The identification and modelling of rockfalls for protection measures in the Western Cape

by
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DECLARATION

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ABSTRACT

Natural slopes and man-made cuttings in weathered, highly jointed or fractured rock with unfavourable bedding planes can result in the release of rock blocks either from above these slopes and cuttings or from the face itself resulting in what is termed a "Rockfall". Rockfalls are a global phenomenon and much research has been done in countries like Switzerland, Italy, United States of America and Canada. Some of these countries have contributed to the field by developing their own software packages to model potential rockfalls or those rockfalls that have already occurred and assist in locating the position of rockfall mitigation measures such as catch fences. This research project covers the occurrence of rockfalls at three specific sites within the Western Cape in South Africa. This project was undertaken as very little is known about rockfalls in the Western Cape, let alone South Africa. And what little is known is not well documented or published.

Three sites were chosen which included Chapman's Peak Drive, Sir Lowry's Pass and The Cliffs. Chapman's Peak Drive is a world renowned pass located on the Western side of the peninsula, whilst Sir Lowry's Pass is located between Somerset West and Grabouw and forms part of the National Route 2. The Cliffs used to serve as a hard rock quarry and is located in Tygervalley and now forms the backdrop to office complexes.

The geology of two of the three sites that were studied is located in the Malmesbury Group, which covers a large percentage of the Western Cape, whereas the third site is located in both the Table Mountain Supergroup and the Cape Granite.

The aim of the research project was to combine the collection of data through fieldwork with rockfall software programs in areas that are known to have experienced rockfalls to assist in mitigating the problem by avoiding over design and thereby reducing the overall cost of the project. This was achieved by the use of ArcGIS 10.0, Rapid Mass Movement System (RAMMS) Rockfall (trial version) and Rocscience Rocfall 4.0. Field inspections were carried out for each of the study areas, followed by terrestrial surveys. The terrestrial survey information was used to produce an ASCII file which is the required input file for RAMMS and produces 3D trajectory paths when a rockfall simulation is run. The trajectories were exported from RAMMS and draped over a 3D rendered a view of each site

for better viewing of the paths. These trajectories were then traced in AutoCAD and imported into the 2D Rocscience Rocfall software. The rockfall simulation was carried out in Rocfall and are presented in this research project.

The outcome of this project concluded that rockfall software programs are undoubtedly useful in engineering design to mitigate rockfalls and reduce overall costs of a project. However, like with anything else man-made, software programs are not without flaws and cannot replace an experienced person in the field. Unrealistic software results can only be distinguished by someone who understands the behaviour of rockfalls as certain parameters such as the coefficients of restitution require educated assumptions since there is no South African field tested database currently. Although creating a local database of these parameters will be a costly undertaking, it would significantly improve the confidence for results produced by the rockfall software programs and therefore, this warrants further research into this field.

OPSOMMING

Natuurlike hellings en mensgemaakte deurgrawings in verweerde, genate of gebreekte gesteentes met ongunstige laagvlakke, kan daartoe lei dat gesteenteblokke van hoër areas of van die rotswand self, los kom. Hierdie verskynsel staan bekend as ‘n “rotsstorting”. Rotsstortings is globale verskynsels en baie navorsing is uitgevoer in lande soos Switserland, Italië, die Verenigde State van Amerika en Kanada. Van hierdie lande het bygedra tot die veld deur hul eie sagteware pakkette te ontwikkel wat potentiële rotsstortings of rotsstortings wat reeds plaasgevind het, te modelleer en om die posisie van rotsstorting versagtingmaatreëls, soos vangnette, vas te stel. Hierdie navorsingsprojek handel oor rotsstortings by drie spesifieke terreine in die Wes Kaap in Suid Afrika. Die projek was uitgevoer omrede daar baie min inligting beskikbaar is oor rotsstortings in die Wes Kaap en, nog meer, Suid Afrika. Die inligting wat bekend is, is nie goed gedokumenteer of gepubliseer nie.

Drie terreine was gekies vir die studie en sluit in Chapman’s Peak Rylaan, Sir Lowry’s Pas en The Cliffs. Chapman’s Peak Rylaan is ‘n wêreldbekende pas wat geleë is aan die Westekant van die skiereiland, terwyl Sir Lowry’s Pas tussen Somerset-Wes en Grabouw geleë is. Die laasgenoemde pas vorm deel van die N2 (Nationale Roete 2). The Cliffs was in die verlede benut as ‘n steengroef en is geleë in Tygervallei. Dit vorm tans die agtergrond vir kantoor komplekse.

Twee van die drie terreine wat bestudeer is, is geleë in die Malmesbury Groep wat ook ‘n groot deel van Wes-Kaap gesteentes uitmaak. Die derde terrein is geleë in beide die Tafelberg Supergroep en Kaapse Graniet.

Die doel van die navorsingsprojek was om die versamelde gebiedsinligting te kombineer met rotsstorting sagteware pakette vir areas waar rotsstortings al plaasgevind het. Hierdeur kan die probleem versag word deur oor-ontwerp te voorkom en daardeur die algehele koste van die projek te verminder. Dit was bereik deur die gebruik van ArcGIS 10.0, Rapid Mass Movement System (RAMMS) Rockfall (proef weergawe) en Rocscience Rocfall 4.0. Gebied

inspeksies was uitgevoer vir elk van die studie areas, gevolg deur landelike opnames. Die informasie verkryg deur die landelike opnames was gebruik om ‘n ASCII lêer te maak, wat die benodigde invoer lêer vir RAMMS is. Wanneer ‘n rotsstorting simulasie gehardloop word, word ‘n 3D trajek geproduseer. Die trajekte was uitgevoer vanaf RAMMS en gedrapeer oor ‘n 3D beeld van elk van die drie terreine vir ‘n verbeterde aansig van die trajekte. Hierdie trajekte was oorgeteken in AutoCAD en in die 2D Rocsceience Rocfall sagteware ingevoer. Die simulasie van die rotsstorting was uitgevoer in Rocfall en word voorgelê in hierdie navorsingsprojek.

Daar kan tot die gevolgtrekking gekom word dat rotsstorting sagteware programme ongetwyfeld nuttig in die ontwerp van rotsstorting versagtingsmaatreëls is en daarby die algehele koste van die projek verlaag. Hierdie sagteware programme is, soos enige mensgemaakte verkynsel, nie sonder foute nie en kan ‘n ervare persoon op terrein nie vervang nie. Onrealistiese resultate van sagteware kan slegs uitgeken word deur ‘n persoon wat die gedrag van rotsstortings verstaan aangesien sekere parameters soos die koëffisiënt van restitusie ‘n ingeligte skatting vereis omdat daar tans geen databasis met gebiedsinligting beskikbaar is in Suid-Afrika nie. Alhoewel die maak van ‘n plaaslike databasis met hierdie parameters ‘n duur proses sal wees, sal dit die selfvertroue rondom resultate geproduseer deur rotsstorting sagteware programme aansienlik verbeter, en om hierdie rede kan verdere navorsing in hierdie gebied geregverdig word.

DEDICATION

This research project is dedicated in memory of *Michelle Steven*, one of the most inspirational and supportive people that I have ever had the pleasure of knowing. I am extremely grateful for having met you and for the impact that you had in my life. As an angel, Rock On.

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1.1 BACKGROUND AND MOTIVATION FOR STUDY

Rockfalls are a major hazard in road and railway rock cuttings in mountainous terrains as well as in quarries, open-pit mines and structures built on or below cliffs. According to Hoek (2007), the number of people that are killed by rockfalls tends to be in the same order as people killed by all other forms of rock slope instability.

The problem of rockfalls is common in South Africa as well. In the Western Cape, several incidents have occurred in recent years. Five fatal incidents caused by rockfalls had occurred at Chapman's Peak Drive in the twelve years prior to the rehabilitation that took place in 2002/2003.

Following the completion of the installation of the rockfall mitigation structures at Chapman's Peak Drive, extensive damage was caused to these rockfall protection measures after heavy rainfalls during July 2004 and August 2004 (Melis, 2004). This incident led to a temporary road closure. The impact of rainfall on rockfall was confirmed during this event. The four incidences of heavy rainfall resulted in several debris flows and rockfalls, most of which were safely intercepted by the catch fences. However, 4 catch fences were breached by large debris flows and as a result, the road was closed from the 23 July 2004 until the 16 September 2004 while repairs and reconstruction of the fences were undertaken (Melis, 2004).

Two years later, on the 5 April 2006, a rockfall event impacted the road at stake value 30 530m and caused damage to a vehicle. Although extensive damage was done to the vehicle bonnet and roof, the occupants of the vehicle were, fortunately, unharmed (Melis, 2006). On the 3 August 2006, another rockfall event occurred at Chapman's Peak Drive breaching 4 fields of Catch Fence 11. The event occurred during the early hours of the morning and no traffic was on the roadway. The severe damage caused to the catch fence resulted in road closure once again from the 3 August to the 4 September 2006 whilst repairs were carried out (Haskins, 2006). The rockfall event also triggered movement in an inactive preexisting debris slide. On the 19 August 2006, this reactivation of the debris slide resulted in a slip failure.

In 2007, another rain event caused further rockfalls and slope instability. A number of catch fences were activated which results in the brake rings being "pulled". An estimated volume of material of 40m^3 of debris breached Catch Fence 2A. In a separate incident, a rock larger than 20m^3 occurred in the vicinity of SV 29 410 – 29 430 which also breached and caused damage to Catch Fences 15 and 15A (Melis, 2007).

Once again, following heavy rains, very large rockfalls occurred on Sir Lowry's Pass and injured 12 people which resulted in the temporary road closure. (Mposo, 2012)

Yet, another event occurred at Chapman's Peak Drive on the 2 June 2013 at stake value 25 180 after heavy rains. The event entailed the falling off completely weathered granite which broke up into debris upon landing on the ground. This event occurred where no protection measures were put in place and although the material landed on the road, no damage was identified on the road (Melis, 2013).

According to the online newspaper news24, on the 17 November 2013, severe weather resulted in road closures along the R44 Clarence Drive, the main road in Kalk Bay between Clovelly and Fish Hoek flooding, mudslides and rockfalls as well as Chapman's Peak Drive (www.news24.com, 2013).

The old quarry in Tygervalley had previously been mined for greywacke and quartzitic sandstone for railway ballast. It was proposed to be developed as a Tyger Waterfront which consisted of 10 storey blocks with parking garages. The quarry side slopes were seen to possibly be unstable and due to the close proximity to the development and potential rockfall hazard, a geotechnical investigation was carried out (Haskins, 2005). Years later a boulder came down and crashed into a window, further protection measures were put into place. In 2014, another boulder rolled into a gabion wall and although it damaged the wall, the boulder was stopped from impacting the building. A few more boulders have been identified on the slope with the potential to release into the gabion wall.

This research study is to understand the causes of rockfall and input realistic data into rockfall models to analyse the behavior of rockfalls and, therefore, design rockfall protection structures with more confidence and decrease the overall cost of the protection measures.

1.2 THE AIM OF THE RESEARCH STUDY

This research study is aimed at using terrestrial survey along with a thorough site reconnaissance to create digital elevation models that represent topographical formations of landforms in as close proximity to the natural landform as possible and analyse rockfalls to identify potential risk locations in and around the Western Cape.

The main aim of the study will be reached by the following objectives:

- Determining the trigger mechanisms that lead to rockfalls in the Western Cape
- Relating weather conditions to the frequency of rockfalls in the Province
- The degree of weathering and impacts of geology on rockfalls
- Boulder size, shape on the kinetic energy and bounce heights of rockfalls
- Rockfall behaviour and the effect of slope angle, length and geology

Detailed mathematical calculations pertaining to parameters such as the coefficient of restitutions and software programming is beyond the scope of works of this research and, therefore, will not be presented.

1.3 IDENTIFICATION OF THE LOCATIONS FOR RESEARCH

The researcher is currently a full-time employee at a well-respected and established consulting firm which focuses purely on geotechnical engineering and engineering geology projects. The researcher has therefore used personal experience on various projects to identify locations for this research topic in and around the local Cape Town Municipal area. The three sites covered in this research project are Chapman's Peak Drive, Sir Lowry's Pass and The Cliffs.

1.4 LIMITATIONS OF RESEARCH

This research study is limited by local rockfall databases or lack thereof. Of the three study areas, only Chapman's Peak Drive has a rockfall database with detailed information and that is also limited to after the reconstruction/rehabilitation of the road. Although rockfalls are often mentioned in the news particularly after heavy rains, no official system has been put in place to keep records of these. Hence, the historical origin of rockfall, size of rock and damage to infrastructure are unknown until a recent event occurs that warrants a rockfall mitigation measure. Certain parameters such as coefficients of restitution are therefore limited to what is available globally and cost aside, should, therefore, be researched in future to create a local database.

1.5 RESEARCH METHODOLOGY

The approach to this research was mainly by practical experience, literature study, field reconnaissance, and software analysis.

This study has been presented in the following chapters:

Chapter 1: Introduction

This chapter provides a clear and concise outline for the motivation of the study, the main aims of the study, the identification of the locations for the research and the approach of research undertaken.

Chapter 2: Literature study

This literature study sets the background for the research study and provides insight into work done on similar research studies including practical and theoretical studies. Various sources of literature were reviewed, studied and referenced to gain a detailed understanding of the various components of this study and provide a clear background for the occurrence of rockfalls in the Western Cape. This chapter explains the phenomenon of a rockfall, the problems of rockfalls in a built environment, the effects of geology on rockfalls and evaluating and predicting problem areas with the potential for rockfalls. The various parameters that have an impact on the behaviour of rockfalls are also discussed. Seasonal changes that bring about heavy rainfall and high wind speeds will be addressed in detail.

Chapter 3: Study areas for rockfall in the Western Cape

Rockfalls can be directly related to the type of geology and the degree of weathering of the rock type. This chapter relates the location of the rockfalls to geology in the Western Cape. Rockfall modelling relies completely on accurate field information input into software programs. The method of obtaining this information includes but not limited to site mapping either from ground level or via rope access depending on the location, terrestrial survey, orthorectified photography for aerial photo interpretation and site experience.

Chapter 4: Software programs

The advancement in software in the last decade has been astounding. The amount of processing capacity that computers have today far surpasses anything we have previously seen and the same is true for the latest software programs. There are a number of different software programs, most of which require the same input parameters. The focus of this chapter is on the extraction of 3D trajectory paths using the 3D program called Rapid Mass Movements (RAMMS), presenting trajectory paths in 3D in ArcGIS and analysing the data in the 2D program called Rocscience Rockfall.

Chapter 5: Conclusions and recommendations

This chapter ties the various components of the research study together and discusses the conclusions and recommendations of the study. The limitations of the 2D software program are also discussed as well as ways to overcome these limitations. This chapter further goes on to recommend future field work and possible changes to the manner in which the rockfall analysis is conducted.

CHAPTER 2 : LITERATURE STUDY

2.1 INTRODUCTION

According to the Washington State Department of Highways, a significant number of accidents and nearly half dozen fatalities have occurred because of rockfalls in the last 30 years (Badger & Lowell, 1992). They also went on to state that '*45% of all unstable slope problems are rockfall related* '. Thirteen rockfall deaths were recorded in the past 87 years in Canada, most of which occurred on the mountainous highways of British Columbia (Hungr & Evans, 1989).

Historically, every winter with recorded high amounts of rainfall has resulted in rockfalls with damage to structures, vehicles, injuries to motorists and in some cases even death. Anyone that has experienced a very wet winter in the Western Cape has more than likely been affected by a road closure due to rockfalls or debris slides. Yet it is ironic that both locals and international tourists are in awe of the Western Cape. It has a breathtaking mountainous topography, with kilometres of road cutting right against a steep rock face. The road cutting meets the coastline in some places whilst others are cut into mountainsides with steep valleys beneath them. The Western Cape has roads that run alongside both the Atlantic and Indian oceans but can be some of the scariest rides when rockfalls occur.

Rockfalls generally occur due to a change in climate or biological event that causes a change in forces acting on a rock. These events may include pore pressure increases due to rainfall infiltration into discontinuities, erosion of surrounding material during heavy rain storms, freeze-thaw processes in cold climates, chemical degradation or weathering of the rock, root growth or leverage by roots in high winds (Hoek, 2007).

Although the most practical way to obtain useful input data for any rockfall software program available, is to physically roll rocks from the slope crest and record its path, the position of impact, the energy at impact and the bounce heights of the boulder. Unfortunately, it is not always possible to do so. Therefore aerial photography mapping from the most recent photographs of the site of interest is very important as well as the site investigation. All valid data obtained from the aerial photography and site investigation will determine how useful any rockfall model is.

The degree of weathering and climatic conditions are vital in predicting an area for potential rockfalls and thus requiring an engineering solution in the form of either catch fences, shotcrete, anchors, pinned mesh or gabion walls.

Understanding what causes rockfalls both in its natural environment and that created by man will assist in preventing any injuries or loss of life as well as damage to structures and vehicles.

This chapter will conclude with a discussion of the design solutions for protection measures from rockfalls in the built environment.

2.2 FAILURE MECHANISMS IN ROCK

Hoek and Bray (1981) described planar, wedge and toppling failure mechanisms of slope whilst Avery (2012) also included Rockslide and Rockfall as modes slope of failure. These are described hereafter.

a) **Planar Failure:** occurs when a geological discontinuity strikes parallel to the slope face and dips into the excavation at an angle greater than the angle of friction.

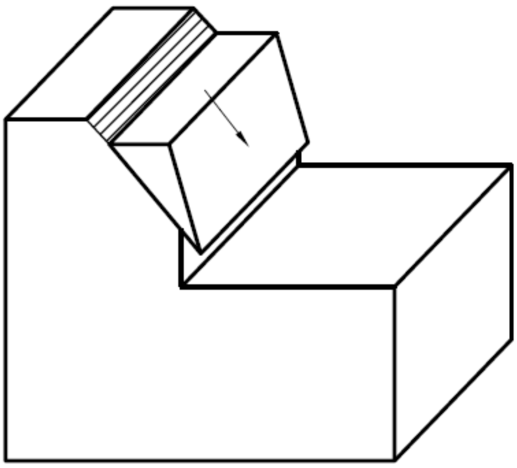


Figure 2.1: An example of planar failure.

b) Wedge failure: when two discontinuities strike obliquely across the slope face and their line of intersection daylights in the slope face, the wedge of the rock resting on these discontinuities will slide down the line of intersection, provided that the inclination of this line is significantly greater than the angle of friction.

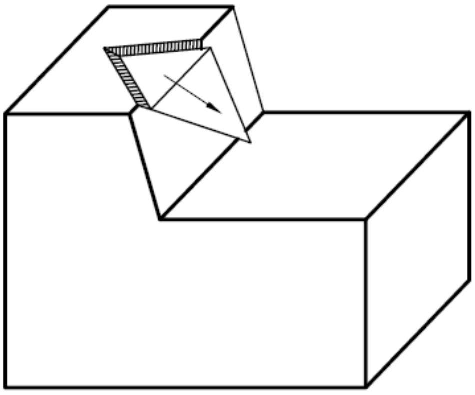


Figure 2.2: An example of wedge failure.

c) Toppling Failure: occurs when two forces cause an overturning moment about a pivot point below the centre of gravity of the block. This mode of failure typically occurs in rock masses with columnar bedding planes and joints.

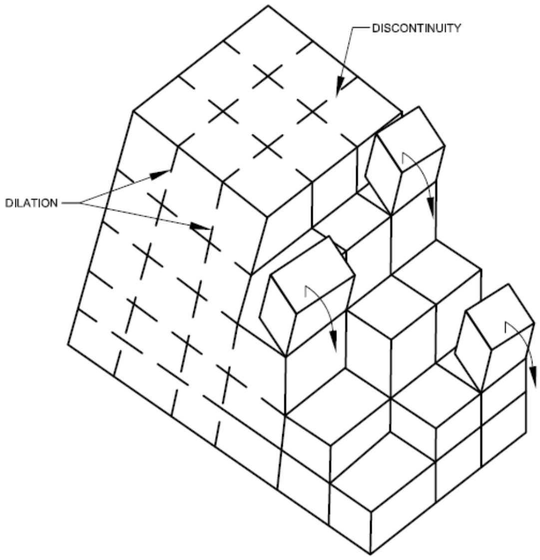


Figure 2.3: An example of toppling failure.

d) **Rockslide Failure:** is a type of landslide caused by rock failure in which part of the plane of failure passes through intact rock and where material collapses en masse and not in individual blocks.

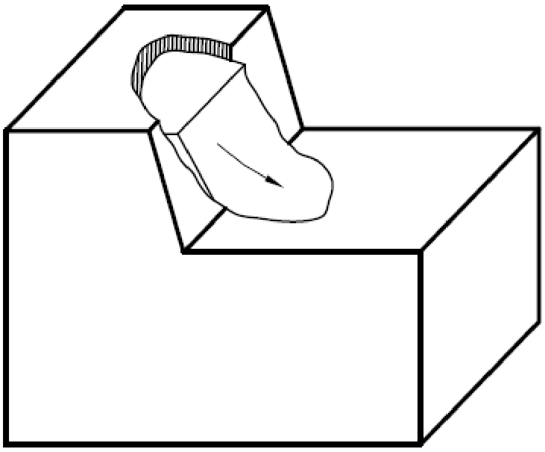


Figure 2.4: An example of rockslide failure.

e) **Rockfall Failure:** occurs where one or more rocks fall freely from a cliff face or rock slope. A rockfall is a fragment of detached rock that moves in a natural downslope motion by free falling, sliding, rolling, or bouncing, along a vertical or sub-vertical cliff or rock slope.

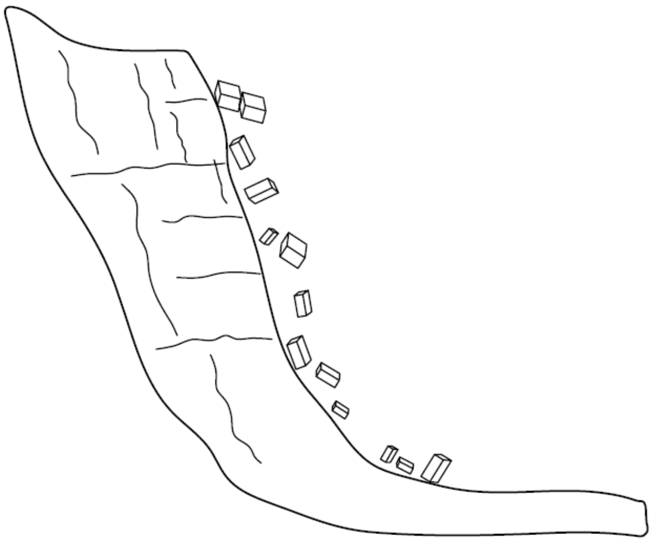


Figure 2.5: An example or rockfall failure

2.3 ROCKFALL

"What is this phenomenon that we refer to as a rockfall?"

Vijayakumar et al (retrieved 2014), described what a rockfall is in the simplest term: "Rockfalls occur when rocks break away from a slope".

Rockfalls can also be described as a fall, slide, slip or roll of a boulder or boulders from either the crest or being dislodged along the length of a slope of cutting. Various trigger mechanisms have been documented to cause rockfalls. These include rain, wind, erosion, freeze-thaw actions, root growth, natural geological discontinuities together with gravity and of course man during construction of a road cut, quarry, cliff face or open pit mine. According to Hoek (2007), "In an active construction environment, the potential for mechanical initiation of a rockfall will probably be one or two orders of magnitude higher than the climatic and biological initiating events described above".

The hazard of a rockfall can be directly related to geology, size and shape of the boulder, length and angle of the slope as well as the roughness of the slope. A boulder initiating its fall from a high, smooth, long slope will have a much higher velocity than a boulder initiating from a talus slope. The talus, scree or gravel material would absorb a significant amount of energy, thereby slowing down or even stopping the boulder (Hoek, 2007).

2.3.1 Trigger mechanisms in rockfall

Mechanisms that trigger rockfalls can be either natural such as the freeze-thaw cycle or anthropogenic such as quarries or open-pit mines (Vijayakumar et al., retrieved 2014).

