x 3 m^3 boulder triggered by 1,000 yr rainfall		1×10^{-4}	0.015			8.4×10^{-11}	
Based on published GNS Maps [d] assumes 1 x 1 m^3 boulder reaches the site boundary	2.4×10^{-5}		0.01	5.6×10^{-2}	1	-	1.3×10^{-8}

Table notes:

a. This is the annual probability of a boulder of a defined size rolling across the site boundary. The calculation of these probabilities is detailed in Table 4.3 of this document. A number of trigger types and other variables such as event return periods were considered during the calculation of these probabilities. Only three different probability numbers were calculated from all considered trigger scenarios and expanding the trigger details within these final calculations only adds to the results table complexity without affecting the end sum of probabilities. Therefore, trigger scenario details are not presented here.

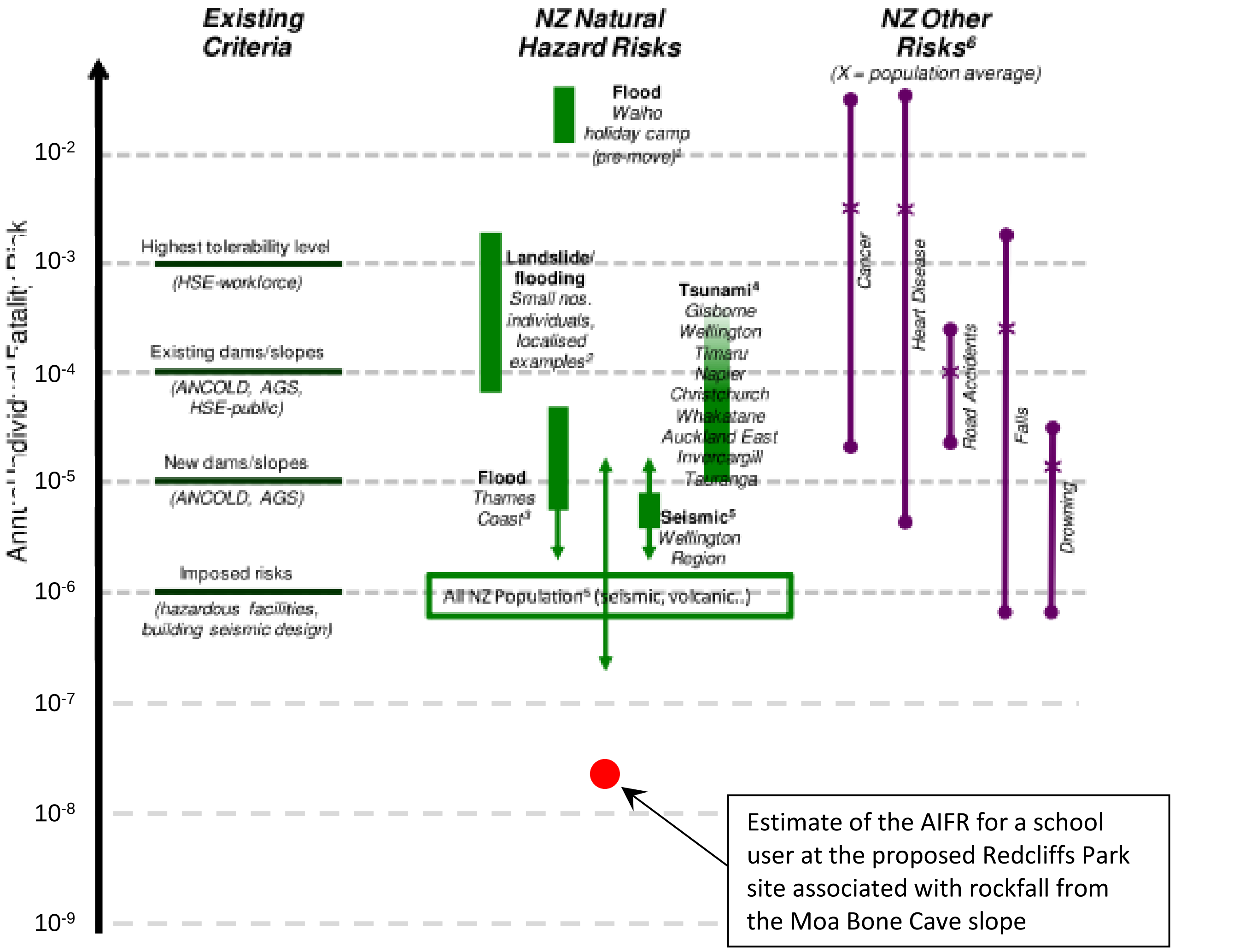
b. The maximum amount of exposure time allowed for the individual to be exposed to the hazard does not vary in response to any other portion of formula, as we assume the individual most at risk is unaware of the hazard and therefore will not actively seek to limit their exposure time.

c. We assume that the individual element at risk (E = 1) will be killed if they are hit by a rolling boulder – hence a vulnerability (V) of 1.

d. The GNS Port Hills reports contain maps and tables of data which can be interpreted to give an "average" probability of the hazard triggering at the site location. The GNS reports do not consider site-specific aspects associated with the current geological condition of the Moa Bone Cave slope, nor a non-residential level of exposure to the risk.

6.3 Risk evaluation and discussion

The AIFR of 1.6 x 10^{-8} is plotted on Figure 6.1 (below), which is adapted from GNS (2012). Inspection of Figure 6 indicates that the level of AIFR calculated for the proposed Redcliffs Park site is several orders of magnitude below other more every day risks that New Zealanders are exposed to, and well below risk tolerability and risk acceptability guidelines used elsewhere in the world.



Notes:
1 Derived by the authors [GNS, 2012] from results of MCDEM risk assessment (Optimx, 2002)
2 Estimated by the authors [GNS, 2012] based on reasonable event return periods and likely consequences – see Report Section 4.1.2
3 Upper estimate for High Risk zones; arrow denotes wide range of risk downwards (URS, 2003)
4 AIFR at 2-4m above sea level, no effectiveness assumed for warning (Webb, 2005)
5 Averages over large populations; arrows denote likelihood of substantial groups of people at higher/lower risk
6 Bars show range of values across age bands for men and women (Ministry of Health, 2008)

Figure 6.1 Comparison of the Redcliffs Park site AIFR with other individual risks in New Zealand. *Figure adapted from Figure 7 in GNS, 2012.*

The risk calculation model we have used to generate the annualised individual life risk for the proposed Redcliffs School site due to the potential rockfall hazard contains a number of assumptions and simplifications, although it uses the appropriate aspects of the rockfall risk methodology used by GNS. The simplifications of the model used in this risk assessment tend to generally increase the degree of conservatism (i.e. tend to a higher level of risk) with regards to the spatial variability and temporal probability associated with a boulder impacting a person on the site.

For example, if we consider the definition of the "space", which represents the physical area that is exposed to the potential rockfall along the site boundary, then any one design boulder traveling over the boundary must occupy 1/29th (or more if a 3 m^3 block) of the line. The risk calculation assumes that an individual may be exposed to the hazard anywhere within a 3 m segment of the boundary line, since they may be hit directly or impacted by only a part of a rolling block as it passes to the left or right of the individual. However, if we were to make the scenario more realistic by introducing depth to the space, and by considering the probability of the design boulder travelling to the maximum predicted distance, the probability of the design boulder encountering the person would reduce and the AIFR would reduce.

Similarly, the time per day for an individual to be exposed to the hazard is based on a very conservative estimate of the duration spent in the PUDO area. In reality, the individual is likely to be exposed to the hazard for only a matter of minutes per day, rather than hours (as currently assumed). Therefore, the temporal probability would be expected to be significantly lower than that use in the risk calculation, which would reduce the AIFR. Even if a PUDO was not located in this area, this level of exposure would be expected to represent the upper bound for any realistic use of the school site by a school user.

In any event, the calculated AIFR for a school user is well below 1×10^{-6}, which is typically considered an acceptable level of individual risk for land use planning purposes.

6.4 Risk treatment options

Although the level of the lives risk calculated for this risk assessment is below widely accepted limits, measures could be contemplated to reduce the risk further. These measures could be targeted at reducing the potential rockfall at the source areas or reducing the potential for the consequences of rockfall.

Further slope stabilisation works such as rockfall netting, rock bolting, cutting back the rock slope and shotcreting, either individually or in some combination, could be considered. To meaningfully reduce the likelihood of a rockfall event from the slope any treatment work would need to address all of the slope face and would involve significant disruption to traffic on Main Road. Although no detailed slope treatment works have been scoped at this stage, we would expect that any work to meaningfully reduce the rockfall hazard would cost of the order of $0.5M - $5M. Further slope treatment work may also be limited by any archaeological desire to protect the Moa Bone Cave from further modification.

A range of measures could be considered to reduce the potential consequences of rockfall. For the school site these could include:

1. Not having the potential PUDO along the Main Road frontage. This is perhaps the most effective risk treatment option since it would significantly reduce the potential exposure time of any individual within the hazard zone and hence significantly reduce the level of risk. Also, given the traffic volumes using Main Road it is most probably not the preferred location for a PUDO for the school.
2. Construct a barrier between the slope and the school site. This would most likely be feasible on the northern side of Main Road adjacent to the school boundary. The barrier could comprise of a 1 – 2 m high gabion basket/green terramesh type structure or possibly an earth

mound, if there is sufficient space for the construction. Based on the RocFall analysis undertaken for this risk assessment such a barrier would be expected to stop any potential boulder roll from getting on to the school site, albeit that the likelihood is considered to be very low.

3 Set the school site boundary at least 6 m to the north, or leave the Main Road portion of the site undeveloped. This would eliminate the risk associated with rockfall.

At this stage, given the low level of life risk to school users associated with the adjacent rock slope, further risk treatment works do not appear warranted.

7 Conclusions

This assessment considers the annualised individual risk to life associated with users of a primary school that may be located on the site, which might arise due to rockfall hazard originating from the rock slope above the Moa Bone Cave. The assessment is part of the Ministry's due diligence process prior to any potential site acquisition and designation.

The proposed site is separated from the adjacent rock slope by Main Road and the associated footpath. The length of the potential boulder runout zone is approximately 100 m long. Only the southern portion of the site boundary, which covers a length of approximately 30 m, is exposed to potential rockfall hazards.

Analysis of the potential rockfall hazard demonstrates that under specific conditions rolling boulders could reach the southern 30 m portion of the property boundary. This would require a medium to large future earthquake or extreme rainfall event to trigger a boulder release from the rock slope, which has recently been subject to rock scaling and slope stabilisation works. The boulder would then have to be of suitable dimension to enable it to bounce or roll across Main Road and the adjacent footpath to get to the property boundary. The boulder roll would then need to occur at a point along the site boundary where a person may be located, at the same time that the person is occupying that specific space (and this ignores the potential for the person to identify the danger and escape the hazardous space).

In the context of the site being developed as a primary school with a student PUDO along the Main Road boundary, the annualised individual lives risk associated with rockfall from the slope above the Moa Bone Cave is of the order of 1.6×10^{-8}. This also assumes that there are no school buildings located within 6 m of the site boundary. The level of exposure assumed for a person using the PUDO is considered to represent the upper bound, or greatest potential exposure, of any likely regular school user.

Uncertainties in the assessment have been considered using sensitivity analysis. Increasing various input parameters by 1 to 2 orders of magnitude does not increase the calculated annualised individual risk level above 1×10^{-6} (1 in 1,000,000) which widely considered to be an acceptable level of individual risk for land use planning purposes.

The level of individual risk is sufficiently low that specific engineering works to reduce the hazard and/or the consequences further are not believed to be warranted. However, there are options that could be considered to reduce the level of risk even further, should this be contemplated.

8 Applicability

This report has been prepared for the exclusive use of our client Ministry of Education, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

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Gordon Ashby
Project Director

gga
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Appendix A: Figures

Notes:

1. Aerial image sourced from Google Earth 2016, copyright Google Earth Image 2017 DigitalGlobe, image date 26/4/2012.
2. Part of CCHMA 2 limit shown is an approximate overlay based on CCC Planning Map 48 and GNS report Figures.