According to Hoek (2007), the causes of rockfall are as follows:

- Pore Pressure increases due to rainfall infiltration
- Erosion of surrounding material
- Freeze-thaw processes in cold climates

- Chemical degradation or weathering of rocks
- Root growth or leverage by roots moving in high winds
- High winds dislodging already loose rocks

Avery (2012) also stated that natural weathering and or rainfall can be a trigger for rockfall. He included the impacts of earthquakes as well as animals traversing along slopes as a trigger mechanism of rockfalls as well.

The climatic effects of weather such as rain and the freeze-thaw conditions have a direct impact on the frequency of rockfalls and this has been established in previous studies (Peckover, 1975). Figure 2.6 illustrates geological conditions that effect rockfall.

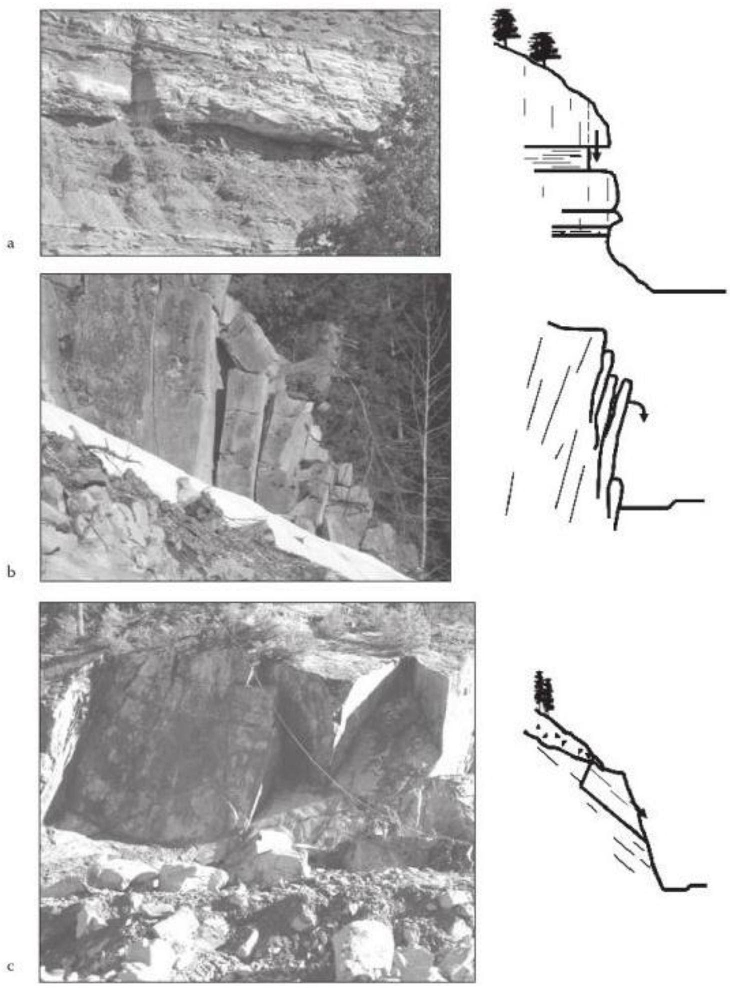


Figure 2.6: Geological conditions that can result in rockfalls. (a) Weathering of weak shale undercuts beds of strong sandstone forming unstable overhangs. (b) Toppling columns in columnar basalt. (c) Persistent discontinuities dipping out of face allow blocks to slide. (Wyllie, 2015)

The figure below shows the rockfall frequency against monthly rainfall levels and average daily temperature over a period of 20 years for an area on the Pacific Coast of western Canada (Wyllie, 2015). This area experiences very wet winters and freeze-thaw cycles frequently.

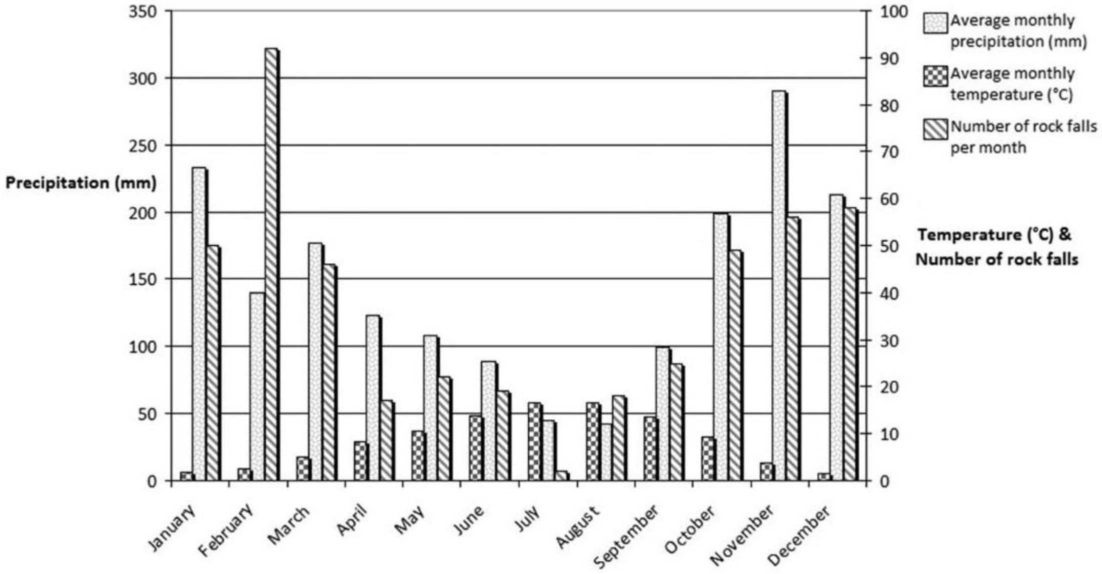


Figure 2.7: Relationship between weather-precipitation and temperature and rockfall frequency (Wyllie, 2015).

In areas that experience more wet conditions, vegetation growth can be significant to the effect of creating and spreading cracks in rock masses. Roots can be strong enough to open and extend cracks, and even fracture intact rock (Wyllie, 2015). This almost creates a snowball effect by allowing deeper penetration of water and ice into the rock face that increases the risk of rockfalls.

Ground motion as a result of an earthquake is a common occurrence in underground mining as well as in mountainous terrain. Depending on the size of the seismic activity, a rockfall can range from a single rock to a massive landslide. The earthquake that occurred in 2011 in Christchurch, New Zealand, measured 6.2 on the Richter scale and caused rockfalls, some of which damaged houses (Wyllie, 2015).

Figure 2.8: Rockfall on to house at 116A Main Road, Radcliffs (GNS Photo-GTH_5823), (Dave, 2011).

2.3.2 Types of motion in rockfall

According to Wyllie and Mah (2005), rocks that fall from slopes with an angle steeper than 75° tend to follow a path close to the rock face. This results in a term called fall. Slopes with an angle of between 55° and 75° bounce and spin and can land further away from the toe of the slope. Slopes with an angle between 40° and 55° will roll down a rock face.

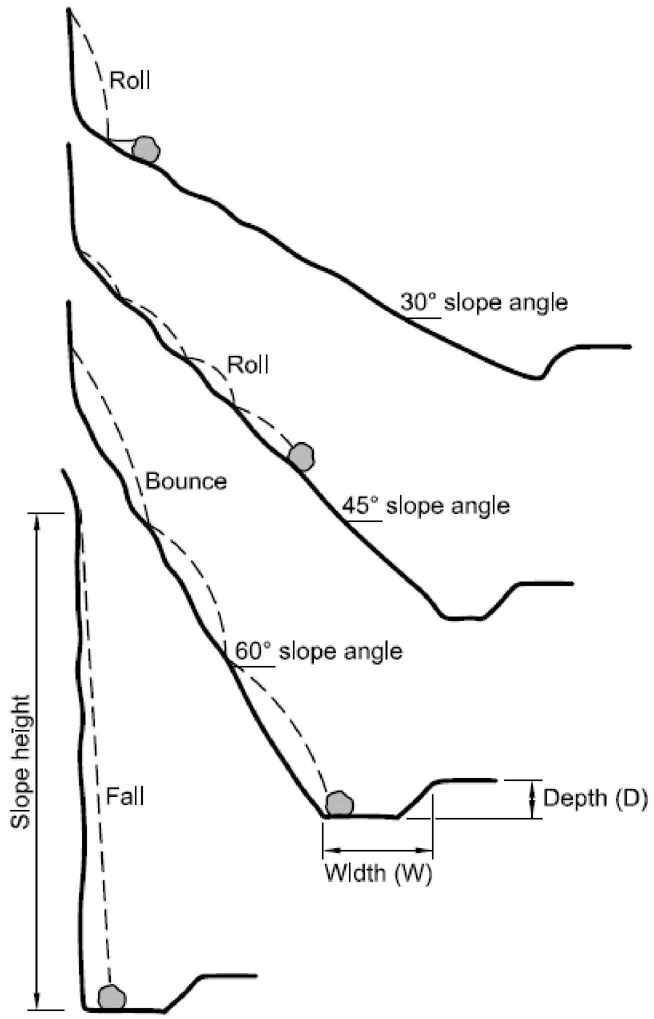


Figure 2.9: Redrawn from the ditch design chart for rockfall catchment (Ritchie, 1963)

2.3.3 Topography

Topography is described as the natural profile of the ground in any given environment. Mountainous environments generally are subject to rockfalls, depending on the steepness of the slope, the geology and the degree of weathering. Anthropogenic environments can also give rise to potential rockfalls such as in the case of road cuttings.

Topography has a direct impact on rockfalls and, therefore, the accuracy of a survey is very important. Survey data are used to create 3-dimensional models of a rockfall study area which can then be used in various 3D rockfall software to determine the trajectories or paths of the rockfall. Inaccurate topographical surveys or survey data that does not have sufficient grid information can be a limiting factor in rockfall hazard assessment (Lan & Martin, 2009) and as a result, the 3 dimensional model that is produced will have inaccurate slope topography, rockfall detachment area, runout distance and ultimately result in inaccurate trajectory paths when used in rockfall software.

The topography of a slope determines the source zones for potential rockfalls. Wyllie (2015) describe 4 types of source zones for rockfalls. This is illustrated in Figure 2.10.

- Rock slope: On a steep, irregular slopes, falls will have widely spaced impacts, high-speed translational and rotational velocities, and high-angle trajectories.
- Colluvium Slope – On slopes that are just steeper than the angle of repose (i.e., if greater than 37 degrees for loose rock fragments), closely spaced impacts and shallow trajectories will occur, but falls will not accumulate on the slope.
- Talus Slope: Falls accumulating on talus slopes form at the angle of repose ranging from about 37° in the upper portion to 32° degrees near the base. Rockfalls undergo a natural sorting when they reach the talus with smaller fragments accumulating near the top and larger ones reaching the base, such that talus deposit enlarges uniformly forming a cone-shaped deposit.
- Run-out zone: A few of the larger, higher energy blocks may move beyond the base of the talus and onto a slope that is flatter than the talus. It has been found that the maximum run-out distance for these blocks is defined by a line inclined at about 27,5° from the base of the steep rock slope; this angle represents the rolling friction coefficient of rockfalls (Hungr and Evans, 1988). Within the run-out zone, rockfalls move in a series of closely spaced impacts or rolling action, which means rocks can be readily stopped in this zone with shallow ditches or low fences.

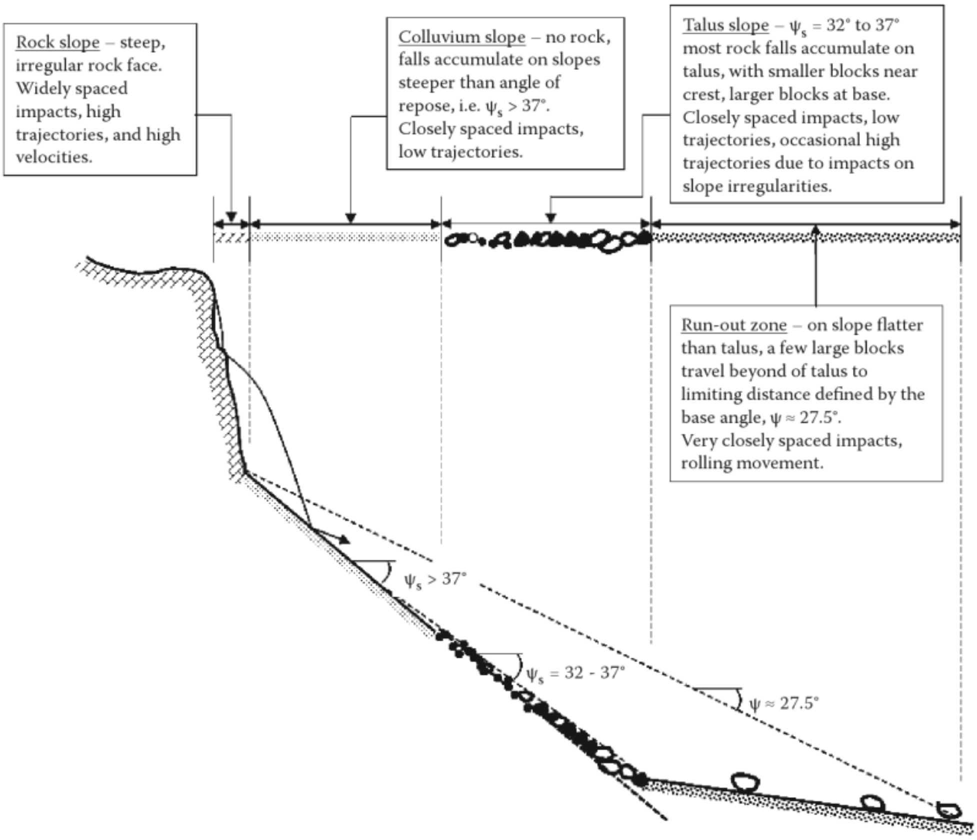


Figure 2.10: Typical slope configuration showing the relationship between slope angle (determined from topography) and rockfall behaviour (Wyllie, 2015)

Topography is a key factor in evaluating dynamic parameters as it affects falling blocks velocities and heights of bounce (Azzoni, La Barbera, & Zaninetti, 1995). More often than not, most rockfall computer analyses are performed on slopes profiles surveyed in low detail since the costs are high and it would entail complex logistics.

Azzoni, La Berbera & Zaninetti (1995) carried out an assessment of the relevancy of topographical detail for computer analysis. The same analysis on the same slope was performed with 152, 79, 43, 25 and 16 points. The results were compared among themselves and with those obtained from an experimental test performed with a block of the same characteristics.

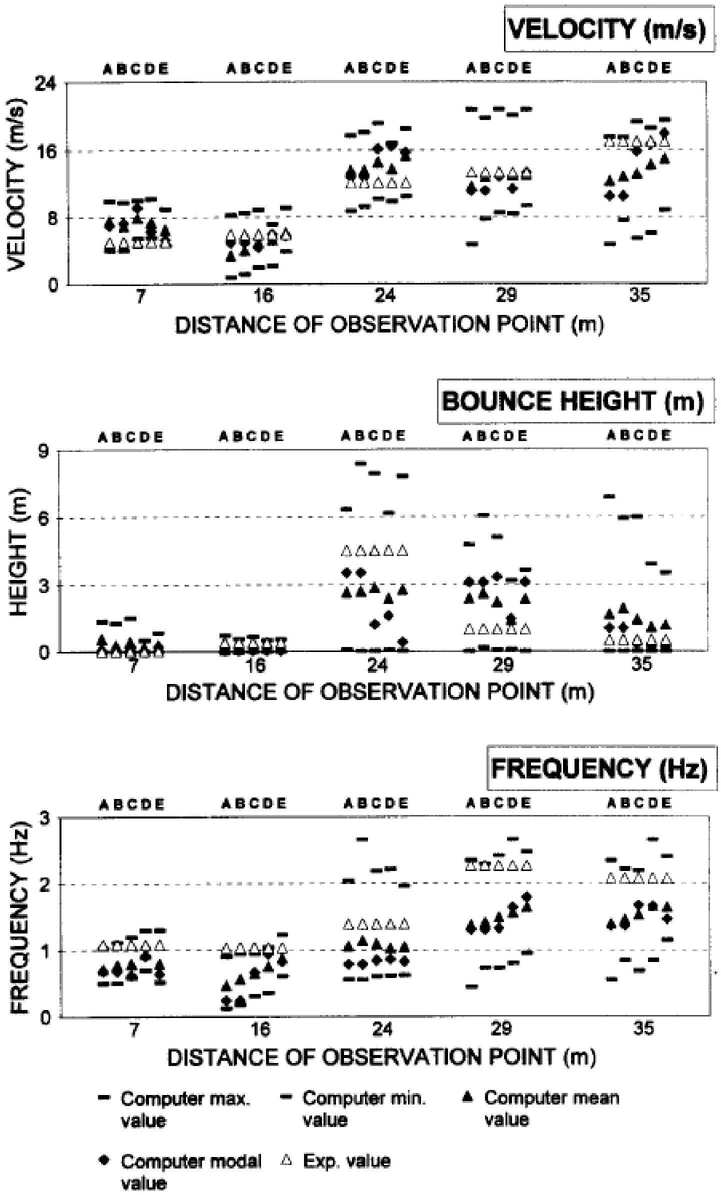


Figure 2.11: Effect of topographical detail on the results of the mathematical rockfall analysis: A =Slope profile with 152 points: B = Slope profile with 79 points; C= Slope profile with 43 points; D = Slope profile with 25 points; E = Slope profile with 16 points. (Azzoni, La Barbera, & Zaninetti, 1995)

The test enabled them to reach the following observations:

- A progressive increase in smoothness corresponds both to an increase in calculated fall velocity and frequency of rotation, and to a decrease in height of the bounce. This result is conservative in respect of fall energy, but not the height of bounce, even though the experimental value still fell within the range calculated by the computer analysis. When analysing rockfalls with low detail topographical surveys, it is thus advisable to design higher fences (rather than stronger) than those hypothesised by the computer.

- Detailed topography is necessary. In particular, detail is especially important in sections where the block bounces and rolls; where free fall is the prevailing motion type, a less accurate survey is acceptable. The most favourable topography is that surveyed at intervals similar to block dimensions since the smaller asperities can already be satisfactorily taken into consideration by the rolling friction coefficient. When such detailed topography is not feasible, there should be at least surveys made of all relevant points of the slope (corresponding to significant changes in the slope angle) and some points taken at reasonable intervals (not greater than 20-50m).
- When a special topographical survey is not available, the maps used for drawing slope profiles should not be scaled at lower detail than 1:200 and 1:1000 for short (tenths of metres) and long (hundreds of metres) slopes, respectively.

2.3.4 Geology

According to Wyllie (2015), rockfall hazards are clearly related to the geology of the slope that is the potential source of falls. He further went on to say that the rock must be sufficiently strong to form a block that will survive impacts during the fall and not breaks into harmless fragments.

Rocks with a higher strength i.e. Malmesbury Shale and quartzitic sandstone in the Western Cape will cause a higher risk than weaker rocks. The weaker rocks, such as siltstone, tend to break up into smaller fragments in contact with the rock face and will therefore not be a hazard.

Detailed geological mapping and literature studies will provide information on the material type of the potential rock blocks for a site of interest which can include size and shape of the rock blocks due to the rock strength, persistence and spacing of the discontinuities.

2.3.5 Natural-manmade slopes

Rockfalls caused in natural slopes are subject to the elements of nature. These include climatic, biological, physical and chemical effects, some of which have been discussed in Section 2.3.1 of this research document.

Manmade slopes are usually constructed by blasting of rock slopes for roads, railways, structures and mining activities. Detailed geological mapping accompanied by laboratory testing to confirm rock strength can be used to determine the correct quantities of explosives as well as the correct diameter and depth of hole used during the blasting of the rock slopes. One of the most common causes of rockfalls for excavated slopes is due to blasting which fractures intact rock, displaces blocks and opens up cracks in the face (Wyllie, 2015). Natural discontinuities such as jointing may also widen depending on the impact of the rock blasting.

As explained in Section 2.3.1, opening up of cracks either natural or caused by blasting in the rock allows water to penetrate into the rock mass, increasing the pressure in the cracks and possibly the freeze-thaw effect in colder climates as well as aids the growth of roots and further dilation of the cracks (Wyllie, 2015).

2.3.6 Rockfall hazard rating systems

Rockfall Hazard Rating Systems or “RHRS is a process that allows agencies to manage the rock slopes along its highway system by providing a rational way to make informed decisions on where and how to spend construction funds” (Pierson, 1991).

The Oregon Highway Division’s RHRS requires competent, suitably qualified persons to evaluate slopes and make decisions on suitable mitigation measures. The 6 main features as listed by Pierson (1991) are as follows:

- A uniform method for slope inventory
- A preliminary rating of all slopes

- The detailed rating of all hazardous slopes
- The preliminary design and cost estimate for most serious sections
- Project identification and development
- Annual review and update

The preliminary rating system divides the rockfall areas inspected during the slope inventory into 3 categories below (Pierson, 1991). This allows for a more detailed investigation into the areas that are classed as high and moderate (Figure 2.12).

CRITERIA \ CLASS	A	B	C
ESTIMATED POTENTIAL FOR ROCK ON ROADWAY	HIGH	MODERATE	LOW
HISTORICAL ROCKFALL ACTIVITY	HIGH	MODERATE	LOW

Figure 2.12: Preliminary Rating System (Pierson, 1991)

Once the rockfall areas have been categorised in accordance with one of the 3 classes above, a more detailed rating is used for each location which classifies each area into 10 categories using a numerical method to score each area. Slopes with higher scores present a higher risk (Pierson, 1991). Figure 2.13 shows the summary sheet for the Oregon Rockfall Hazard Rating System, whilst Figure 2.14 shows the summary sheet for the Colorado Rockfall Hazard Rating System.

CATEGORY	RATING CRITERIA AND SCORE			
	3 POINTS	9 POINTS	27 POINTS	81 POINTS
SLOPE HEIGHT	25 FEET	50 FEET	75 FEET	100 FEET
DITCH EFFECTIVENESS	Good catchment	Moderate catchment	Limited catchment	No catchment
AVERAGE VEHICLE RISK	25% of the time	50% of the time	75% of the time	100% of the time
PERCENT OF DECISION SIGHT DISTANCE	Adequate sight distance, 100% of low design value	Moderate sight distance, 80% of low design value	Limited sight distance, 60% of low design value	Very limited sight distance 40% of low design value
ROADWAY WIDTH INCLUDING PAVED SHOULDERS	44 feet	36 feet	28 feet	20 feet
GEOLOGIC CHARACTER — CASE 1 — STRUCTURAL CONDITION	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
GEOLOGIC CHARACTER — CASE 1 — ROCK FRICTION	Rough, Irregular	Undulating	Planar	Clay infilling, or slickensided
GEOLOGIC CHARACTER — CASE 2 — STRUCTURAL CONDITION	Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion features
GEOLOGIC CHARACTER — CASE 2 — DIFFERENCE IN EROSION RATES	Small difference	Moderate difference	Large difference	Extreme difference
BLOCK SIZE / VOLUME OF ROCKFALL/EVENT	1 Foot / 3 cubic yards	2 Feet / 6 cubic yards	3 Feet / 9 cubic yards	4 Feet / 12 cubic yards
CLIMATE AND PRESENCE OF WATER ON SLOPE	Low to moderate precipitation; no freezing periods; no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High precipi-tation and long freezing periods or continual water on slope and long freezing periods
ROCKFALL HISTORY	Few falls	Occasional falls	Many falls	Constant falls

Figure 2.13: Summary sheet of the Oregon Rockfall Hazard Rating System (Pierson, 1991).

Rockfall Hazard Rating System

FACTOR			RANK			
			3 Points	9 Points	27 Points	81 Points
SLOPE PROFILE		Slope Height	25 to 50 ft	50 to 75 ft	75 to 100 ft	100 ft
SLOPE PROFILE		Segment Length	0 to 250 ft	250 to 500 ft	500 to 750 ft	750 ft
SLOPE PROFILE		Slope Inclination	15 to 25 degrees	25 to 35 degrees	35 to 50 degrees	50 degrees
SLOPE PROFILE		Slope Continuity	Possible launching features	Some minor launching features	Many launching features	Major rock launching features
GEOLOGIC CHARACTERISTICS		Average Block or Clast Size	6 to 12 in.	1 to 2 ft	2 to 5 ft	5 ft
GEOLOGIC CHARACTERISTICS		Quantity of Rockfall Event	1 cu ft to 1 cu yd	1 to 3 cu yds	3 to 10 cu yds	10 cu yds
GEOLOGIC CHARACTERISTICS	CASE 1	Structural Condition	Discontinuous fractures, favorable orientation	Discontinuous fractures, random orientation	Discontinuous fractures, adverse orientation	Continuous fractures, adverse orientation
GEOLOGIC CHARACTERISTICS	CASE 1	Rock Friction	Rough, irregular	Undulating smooth	Planar	Clay, gouge infilling, or slickensided
GEOLOGIC CHARACTERISTICS	CASE 2	Structural Condition	Few differential erosion features	Occational erosion features	Many erosion features	Major erosion features
GEOLOGIC CHARACTERISTICS	CASE 2	Difference in Erosion	Small difference	Moderate difference	Large difference	Extreme difference
Climate and Presence of Water on Slope			Low to moderate precipitaion; no feezing periods; no water on slope	Moderate precipitation or short freezing periods, or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High Precipitation and long freezing periods,or continual water on slope and long freezing periods
Rockfall History (From Ride Through)			Few falls	Occasional falls	Many falls	Constant falls
Number of Accidents Reported in Mile			0 to 5	5 to 10	10 to 15	15 and over

Figure 2.14: The Colorado Rockfall Hazard Rating System (Andrew, 1994)

An assessment of a high rockfall risk for a stretch of road in Southern Italy was carried out by Budetta and Nappi (2013) using 3 methods for rockfall hazard ratings. The first method was the Oregon Rockfall Hazard Rating System described above, the second method is a modified version of this method and the third method is a modified method of the Colorado Rockfall Hazard Rating System. The comparisons between the criteria and the overall assessment of the three methods are tabulated in Table 2.1.

Table 2.1: General comparison between criteria and concise overall assessment (Budetta & Nappi, 2013)

Criteria	RHRS	mRHRS	CRHRS
Needed data and equipment	Road geometry, topographic maps, traffic data, qualitative geologic surveys, rockfall history, climate conditions (at small/medium scale), levelling rods.	Road geometry, traffic data, geostructural and geomechanical data, rockfall database, climate conditions (at large scale), terrestrial photogrammetry, levelling rods.	Road geometry, topographic maps, orthophotos, traffic data, qualitative and quantitative geologic surveys, rockfall history, climate conditions (at small/medium scale), levelling rods.
Needed expert knowledge	Adequate (geometer, undergraduate studies in geology or environmental engineer).	In-depth (graduate studies in geology or engineering geology).	Good (graduate studies in geology or engineering geology).
Ease of use	Easy but subjective and based on not very geological factors, qualitatively described. It applies along many kilometres of roads.	Complex but objective. It applies to limited road stretches.	Fair but sometimes subjective. Several topographical and geological data are required. It applies along various kilometres of roads.
Flexibility of the system	Very flexible (it applies to all lithologic settings).	Not very flexible (mainly it applies to sedimentary rock masses with clear discontinuity patterns).	Flexible (it applies to sedimentary, block-in-matrix and crystalline rock masses).
Overall assessment	Unreliable (due to its subjectivity).	Very reliable but laborious.	Reliable. It is possible to perform statistical analyses in order to predict the rockfall hazard.

In each of its current state, none of the above rating systems can be used in its entity in the African environment. For example, due to the variable degrees of geological weathering, a slope cannot simply be placed in a category based on height and or angle. This will be proven by using data from the projects presented later in this research project. African or South African roads are limited to the amount of space set aside for the road reserves and therefore, the option of using a ‘ditch’ is not available locally. Further research is required locally with the ultimate goal to be the development of a new rating system which is relevant to these conditions.

2.3.7 Effects of geology on rock blocks

Understanding the geological composite of an area of interest is paramount to understanding the dynamics of the potential for the release of blocks resulting in rockfalls. The three main origins of rock groups are sedimentary, igneous and metamorphic (Bell, 2007). This information along with the geological history of an area can greatly assist in rockfall analysis as the general bedding plane thickness, joint spacing and strength of the rock is mostly well documented in well-developed areas. A well-educated and experienced assumption can be made regarding the potential block sizes, shape and hardness for input parameters for rockfall software.

2.3.7.1 Discontinuities

A discontinuity represents a plane of weakness within a rock mass across which the rock material is structurally discontinuous (Bell, 2007). A bedding plane, joint, cleavage, fracture, fissure, foliation, crack, fault plane or schistosity in a rock can all be defined as a discontinuity. When a discontinuity occurs multiple times with the same characteristics, it is assumed to be a set, two or more joint sets with the same characteristics are termed a joint system (Bell, 2007). If two or more dominant discontinuities intersect each other to form a block and under tension, that block can release from a slope face and become a potential risk for rockfalls.

The rock type comprising slopes can vary significantly. The instability of a rock mass with high material strength will be determined by the discontinuities in rock. Whereas a rock mass with a weak strength will determine the stability of the slope (Harber et al, 2000).

2.3.7.2 Shape and size of rock blocks

Rock blocks' shape and size are determined by geological factors such as rock type which will determine rock strength and, therefore, the weathering pattern. For example, corestones tend to develop in the Cape Granite Suite giving rise to much more rounded blocks whereas quartzitic sandstone from the Cape Supergroup are much more resilient to weathering and form a more angular block. Discontinuities such as joints also determine the size of blocks by their spacing and orientation

(Hoek, 2007). He further stated that as a result of gravity loading, a block will fall and because of its shape, there is no restraint from the three bounding discontinuities. In other words, three discontinuities create a wedge and will not prevent a rock from falling due to gravity.

Bell (2007) stated that "block size provides an indication of how rock mass is likely to behave because block size and interblock shear strength determine the mechanical performance of a rock mass under conditions of stress". Discontinuity spacing determines the block size and is tabulated in Table 2.2.

Table 2.2: Block size equivalent discontinuity spacing (after Anon, 1977) (cited from Bell, 2007)

Term	Block size	Equivalent discontinuity spacings in blocky rock	Volumetric joint count (J_v)* (joints/m^3)
Very large	Over 8 m^3	Extremely wide	Less than 1
Large	0.2–8 m^3	Very wide	1–3
Medium	0.008–0.2 m^3	Wide	3–10
Small	0.0002–0.008 m^3	Moderately wide	10–30
Very small	Less than 0.0002 m^3	Less than moderately wide	Over 30

*After Barton (1978)

2.3.7.3 Hardness and density

Rock hardness is determined by the Mohs scale. This is a simple scale which qualifies the hardness of a rock by the scratch resistance of various minerals whereby the harder mineral is able to scratch a softer mineral (Moh's Scale, 2015). The Mohs scale has numerical numbers 1 to 10, with each number being assigned a specific mineral. Talc is represented by number 1 and is the softest mineral on the scale, whilst diamond is assigned number 10 and is the hardness known mineral on earth.

Depending on the percentage composition of the various mineral that constitutes a given rock type, the hardness of the particular rock can be determined. The harder a rock is, the more difficult it will be to break-up, therefore from a rockfall perspective, it is likely to cause more damage to anything in its path.

Density is defined as the mass of a substance per unit volume and is closely related to specific gravity. However, specific gravity is dimensionless whereas the unit of measure for the density of rocks is tonnes per cubic meter (t/m^3). Rocks of the same class will have a range of densities as density is directly related to their percentage of mineral composition. Therefore, rock density has a major impact on rock classes. For example, igneous rocks will be denser than sedimentary rocks as the mineral composition of sedimentary rocks generally feldspars and quartz have a lower density than mafic minerals (Western Oregon University, 2005). The relationship between density and mass is defined as follows:

$$\text{Density } (\rho) = \text{Mass } (M) / \text{Volume } (V)$$

The density ranges for different rock classes is well documented and can be assumed as an input parameter for software programs from previous work carried out in an area of interest. One of the most important input parameters required in most software packages is the mass of the simulated block. Using the formula above the mass can be determined for a block of any size. Therefore understanding the density of different rock classes and its impact on rock mass will result in a more accurate rockfall simulation in any given software package. The density range for a few common rock types are:

- Shale: 2.4 – 2.8 t/m^3,
- Quartzite: 2.6 – 2.8 t/m^3
- Granite: 2.6 – 2.7 t/m^3

2.4 START LOCATION AND INITIAL VELOCITY OF ROCKFALLS

The start location and initial velocity parameters are required in most rockfall software programs. The start location is usually determined by the height of the slope i.e. in most cases the rockfalls tends to “start” at the top of a rock slope. However, depending on the geological condition of the rock face, there are instances where rockfalls can occur from any location along the slope. The higher the slopes, the more potential energy the rockfall will have compared to rocks falling from a lower slope or lower down on a slope face (Pierson, 1991). Refer to Figure 2.13, a summary sheet of the Oregon Rockfall Hazard Rating System.

The slope gradient also has an effect on the velocity of the rock, i.e. the steeper the slope gradient, the higher the velocity of the rock will be. In addition to the mean slope gradient, the velocity is also dependent on the size of the rock, the material covering the slope such as soil, scree and vegetation (Dorren, 2003). Smaller rocks have a lower kinetic energy than larger rocks and, therefore, will slow down more easily than larger rocks, smaller rocks will also be slowed down or stopped completely by trees or other vegetation as well as become trapped in depressions between larger rocks on talus slopes (Dorren, 2003).

In computer analysis, it is necessary to “move” the block and provide an initial velocity of 1-3m/sec, in particular on rough or low inclination slopes (Azzoni, La Barbera, & Zaninetti, 1995). For steep slopes, the starting velocity is not as relevant since the fall is influenced by the force of gravity.

2.5 TANGENTIAL COEFFICIENT (Rt) AND NORMAL COEFFICIENT (Rn) AND THEIR EFFECT ON ROCKFALL

The Lumped Mass Analysis approach is currently being used extensively in rockfall simulations and considers the rock as a dimensionless point mass. It calculates rockfall trajectory based on user-input parameters such as the normal coefficient of restitution (Rn) and the tangential coefficient of frictional resistance (Rt) (Chai, Vacoub, & Charbonneau, 2013).

In a lumped mass model, the coefficient of restitution needs to take into consideration the total behaviour of the rockfall.

Azzoni, La Berbera & Zaninetti (1995), used a mathematical model to analyse and predict rockfall trajectories on two different slopes, where in situ tests had been carried out. Dynamic coefficients values specially designed CADMA rockfall program was used in the analysis. The CADMA model was developed in 1987 according to a method established by Bozzolo and Pamini in the early 1980s. The model was based on rigid body mechanics. Using the data from the computer analysis, a comparison between experimental and calculated values of velocity, height of bounce and frequency of rotation of two different slopes at Strozza quarry (Figure 2.15) are shown in Figure 2.16 and 2.17.

The diagrams also highlighted the relation between experimental values and the values provided by the computer analysis for each slope, average value of the maximum, minimum, mean and modal values; and the overall maximum calculated value. The values were assessed at specific observation points placed at critical positions on the slopes. Azzoni, La Berbera & Zaninetti (1995), then drew the following conclusions:

- Translational and rotational velocity and energy: The program is generally able to make correct or acceptable predictions of these parameters. The experimental velocity values generally fell within the range of the predicted values and is always described satisfactorily by the mean and modal values.
- The height of bounce: If the topographical input is good, the program is generally able to find correct results for this parameter. In the sections beneath the steep rock slopes, it tends to slightly underestimate the values, though in this case a possible inaccuracy in the experimental values due to over-estimation should be taken into account.
- Run-out distance: The results provided by the program for this parameter is acceptable. The ditch stopped 80% of the falling blocks.

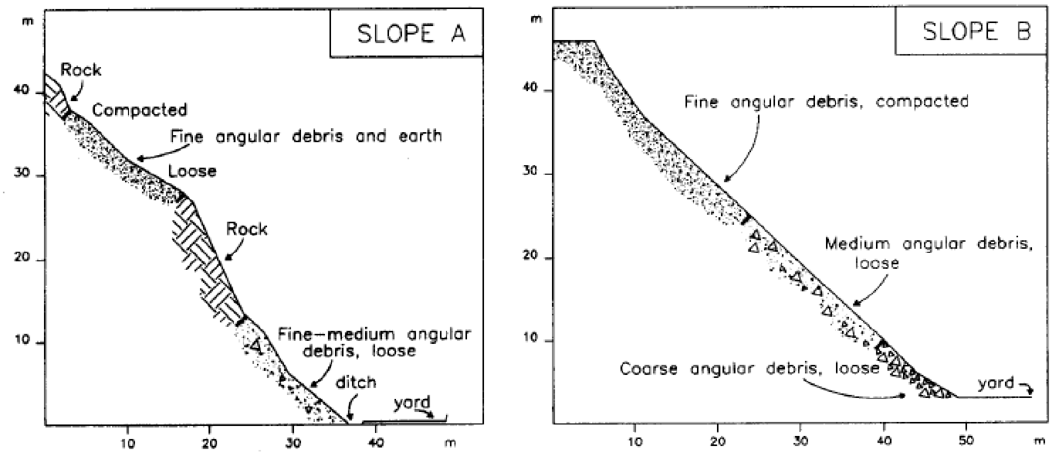


Figure 2.15: Topographical profiles of the test slopes (Azzoni, La Barbera, & Zaninetti, 1995).

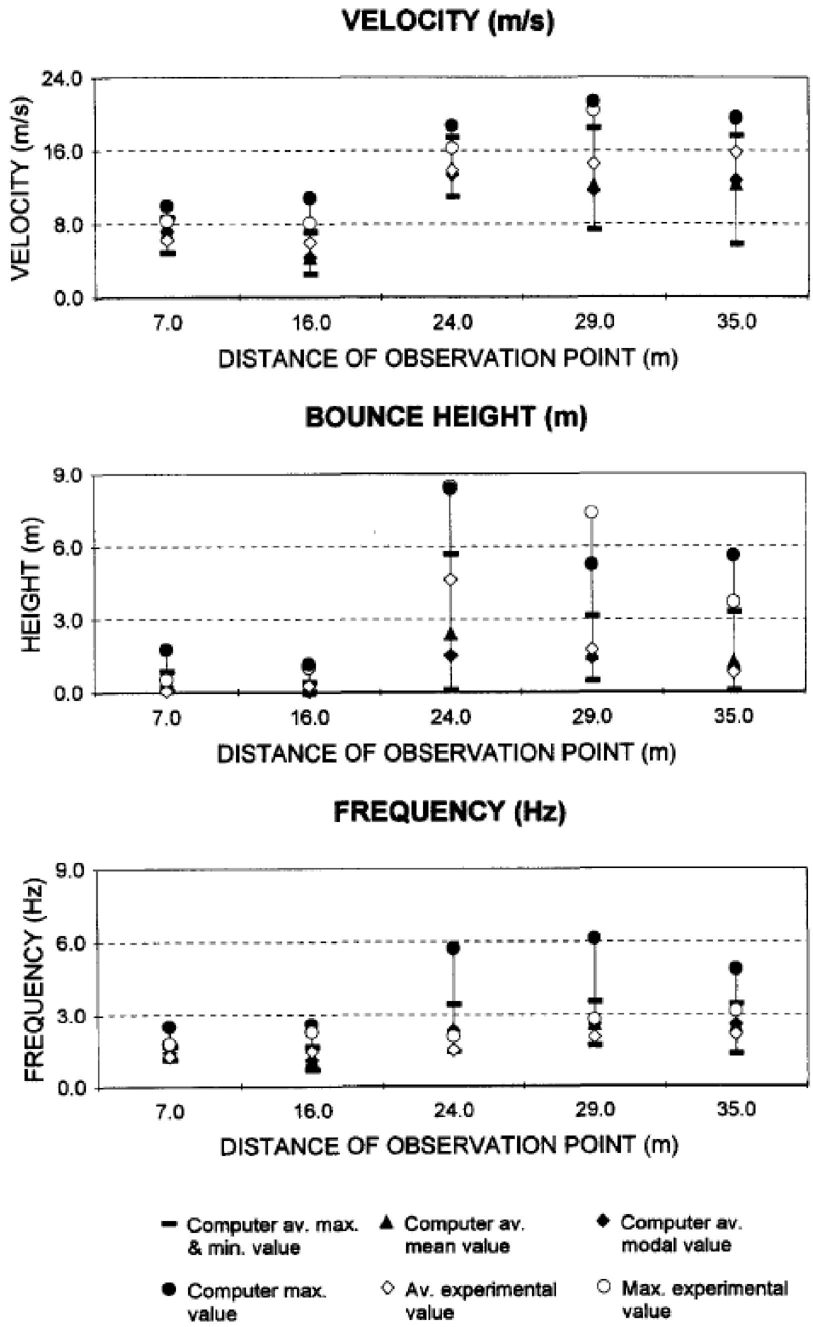


Figure 2.16: Comparison between the computer analysis results and the experimental data, for slope A. (Azzoni, La Barbera, & Zaninetti, 1995).

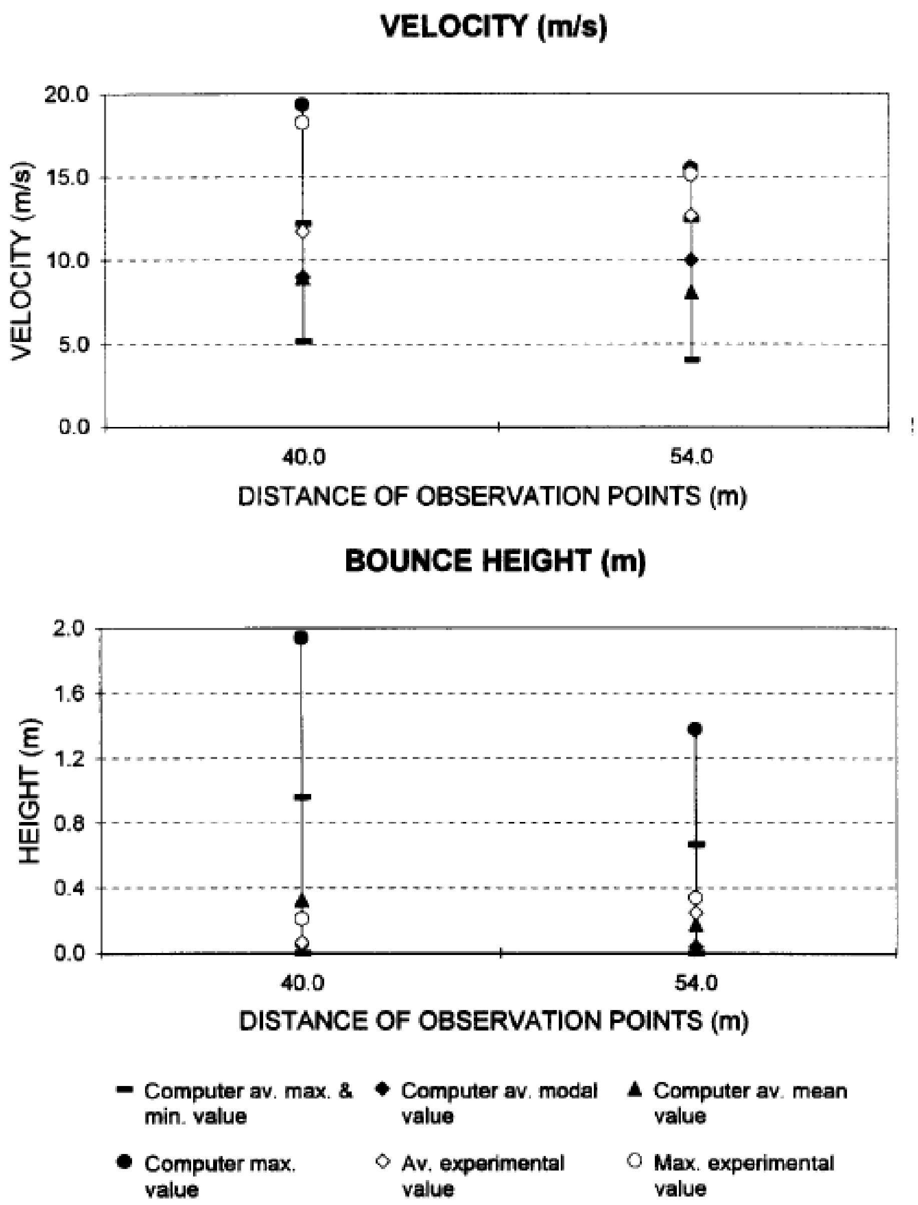


Figure 2.17: Comparison between the computer analysis results and the experimental data for slope B. (Azzoni, La Barbera, & Zaninetti, 1995).

Table 2.3. Values of the restitution and rolling friction coefficients adopted for the calibration of the mathematical model (Azzoni, La Barbera, & Zaninetti, 1995)

	Maximum restitution coefficient	Rolling friction coefficient	
Block size		0.3 m^3	1.2 m^3
Rock (limestone)	0.75–0.90	0.40–0.45	0.40
Fine angular debris and earth, compacted (gravel and cobbles, dia <20 cm)	0.55–0.60	0.50–0.60	0.40
Fine angular debris and earth, soft	0.35–0.45	0.70–0.80	0.60–0.70
Medium angular debris with angular rock fragments (20–40 cm dia)	0.45–0.50	0.60–0.70	0.50–0.60
Medium angular debris with scattered trees	0.40–0.50	0.70–1.00	
Coarse angular debris with angular rock fragments (40–120 cm dia)	0.55–0.70	0.65–1.20	0.60–0.80
Earth with grass and some vegetation	0.50–0.60	0.55–0.65	0.45–0.50
Ditch with mud	<0.20	0.85	
Yard (flat surface of artificially compacted ground)	0.50–0.65	0.50–0.65	
Road	0.75	0.40–0.45	

The restitution coefficient and the rolling friction coefficient were evaluated mathematically by back-analysis and by the in-situ tests carried on in Strozza, Italy (Azzoni, La Barbera, & Zaninetti, 1995). The two approaches rendered similar results. The assessment of the restitution coefficient was obtained by taking into account different falls. The values represented in Table 2.3 respond to the maximum values of the restitution coefficient assessed for different geological types.

2.5.1 Tangential coefficient of restitution (Rt)

The tangential coefficient defines the ratio of the outgoing velocity (tangential to the surface) to the incoming velocity (tangential to the surface) (www.rocscience.com).

The tangential coefficient of restitution (Rt) is an experimental parameter that is measured by vegetation and slope material. The range of Rt is relatively large compared to the range of suggested values for Rn. Rt has a range of 0.5 to 1.0. However according to Chai et al. (2013), the empirical parameter Rt can be obtained through the Rigid Body Impact Mechanics (RBIM). This is done using only the material parameters Rn and the dynamic friction coefficient (μ). Using the rigid body impact mechanics, Chai et al. (2013) introduced the effect of size and shape of the block of rock and its interaction with the slope to calculate rockfall trajectory and thereby obtain Rt as a result.

The two-dimensional Rocscience Rockfall 4.0 software, however, uses the lumped mass analysis approach and makes the following assumptions (www.rocscience.com).

- Each block of rock is modelled as a particle
- The block of rocks is not considered to have any size, only mass (used to calculate the kinetic energy for graphs and results)
- Air frictional resistance is not considered
- The slope is modelled as one continuous group of straight line segments

Table 2.4: Apparent Rt results for rocks with various shapes in RBIM (reproduced from Chai et al. (2013))

Shape of the rock	**Minimum tangential Coefficient (Rt)**	**Maximum tangential Coefficient (Rt)**	**Average Tangential Coefficient (Rt)**
Sphere	-	-	0.714
Circle	-	-	0.667
Rhombus*	0.629	1.337	0.929
Hexagon*	0.670	1.169	0.987
Oval*	0.624	1.325	0.987

*The Rt results are obtained from one thousand rock blocks thrown at arbitrary impact angles.