Approx Scale 1:2000

0 20 40 60 80 100 (m)

LEGEND

Cliff Collapse Management Area 2 (CCHMA 2) eastern limit

Moa Bone Cave rock face

Land Parcel Appellations

RES 4601

Lot 3 DP 47479

Lot 2 DP 47479

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DRAWN	AMMW	Jan. 17
DRAFTING CHECKED	BMCD	Mar 17
APPROVED	GGA	Mar 17

FILE : 1001107 – Risk Figures.pptx

APPROX. SCALE (AT A4 SIZE) 1:2000

PROJECT No. 1001107

MINISTRY OF EDUCATION

PROPOSED REDCLIFFS SCHOOL SITE

REDCLIFFS PARK, CHRISTCHURCH

Site Location & CCHMA 2 CCC Planning Map 48

FIG. No. Figure 1

REV. 0

Notes:

1. Image sourced from Google Maps, Street View January 2008.

LEGEND

Rockfall/slide source areas, Feb 2011

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DRAFTING CHECKED	BMCD	Mar 17
APPROVED	GGA	Mar 17
FILE : 1001107 – Risk Figures.pptx		
APPROX. SCALE (AT A4 SIZE) Not to scale		
PROJECT No. 1001107		

MINISTRY OF EDUCATION

PROPOSED REDCLIFFS SCHOOL SITE
REDCLIFFS PARK, CHRISTCHURCH
2008 Street View image of Moa Bone Cave rock face

FIG. No. Figure 2

REV. 0

Important notice

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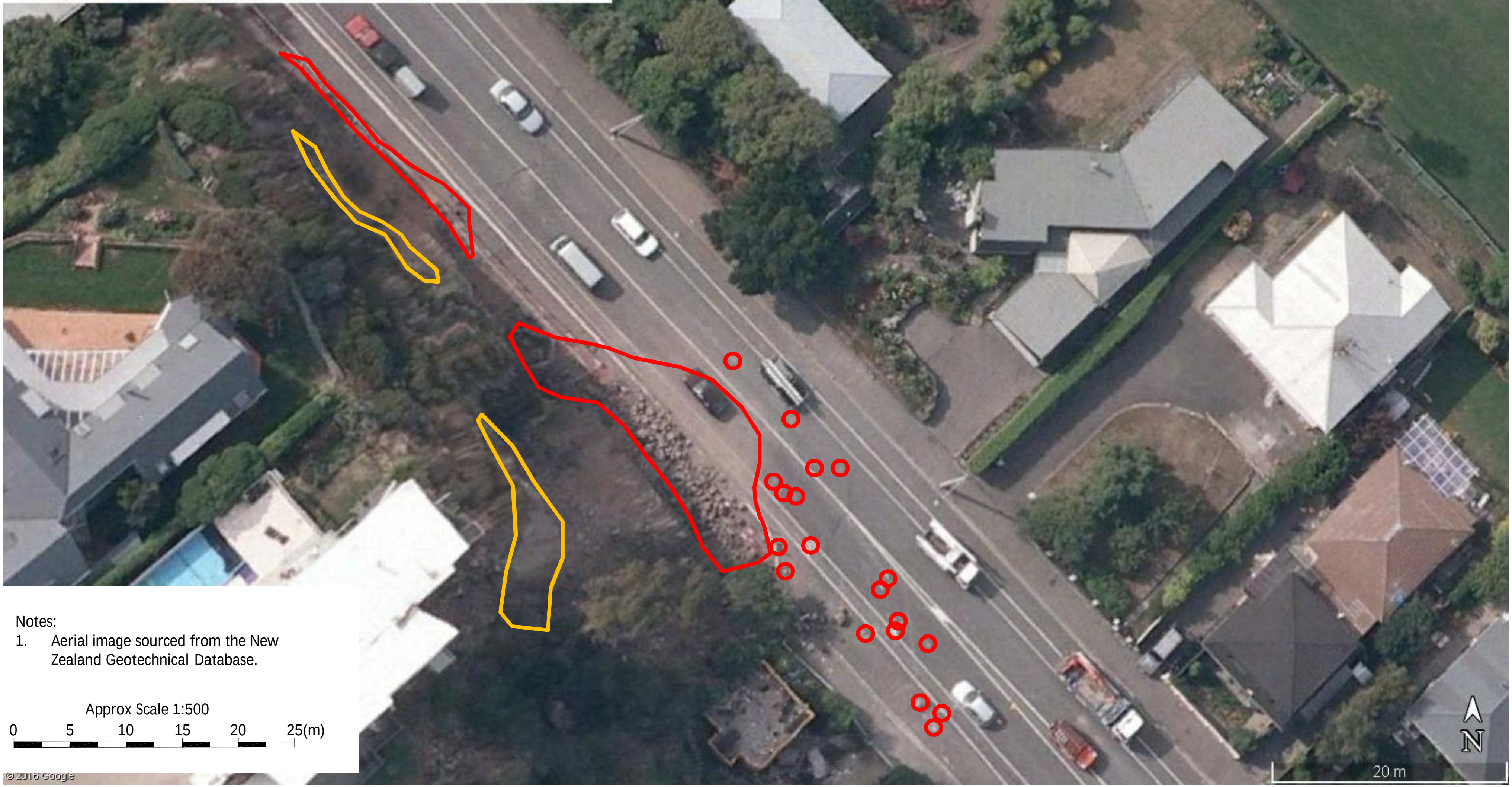

Notes:

1. Aerial image sourced from the New Zealand Geotechnical Database.

Approx Scale 1:500

0 5 10 15 20 25(m)

LEGEND

- Rockfall/slide source areas
- Boulder impact location on road
- Rock slide debris, cleared from road

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DRAWN	AMMW	Jan. 17
DRAFTING CHECKED	BMCD	Mar 17
APPROVED	GGA	Mar 17
FILE : 1001107 – Risk Figures.pptx		
APPROX. SCALE (AT A4 SIZE) 1:500		
PROJECT No. 1001107		

MINISTRY OF EDUCATION

PROPOSED REDCLIFFS SCHOOL SITE

REDCLIFFS PARK, CHRISTCHURCH

Annotated Aerial Image 24 February 2011

FIG. No. Figure 3

REV. 0

Notes:

1. Image sourced from Google Earth 2016, copyright Google Earth Image 2017 DigitalGlobe, image date 26/4/2012.
2. 3D oblique view 2012 aerial image and 2012 LiDAR.

LEGEND

- Cliff Collapse Management Area 2 (CCHMA 2) eastern limit
- Scaled and excavated areas 2015 to 2016
- Rock bolts x 2

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APPROX. SCALE (AT A4 SIZE) Not to scale		
PROJECT No. 1001107		

MINISTRY OF EDUCATION

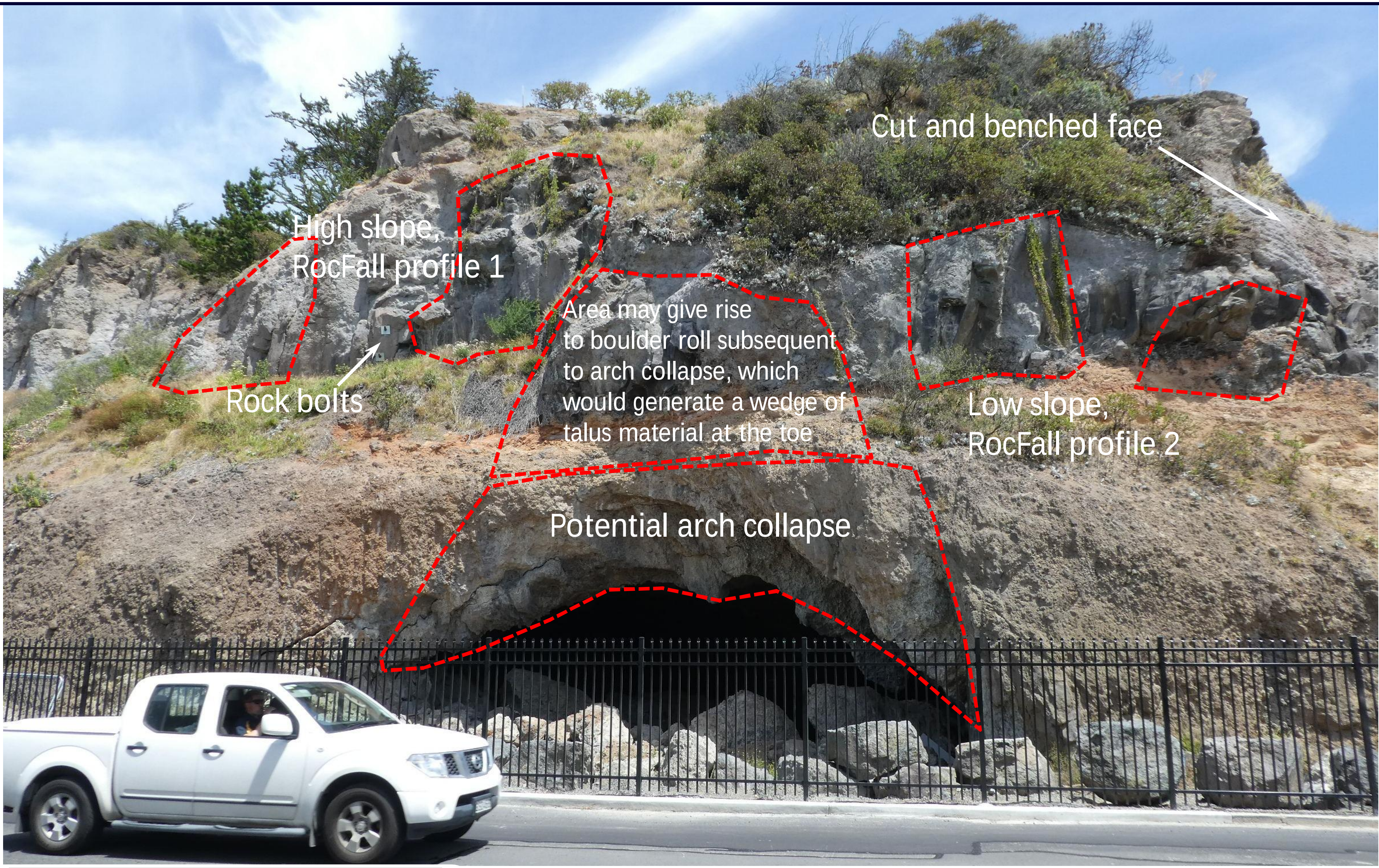
PROPOSED REDCLIFFS SCHOOL SITE

REDCLIFFS PARK, CHRISTCHURCH

2012 Google Earth Oblique View of Moa Bone Cave

FIG. No. Figure 4

REV. 0



LEGEND

Potential source areas for rockfall/slides

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APPROVED	GGA	Mar 17

FILE : 1001107 – Risk Figures.pptx

APPROX. SCALE (AT A4 SIZE) Not to scale

PROJECT No. 1001107

MINISTRY OF EDUCATION

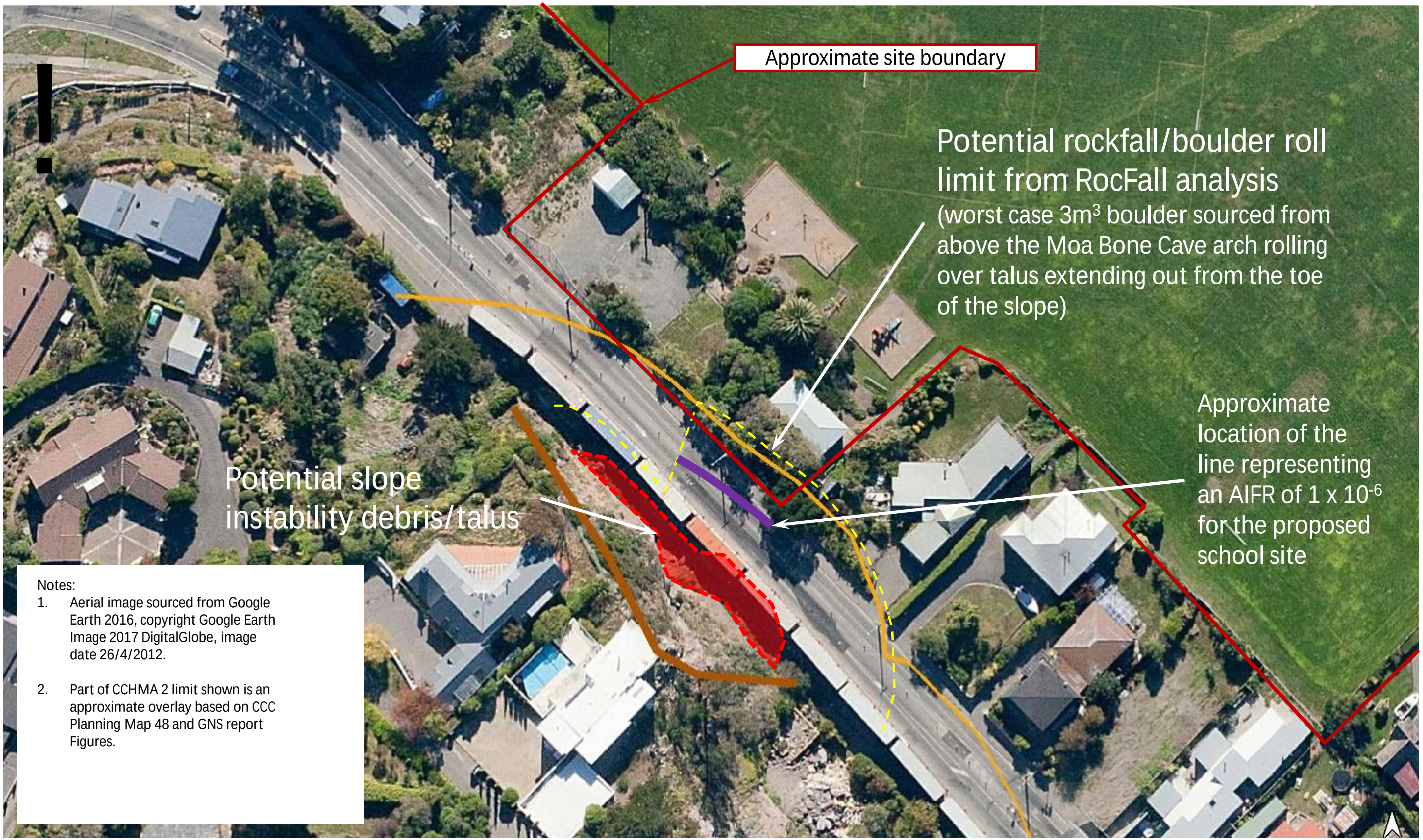
PROPOSED REDCLIFFS SCHOOL SITE

REDCLIFFS PARK, CHRISTCHURCH

Moa Bone Cave Rock face Future Rockfall Source Areas

FIG. No. Figure 5

REV. 0



Notes:

1. Aerial image sourced from Google Earth 2016, copyright Google Earth Image 2017 DigitalGlobe, image date 26/4/2012.
2. Part of CCHMA 2 limit shown is an approximate overlay based on CCC Planning Map 48 and GNS report Figures.