2.5.2 Normal coefficient of restitution (Rn)

The normal coefficient defines the ratio of the outgoing velocity (normal to the surface) to the incoming velocity (normal to the surface) (www.rocscience.com).

Chai et al. (2013) describes the normal coefficient of restitution (Rn) as a classical parameter known as material property that is determined by the rigidity of the contacting slope. This parameter defines the fractional change in velocity of the particle during impact in the direction normal to the slope (Vijayakumar et al., 2012).

In the paper Effect of Rockfall Shape on Normal Coefficient of restitution, Vijayakumar et al. (2012) shows a simple mechanistic model that the calculated normal coefficient of restitution with values larger than 1.0, evident in some rockfall field data is due to the eccentricity of the rock shape and its rotational energy.

2.6 THE PROBLEMS ASSOCIATED WITH ROCKFALL IN THE BUILT ENVIRONMENT

Govorusko (2012) described “the effects of rockfalls on transport to include blockage of highways and railways by the deposited layer, damage to roadbeds, and destruction of engineering structures which result in traffic disturbances”.

2.6.1 Roads

The Snowdonia National Park, North Wales has a highway network that passes through mountainous, rocky terrain with the potential for rockfalls from both natural and man-made slopes (Nichol, 2006). The rock type ranges from acid igneous rocks with rhyolitic intrusion into the rhyolite lava flows and pyroclastics of the Conwy Rhyolite Formation (Nichol, 2006).

Local examples include one of the Western Capes’ iconic locations, Chapman’s Peak Drive. After a fatal incident in 2002, this route underwent a complete rehabilitation which included rockfall catch fences, gabion walls, and cantilever structures. The geology comprises basement granite which is overlain by interbedded sandstone and siltstone of the Cape Supergroup.

During the winter months, heavy rainfall triggers rockfall events, particularly in the Western Cape. Another well-known local pass, Sir Lowry’s Pass is one such site, whereby a large block was released and landed on the roadway in July 2012, almost impacting two vehicles that were travelling on the road that night. Fortunately, no fatalities had occurred. The researcher has personally supervised the rockfall protection measures that were installed in the Malmesbury shale over a period of seven months from November 2012 to July 2013.

2.6.2 Railways

There are a number of documented events of rockfalls having occurred across the world in the built environment. One such event occurred in Mumbai-Pune, India's first expressway. During 2003 and 2004, a number of rockfalls and landslides occurred resulting in fatalities (Kumar et al., 2010). The main rock type in this area was basalt.

A well-known rockfall event occurred in Frank, Canada in April of 1903 (Govorushko, 2012). This event buried 1,6km of railway lines and caused 70 fatalities. The mountains in this area consisted of a limestone layer overlying shale and sandstone.

In February 2014, the Annot derailment occurred in France when the train was hit by a rockfall. Twenty people were left injured and two fatalities occurred (Meilhan, 2014). The train had been travelling from Nice to Digne-Les-Bains(Meilhan, 2014).

2.6.3 Structures

Afyon Castle, Turkey is located on a steep hill, 226m high. Settlements in close proximity to the castle were at risk for rockfalls as the volcanic trachitic andesite that constitutes the hill along with the columnar jointing give rise to blocks of various sizes which could potentially cause damage or worse to the settlements (Topal et al., 2006).

A proposed housing development of two sites at Sandy Bay on the east coast of Gibraltar was at risk of rockfalls from the cliff face of the Rock of Gibraltar. This area was known to have experienced rockfalls in the past, some of which resulted in fatalities. The slopes of Gibraltar comprised three types of material which included cemented aeolian sand, cemented scree breccia and limestone (Massey et al., 2006).

In 1991, about 22 million m^3 of rock fell from a cliff near the village of Randa, Switzerland. A few weeks later another 7 million m^3 of rock fell interrupting the road and railway connecting Zermatt to the Rhone valley. In addition, the debris cone dammed the Mattervispa River creating a lake that flooded part of a settlement in Randa (Sartori et al., 2003). The main rock types were granite and metagreywackes.

The impact of rockfalls on archaeological sites and historical monuments in the Greek territory are significant due to the mountainous landscapes and the sites are located near or on steep rock slopes. The instability of the limestone where the Monemvasia historical site is situated in Southern Greece poses a threat to the town located at the bottom of the slope (Saroglou et al., 2012).

2.6.4 Open pit mines

Rockfalls in an open pit environment is a very challenging problem and requires mitigation on a large scale at minimal cost since in most situations the mitigation measure is temporarily required to keep the workers safe for the limited time period that a particular cutting is in operation.

The Mount Keith Nickel operation North of Leinter in Western Australia experienced rockfall problems above a ramp. The initial solution to the problem was to create a berm, however, the berm collapsed in one section exposing the ramp to rockfalls (Geobrugg, 2008). See Figure 2.9. In this case, the ramp was required for the life of the pit and tecco mesh was used to stabilise the area.

Figure 2.18: Location where the berm was lost (Geobrugg, 2008).

The Fimiston Superpit of Kalgoorlie Consolidated Gold Mines in Kalgoorlie, Western Australia was faced with a situation whereby the haul ramp was at a risk for potential rockfalls which could endanger the lives or the employees travelling that ramp as well as the vehicles both heavy and light making use of the ramp (Geobrugg, 2008). The rock material belongs to the Golden Mile Dolerite.

2.7 OCCURRENCE OF ROCKFALL IN RELATION TO GEOLOGY IN SOUTH AFRICA

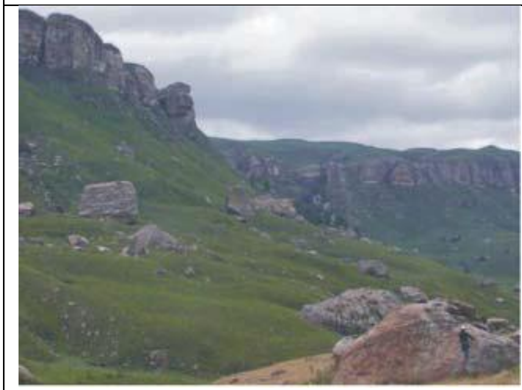
It is well recognised that geology significantly impacts the occurrence of rockfalls in South Africa. This is due to the difference in rock types and their behaviour to weathering and erosion processes. Geological structures associated with certain rock formations can give rise to bedding planes, laminations, joints, faults, and folds. Strength characteristics of rock masses can be influenced by bedding planes, changes in lithology and the dip and strike of stratigraphy (Singh et al., 2011).

In unweathered rock types, the mineral composition is of little significance; however the strength of the discontinuity and not the rock strength determines stability (Singh et al., 2011). Rocks that experience weathering to a higher degree can result in rock material of a lower strength than the discontinuity due to the weathering of clay minerals.

Interbedded sandstones and shales experience higher degrees of weathering erosion than if the rock units were present on their own. This occurs as a result of water being transferred from the coarser grained sandstones to the finer grained siltstones resulting in a loss of strength and weathering (Singh et al., 2011). This in effect is present all along Chapman's Peak Drive in the Cape Supergroup.

2.7.1 Natural slopes

Table 2.5: Images showing areas that have experienced natural landslides, in particular, rockfalls (Singh et al., 2011)

 The towering quartzite cliff failure scarps above the dammed Mutale River, Soutpansberg mountains. Past seismicity, toe undercutting and rock shear failure occurred.	 Large folded sandstone/mudstone intact blocks dipping into failed slope at steep angles form part of the Meander Stream paleo- landslides debris.
 Widespread rockfall scree characterises many slopes below the distinct Clarens Formation Cliffs in the uKhahlamba Drakensberg mountains.	 Aerial view of Lake Fundudzi: A paleo feature formed by a rock avalanche 20000 years ago –(Van der Waal, 1987, G Chiliza, 2008).

Singh et al., (2011) completed a detailed report listing a number of areas that have experienced landslides including rockfalls. Some examples include the quartzite cliff failure scarp above the Mutale River, Soutpansberg Mountains, and the sandstone/mudstone intact blocks dipping into failed slope at steep angles and the occurrence of a rock shear failure, widespread rockfall scree below the distinct Clarens Formation Cliffs in the uKhahlamba Drakensberg Mountains and a paleo feature formed by a rock avalanche 20000 years ago in the vicinity of Lake Fundudzi.

2.7.2 Manmade cuttings/activity

Varying geology, topography, high relief, steep terrain, humid climates and seismicity make some areas in South Africa susceptible to rockfall (Singh, et al., 2011). Some examples include Kaaimans Pass which experienced a slope failure in 2006 and resulted in road closure for 2 days, tailings dam failure at Merriespruit in 1994 resulting in fatalities, a debris flow in Stanger (KwaDukuza) in 1987, ongoing rockfalls in Highmoor Nature Reserve, large rock slides at Outeniqua Pass in January 2011 which also resulted in road closure and of course the well documented Chapman's Peak Drive which also resulted in fatalities prior to its rehabilitation in 2003 (Singh, et al., 2011).

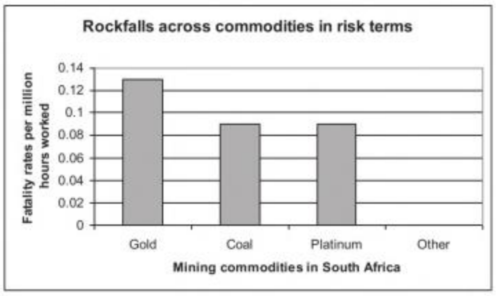


Figure 2.19: Rockfall fatal incidents expressed in terms of fatality rate per million hours worked (Brune, 2010)

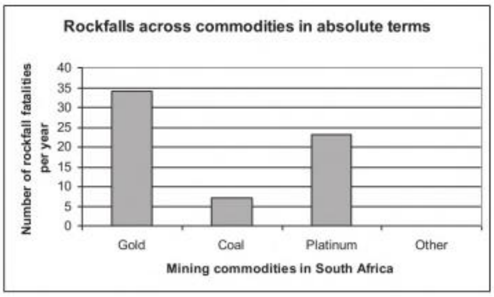


Figure 2.20: Rockfall fatal incidents expressed in terms of number of fatalities (Brune, 2010)

Rockfalls in the South African mining industry pose an unacceptable risk (Brune, 2010). The method of mining both gold and platinum in South African mines is mainly drilling and blasting which exposes mining teams to fall of ground or rockfalls. Figures 2.19 and 2.20 show plots of these statistics. Gold mining contributes the greatest number of fatal rockfall accidents in terms of risk and absolute numbers (Brune, 2010).

Table 2.6: Images showing areas that have experienced landslides in particular rockfalls due to the influence by man (Singh et al., 2011)

 Kaaimans Pass: August 2006: Failure site - Highway, House on the left and railway below affected (M Mohlabane, BKS)	 Kaaimans Pass: Failure 2 site – dip slope translational type failure (M Mohlabane, BKS)
 Ongoing rockfalls in Highmoor Nature Reserve.	 Outeniqua Pass: N12 highway, January 2011 Large rockslides caused road closure.

Whilst working on a gold mine as a trainee rock engineer, the researcher was subject to a number of rockfall incidents. The steeply dipping hanging wall can be seen in Figure 2.21 supported by rockprops. The orebody mined for gold at this shaft occurs in the quartz pebble conglomerate of the Witwatersrand Basin. This is a clear example of the dangerous underground mining conditions as a direct result of geological rock type and features. Although this research project does not address rockfall underground, this information has been included in the literature study chapter to bring attention to the fact that rockfalls do not only occur on the surface.

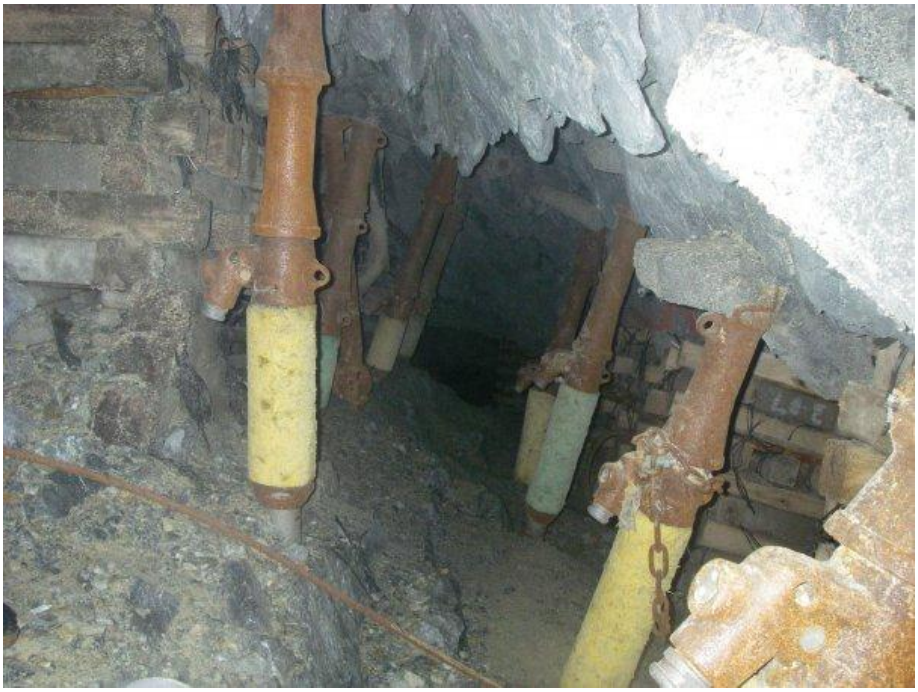


Figure 2.21: Rockprops installed at 3 shaft at Goldfields, Kloof Mine (S. Surujbally, 2007).

2.8 EVALUATION AND PREDICTION OF ROCKFALLS

Well, recorded rockfall history, along with detailed engineering geological mapping can assist in predicting potential rockfalls, however, it is virtually impossible to predict all rockfalls in a potential risk zone. Evaluating all known rock properties, such as rock strength, the degree of weathering, discontinuity spacing and infill can also assist in predicting the size of rockfall as well as the kinetic energy and bounce height.

2.8.1 Topographical surveys

Topographical surveys are generally used during the design phase of a project. However, for rockfall studies, it is a very useful component to have at the preliminary reconnaissance phase of a project. The survey gives an indication of the ground landforms and features and can sometimes identify geological structures as well. Certain features such as gullies, cliffs and overhangs that occur in mountainous terrain can help determine the type of material of which they are composed of (Bell, 2007).

2.8.2 Aerial photo interpretation (API)

Organisations like the National Geo-Spatial Information Centre produce and have on record a number of years' worth of geo-rectified photographs which can be used as stereo pairs. Aerial photo interpretation is probably most useful to identify lineaments that cannot be seen during a site walk over due to vegetation cover (Wyllie and Mah, 2005).

2.8.3 Site walk over

A preliminary reconnaissance involves a walk over of the site (Bell, 2007). The walk over generally provides indications of the zones where detailed engineering geological mapping may be required. Details of all unfavourable discontinuities would assist in determining the risk of rockfall. Specifics pertaining to the rock block size and shape can also be determined by detailed mapping which will be required for use in software programs. Average slope lengths and angles can also give an indication of possible kinetic energy produced by potential rockfalls from any literature obtained during the desk study.

2.8.4 Site Inspection/Investigation

Depending on the nature of the site and what the requirements are to stabilise the slope, either a site inspection or an in-depth site investigation can be done. The extent of the site investigation is dependent on the size and importance of the construction operation (Bell, 2007).

The three sites used in this research project were inspected visually, mainly via rope access. Rope access is usually done by professionally trained personnel to work at heights. When working in the field of rockfall, it is best to acquire a certain degree of training to be able to manipulate the ropes correctly and safely to avoid endangering anyone else working on the slope.

Other locations may require an investigation which includes core drilling, profiling, sampling and testing of recovered core. The location and depth of the boreholes can be determined by the geological conditions (Bell, 2007). Profiling of recovered core, as well as laboratory testing, can assist in determining rock strength and probable block size from discontinuity spacing. It is important to note that weaker rock types such as shale are highly susceptible to degradation when exposed to the atmosphere (Wyllie and Mah, 2005) and should be logged immediately to avoid recording rock conditions that are not present on site.

2.8.5 3D modelling

The WSL Institute for Snow and Avalanche Research in collaboration with the Swiss Federal Institute for Forest, Snow and Landscape research in Switzerland created the rockfall module called RAMMS (Christen et al., 2015). The Rapid Mass Movement System (RAMMS) for rockfall software was used to create the 3D trajectories or paths used in the 2D modelling. At the time of compiling this research project, this software was still in its trial phase and a few bugs were discovered whilst running the software producing extremely high bounce heights. The software developers believed it to be a problem with the ASCII grid file that creates a TIN (triangulated irregular network) model, however, they were unable to confirm this when the model was sent to them. Therefore, in the interest of providing realistic, accurate data, the researcher used the 3D trajectories created by the software as rocks do not travel in a straight line unless released from a sheer vertical face without coming into contact with any slope surface. These 3D trajectories were then used as input slope parameters in the 2D software to run the model as it has proven to provide more realistic output values and has successfully been used on the award-winning Chapman’s Peak Drive project.

There are a number of other 3D software packages available, however, most are designed for snow covered areas with thick vegetation and are not conducive to the South Africa environment. Rockyfor3D is one such software program whereby the 3D rockfall simulation model that calculates trajectories of single, individually falling rocks in three dimensions (Dorren, 2012). The model combines physically based deterministic algorithms with stochastic approaches, which makes Rockyfor3D a so-called probabilistic process-based rockfall trajectory model (Dorren, 2012). Rockyfor3D can be used for regional, local and slope scale rockfall simulations (Dorren, 2012).

Colorado Rockfall Simulation Program (CRSP) 3D is another 3D rockfall software which was designed by the Federal Highway Administration (www.geotechpedia.com). The Discrete Element Method is used by CRSP-3D as its numerical approach which includes the equations of motion to model the movement of rockfall on a slope surface more accurately (www.geotechpedia.com). This includes impact, rolling, launching and sliding on the slope surface. Different trajectories can be modelled on a slope and block shapes can be built to suit each specific site. The software program was not available for purchase during this research project.

2.8.6 2D modelling

Research has found that the following rockfall software programs are being used around the world, however not all of them are freely available as most of the programs are developed in-house for large corporations or institutes and it becomes their selling point in convincing clients to make use of their services.

- Rockfall V7.1 by Dr. R.M Spang and Dr.Ing. B. Romunde;
- Eboulment by Descoeudres 1087 and Dudt and Heidenreich 2001;
- Zinggler + GEOTEST by Andre Zinggler and Robert Pfeifer;
- RocFall by Stevens Warren D;
- CRSP (Colorado Rockfall-Simulation Program) by T.J. Pfeiffer, C.L. Jones, J.D. Higgins, R.D. Andrew, R. Black and R.J. Schultz
- RockFall Analyst by H. Lan, C.D. Martin and C.H. Lim.

Rocscience's RocFall software program has been the software of choice for this research study firstly because the consulting company that the researcher is employed by owns a license to the software and secondly because it has been proven to be successful for its use on the Chapman's Peak Drive rehabilitation construction project.

2.8.7 Software program input data

Most 3D software programs require a triangulated irregular network (TIN) model. The software connects surface points that are closest together to create triangles that cover an entire surface. The input file, in this case, is an ASCII grid file. It creates square grid points with x, y and z data. ASCII grids can be created in ArcGIS using a raster file of the area of interest. Once the ASCII grid has been created, this is uploaded into a software program such as RAMMS and the software automatically creates a TIN. The TIN then becomes a 3D surface from where rockfall can be modelled.

Two-dimensional software programs such as RocFall require a slope surface to model rockfall. The slope surface can generally be cut as a cross-section from a detailed topographical survey. Most software programs allow the user the option to manually input each slope vertex (point) in x, y, z format or the user can input a Drawing eXchange Format (dxf) file with the slope surface already drawn in.

Input parameters for RAMMS and RocFall software packages include:

- Initial Velocity
- Block Mass
- Point or Line Seeder (2D) or Point of release or Release line (3D)
- Material Type
- Rn and Rt

These parameters are determined from visual field investigations, literature and past experience.

2.8.8 Trajectories

A trajectory is a path that a rock or mass of rocks follows either along a slope or in free fall on a slope. The slope geometry determines the fall trajectory once a block has been released (Hoek, 2007). Dorren et al., (2011) introduced a 6 phase workflow to studying rockfall trajectories. This included a preparation phase, a definition of the release scenarios, rockfall simulation, validation of the simulated results, fixation of the model results and transformation into rockfall process maps.

Depending on the degree of details required for a particular project, not all 6 phases may be used.

2.9 CASE STUDIES USING ROCKFALL SOFTWARE

The bouncing phase of a falling rock was investigated by the coefficient of restitution (CoR) which represents energy dissipation as a result of a collision with a surface (Saeidi, Gratchev, Kim, & Chung, 2014). Different definitions of CoR have been adopted over the years by researchers. The kinematic coefficient of restitution (CoR_k) is based on Newton's collision theory where Vb and Va are the block velocities before and after impact respectively.

$$CoR_k = V_a/V_b$$

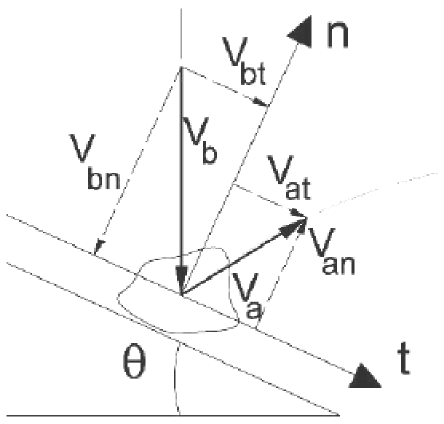


Figure 2.22: Definition of rock velocity components in regard to the rock trajectory (Saeidi, Gratchev, Kim, & Chung, 2014)

Most popular definitions used is presented in terms of normal and tangential components of the CoR_k denoted by CoR_n and CoR_t:

$$CoR_n = V_{an}/V_{bn},\ CoR_t = V_{at}/V_{bt}$$

Where V_{an} and V_{bn} are the normal components of velocity before and after impact respectively, and V_{at} and V_{bt} are the tangential components of velocity before and after impacts. The influence of block characteristics such as material, shape, weight and size could affect CoR.

Ritchie (1963) found that the impact angle, the velocity of the falling rock and bounce height can be affected by surface roughness. Wang and Lee (2010) cited in Saeidi, Gratchev, Kim and Chung (2014) performed a computer model, simulating a slope with different inclinations and roughness values. Their findings were stated that the more irregular surface led to rolling or sliding other than bouncing though they did not address the effect of roughness on the CoR.

Saeidi, Gratchev, Kim and Chung (2014) found that despite all the research that was previously done, there still was no research performed to establish a relationship between the CoR and surface roughness in natural rock materials. They set up an experiment using two greywacke rock specimens from the Brisbane area to use as the impact surface. The used the Barton and Choubey method to determine the joint roughness coefficient (JRC) after recording the roughness profiles using the Barton's comb method. They found that sample A was characterised by a wider range of JRC and, therefore, had a rough surface with a higher degree if unevenness and indentation. Sample B had a smoother surface with a lower JRC.

The test procedure involved dropping a round shaped greywacke specimen weighing 30g and capturing its trajectory with a high-speed camera. The point of impact of the falling rock was captured using another camera. The data was analysed by recording the time interval and the distance of the mass centre of the falling from the impact point over the 6 frames, before and after impact. The equations discussed earlier was used to calculate the restitution coefficients. They also linked the corresponding JRC value at the point of impact to the restitution coefficients (See Table 2.7).

Table 2.7: The plan of the laboratory tests and the average values of the CoR (Saeidi, Gratchev, Kim, & Chung, 2014)

Surface	Falling height (cm)	Test Series	Surface angle (deg)	No. of tests	CoR_k		CoR_n		CoR_t	
					Mean	St.d.	Mean	St.d.	Mean	St.d.
Rock Surface One	70	S1F7000w1	0	12	0.40	0.11	-	-	-	-
		S1F7020w1	20	29	0.48	0.12	0.31	0.12	1.04	0.41
		S1F7030w1	30	29	0.54	0.14	0.40	0.16	0.71	0.43
	110	S1F11000w1	0	19	0.35	0.15	-	-	-	-
		S1F11020w1	20	32	0.40	0.16	0.25	0.12	0.83	0.61
		S1F11030w1	30	26	0.50	0.12	0.33	0.18	0.77	0.21
Rock Surface Two	70	S2F7000w1	0	22	0.41	0.13	-	-	-	-
		S2F7020w1	20	23	0.49	0.10	0.38	0.11	0.93	0.41
		S2F7030w1	30	28	0.59	0.08	0.32	0.14	1.00	0.28
	110	S2F11000w1	0	22	0.39	0.08	-	-	-	-
		S2F11020w1	20	18	0.52	0.09	0.35	0.13	1.11	0.36
		S2F11030w1	30	26	0.52	0.11	0.34	0.13	0.81	0.30

The rock with a smoother surface and lower JRC value had a standard deviation of the CoR_k and CoR_n with a range of 0.08-0.13 and 0.11-0.14, respectively. Whilst the rock with a more rough surface had higher standard deviations from 0.11-0.16 and 0.12-0.18 for the CoR_k and CoR_n, respectively. The standard deviations for the CoRt showed a large variability. It is important to note that the rock was considered a weightless point or an object whose weight is concentrated in a point and, therefore, the size, shape and angular velocity of falling rock were not considered (Saeidi, Gratchev, Kim, & Chung, 2014).

Ferrari, Giani, & Apuani T (2013) performed rockfall tests on a talus slope on the Italian Alpine valley of Grosina. They also used the Joint Roughness Coefficient to classify the discontinuity planes and the result ranged from 6-8, indicating very smooth discontinuities. After a block a released and rebounds, it can be described using the normal and tangential restitution coefficients (Kn and Kt), expressed by the ratio between the velocity after and before impact, respectively normal and tangential to the slope.

Kn and Kt quantify the loss of energy which occurs during impacts, and their values depend basically on the outcropping material and the presence of obstacles (Ferrari, Giani, & Apuani, 2013). Rebound models can be used to simulate the motion of the falling rock. The models are be separated into two types i.e. lumped-mass (models the block as a single material point) and rigid body approaches (accounts for the shape of the block. Both models were used by Ferrari, Giani, & Apuani T (2013). They also explained that two different approximations of slope topography exist, the 2D slope profile and the 3D grid or digital elevation model. They used the software Rotomap which uses a 3D grid on the lumped-mass approach, and Colorado Rockfall Simulation Program (CRSP) which uses a 2D section and employs the rigid body model. Rockfall parameters depend on the outcropping material and the presences of obstacles, therefore, areas are generally subdivided into homogenous regions.

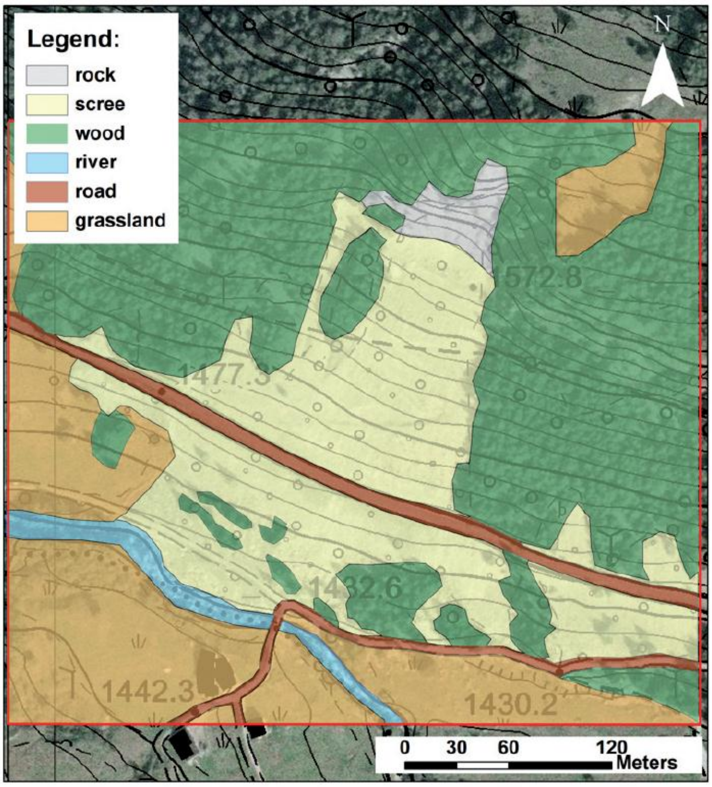


Figure 2.23: The modelled domain subdivided into units, on the basis of the outcropping substratum and the presence and kind of vegetation cover (Ferrari, Giani, & Apuani, 2013).

For the first set of simulations, the coefficients were used from bibliographic values obtained in similar geological and geomorphological conditions. In the simulation, all the blocks reached the Rosaco River and some of them were able to go up the slope beyond the river (Figure 2.24 (a)). During an event that occurred in 2010, some blocks stopped on the road and on a terrace situated at the bottom of the cliff (this had been created to hold falling blocks). Although the bibliographical values were carefully selected and from similar contexts, they should always be calibrated (Ferrari, Giani, & Apuani, 2013).

Table 2.8: Motion parameters assigned to homogeneous units, derived both from literature and site-specific back-analysis approaches. Kn and Kt are respectively the normal and tangential restitution coefficients, μ is the dynamic rolling friction coefficient and ε the slope roughness (Ferrari, Giani, & Apuani, 2013).

	bibliography				*back-analysis*			
Unit	Kn	Kt	μ	ε	Kn	Kt	μ	ε
Rock	0.57	0.73	0.64	0.35	0.60	0.80	0.20	0.35
Scree	0.41	0.65	0.62	0.30	0.40	0.63	0.65	0.60
Wood	0.28	0.49	0.73	0.90	0.20	0.40	0.70	0.90
River	0.30	0.65	0.60	0.40	0.20	0.40	0.60	0.70
Road	0.40	0.90	0.55	0.05	0.40	0.90	0.20	0.45
Grassland	0.29	0.48	0.58	0.15	0.40	0.50	0.30	0.35

Calibration of the coefficients on specific investigations play an important role in modelling but it is not always possible as previous rockfall events are not always known and their features are not identifiable. Often only the stopping points off blocks are known, but not the precise location of the release areas (as in the case of this study), cautionary results have been obtained using the bottom of the cliff as the source point (Ferrari, Giani, & Apuani, 2013).

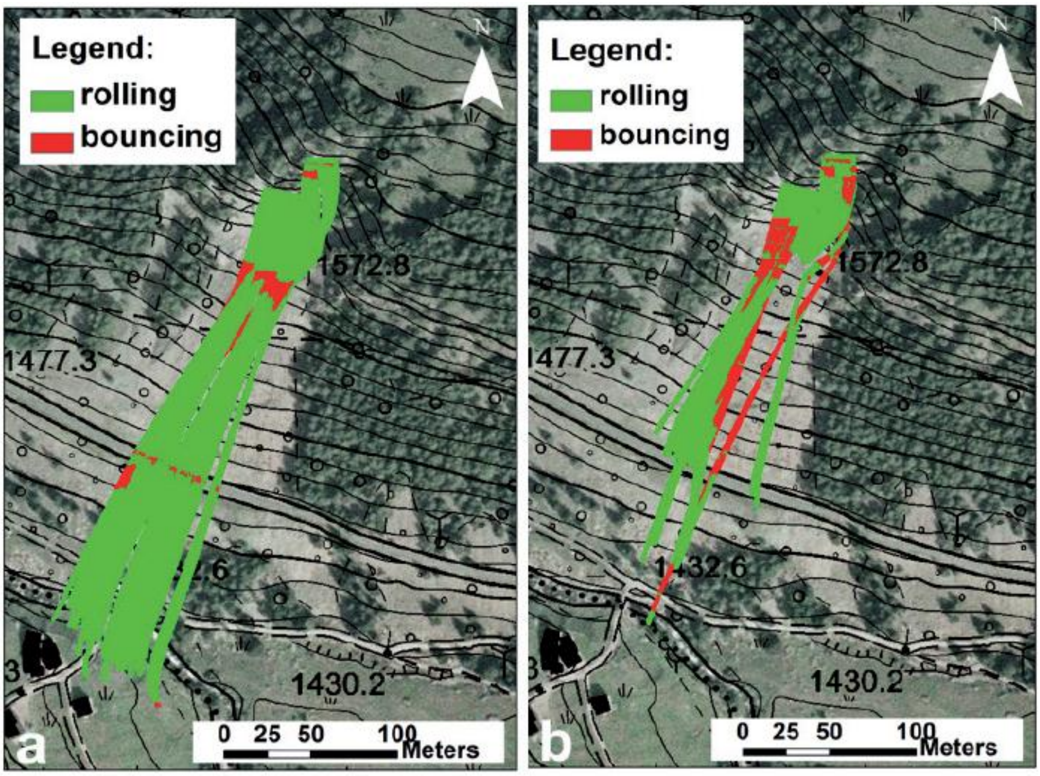


Figure 2.24: 3D paths of the falling block obtained from the literature (a) and back-analysis (b) (Ferrari, Giani, & Apuani, 2013).

The in-situ tests were carried out with carefully chosen blocks of specific sizes and shapes. The blocks had an average volume of 0.8m^3. The blocks were pushed down the slope and fixed cameras recorded both the lateral and frontal directions of the fall. The exact stopping position of the blocks was measured by a Global Positioning System (GPS). In the 3D model 70% of all blocks, that have not been subject to fragmentation were stopped. Whilst fragmented blocks were able to reach further than those forecasted by the simulations. One thousand blocks were used in the simulation, knowing the precise starting position and dimension (or mass in lumped-mass method). Using the videos, each frame has been studied and the direction of the normal and tangential slope has been determined.

The Kn and Kt values were computed and show very scattered and variable values compared to that in the literature. Although Kt values are in relatively good accordance with common bibliographic values for bare talus slopes, which ranges from 0.55-0.80. Whilst the Kn values that have been computed are extremely high. K above one should mean that the block gains translational velocity during impact, which is unlikely. One of the ways to explain this greater value is that Kn can be linked to the small grain size of the outcropping material, high slope angle and small incidence angle. Therefore, the steeper the slope is, smaller the impact angle will be, hence, Kn increases with the decrease of impact angle or equally with the increase of slope angle.

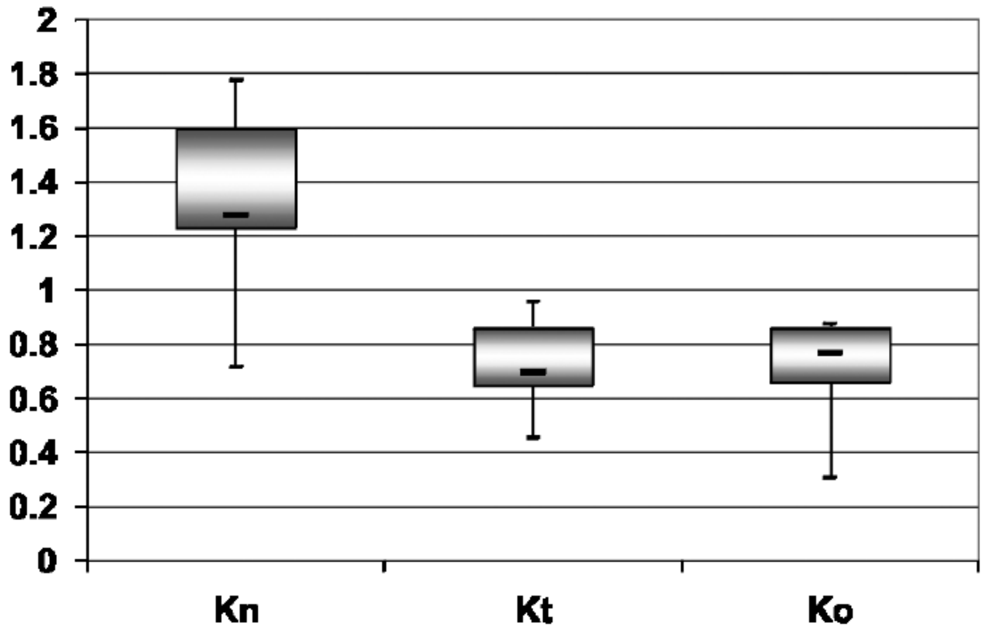


Figure 2.25: Box-plots of normal (Kn), tangential (Kt) and overall (Ko) restitution coefficients, calculated from Grosina Valley in situ tests (Ferrari, Giani, & Apuani, 2013).

Ferrari, Giani, & Apuani T (2013), found that the 2D model, with the rigid-body approach, has proved to be more cautionary that the 3D lumped-mass model.

Berger and Dorren (2006) approached consultancies that make use of rockfall simulation software as well as rockfall software developers to use their programs to predict the trajectories of 100 rock blocks in 2D or 3D using a digital elevation model of a site in the French Alps. This data was compared to data obtained from running experiments with real size rockfalls at the same site. They provided the following additional data to all the participants:

- Geographic location of the experiment site
- The form and volume of rock used during the experiments
- The locations of two calculation screens on the main path.

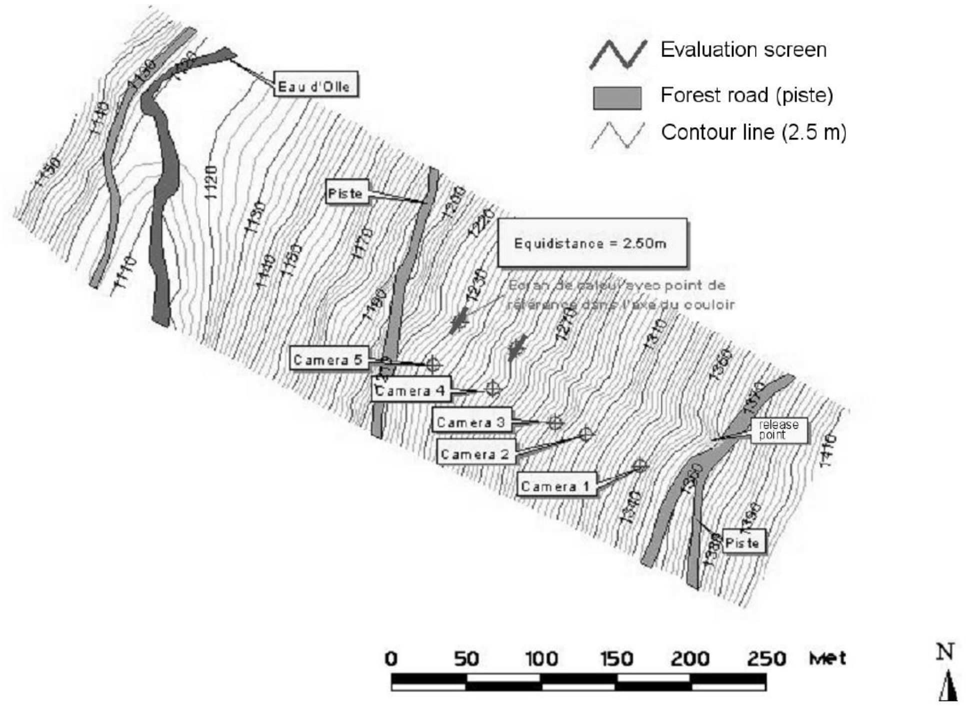


Figure 2.26: Map showing the topography of the experimental site (Berger & Dorren, 2006)

The participants had to characterise the soil on their own. The following was required by each participant:

- Calculate the mean and maximum velocity
- The kinetic energy
- Jump height of each rock
- The stopping points of each rock

Seventeen participants from four countries undertook to carry out the simulation, however, only 12 participants returned their results. Of the 12 participants, only 3 were able to simulate the same rockfall kinematics and trajectories with an error of +/- 20%. The observed stopping distance was simulated by 7 participants with an error of +/-10%.

Table 2.9: Values observed at the two evaluation screens (Berger & Dorren, 2006)

	Rebound height (m)				Velocity (m/s)				Kinetic energy (kJ)			
	Max.	Min.	Mean	Std.	Max.	Min.	Mean	Std.	Max.	Min.	Mean	Std.
Screen 1	5,0	0,0	1,4	1,1	28,1	1,8	12,5	5,2	786,4	3,3	204,9	168,8
Screen 2	6,2	0,0	1,6	1,4	28,9	4,5	13,8	5,5	958,3	21,1	244,5	196,3
Measurement error	+/- 5%				+/- 5%				+/- 15%			

Table 2.9 compares the simulated data with the observed data from the real-size experiments. Berger and Dorren (2006), then calculated a ratio that represents the difference between the simulated and observed value (Table 2.10). The ratio corresponds to the:

simulated value*100/observed value

A ratio higher than 100% represents underestimation.

Table 2.10: Comparison between observed and simulated values expressed in ratios (Berger & Dorren, 2006)

	Ratio Vmax Screen1	Ratio Vmax Screen 2	Ratio Hmax Screen 1	Ratio Hmax Screen 2	Ratio Emax Screen 1	Ratio Emax Screen 2
Part. 1	103	92	135	143	91	101
Part. 2	102	97	63	109	n.a.	n.a.
Part. 4	49	36	91	70	12	14
Part. 7	138	124	535	732	n.a.	n.a.
Part. 8	57	56	56	65	37	34
Part. 9	39	32	0	0	18	15
Part. 11	72	73	42	54	74	78
Part. 12	37	24	4	6	8	16
Part. 13	69	63	38	37	73	72
Part. 14	78	77	79	69	87	79
Part. 15	183	172	101	109	472	513
Part. 17	90	81	117	113	87	96

Part. = Participant

An important point to note is that the maximum errors were in the order of 400%. One of the significant findings of the test was that two different users can obtain invalid or very accurate results with the same model. Berger and Dorren (2006) confirmed that the role of the expert is crucial in hazard expertises that make use of rockfall simulation models.

2.10 OTHER METHODS OF PREDICTING ROCKFALLS

Hoek (2007) stated that "*It is neither possible nor practical to detect all potential rockfall hazards by any techniques currently in use in rock engineering*". He elaborated on this statement by explaining that in some cases when dealing with boulders at the crest of a slope face, the rockfall hazards are obvious, however when a block is suddenly released from a relatively sound rock mass, that is when a dangerous rockfall can occur.

An important point to note is that although a thorough inspection can be carried out of a rock face, it should not be taken for granted that all rockfall hazards will be detected during the inspection (Hoek, 2007).

However, historical data is one method which can assist in predicting the risk of rockfalls for a particular area. For example since the construction of Chapman's Peak Drive, Melis and du Plessis has set up an ArcGIS database which records the occurrence of a rockfall along with details such as chainage along the road, position in the road that the rock landed, possible release zone, block size, type of block, and any damage to the road. Using this information a "Level of Significance is assigned to the rockfall from Level 1 to Level 4 with Level 1 being the least dangerous and Level 4 being a road closure situation". Historical data can narrow down the possible risk areas and thereby decrease the amount of work required to carry out a more detailed inspection.

Generally, there are little or no historical data as it would be a costly undertaking to create such a database.

As with most places when it comes to rockfall, the reaction is reactive and not proactive. The rockfall management team at the Tennessee Department of Transportation (DOT) was no different. Remediation was only carried out following a rockfall event. Their approach was haphazard and no mechanism was in place on a statewide basis. The state had an unknown number of rockfall problem sites and an unknown level of hazard. They had no systematic program to rate hazards, estimate costs or to let mitigation projects (Bateman, 2010).

The state initiated a research project to develop a hazard rating system to produce a statewide map (Bateman, 2010). They developed a rockfall database using the geographic information systems (GIS) to display, analyse and prioritize rockfall hazards. They modified the Oregon Rockfall Hazard Rating System into the Tennesse Rockfall Hazard Rating System. The Tennessee RHRS included the identification of the rockfall failure modes expected at a site such as planar, wedge, topple, differential weathering or raveling. This system also required data such as cut height and length, average daily traffic, roadway width, decision sight distance, rockfall history, ditch effectiveness, the presence of water, geologic failure mode, and the extent of the potential failure area. The result was a maximum score of 800 points. A site above 350 points was classified as a priority.

Using this rating system, 3 contracts were awarded, the first for $780,000 which was used to mitigate 0.3 miles of highway using rockfall fences. The second contract was for $1,2million to mitigate 0.5miles of the I-40 in Cocke County. Mitigation measures included the installation of catch fences, draped wire mesh and a hybrid wire mesh system. The third contract was for $537,000 to mitigate 0.65 miles of the I-440 in Nashville. Mitigation measures included barring, trimming of the slopes, cleaning and regrading the catchment ditch and the installation of a catch fence.

The cost of the 3-year research effort was $1 million. Although, at the time it was too early to quantify the financial benefits of the research, recovering the investment and savings was a realistic expectation based on their past experience of road closures, property damage, fatalities and inconvenience to motorists.

Large-scale structural and engineering geological mapping can also assist in determining locations of possible rockfall risks and narrowing down the size of the higher risk areas. For example, areas with unfavourable joint sets that are closely spaced can be earmarked for a more detailed inspection.

Predicting rockfalls is a difficult task, made more so by complex geological conditions, many of which cannot be seen on the surface. The most common method of mapping possible rockfalls is generally isolated to specific locations and on the surface only. Arosio, et al., 2009 described acoustic emission/microseismic monitoring that may provide a deeper insight of stress and strain conditions within the sub-surface rock mass. They further went on to explain “that the capability to detect microseismic events originating within an unstable rock mass is a key element in locating growing cracks and, therefore, understanding the slide kinematics and triggering mechanism of future collapses".

Acoustic Emission/Microseismic (AE/MS) is a technique that has been in use for over 60 years in a wide range of applications. AE/MS activity originates as an elastic stress wave at locations where the material is mechanically unstable (Arosio, et al., 2009). However, microseismicity cannot predict potential rockfalls on its own. It can assist in building a network of historical data which can be used in conjunction with geological mapping and other geodetic measurements as a means to predict rockfall.

2.11 ENGINEERING MITIGATIONS TO THE ROCKFALL PROBLEM

Wyllie and Mah (2005) described rockfall stabilisation into three categories:

- Reinforcement
- Rock removal
- Protection

Depending on the specific site, the three categories above are subdivided into specific rock stabilisation measures. Slopes requiring stabilisation next to roads or railway lines may have limited space and, therefore, the most common type of rockfall stabilisation 'Ditches' will not be able to be used in these situations. Although more costly, it may be more conducive to consider other methods of rockfall stabilisation in such situations.

From personal experience, it is generally easiest to bar down any loose rock on the face that can be done so safely and with minimal or no damage to the road, railway or structures below. Catch fences, pinned and or drape mesh, rock bolting, reinforced shotcrete and gabion walls can then be considered as the method of rockfall mitigation depending on the other factors that influence the rockfall hazard mapping. Figure 2.27 divided rockfall mitigation measures into protection and stabilisation measures, followed by a further subdivision into reinforcement and rock removal categories.

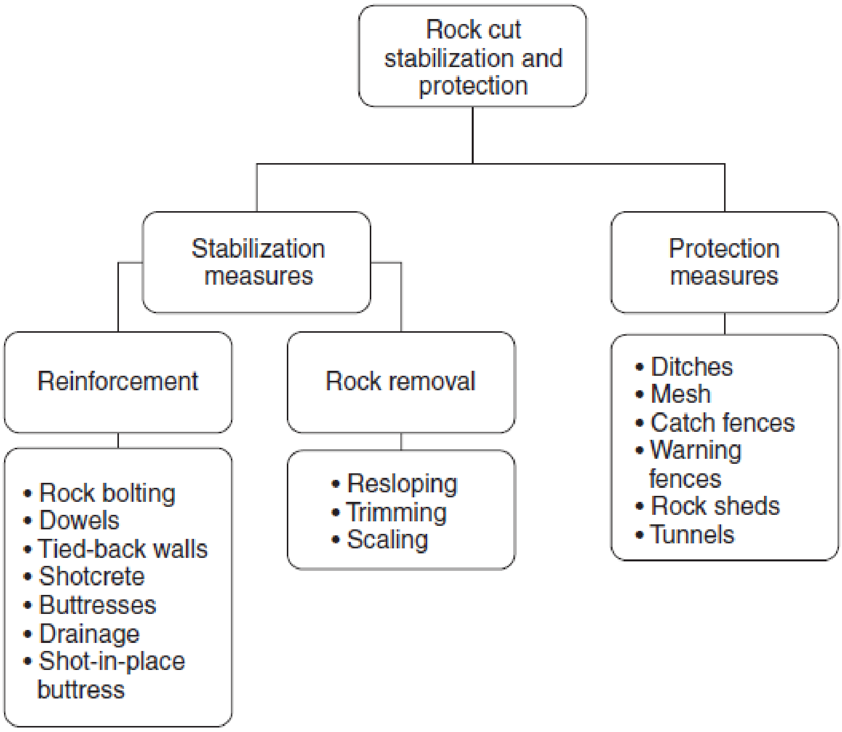


Figure 2.27: Rock Slope Stabilisation Measures (Wyllie and Mah, 2005)

Other than the commonly known protection measure types such as ditches and fences, Hoek (2007), included berms, rockshed and fills as rockfall protection measures.