LEGEND

- Cliff Collapse Management Area 2 (CCHMA 2) eastern limit
- Moa Bone Cave rock face

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DRAWN	AMMW	Jan. 17
DRAFTING CHECKED	BMCD	Mar 17
APPROVED	GGA	Mar 17
FILE : 1001107 – Risk Figures.pptx		
APPROX. SCALE (AT A4 SIZE) 1:1000		
PROJECT No. 1001107		

MINISTRY OF EDUCATION

PROPOSED REDCLIFFS SCHOOL SITE

REDCLIFFS PARK, CHRISTCHURCH

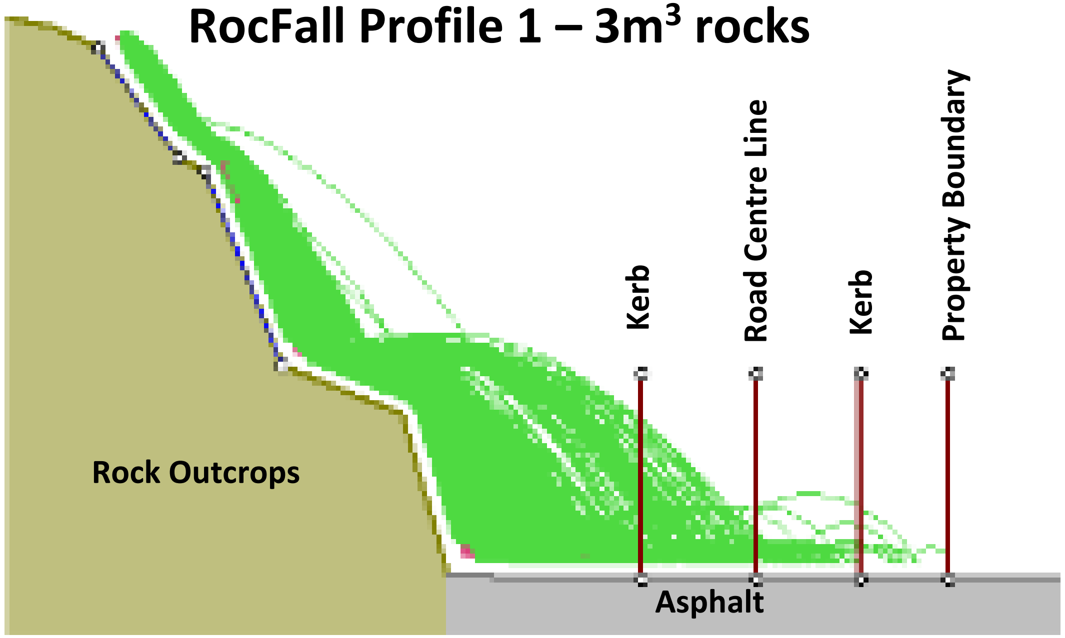
Assessed limits of future debris and individual rockfall

FIG. No. Figure 6

REV. 0

Appendix B: RocFall Analysis Outputs

RocFall Profile 1 – 3m³ rocks



Parameters:

Rock Outcrops – R_n = 0.53 +/- 0.04, R_t = 0.99 +/- 0.04, DF = 0.84 +/- 0.04, RR = 1.31 +/- 0.02

Asphalt – R_n = 0.4 +/- 0.04, R_t = 0.9 +/- 0.03, DF = 0.78 +/- 0.04, RR = 0.425 +/- 0.01

Model inputs:

Rigid body, rock types square and super ellipse^6, scale R_n by mass where C = 1000, horizontal velocity 1.5 m/s

Model outputs:

0.59% of rocks passing centre line of the road

0.08% of rocks passing curb of the road furthest from the cliff

0% of rocks passing footpath furthest from the cliff

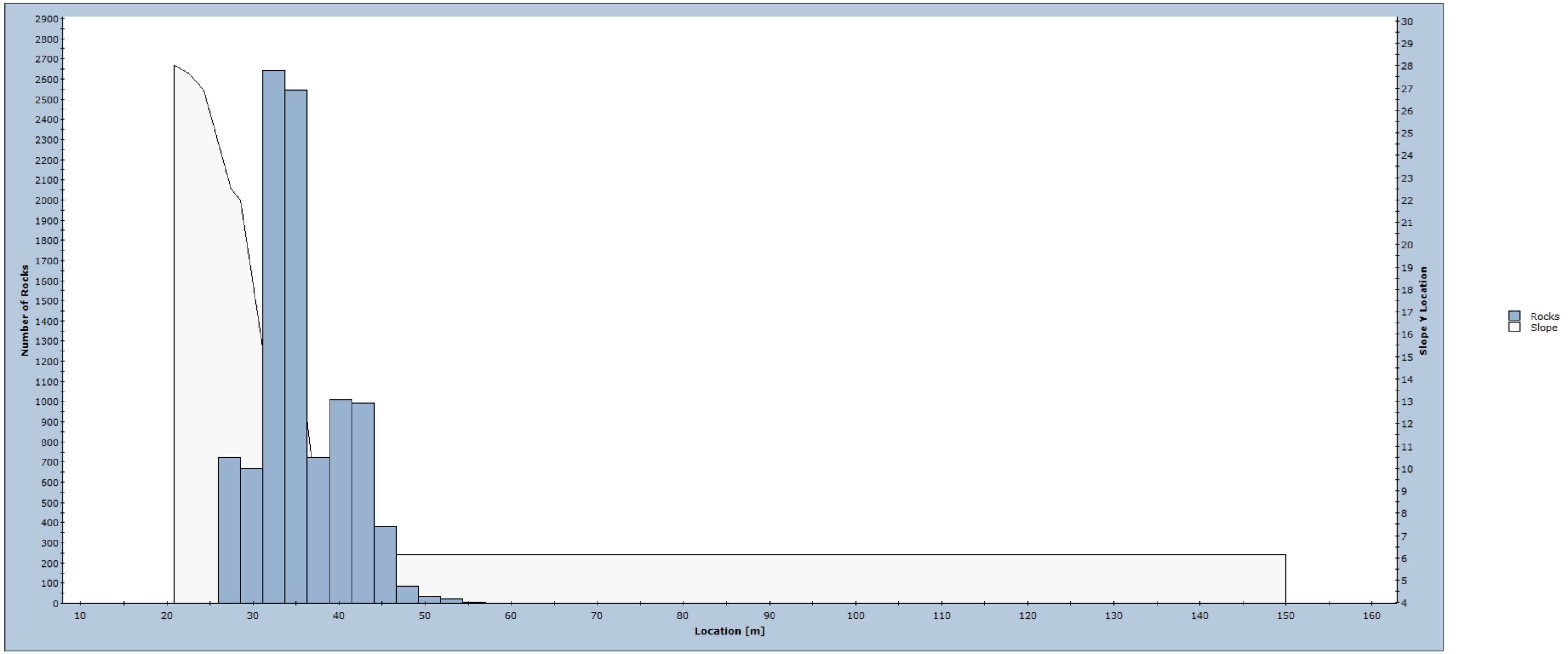
RocFall Model

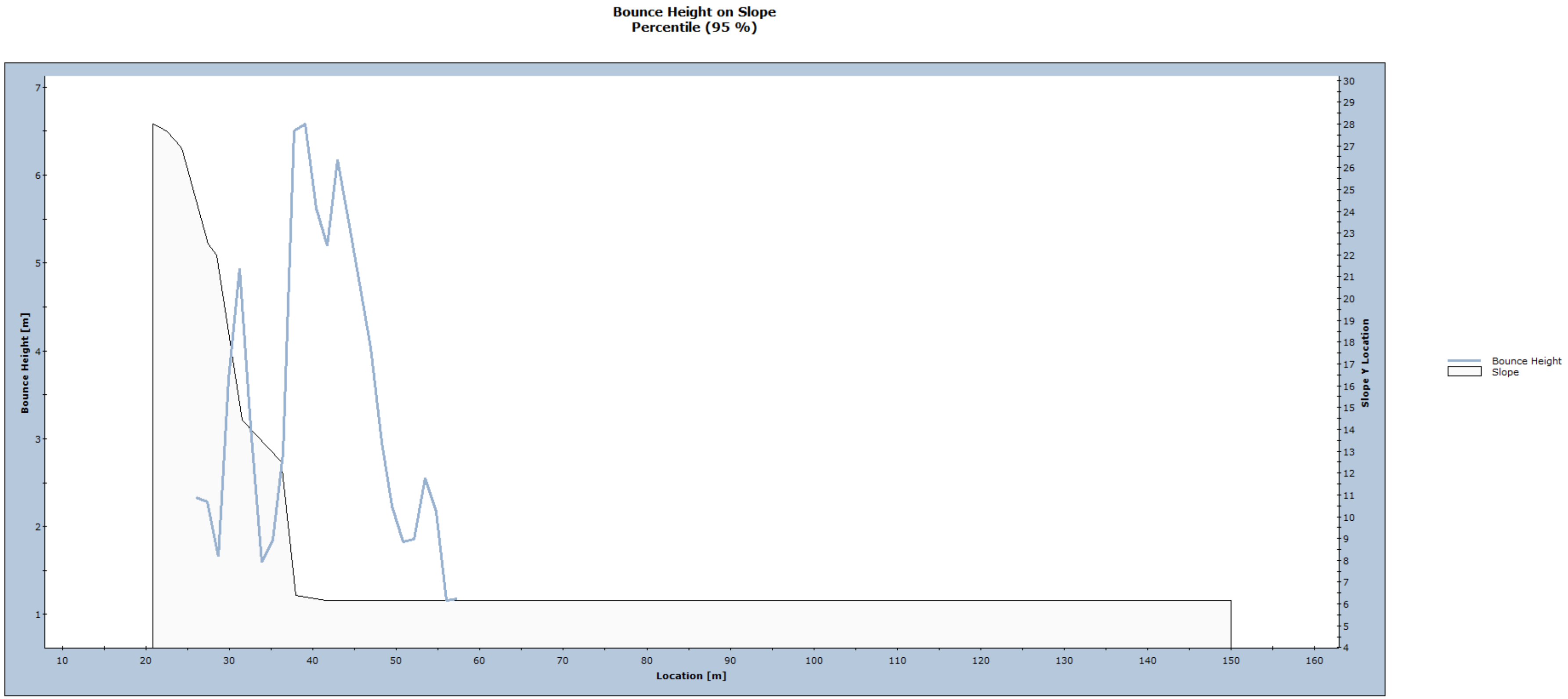
12/01/2017

T+T reference 1001107

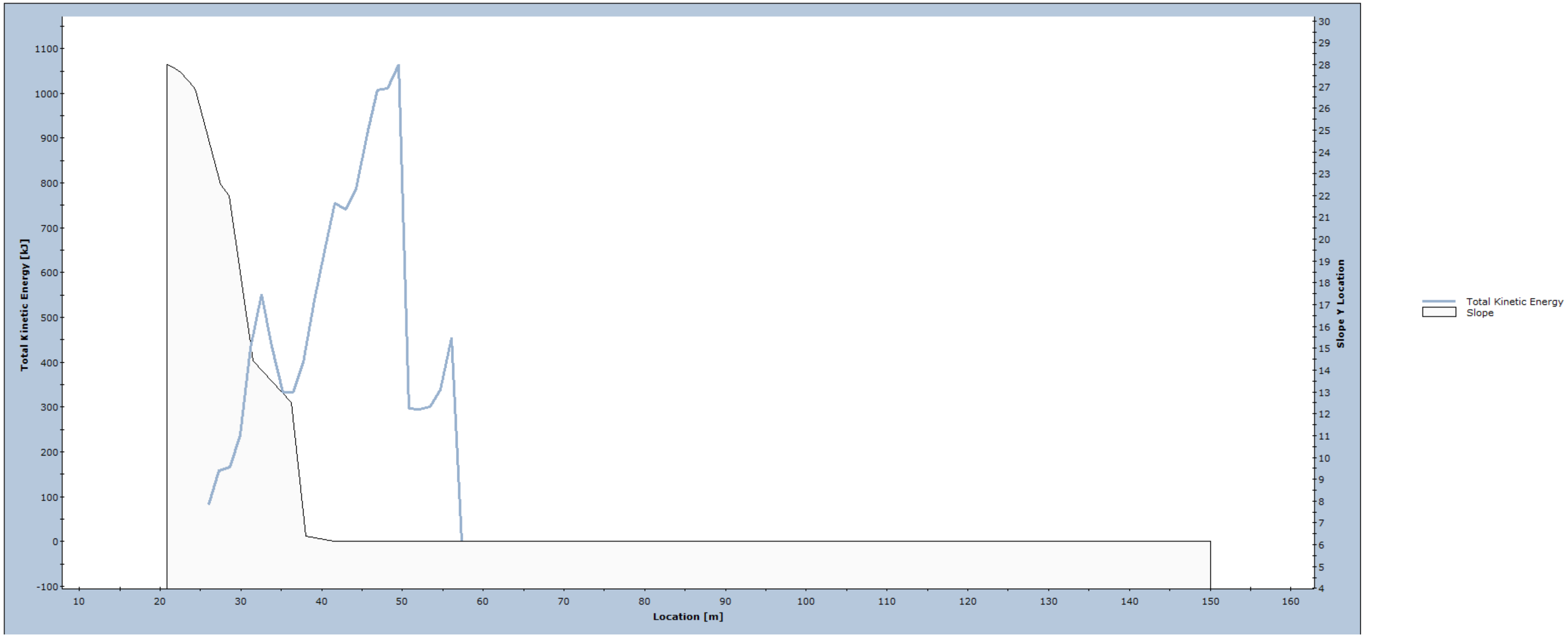
Model by adw

Distribution of Rock Path End Locations

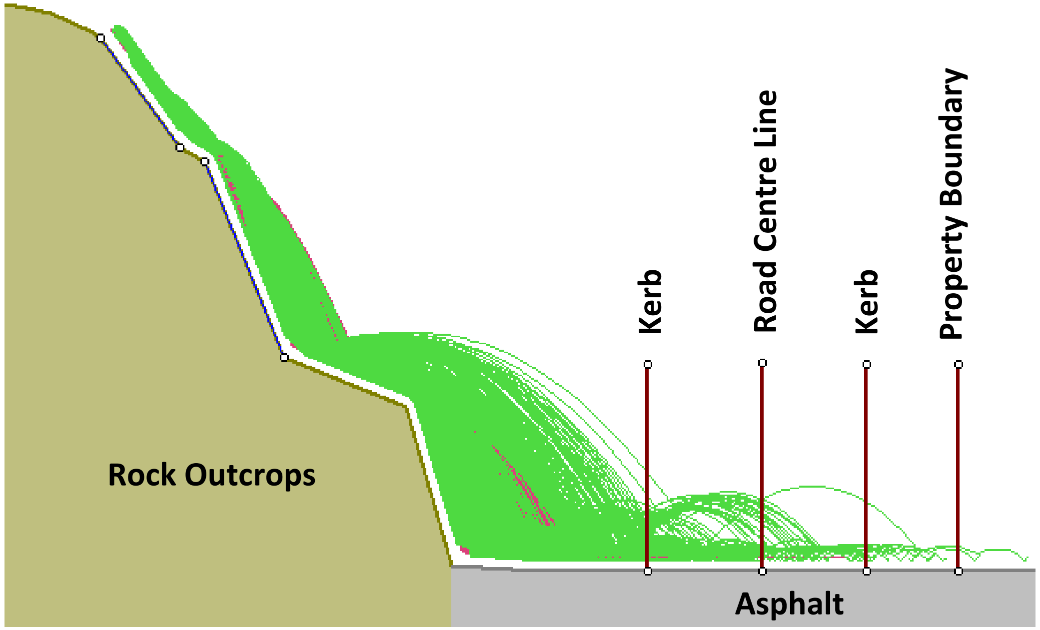



Bounce Height on Slope
Percentile (95 %)
Bounce Height [m]
Slope Y Location
Location [m]
Bounce Height
Slope
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160

Total Kinetic Energy on Slope
Percentile (95 %)



RocFall Profile 1 – 1m³ rocks



Parameters:

Rock Outcrops – R_n = 0.53 +/- 0.04, R_t = 0.99 +/- 0.04, DF = 0.84 +/- 0.04, RR = 1.31 +/- 0.02

Asphalt – R_n = 0.4 +/- 0.04, R_t = 0.9 +/- 0.03, DF = 0.78 +/- 0.04, RR = 0.425 +/- 0.01

Model inputs:

Rigid body, rock types square and super ellipse^6, scale R_n by mass where C = 1000, horizontal velocity 1.5 m/s

Model outputs:

0.44% of rocks passing centre line of the road

0.13% of rocks passing curb of the road furthest from the cliff

0.02% of rocks passing footpath furthest from the cliff

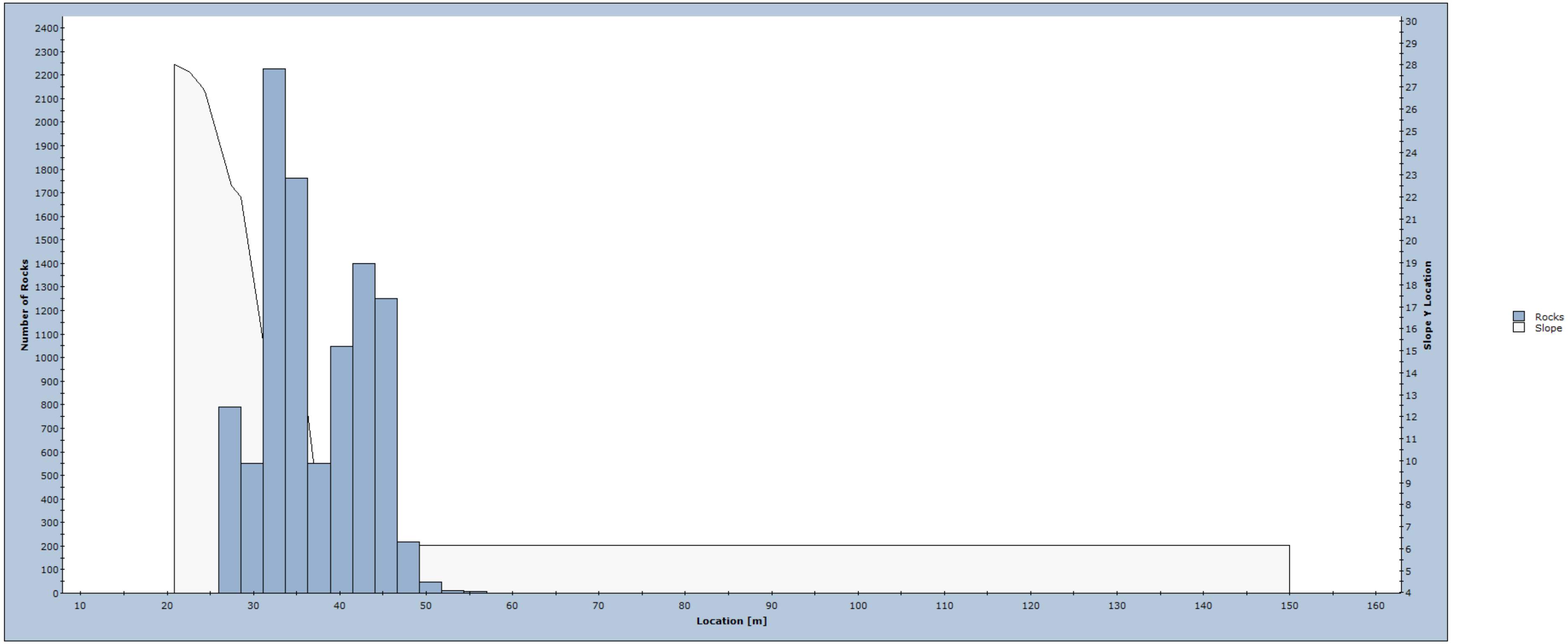
RocFall Model

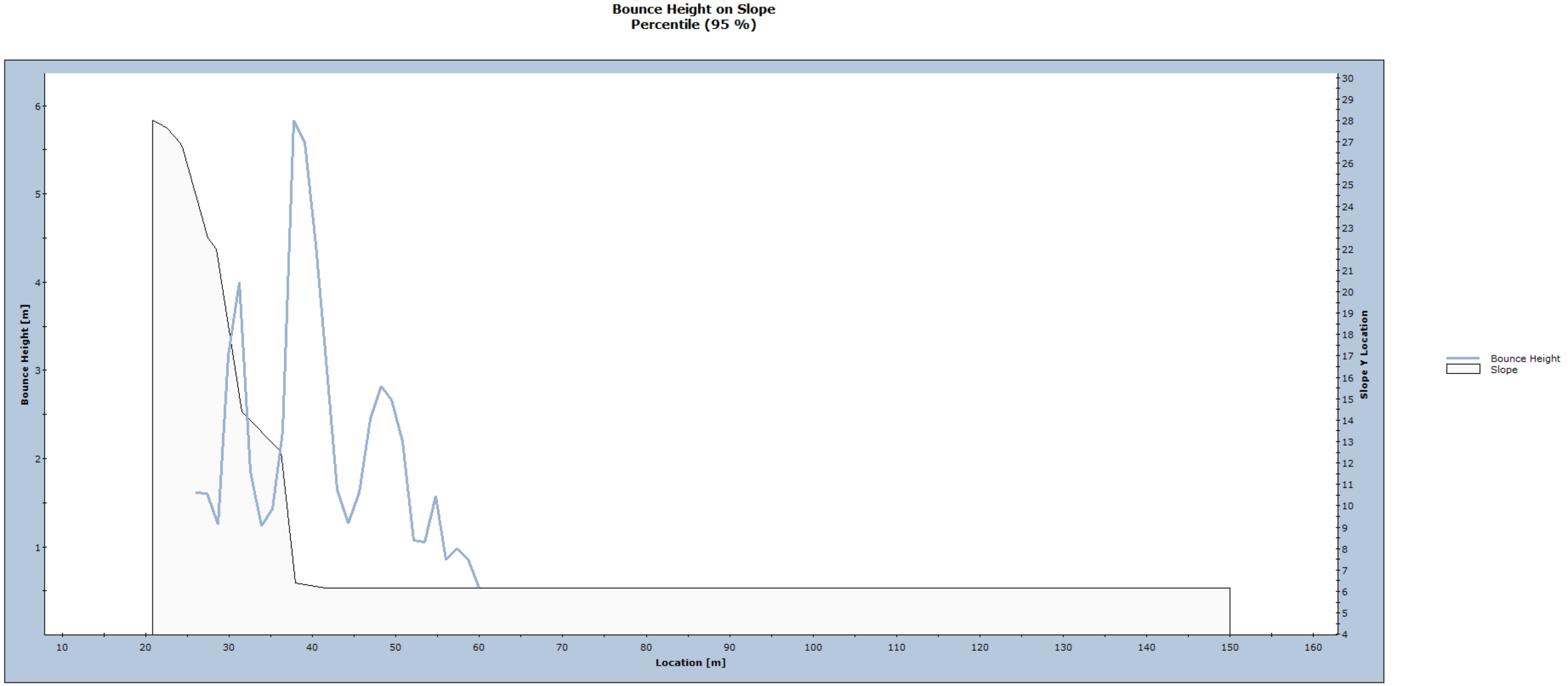
12/01/2017

T+T reference 1001107

Model by adw

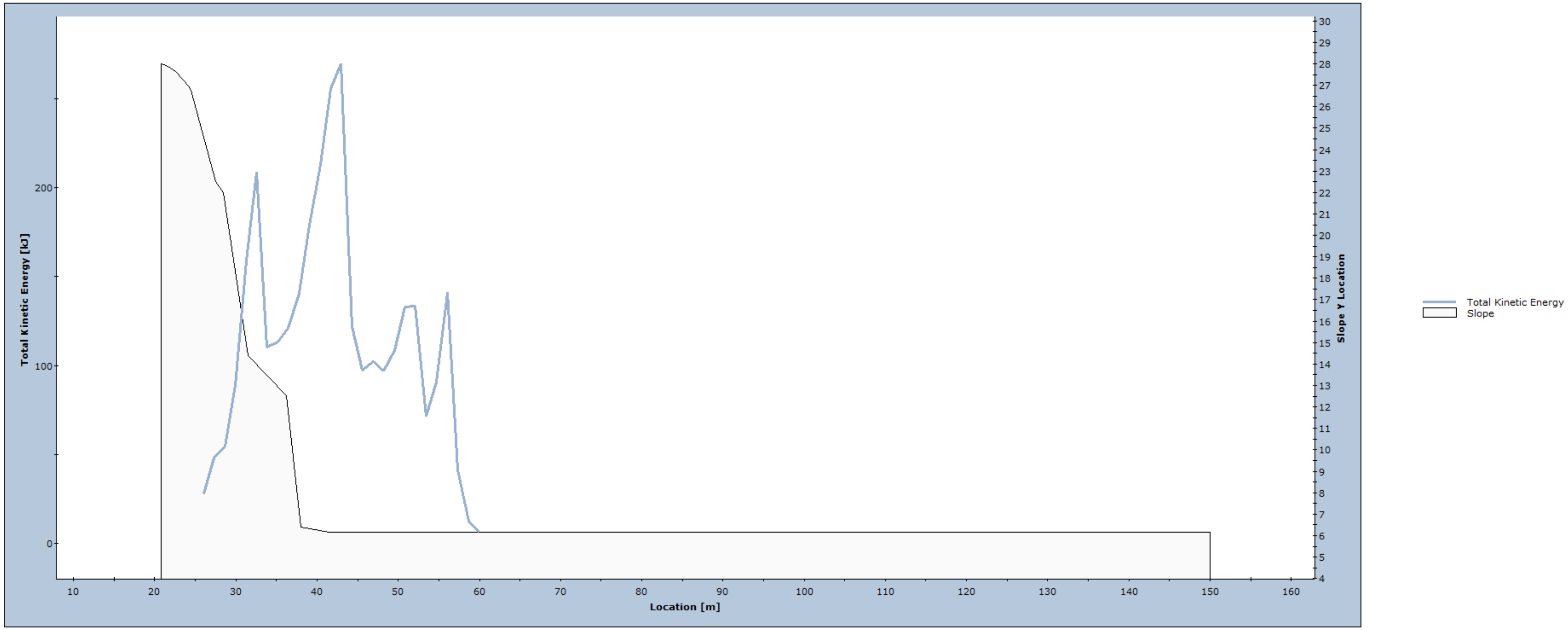
Distribution of Rock Path End Locations



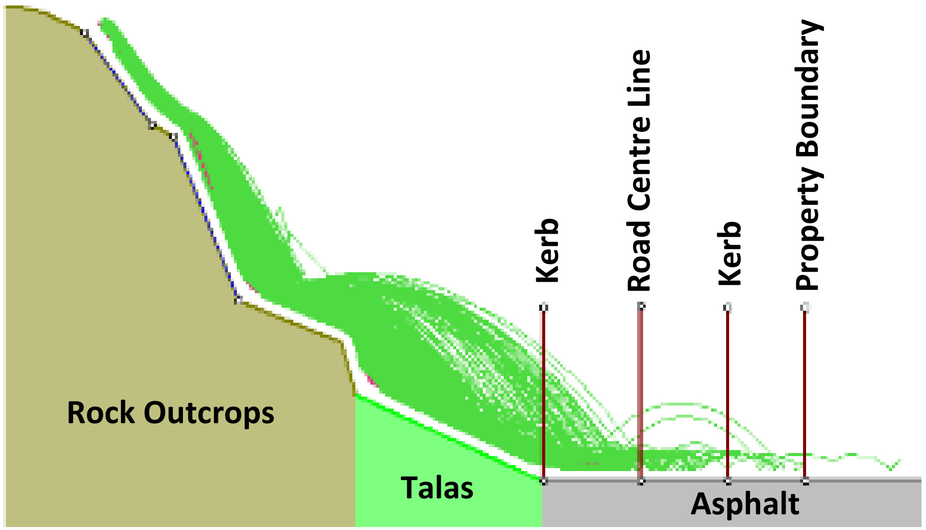


Bounce Height on Slope
Percentile (95 %)
Bounce Height [m]
Slope Y Location
Location [m]
Bounce Height
Slope

Total Kinetic Energy on Slope
Percentile (95 %)



RocFall Profile 1 with talus – 3m³ rocks



Parameters:

Rock Outcrops – R_n = 0.53 +/- 0.04, R_t = 0.99 +/- 0.04, DF = 0.84 +/- 0.04, RR = 1.31 +/- 0.02

Talas – R_n = 0.32 +/- 0.04, R_t = 0.8 +/- 0.04, DF = 0.5 +/- 0.04, RR = 0.3 +/- 0.04

Asphalt – R_n = 0.4 +/- 0.04, R_t = 0.9 +/- 0.03, DF = 0.78 +/- 0.04, RR = 0.425 +/- 0.01

Model inputs:

Rigid body, rock types square and super ellipse^6, scale R_n by mass where C = 1000, horizontal velocity 1.5 m/s

Model outputs:

0.55% of rocks passing centre line of the road

0.10% of rocks passing curb of the road furthest from the cliff

0.01% of rocks passing footpath furthest from the cliff

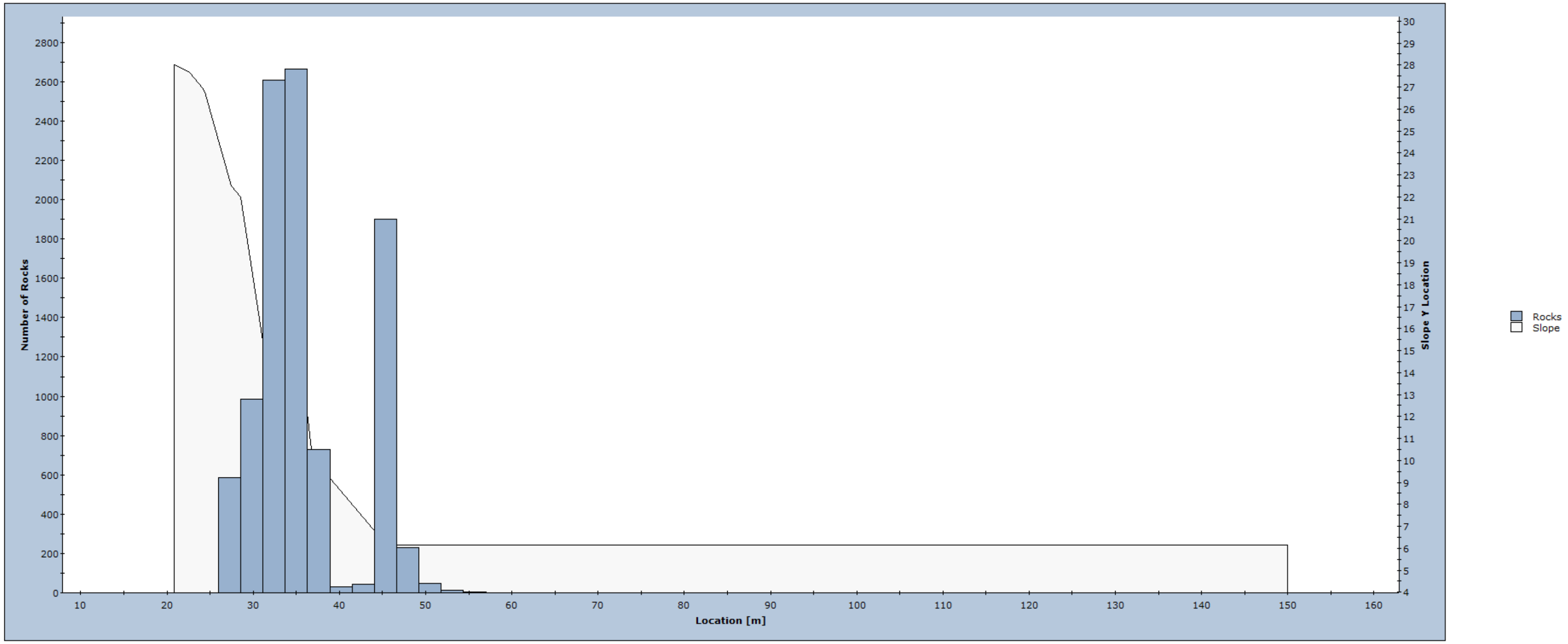
RocFall Model

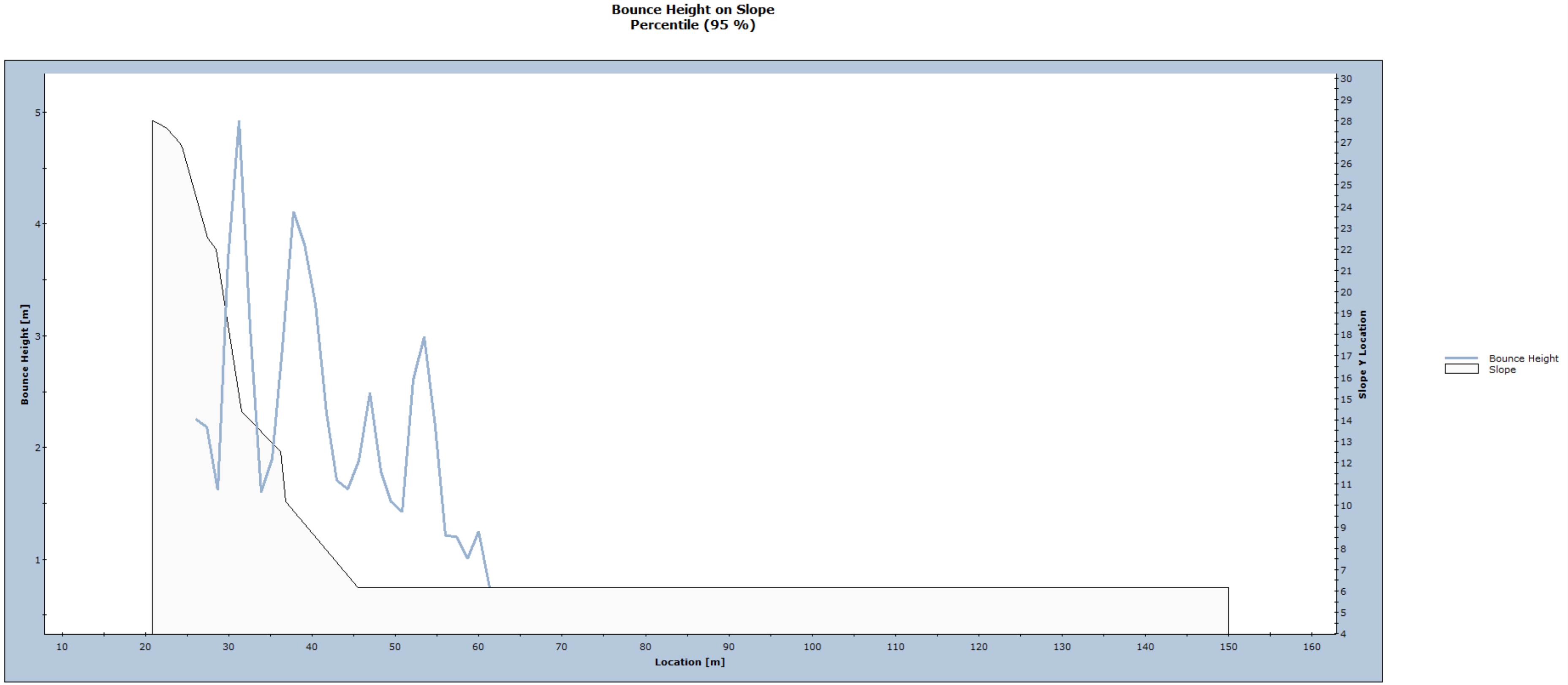
12/01/2017

T+T reference 1001107

Model by adw

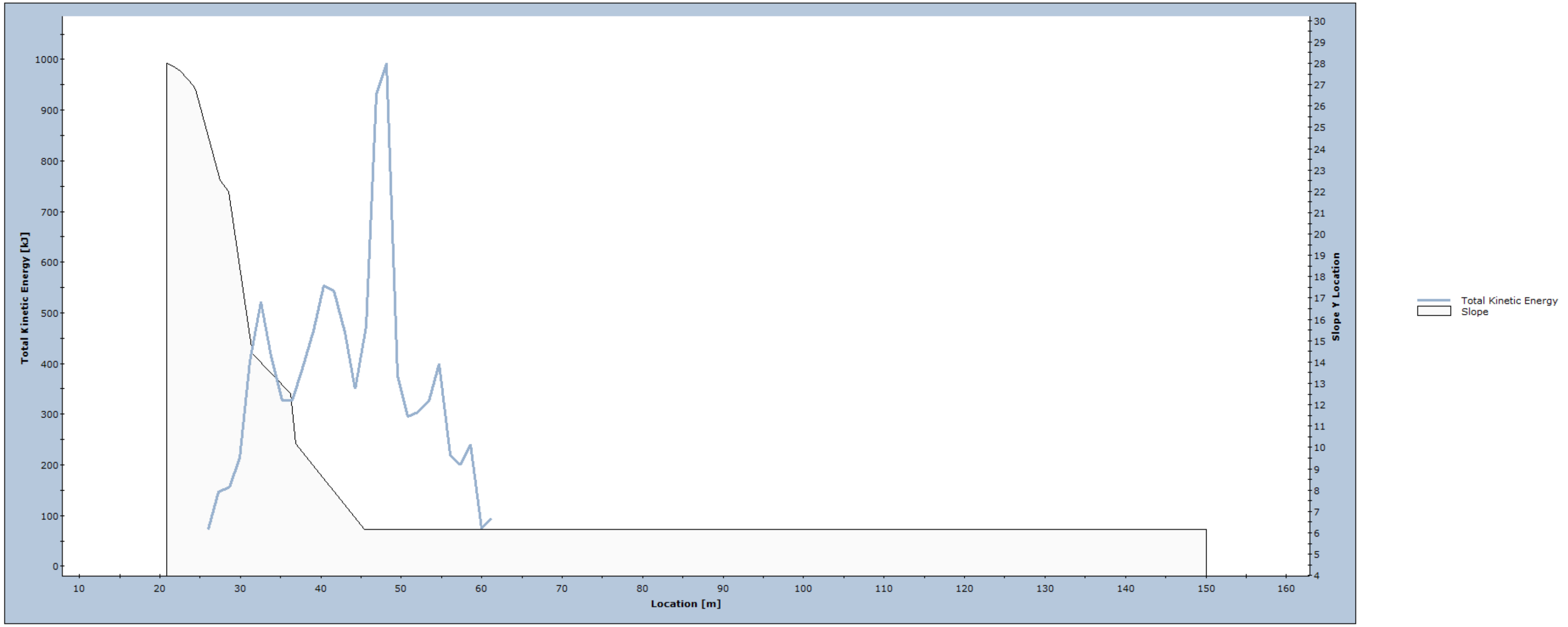
Distribution of Rock Path End Locations



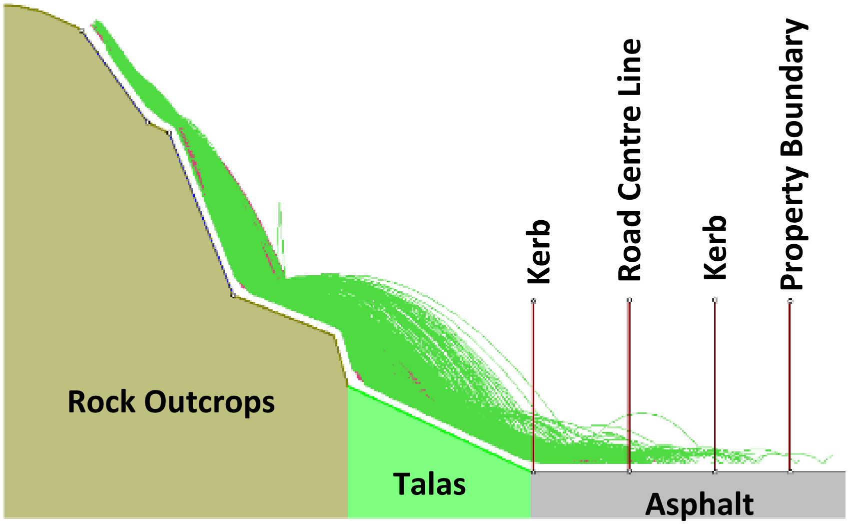


Bounce Height on Slope
Percentile (95 %)
Bounce Height [m]
Slope Y Location
Location [m]
Bounce Height
Slope