Wyllie and Mah (2005), described other aspects to consider when choosing rockfall mitigation measures are topography, construction access, waste disposal, aesthetic, dust, noise and ground vibration, biological and botanical effects and cost of construction.

Geological factors such as unfavourable discontinuities on steep slopes at road cuttings can result in slope failure as well as the development of rock blocks. A common practice is to flatten off the slope by cutting it back at a shallower angle. This, however, can lead to other problems such as exposing a large surface area to rainfall which will ultimately increase weathering of the rock face. Another problem that can arise should this cutting be below a steep slope, is the increased length of the overall slope by cutting it back. This would result in an entirely new set of rock stability problems (Wyllie and Mah, 2005).

Construction access can limit the choice of rockfall mitigation measures. For example, when working on a road cutting with steep topography and one lane closure, the size of vehicles, drill rigs, cranes etc. has to be taken into consideration to avoid any risks to safety.

Waste disposal can be a costly affair and in most urban areas disposing of waste rock means carting it away from the site. Dumping the waste rock below the slope would be the most cost-effective method of disposal (Wyllie and Mah, 2005), however, most areas have to follow an environmental impact assessment and such means of disposal are not allowed.

Aesthetics have become an important part of rockfall mitigation, particularly in the last decade or so. Engineers have become much more vigilant in matching the colour of the catch fence posts and ringnets for example to the surrounding slopes so as to have the catch fence blend into the environment. Gabion walls are packed with rocks that match the rock type and colour of the site where they are to be installed. Slopes with pinned or draped mesh can be covered with a coloured plastic coating which not only assists in reducing corrosion of the mesh but also assists in blending the mesh with the environment. Hydro-seeding is also an option over the mesh to have a more natural looking slope. There is also an option to colour shotcrete to match the rock colour that it is applied to.

Dust, noise and ground vibration can be a problem in urban environments. Generally, health and safety consultants are employed on every contract to ensure that such conditions are limited and are of no danger to the workers and surrounding communities. Ground vibration can be a problem if there are any structures in close proximity to the site particularly structures built on problem soils.

Along with health and safety consultants, each contract also employs an environmental consultant. These consultants deal with the biological and botanical effects of any type of construction in the area. The researcher has worked on contracts where snakes and plants have been removed from the site and relocated to elsewhere in the area. We have had a number of occasions where pinned mesh had to be cut around protea trees in order to stabilise the slope and also protect the trees in place.

Ultimately, the cost of construction is usually what determines the final type of rockfall mitigation measure put into place. Currently, the world's two largest producers of rockfall stabilisation products are Maccaferri in Italy and Geobrugg in Switzerland. Importing products to African countries with a weaker currency substantially increases the cost of a project.

2.12 CONCLUSIONS

During this literature research study, it became apparent that although research on rockfall has been carried out since the 19th century (Dorren et al., 2011), very little information was available regarding rockfall history, prediction of rockfalls and mitigation measures in South Africa, let alone the Western Cape. Although the geology, climate and vegetation vastly differ from countries like Switzerland and Italy, their research can be adapted to suit local conditions and manipulate software data input to accommodate our rockfall problem areas. This significantly increases the engineers' ability to design rockfall measures more accurately and at a lesser cost, however, proper field studies to determine the behaviour of rockfalls in the Western Cape will be invaluable to all future rockfall modelling problems.

The aim of this research study will be to model and predict potential rockfalls in the Western Cape and in doing so determine the appropriate and most cost-effective mitigation measure. A desk study including aerial photo interpretation and the terrestrial survey will be included. Rockfall 3D trajectory modelling, presentation of 3D site views in ArcGIS and 2D rockfall modelling will be undertaken in the research study areas and presented in the chapters that follow.

CHAPTER 3 : STUDY AREA FOR ROCKFALLS IN THE WESTERN CAPE AND SOFTWARE PROGRAMS

3.1 METHODOLOGY

This research project entails a detailed desk study which includes sourcing geological and topographical maps as well as aerial photographs for use in stereographical analysis. The desk study was followed by a site walkover which included a detailed photographic record of each site in determining the location of any potentially loose blocks. The desk study was followed by a detailed topographical survey which was used as the basis for the rockfall simulation. The 3-dimensional survey was used in the 3D software to determine the rockfall trajectories. A digital elevation model was also created from the survey data to present the rockfall trajectories.

3.2 INTRODUCTION

Crosta et al (2014) stated that “Rockfall risk analysis for mitigation action design requires evaluating the probability of rockfall events, the spatial probability and intensity of impacts on structures, their vulnerability, and associated expected costs for different scenarios”.

This research document is based on almost a decade of the researcher’s personal experience working on various rockfall projects. A collection of data from these projects as well as the use of various software programs to determine impacts of rockfalls to assist in design and rockfall mitigation measures. This chapter will provide detail on the procedures required to collect field data as well as provide educated assumptions for software input parameters that cannot be obtained in the field. This includes:

- Desk study
- Site Walkover
- Terrestrial Survey

The study areas were chosen from previous projects that were undertaken whilst working as an Engineering Geologist at a well-established consulting firm. The study areas were distributed across the Western Cape region and the following chapter will include the general geology of the sites which will directly impact the choice of input data for the software programs.

3.3 STUDY AREAS

The three projects chosen for inclusion in this research project lie between the western end of Cape Town and the eastern end of Sir Lowry's Pass. All three sites form part of different geological formations which will assist in analysing the behaviour of rockfall from different material types. The sites used in this research project include Chapman's Peak Drive, Sir Lowry's Pass and The Cliffs. The localities of those can be seen in Figure 3.1.

These three study locations have been selected for this research project as all of them have experienced rockfalls of varying sizes and damages to property and infrastructure. Many injuries and a limited number of fatalities have impacted the local community and has required mitigation measures to prevent or limit future rockfalls. The field of rockfall studies is extremely limited if not non-existent at Western Cape universities and it is the researcher's aim to bring more awareness, interest and understanding of the field to future students. Rockfall is a significant problem in the Western Cape and is not taken seriously until damage to infrastructure or even loss of life is experienced.

A detailed desk study was carried out on each of the study areas. This included the study of geological maps, topographical maps, aerial photography and any reports available from previous investigations. A brief description of the general geology of the study areas will be presented followed by a detailed description of the local geology.

The top right-hand corners of Figure 3.2, Figure 3.3 and Figure 3.4 show an enlarged aerial view of the sites.

Figure 3.1: Topographically map showing the 3 study areas (3318_2000_ED7; 1:250 000, Department of National Geospatial Information)

3.3.1 Location of Study Area A: CHAPMAN'S PEAK DRIVE (YEAR: 2007)

This site is located on the western end of the peninsula of Cape Town, Western Cape, South Africa. The northern end of this 8km route begins at km 24,1 in Hout Bay and travels southerly to end at km 32,1in Noordhoek. The pass section of the route starts at km 28,6 at the "Lookout point" and ends at km 32,1. The pass section is the area where the catch fences have been installed as the geological conditions change from highly to completely weathered granite. This is overlain by interbedded sandstone and shale with less weathered granite exposed in some areas.

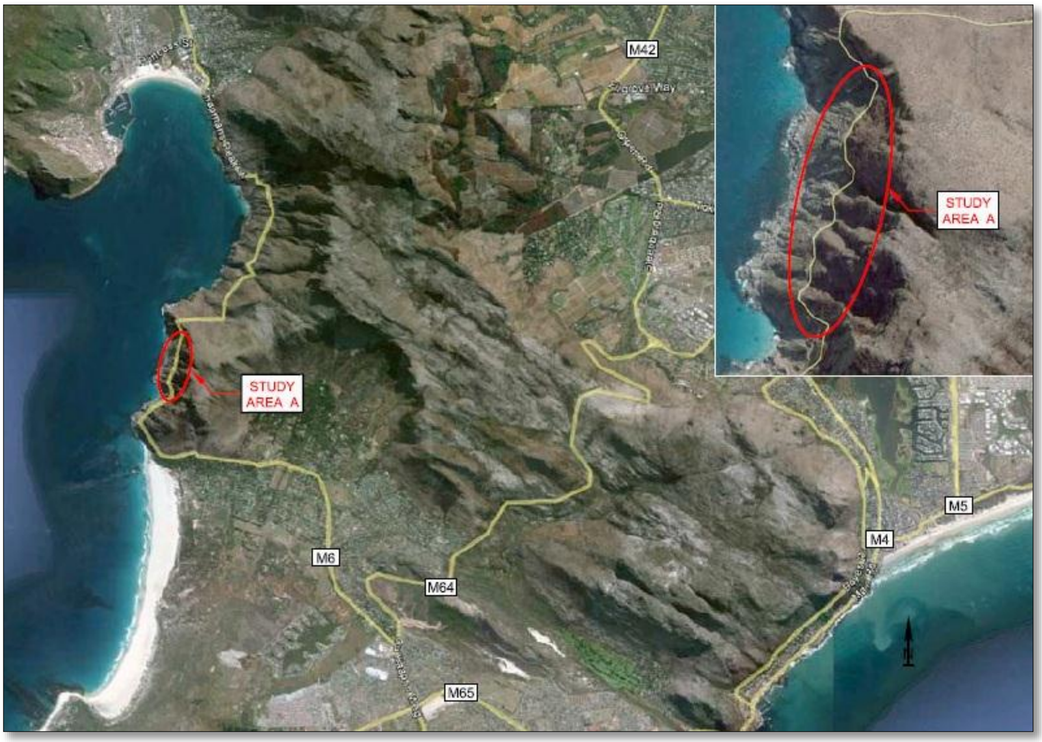


Figure 3.2: Locality Plan of Area A: Chapman's Peak Drive (3418AB_03&08_2010_RGB_RECT, Department of National Geospatial Information)

3.3.2 Location of Study Area B: SIR LOWRY'S PASS (YEAR: 2013)

This site is located on the slopes of the Hottentots Holland mountain range and cuts through the National Route 2, approximately 15km east of Somerset West, Western Cape, South Africa. The approach to the site from the west is a steeply winding road which crosses over a railway bridge before the climb continues beyond the site and levels off closer to the look-out point.

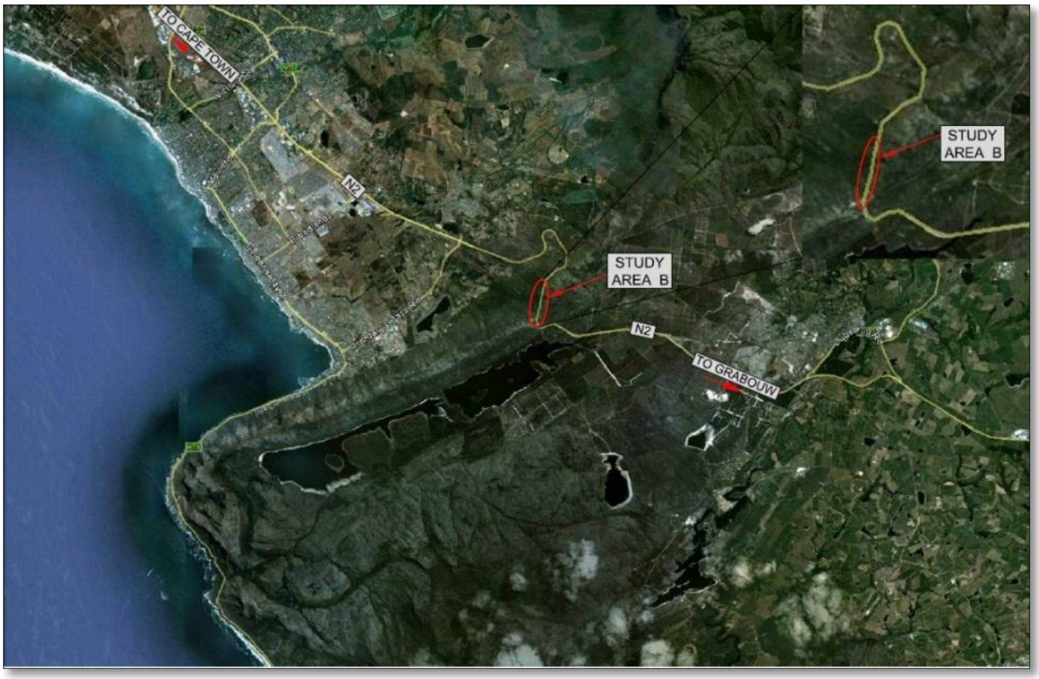


Figure 3.3: Locality Plan of Area B: Sir Lowry's Pass (3418BB_14_2010_307_RGB; Department of National Geospatial Information)

3.3.3 Location of Study Area C: THE CLIFFS (2015)

This site is located at the base of the old Tygerberg quarry in Tyger Valley close to the National Route 1 in the Western Cape, South Africa. The entrance to the office park is at the intersection of Carl Cronje drive and Bill Bezuidenhout Avenue. The study area is the rock face on the northwest corner of the quarry wall.

Figure 3.4: Locality Plan of Area C: The Cliffs (3318DC_13_2010_307_RGB_RECT, Department of National Geo-spatial Information)

3.4 DESK STUDY

3.4.1 Historical field data collection

Chapman's Peak Drive has had a team of people working under Entilini Concession that records any rockfalls that occur on the road. The information recorded includes the rock type, size of the rock, where the rock landed, where the rock originated from and any damage to infrastructure. Therefore, over 10 years' worth of data has been recorded since the inception of the re-aligned road in 2003.

The original field work and rockfall studies were undertaken in 2003 which will not be included in this research study. In 2007, a damage event occurred which resulted in a number of fences being breached, however these fences performed as designed. This research study will concentrate on re-running the rockfall simulations for the fences impacted during this damage event.

Sir Lowry's Pass only has information that has been recorded by routine road maintenance and it is not freely available. In 2012, a rockfall incident occurred on the pass nearly missing two vehicles resulting in damage to the left lane eastbound. The surrounding areas were then investigated visually in detail followed by a rockfall analysis. The outcome of this will be presented in this research project.

The Cliffs has had a few incidents since the completion of the office buildings, however, the detail regarding each incident is limited. The trustees of the office complex have limited funds and it was imperative that the field data collected as well as the analysis be completed within a specified budget but provide the client with all the necessary information to mitigate the problem and provide all tenants of the building with a safe working environment.

3.4.2 Topography

Topography determines the relief and landforms and can be used to assess the stability of slopes and detect old landslides (Bell, 2007). The type of design suitable for a particular site depends on the topography (Wyllie and Mah, 2005). Bounce height and impact energies of rockfalls are also influenced by topography.

During the desk study phase of an investigation, the topographical map can be very useful in determining the slope steepness, gulleys, water features and mining activities in the area.

Accessing topographical maps to determine the nature of a site is a relatively cheap option before a more expensive detailed terrestrial survey can be done. In some instances, the topographical map can provide just as much information as a terrestrial survey would, however when it comes to rockfall modelling, a terrestrial survey is required to determine the slope surface on which to model the rockfalls.

Study Area A: Chapman's Peak Drive

Although the topographical map below has been reduced to cover the study area, on a larger scale, features such as rivers, boundary lines and trig beacons can be identified for use in the desk study.

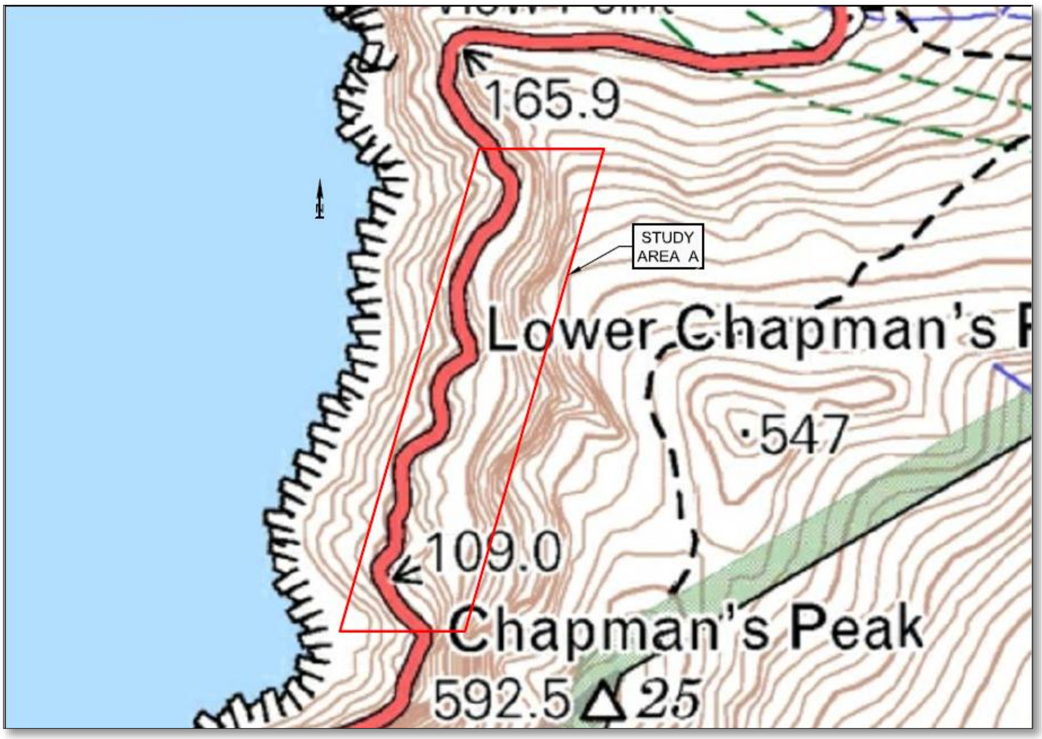


Figure 3.5: Topographical map of study area A (3318_2000_ED7_MD_200003_GEO, 1:50 000, Department of National Geo-spatial Information)

Study Area B: Sir Lowry's Pass

The railway lines and bridges can be identified as well as the extent of the boundary lines. Work to be carried out on this site was to be kept in the road reserve as anything out the road reserve belonged to Cape Nature. Damage to vegetation, drilling, and possible grout spillages were seen as a problem and access routes to the site had to be determined via the road reserve only.

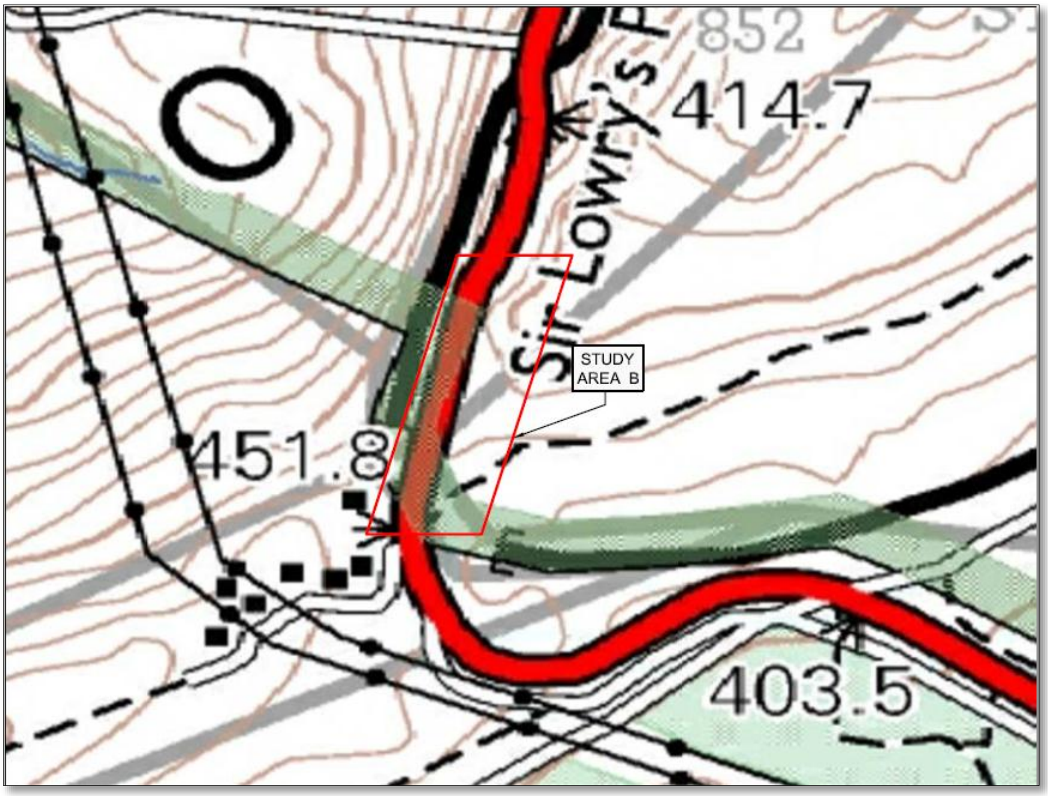


Figure 3.6: Topographical map of study area B (3418_2000_ED5_GEO, 1:50 000, Department of National Geospatial Information)

Study Area C: The Cliffs

This study area is slightly different from study area A and B as it is in the middle of an office complex. The topographical map outlines the extent of the previously mined area which is now the location of the office complex. The office complex is designed around the water body as its main selling feature.

Figure 3.7: Topographical map of study area C (3318DC_2000_ED9_GEO, 1:50 000, Department of National Geospatial Information)

3.4.3 Geology

3.4.3.1 General geology of the Western Cape

The general geology of the Western Cape is presented in Figure 3.8 with the study areas shown in black.

The Malmesbury Group (grey) is one of the oldest deposits in the Western Cape and South Africa. It covers roughly 20 000km^2 around the Cape Town area. The stratigraphy of the Malmesbury Group is poorly known due to the Cape Supergroup (light purple) overlying a large extent of it. The Cape Supergroup comprises sandstones, shales and quartzites of the Palaeozoic age. These formations vary in thickness and lie unconformably upon older formations and are overlain unconformably by the basal beds of the Karoo Supergroup (Haughton, 1969). The Cape Peninsula pluton forms the bedrock of the major part of the peninsula but is mostly covered by the Table Mountain sandstone of the Cape

Supergroup. Intense folding and faulting has occurred across the Western Cape giving rise to some of the most interesting geological features but also creating many potential rockfall hazards.

Figure 3.8: Geology of the Western Cape (3318 Cape Town 1990, 1:250 000; Geological Survey)

3.4.3.2 Geology of study areas

A. Chapman’s Peak Drive

The geology of Chapman’s Peak Drive comprises interbedded sandstones and siltstones of the Cape Supergroup, nonconformably overlying the granite of the Cape Granite Suite. A number of large faults are present giving rise to highly fractured and disturbed rock masses some of which directly influenced the rockfall mitigation type, an example is a half tunnel that had to be blasted into the mountainside to serve as a rockfall protection measure as well as stabilise the slope.

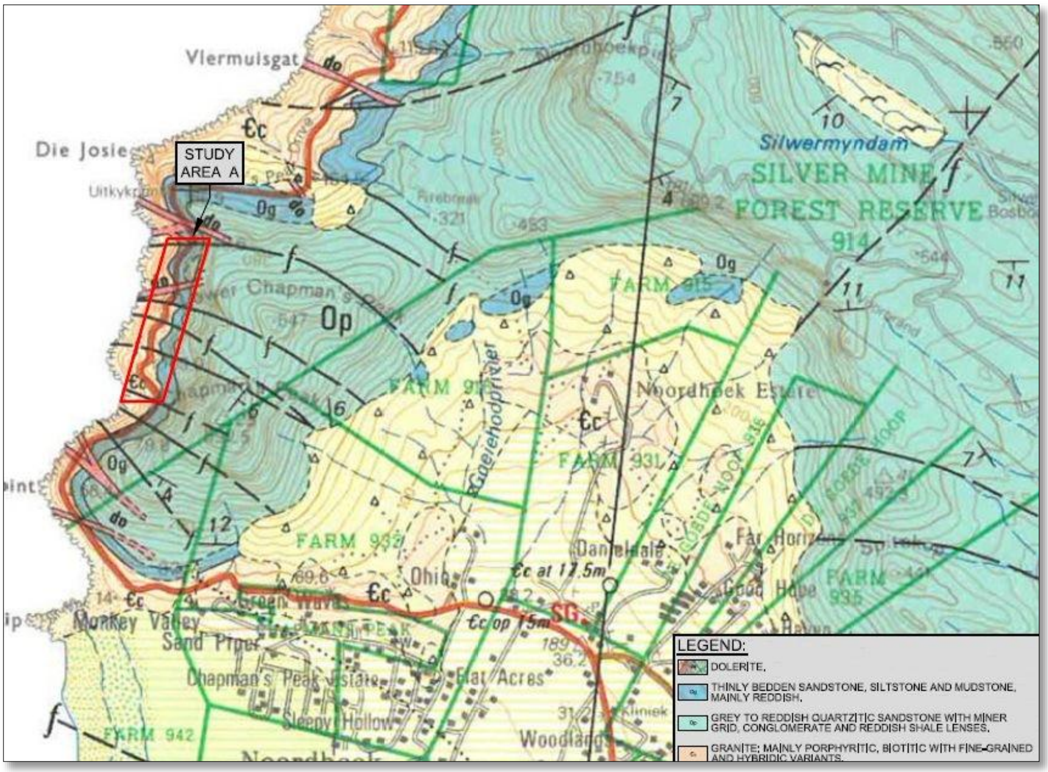


Figure 3.9: Geology of the Site A: Chapman's Peak Drive (Kaapse Skiereiland, 1984, 1:50 000, 3418AB and AD)

B. Sir Lowry's Pass

This site forms part of the Cape Fold Belt. According to published geological maps and literature, the cutting is in slightly to highly weathered, medium to widely jointed, argillaceous and quartzitic sandstone of the Peninsula Formation, Table Mountain Group. This Formation dips steeply towards the East and has been heavily affected by faulting and folding.

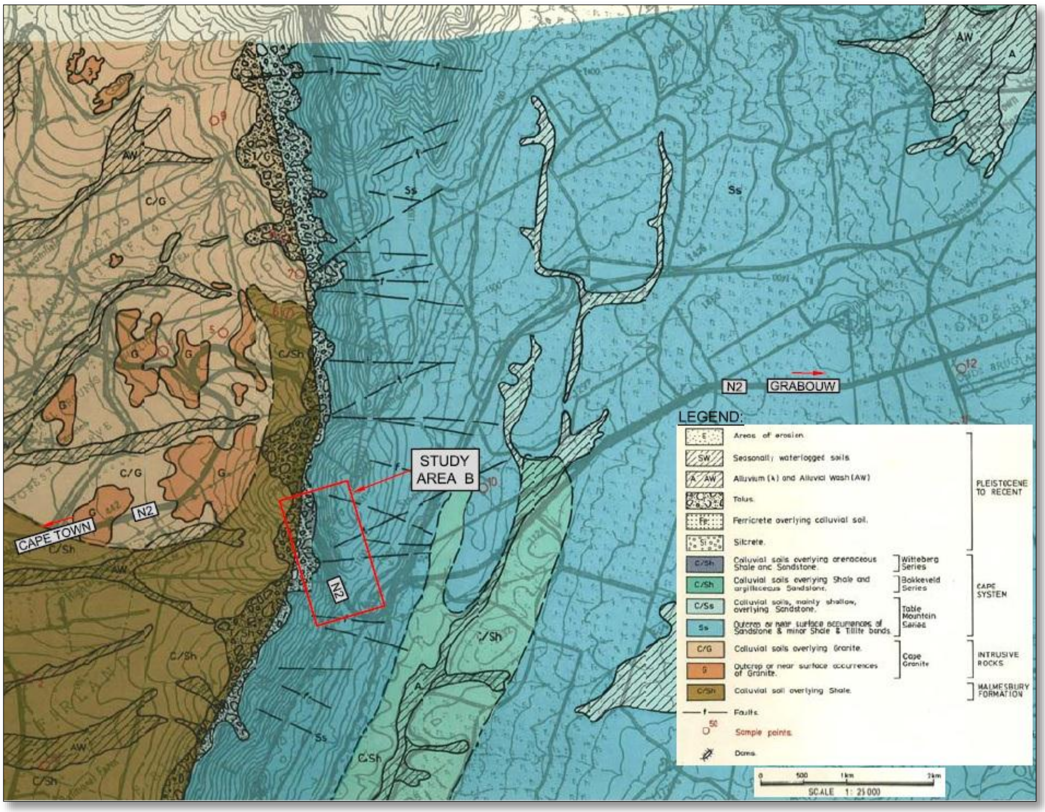


Figure 3.10: Geology of the Site B: Sir Lowry's Pass (Engineering geology map of Somerset West and Hangkilp area Cape Province, Republic of South Africa, M.J. Mountain & Associates, Jan 1980)

C. The Cliffs

The rock that had been mined in the quarry consists of steeply dipping beds of greywacke and quartzitic sandstone of Tygerberg Formation, Malmesbury Group. The rock comprises dark grey with occasionally dark green, moderately to widely jointed, well and thickly bedded, hard rock beds of greywacke and quartzitic sandstone. Localised, closely jointed zones occur. Tectonic deformation has resulted in the beds dipping steeply at 69° to the west with a series of intersecting joints sets.

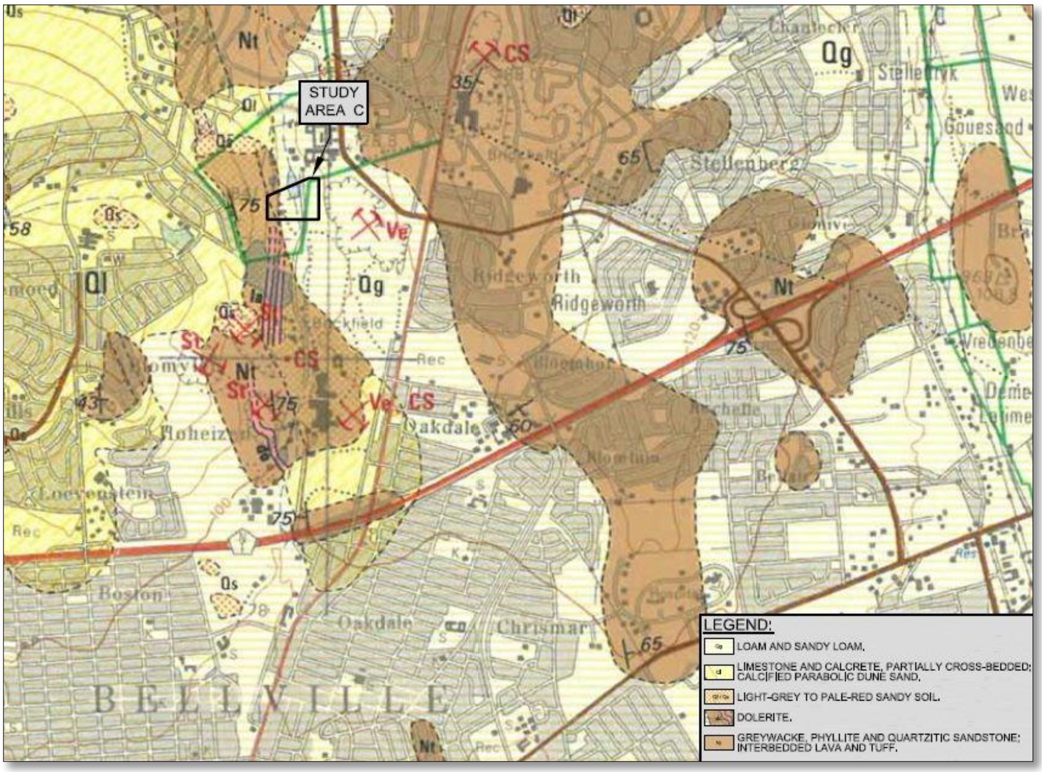


Figure 3.11: Geology of the Site C: The Cliffs (3318DC Bellville 1984, 1:50 000, Geological Survey)

3.5 FIELD DATA COLLECTION

3.5.1 Photographic data

Taking photographs on site from different angles and locations can greatly assist the desk study and more so during the rockfall analysis. The photographs can be used in identifying specific areas of concern that can be mapped and modelled in the software programs.

The saying “A picture paints a thousand words” cannot be truer in the field of rockfall studies. Therefore, a few photographs taken for each of the 3 study areas at various phases of the projects is presented.

Site A: Chapman’s Peak Drive

The image below shows a massive sandstone block that intersected catch fence 15 and landed just short of the road. The angular nature of the block indicates that this block released from the Cape Supergroup higher up and was not part of the talus boulders that are scattered across the mountain.

Figure 3.12: Large boulders breaching catch fence 15. (Photo by S. Surujbally 2007)

Figure 3.13 shows multiple boulders caught in catch fence that has been breached. Catch fence 15b actually is located directly above catch fence 15 and was, therefore, Figure 3.12 as well. Breaching two catch fences slowed down the block and, therefore, it did not go further and land on the road.

Figure 3.13 Multiple boulders breaching Catch Fence 15B (Photo by S. Surujbally 2007)

Site B: Sir Lowry's Pass

The area where fresh, light brown rock can be seen just below the rope access person and towards the right of the figure is the location where the large wedge released from and landed on the road. The remaining wedge was seen to be a potential problem in the near future and was stabilised using rock bolts.

Figure 3.14: Area where the wedge was released and landed on the road, remaining wedge required stabilisation (Photo by S. Surujbally 2012).

Further site inspections concluded that there was a need for stabilisation and rockfall mitigation for a larger area along the pass. The figure below shows a team of rope access personnel assisting the engineer with the setting out of the catch fence.

Figure 3.15 Visual inspection of the site and setting out of catch fence (Photo by S. Surujbally 2013).

The geology of the area seen in Figure 3.16 was highly to completely weathered and required a thorough inspection and barring down of potentially loose material before pinned mesh could be installed. During the process a block bounced across the four lanes and landed on the southern side of the road reserve, confirming that if these blocks were left on the rock face, they would come down over time and may result in disastrous consequences for motorists.

Figure 3.16: Barring down of loose rocks from the cutting face by rope access team (Photo by S. Surujbally 2012).

Site C: The Cliffs

A steep, high cliff that used to be a quarry forms the backdrop to this building complex. A large rock released and impacted the gabion wall causing damage to it. The figures below show both sides of the gabion wall whereby the impact was significant enough to create a bulging effect on the outside of the wall.

Slope side of Gabion Wall

Gabion Wall bulging on the outside

Figure 3.17: The gabion wall that was damaged during the rockfall (Photos by S. Surujbally 2015).

This figure shows the old quarry face which is described above with potential loose boulders.

Figure 3.18: Area of concern for potential rockfalls (Photo by S. Surujbally 2015)

A few specific larger boulders were identified to be a possible rockfall problem and these were modelled separately and will be discussed in the next chapter.

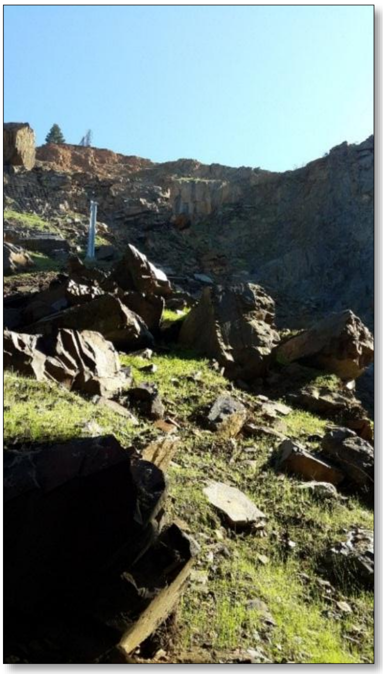


Figure 3.19: Area modelled for potential 10m^3 rockfall in "S" sections (Photo by S. Surujbally 2015)

3.5.2 Terrestrial survey

A good quality terrestrial survey is very important as it determines the quality and accuracy of the digital elevation model. The direction and length of the trajectory paths are then determined from the digital elevation model or the TIN.

The contours (lines on a map or drawing that joins points of equal elevation) displayed for all 3 study areas is at 5m spacing for viewing purposes. The TIN model was created using a more detailed 1m spaced contour interval to create a 3D representation of the site to be more realistic.

Before a 3D model can even be produced or rockfall trajectories created, an experienced engineer will be able to make an educated estimate of the likely paths that a potential rock can follow just by looking at a good quality survey.

Site A: Chapman's Peak Drive

Gulleys and steepened areas of the mountain face can clearly be seen on the contours indicating what the 3D view of the site will be even before the 3D model can be created. This survey covers a significantly large area (Figure 3.20). Another aspect that terrestrial surveys are useful in is determining the land ownership and boundaries. Problems arose from this site as Entilini Concession is responsible for the safety of the road users, however in most instances, the rockfalls originate from higher up and this area falls within the South African National Parks. The problems with land ownership will not be discussed any further in this research project.

Site B: Sir Lowry's Pass

The closely spaced contour lines show the steepness of the mountain face above the roadside cutting which would create a slope surface for rockfalls with high kinetic energies depending on the slope length (Figure 3.21). Rockfalls that tend to originate from higher up on a mountain face will gravitate towards the gulleys resulting in a change in trajectory direction. The concentric circles define the mountain tops with the valleys in-between creating an undulating surface.

Site C: The Cliffs

The detail of the contours for this study area shows the overhangs, cliffs and gulleys which will have a significant impact on the rockfall trajectories, kinetic energies and bounce heights. The closely spaced contour lines indicate the steep rock faces particularly near the crest of the cutting (Figure 3.22). The contours tend to be slightly wider spaced below the crest and then display a few more steep faces with closely spaced contours on the descend to ground level

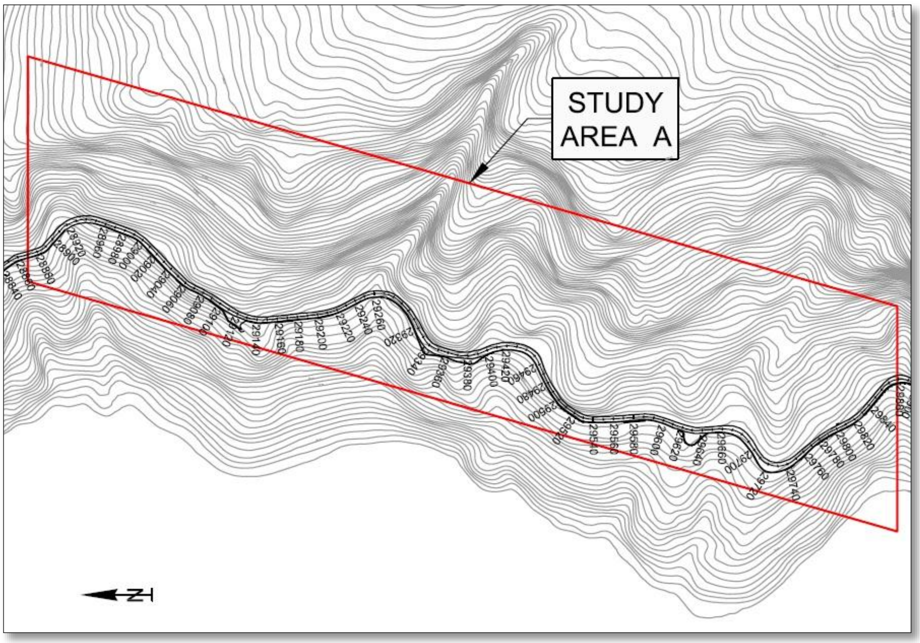


Figure 3.20: Terrestrial Survey of the Study Area A

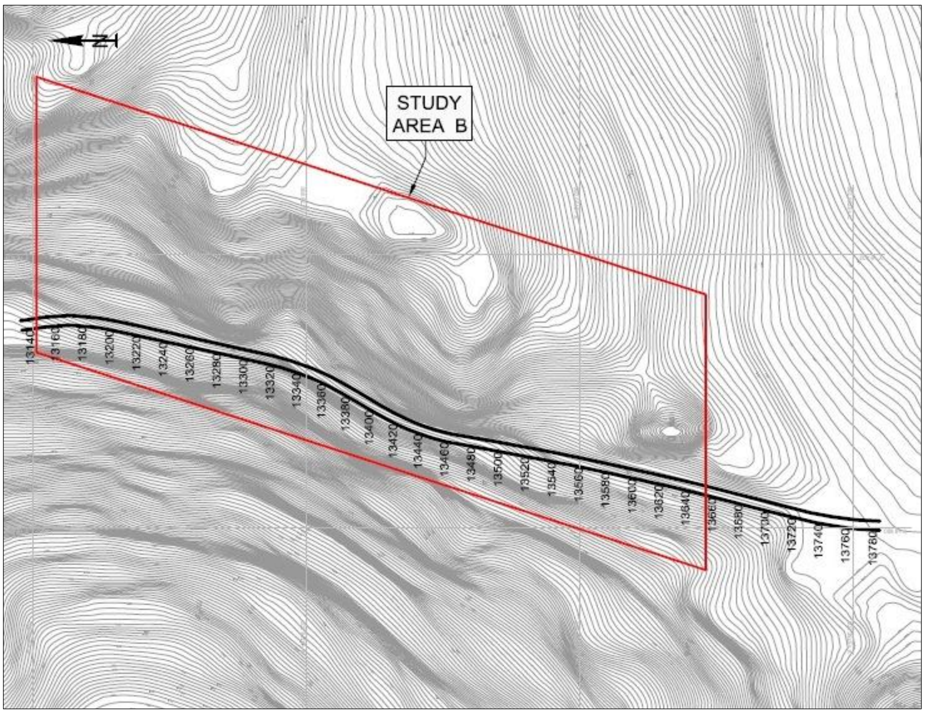


Figure 3.21: Terrestrial Survey of the Study Area B

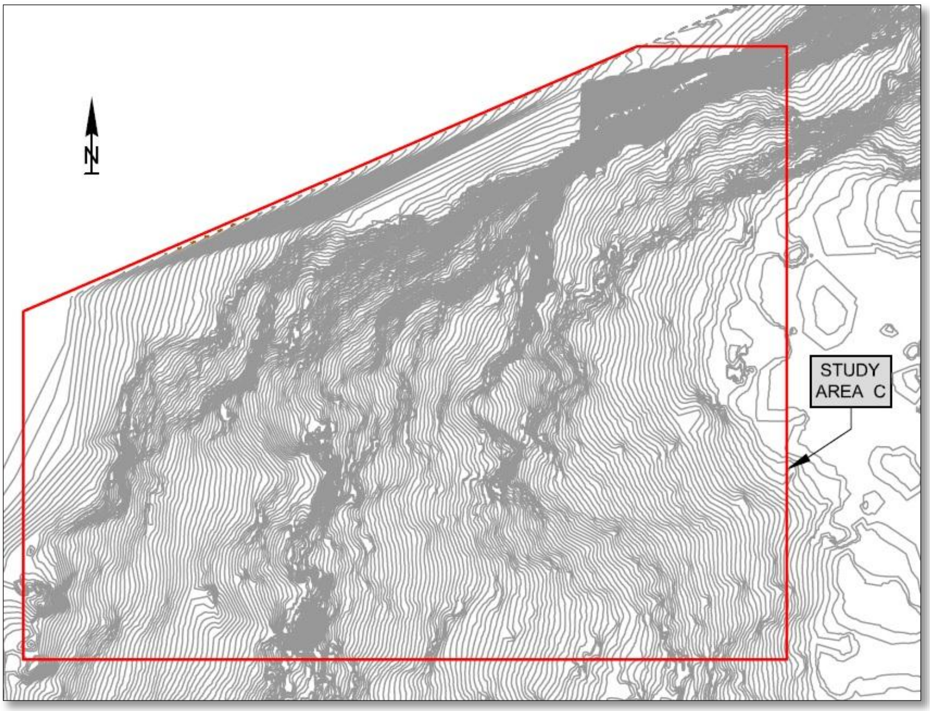


Figure 3.22: Terrestrial Survey of the Study Area C

3.6 SOFTWARE PROGRAMS

This research study aims to determine the extent to which a detailed site investigation coupled with good input data for software programs can assist the design engineer in determining the location of specific rockfall mitigation measures.

Three different software packages were used in this research project. The first being ArcGIS 10.0 which was used to create the relevant ASCII files for the 3D software. The 3D software uses the ASCII file to create a digital elevation model over which the rockfall simulation would be applied.

Two types of rockfall software were used as part of the analysis, the 3D software RAMMS or Rapid Mass MovementS: Rockfall and the 2D software Rocscience's Rocfall 4.0. This research project was carried out using the trial version of the 3D software RAMMS as the program was released after the software analysis was completed. Therefore, it was used only to determine the 3D trajectory paths of the rockfalls and any further rockfall details was determined in the 2D Rocfall software. Rocks follow the topography of a site and rarely fall in a straight path from their point of release, therefore, was it was decided to use the 3D software to determine the 3D trajectory path and use these paths in 2D to simulate a more realistic rockfall path.

ArcGIS was also used to create a Digital Elevation Model (DEM) from the terrestrial survey to present the trajectories output in 3D. This will be presented in Section 4.2. The 3D trajectory paths were exported from RAMMS as shape files, imported into ArcGIS and exported as a dxf file for use in AutoCAD. In AutoCAD, the trajectory paths could be traced and each trajectory could be saved as a separate dxf file for use in Rocfall for the 2D rockfall simulation.

According to the WSL Institute for Snow and Avalanche website and without going into detail, RAMMS is a reliable numerical simulation tool yielding runout distance, flow heights, flow velocities and impact pressure of dense flow snow avalanches, hillslope landslides and debris flows. It has been developed by a team of experts at the WSL Institute for Snow and Avalanche Research SLF and the Swiss Federal Institute for Forest, Snow and Landscape Research WSL (www.ramms.slf.ch, 2015). In April 2015, RAMMS: Rockfall was released in collaboration with the Centre of Mechanics.

Rocscience software packages have been created by geotechnical engineers in Canada since 1996 including Rocscience Rocfall. “Rocfall is statistical analysis program designed to assist with the assessment of slopes at risk for rockfalls” (www.rocscience.com, 2015). This software was used on sections taken from the study areas to determine the extent of possible risk by rockfalls. The program determines energy, velocity and bounce heights of the virtual rocks as well as the location of their end points for the entire slope (www.rocscience.com, 2015).

CHAPTER 4 : SOFTWARE RESULTS AND INTERPRETATION

4.1 RAMMS: Rockfall

The terrestrial survey was used to create an Esri ASCII grid and was imported into the RAMMS software. The software automatically creates a digital elevation model based on the ASCII grid. The size of the block is input into the software as well as the location from where the simulated rockfall originates. The software then produces the trajectory path based on all the input information. It relies heavily on the accuracy of the terrestrial survey. In the event that there are a few outlier points, this sometimes can result in very high kinetic energy and or bounce heights and the software user will have to use their discretion when interpreting and presenting the data.

As mentioned above, this software was still in a trial phase when this research project was undertaken and therefore, only the 3D trajectory paths were exported as shapefiles and presented in 2D on the terrestrial survey in Figure 4.1, Figure 4.2 and Figure 4.3. These trajectory paths were then used to run the rockfall simulations in the tried and tested Rocscience Rocfall software and the results are presented in Section 4.3.