Total Kinetic Energy on Slope
Percentile (95 %)



RocFall Profile 1 with talus – 1m³ rocks



Parameters:

Rock Outcrops – R_n = 0.53 +/- 0.04, R_t = 0.99 +/- 0.04, DF = 0.84 +/- 0.04, RR = 1.31 +/- 0.02

Talas – R_n = 0.32 +/- 0.04, R_t = 0.8 +/- 0.04, DF = 0.5 +/- 0.04, RR = 0.3 +/- 0.04

Asphalt – R_n = 0.4 +/- 0.04, R_t = 0.9 +/- 0.03, DF = 0.78 +/- 0.04, RR = 0.425 +/- 0.01

Model inputs:

Rigid body, rock types square and super ellipse^6, scale R_n by mass where C = 1000, horizontal velocity 1.5 m/s

Model outputs:

1.0% of rocks passing centre line of the road

0.15% of rocks passing curb of the road furthest from the cliff

0.02% of rocks passing footpath furthest from the cliff

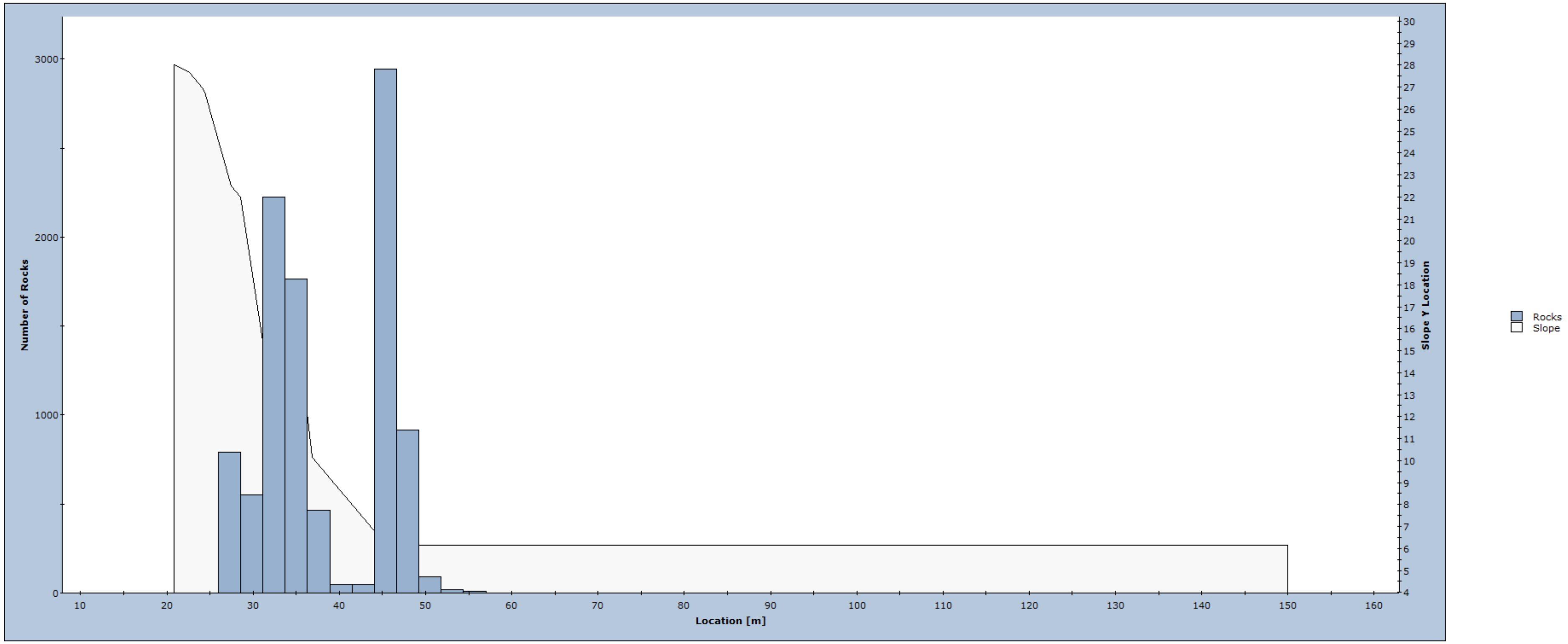
RocFall Model

12/01/2017

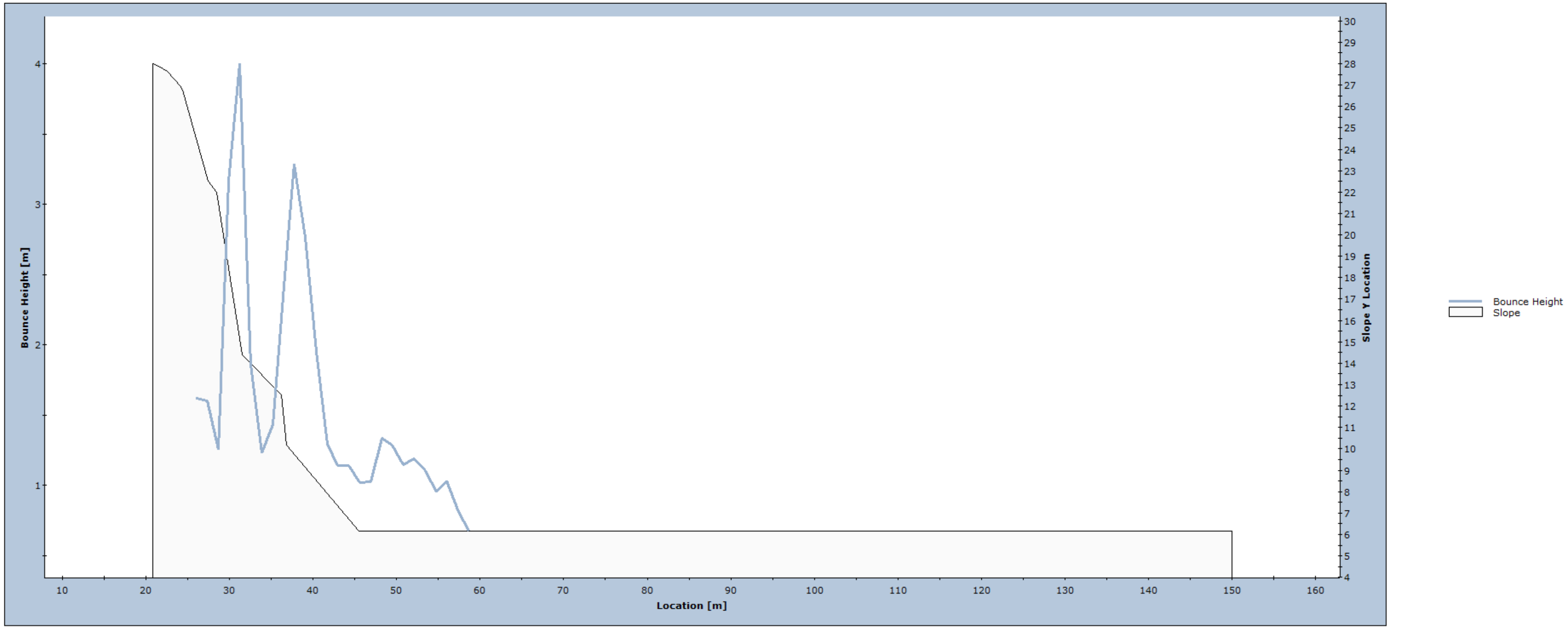
T+T reference 1001107

Model by adw

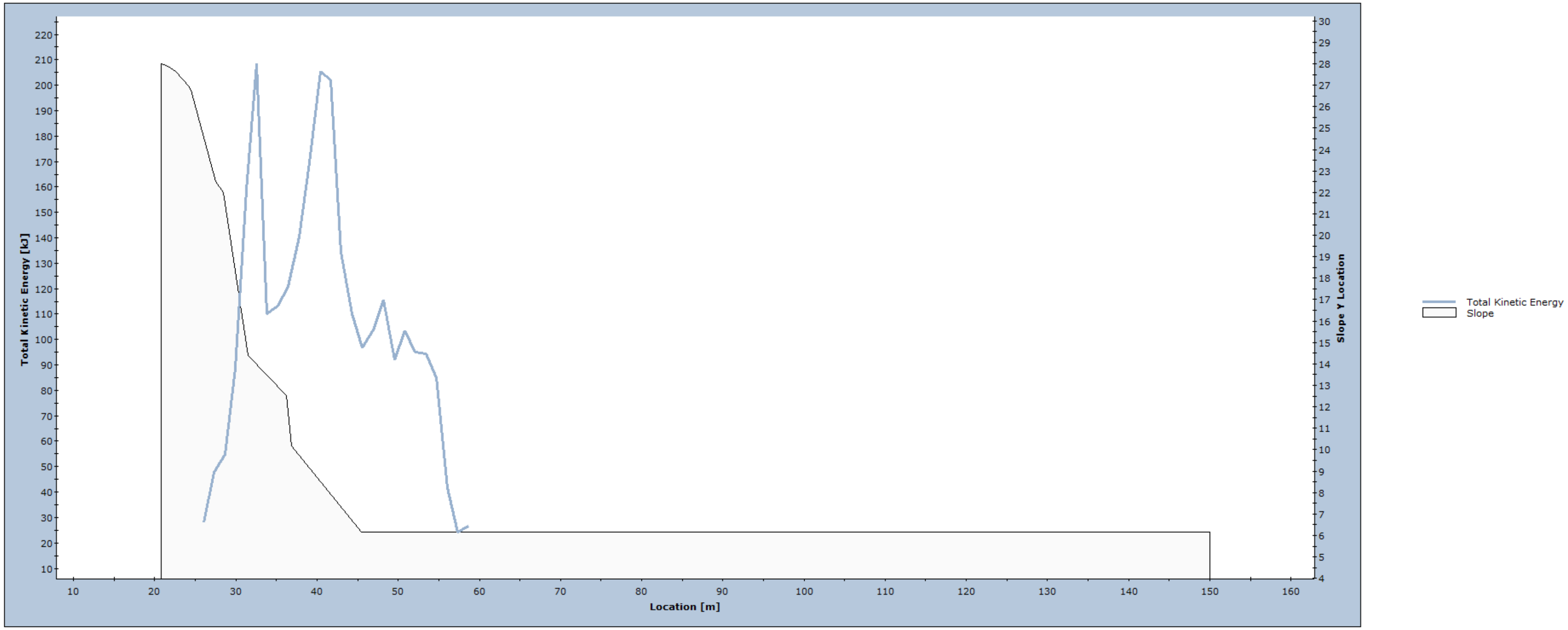
Distribution of Rock Path End Locations



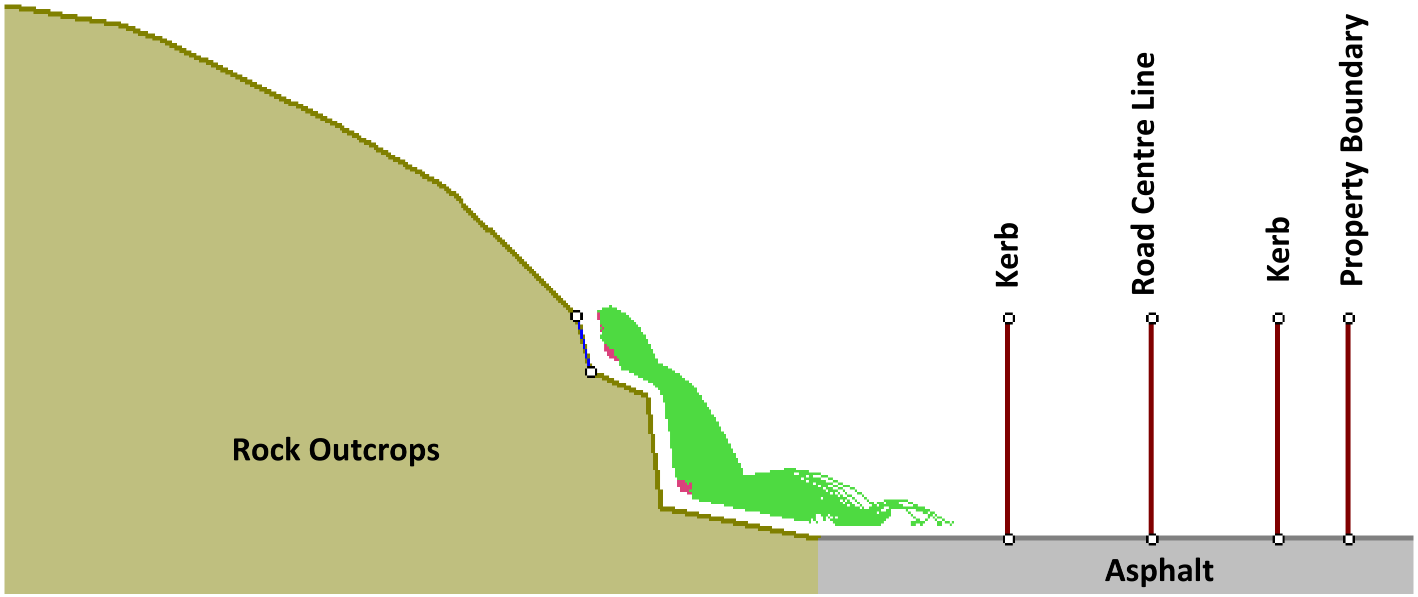
Bounce Height on Slope
Percentile (95 %)



Total Kinetic Energy on Slope
Percentile (95 %)



RocFall Profile 2 – 3m³ rocks



Parameters:

Rock Outcrops – R_n = 0.53 +/- 0.04, R_t = 0.99 +/- 0.04, DF = 0.84 +/- 0.04, RR = 1.31 +/- 0.02

Asphalt – R_n = 0.4 +/- 0.04, R_t = 0.9 +/- 0.03, DF = 0.78 +/- 0.04, RR = 0.425 +/- 0.01

Model inputs:

Rigid body, rock types square and super ellipse^6, scale R_n by mass where C = 1000, horizontal velocity 1.5 m/s

Model outputs:

No rocks entering road lane closest to cliff

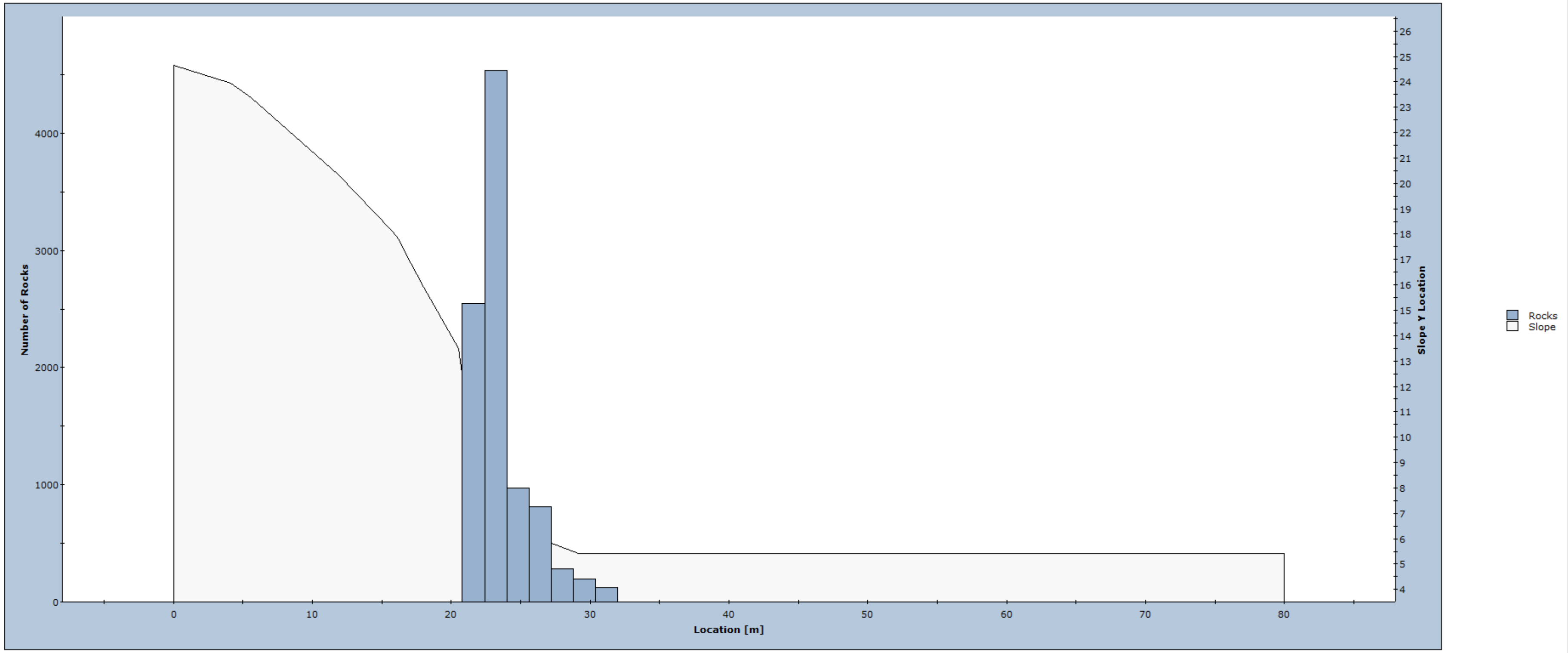
RocFall Model

12/01/2017

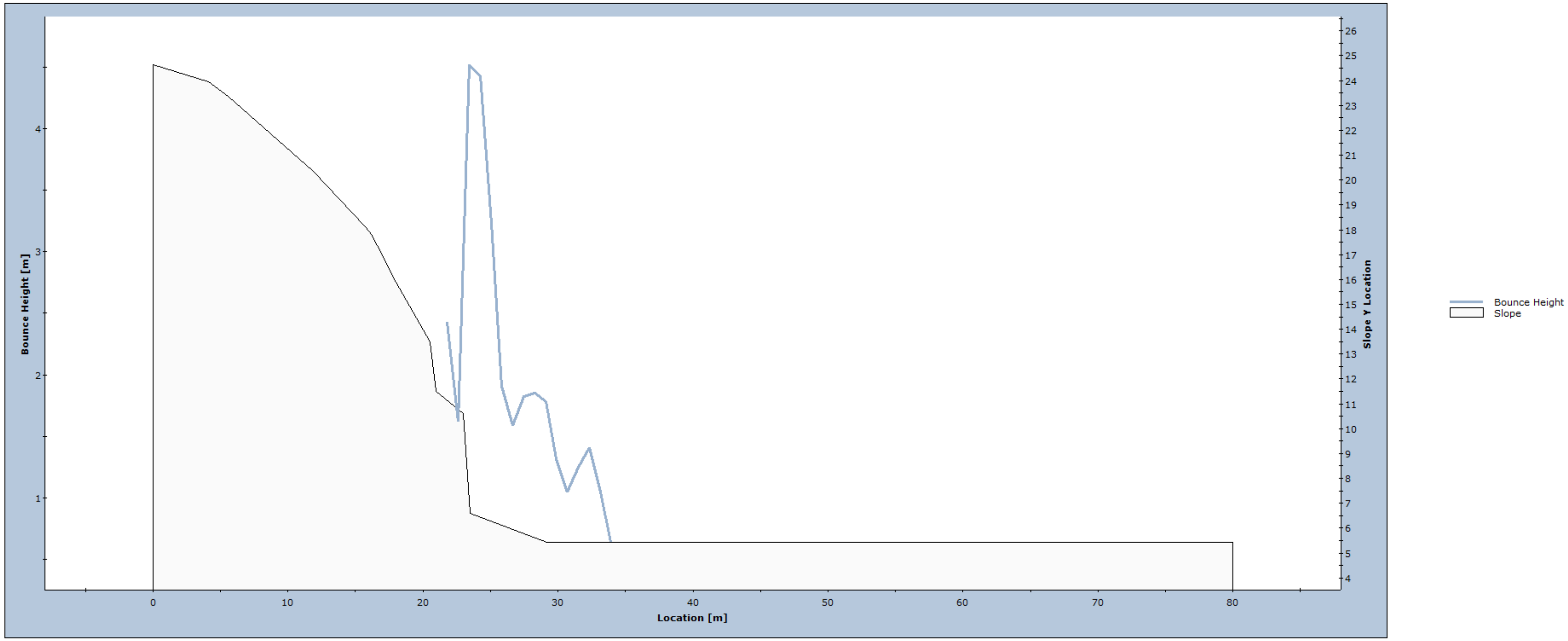
T+T reference 1001107

Model by adw

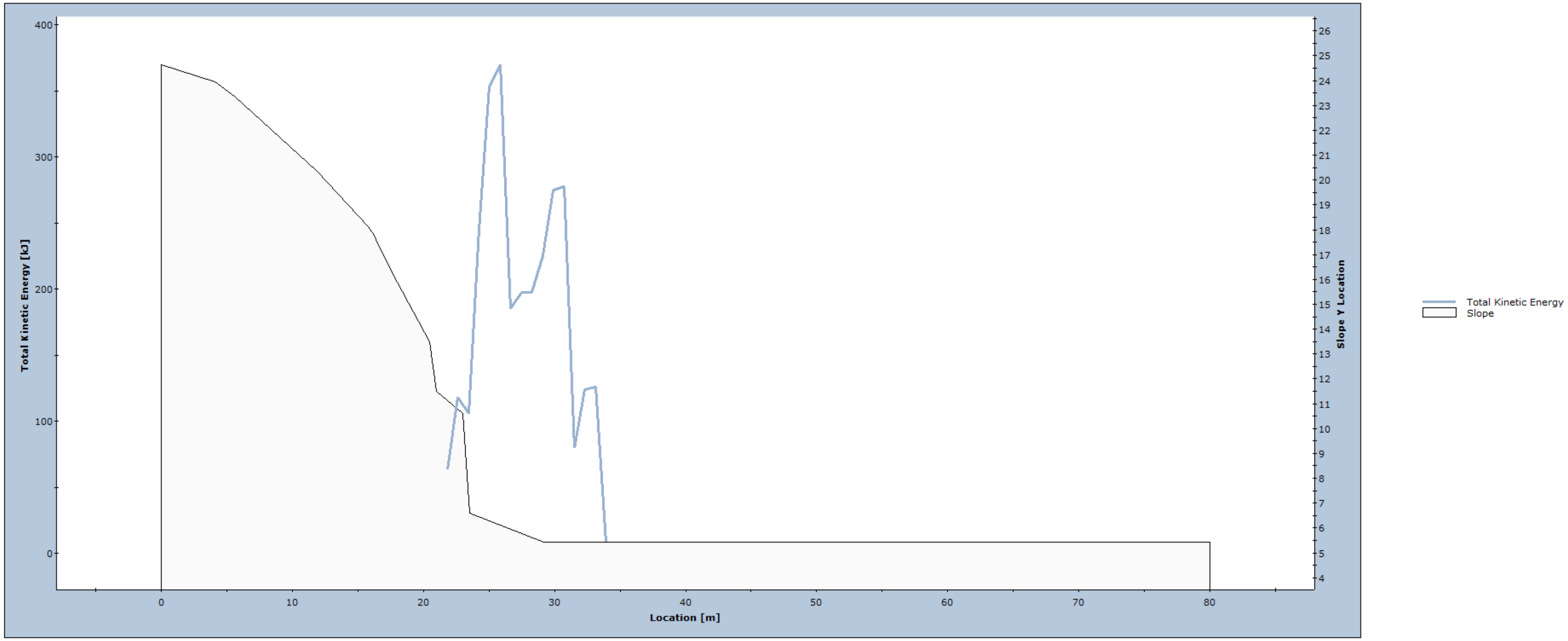
Distribution of Rock Path End Locations



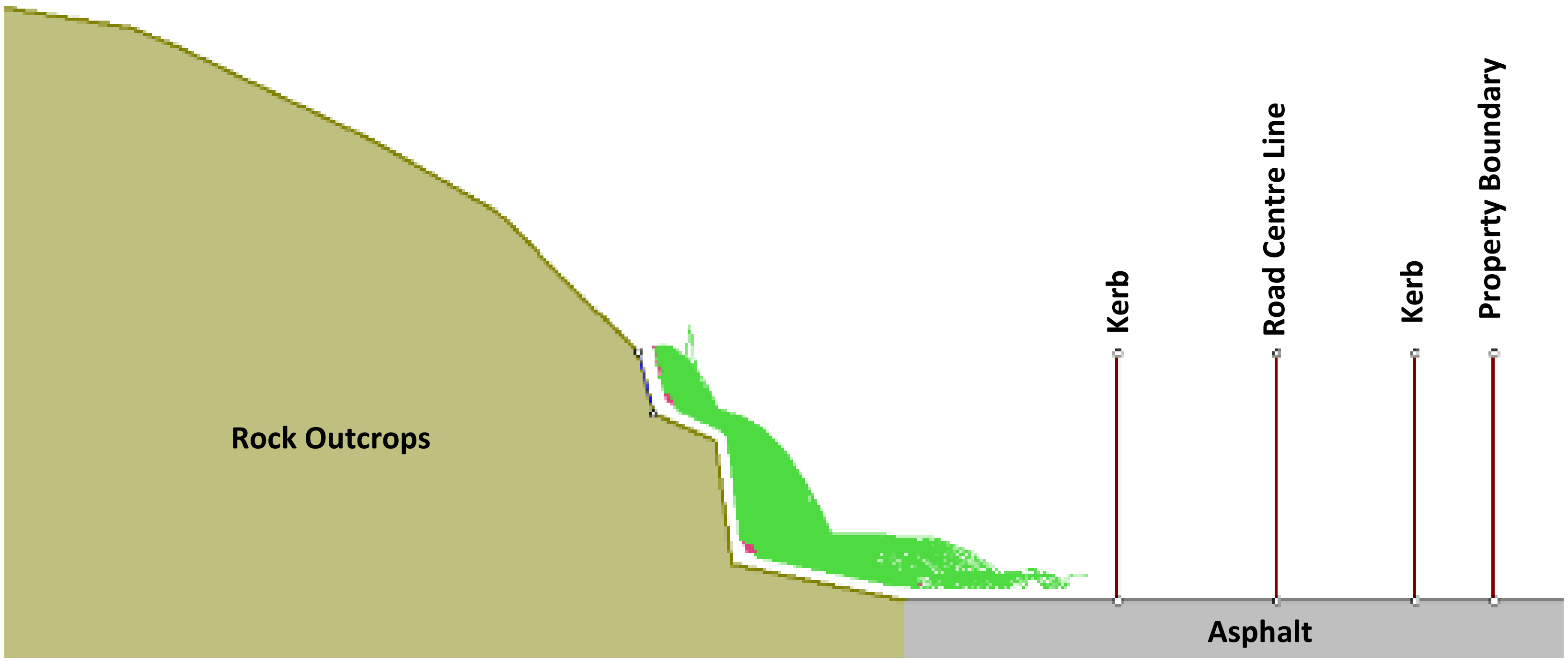
Bounce Height on Slope
Percentile (95 %)



Total Kinetic Energy on Slope
Percentile (95 %)



RocFall Profile 2 – 1m³ rocks



Parameters:

Rock Outcrops – R_n = 0.53 +/- 0.04, R_t = 0.99 +/- 0.04, DF = 0.84 +/- 0.04, RR = 1.31 +/- 0.02

Asphalt – R_n = 0.4 +/- 0.04, R_t = 0.9 +/- 0.03, DF = 0.78 +/- 0.04, RR = 0.425 +/- 0.01

Model inputs:

Rigid body, rock types square and super ellipse^6, scale R_n by mass where C = 1000, horizontal velocity 1.5 m/s

Model outputs:

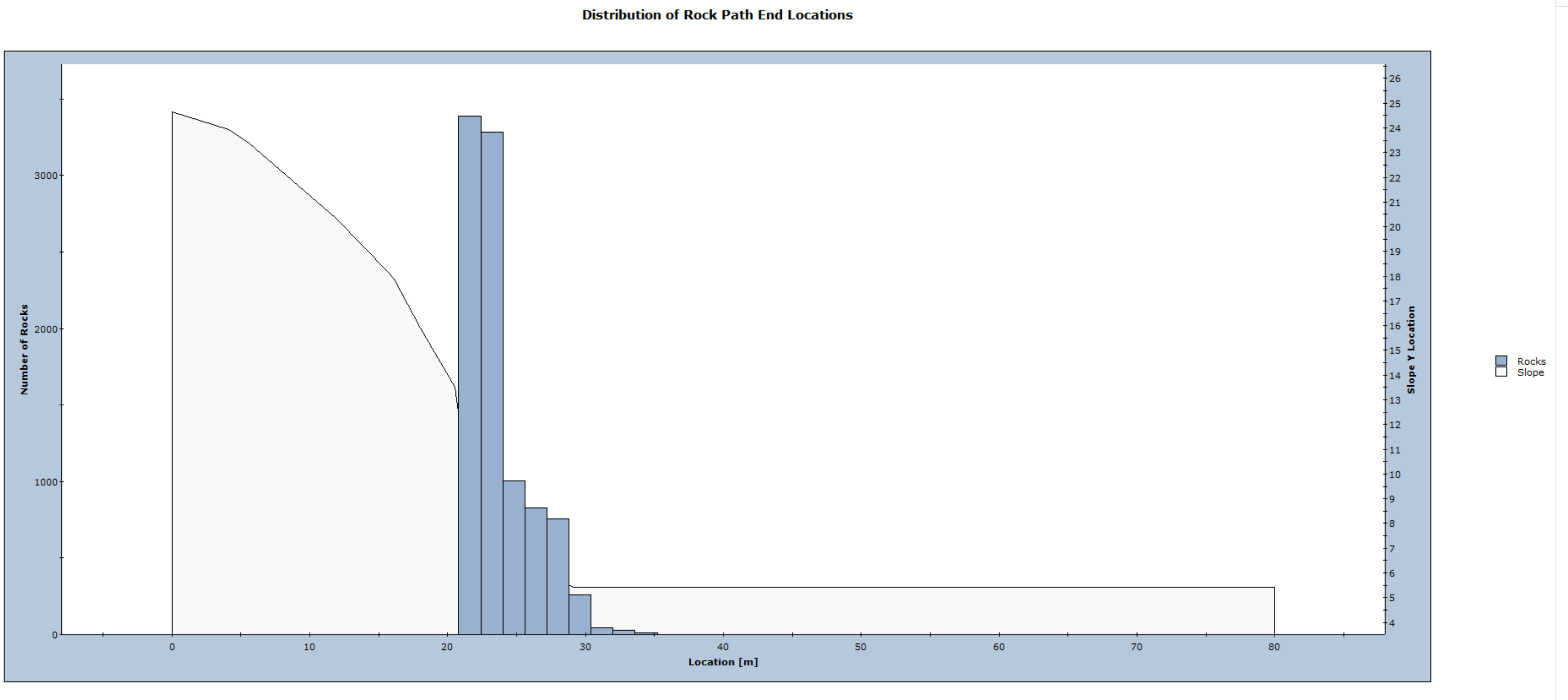
No rocks entering road lane closest to cliff

RocFall Model

12/01/2017

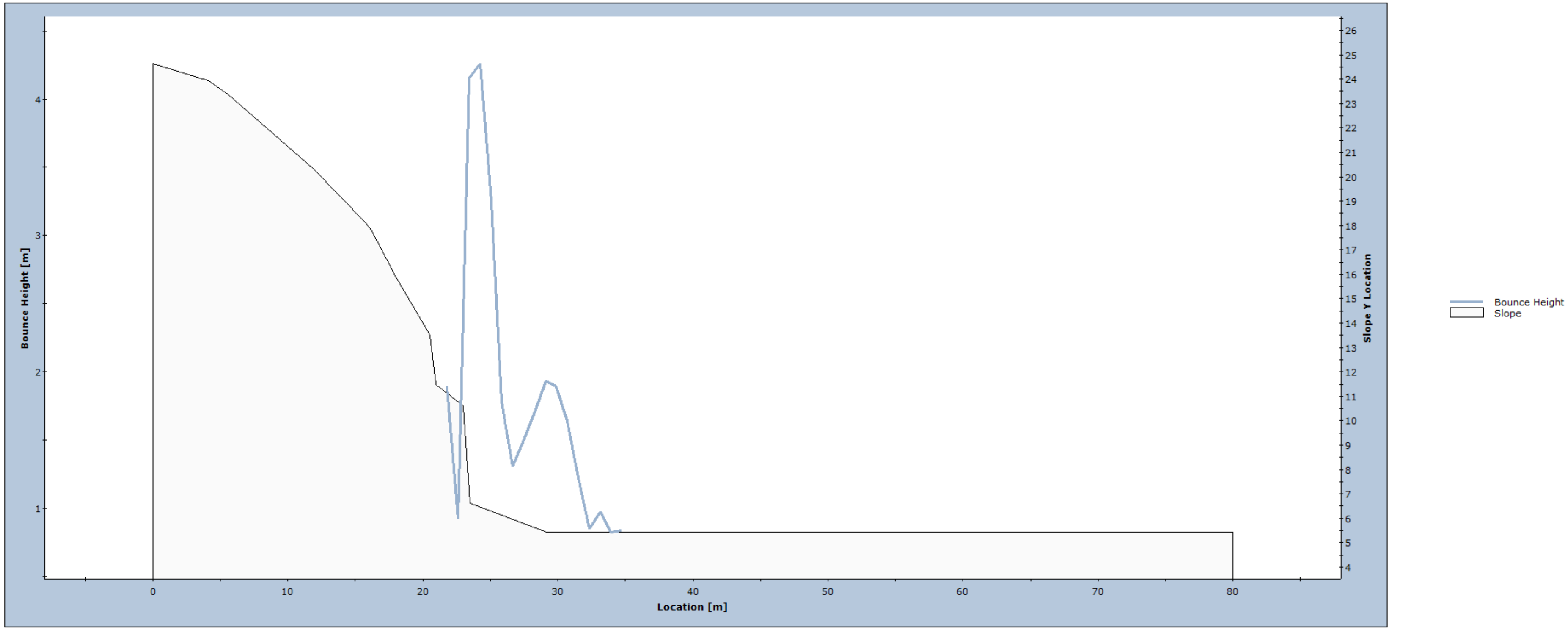
T+T reference 1001107

Model by adw

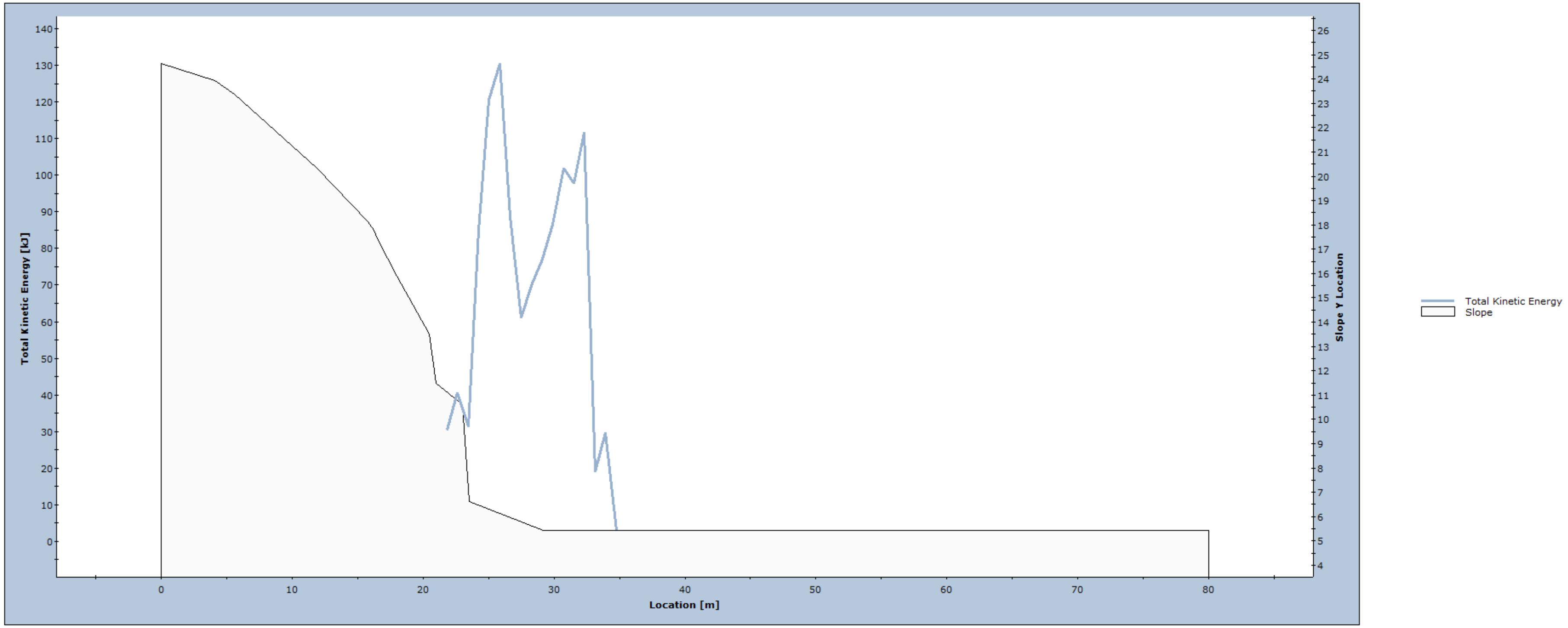


Distribution of Rock Path End Locations
Number of Rocks
0
1000
2000
3000
Location [m]
0
10
20
30
40
50
60
70
80
Slope Y Location
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
Rocks
Slope

Bounce Height on Slope
Percentile (95 %)



Total Kinetic Energy on Slope
Percentile (95 %)



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