4.1.1 Chapman's Peak Drive

Eleven trajectories or rock paths that intersect the catch fences that experienced damage following a heavy rainfall event were chosen for analysis in the 2D rockfall software program and are presented in Figure 4.1.

The length and slope angle of each of the sections shown in Figure 4.1 is tabulated. The slope lengths range from 94,85m to 194,65m. Slope length is an important feature to take note of as rock blocks tend to lose energy when travelling down very long slopes and generally stop before reaching the road. However, in cases where the slope profile comprises clean hard rock, the rock block can gain momentum and travel at higher energies and bounce much higher.

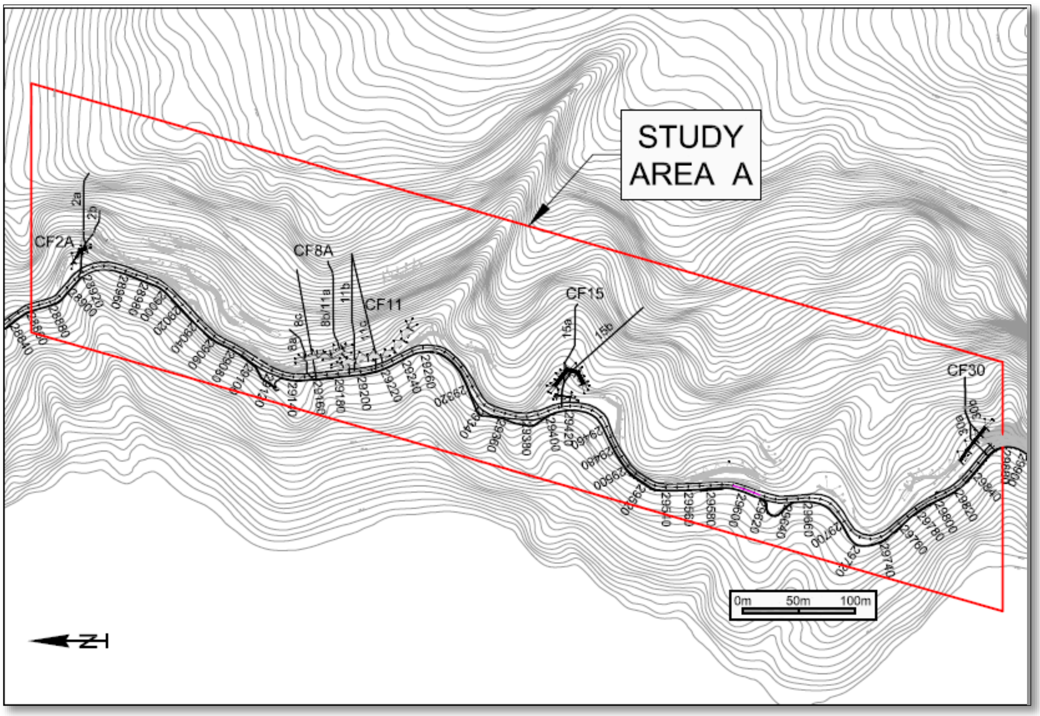


Figure 4.1: Survey indicating the trajectory path determined by RAMMS at Study Area A

Table 4.1: Slope length and angle of Area A's sections

Section Name	Slope Length (m)	Slope Angle (°)
2a	181,50	59
2b	94,85	52
8a	72,95	53
8b	193,48	59
11a	161,95	53
11b	192,52	57
11c	194,65	58
15	113,63	36
15b	173,52	59
30a	110,53	50
30b	106,00	51

4.1.2 Sir Lowry's Pass

A total of twelve trajectories were chosen to be analysed in the 2D rockfall simulation software with two trajectories at the estimated location for each of the potential rockfall mitigation measures.

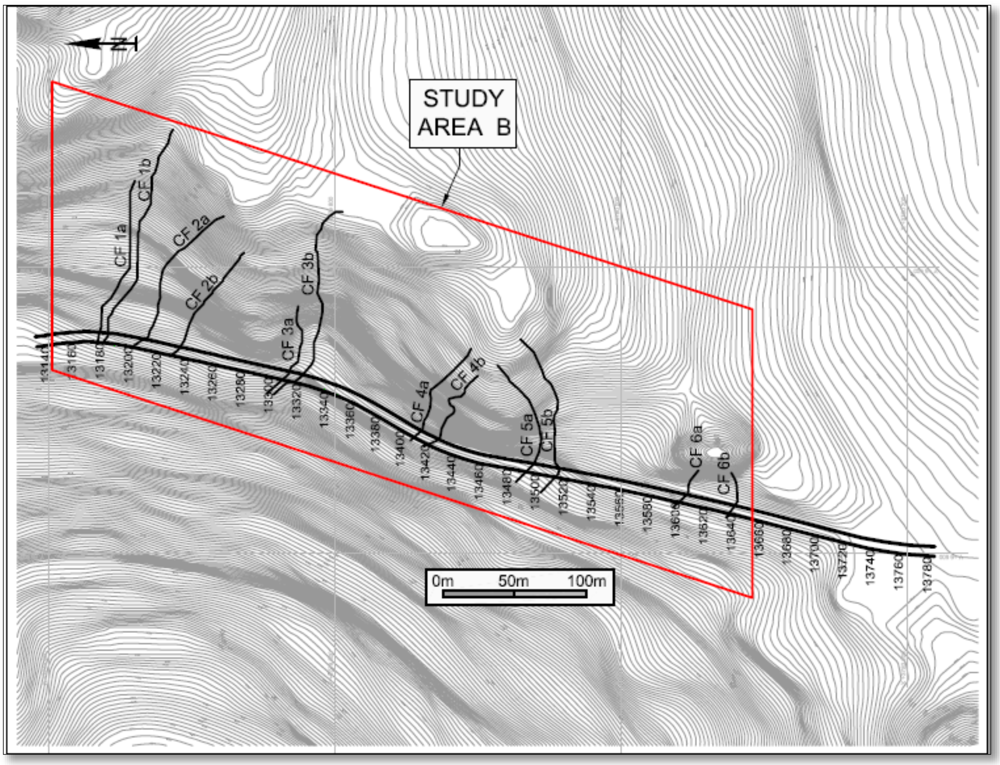


Figure 4.2: Survey indicating the trajectory path determined by RAMMS at Study Area B

The trajectories have a much wider length range on this site, ranging from 37,76m to 177,67m and this is consistent with the topography of the area. Steeper, higher mountains will create longer slope lengths whilst less mountainous sections will create shorter slope lengths.

Table 4.2: Slope length and angle of Area B's sections

Section Name	Slope Length (m)	Slope Angle (°)
1a	138,00	33
1b	177,67	33
2a	143,61	44
2b	115,46	46
3a	79,10	38
3b	169,46	38
4a	100,83	46
4b	85,21	50
5a	106,89	40
5b	130,37	34
6a	37,87	40
6b	37,76	34

4.1.3 The Cliffs

Seventeen trajectories were analysed in the 2D rockfall software program, eleven of which were analysed for the typical $1m^3$ rock block scenario and the other six were analysed for a $10m^3$ rock block.

Two different sets of rockfall simulations were carried out in this study area. The "CS" trajectories originated from the crest, whilst the "S" trajectories originated from an area identified to have potentially larger rockfalls. The slope lengths did not change significantly across the areas of interest.

The two different blocks sizes and the two different origins of trajectories were only modelled for this study area as it was clearly identified during the site inspection the need to model the larger blocks separately as they were located lower down the slope.

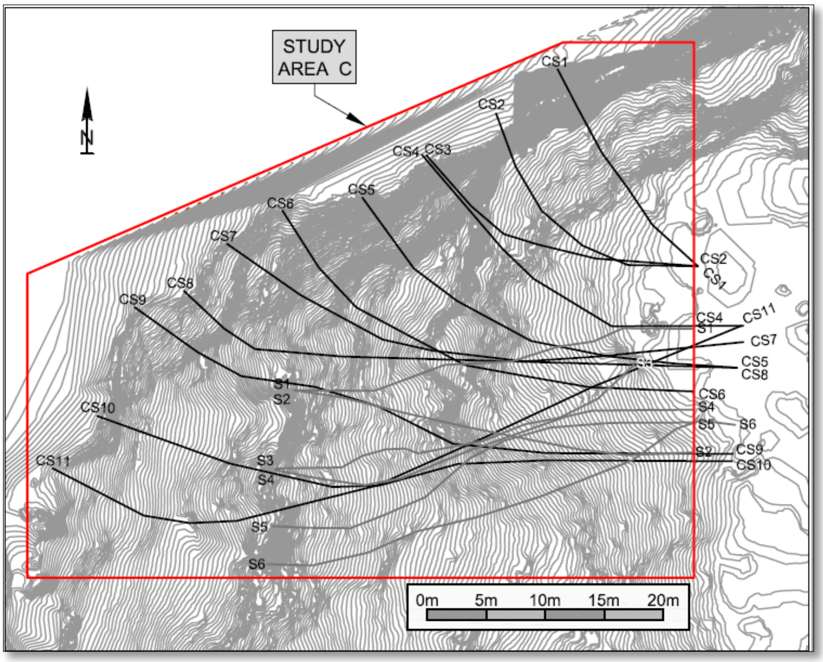


Figure 4.3: Survey indicating the trajectory path determined by RAMMS at Study Area C

Table 4.3: Slope length and angle of Area C's sections

Section Name	Slope Length (m)	Slope Angle (°)
CS1	46,26	75
CS2	46,26	68
CS3	48,59	62
CS4	49,30	57
CS5	52,00	53
CS6	56,26	52
CS7	62,89	46
CS8	66,55	45
CS9	48,59	62
CS10	52,00	53
CS11	76,97	40
S1	45,10	42
S2	45,18	42
S3	42,46	44
S4	47,24	41
S5	48,12	43
S6	45,18	42

4.2 ArcGIS 10.0

ArcGIS 10.0 was used to create a digital elevation model (DEM) using the terrestrial survey and draping an image over the DEM. The 3D trajectories created by the RAMMS 3D rockfall software was exported as a shapefile and added to ArcGIS which is presented in three views for each site below.

4.2.1 Chapman's Peak Drive

The 3D trajectories on which the 2D modelling has been carried out on is shown in yellow on the images below. Two of the most dominant trajectory paths have been chosen at each of the areas damaged during the rain event. The three views shown below should show that some rocks do not fall in a straight path down a slope particularly in the topographical conditions as seen on this site. Gulleys, ledges and overhangs can deflect a rockfall trajectory in a completely different direction from its start location. However, at this scale, it is difficult to view the change in direction clearly.

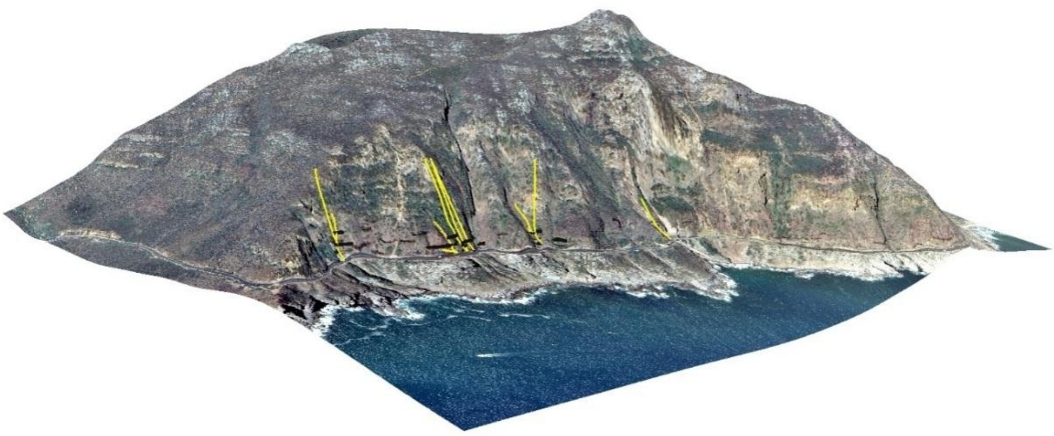


Figure 4.4: 3D View of the site looking South (Exported from ArcGIS 10.0).

Figure 4.5: 3D View of the site looking straight on (Exported from ArcGIS 10.0).

Figure 4.6: 3D View of the site looking North (Exported from ArcGIS 10.0).

4.2.2 Sir Lowry's Pass

The 3D trajectories on which the 2D modelling has been carried out on is shown in yellow on the images below. This set of trajectories shows the change of direction of the rockfall paths in much more detail as we are dealing with much shorter slopes than in the case of Chapman's Peak Drive.

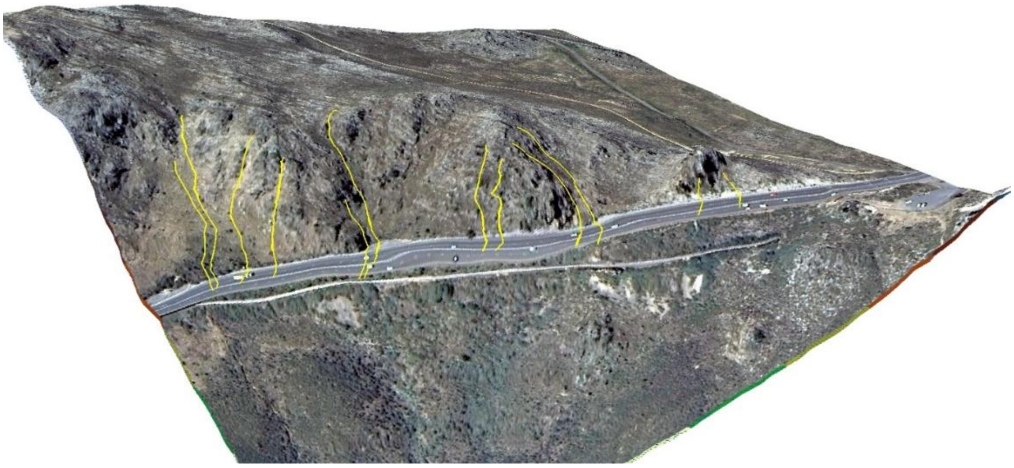


Figure 4.7: 3D View of the site looking east.

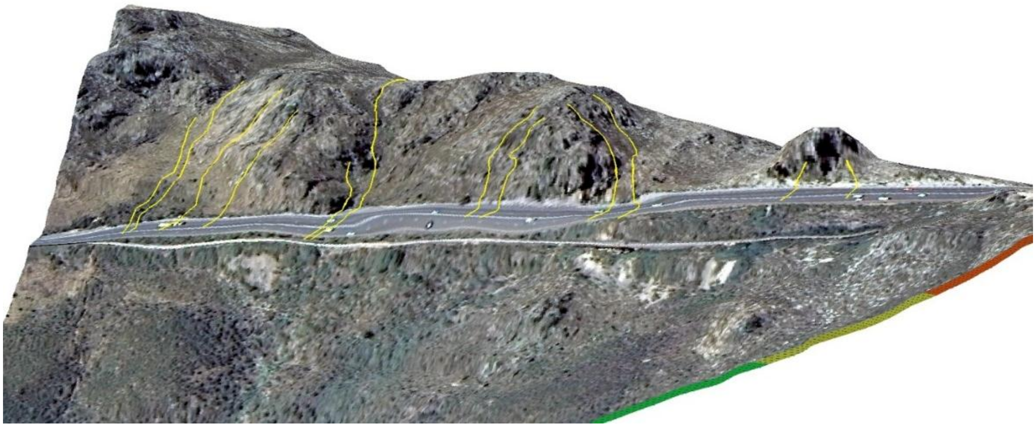


Figure 4.8: 3D View of the site looking straight on.

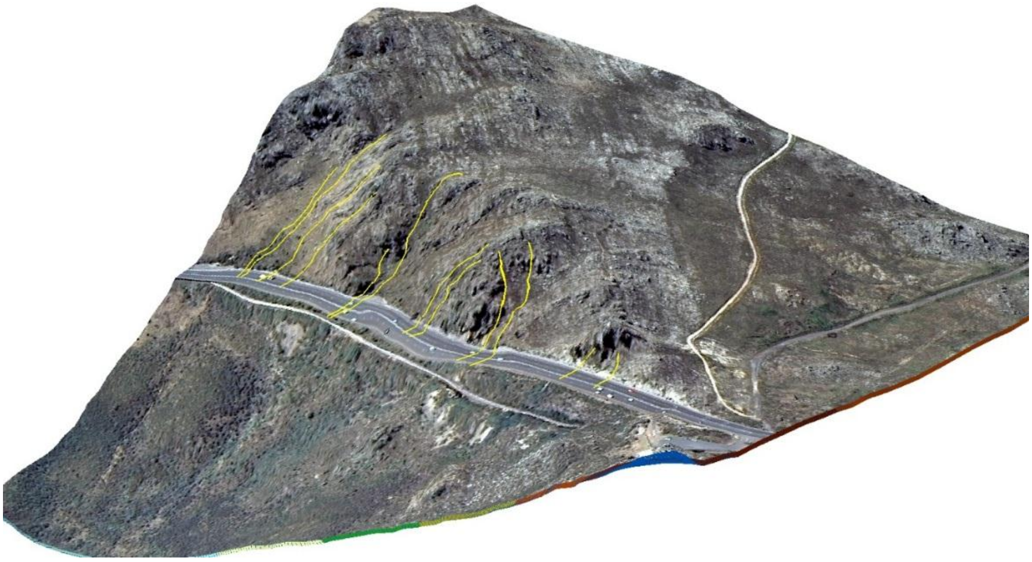


Figure 4.9: 3D View of the site looking west.

4.2.3 The Cliffs

The 3D trajectories that represent the “CS” sections are shown in green whilst the “S” sections are shown in blue on the images below. The 3D images clearly show the area with potentially larger rock blocks at the start of the “S” sections. The three different views show the deflection paths that the rock incurs when it comes into contact with a boulder or more rugged terrain. Some of the trajectories tend to extend beyond the image and this is due to a glitch in ESRI grid file when the topographical survey data was compiled.

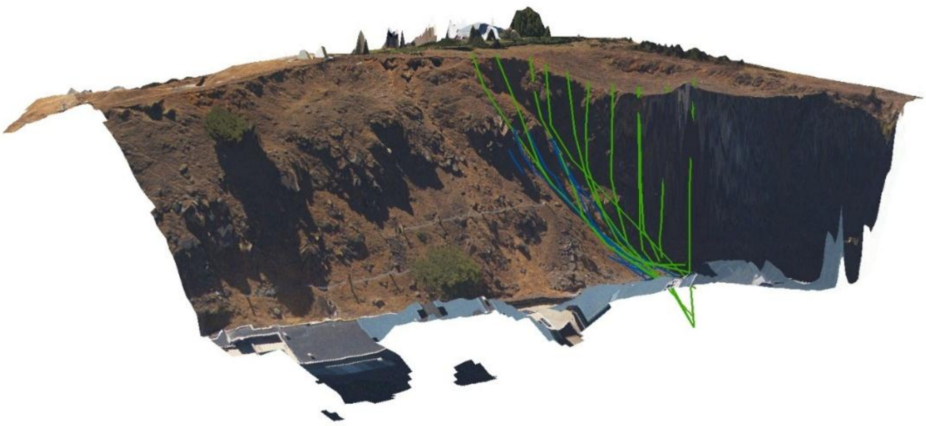


Figure 4.10: 3D View of The Cliffs site looking north.

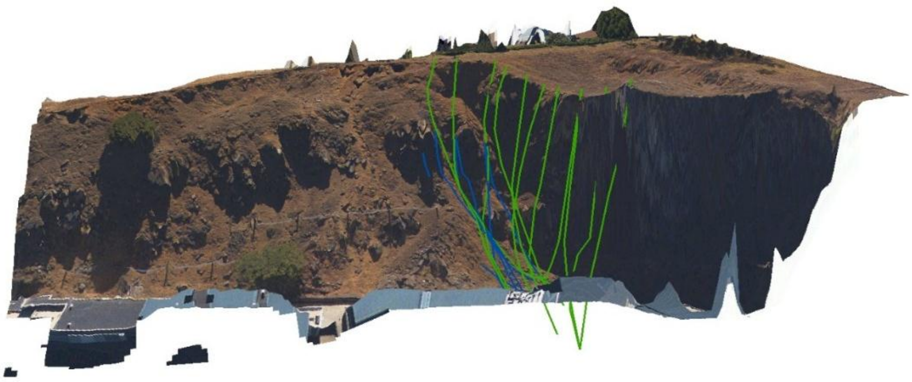


Figure 4.11: 3D View of The Cliffs site looking straight on.

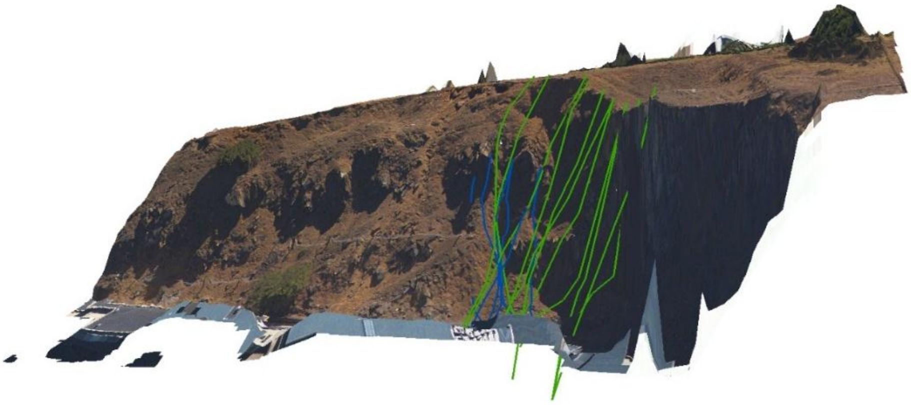


Figure 4.12: 3D View of The Cliffs site looking south.

4.3 ROCSCIENCE RocFall

Using the 3D trajectories that were obtained from the software RAMMS, a 2D section was drawn in AutoCAD as a dxf file. These dxf files were imported into the 2D Rocscience Rocfall software and results of which are tabulated in this chapter for each of the different study areas.

Once the dxf file is imported into the software, either a default material type or a custom one can be assigned to the various sections of the slope profile. The material type assigns the Rt and Rn values that take slope roughness into account.

In order to create a realistic output, 1000 rocks were modelled as a line seeder. A line seeder initiates the rockfalls and requires the mass of the desired block to be modelled as well as an initial velocity (www.rocscience.com). The line seeder was drawn to simulate rockfalls along the entire length of slope and not just at the crest. Therefore depending on where the mitigation measure such as a catch fence is placed, a number of rockfalls may still reach the road as these rocks are initiated below the catch fence. A data collector collects the statistical results of the simulation which is used to assist in determining designs for rockfall mitigation (www.rocscience.com). The data collector can be placed at any point along the slope profile depending on where the user would like to obtain his/her results.

The kinetic energy is presented in kilojoules and the bounce height measured in meters. The sections are drawn using elevation above mean sea level therefore in the case where a negative value is presented for the bounce height, it indicates that the rock bounced “x” meters below the top of the catch fence or gabion wall. Positive bounce heights indicate that the rock bounced over the mitigation structure. The results are tabulated at 100%, 98%, 95%, 75% and 50% of the simulated rockfalls and presented in Appendix A. The results at 100% of the simulated rockfalls are tabulated for each study area in this chapter.

The graphical presentation for each of the rockfall simulations before and after a mitigation measure is put into place can be seen in Appendix B. For Chapman’s Peak, however, the simulation was run with the catch fences in place as the damage event that occurred was after the catch fences were installed.

The figure below is an example of the graphical 2D simulation output. The slope profile is the shape of the slope as surveyed on site. It is required to be input on a 1:1 scale in order to maintain the correct slope angle and length during the simulation. The line seeder is used to initiate and simulate the rock blocks. The barrier represents the mitigation type, in the case of this research project, either the catch fence or gabion wall and can be assigned a specific energy capacity. A data collector is as the name suggests, a collector of both the kinetic energy and bounce height data at the point where the data collector is placed. The rockfall runs are presented in red and show the behaviour of the simulate rock blocks as they roll, bounce, slide and fall down the slope.

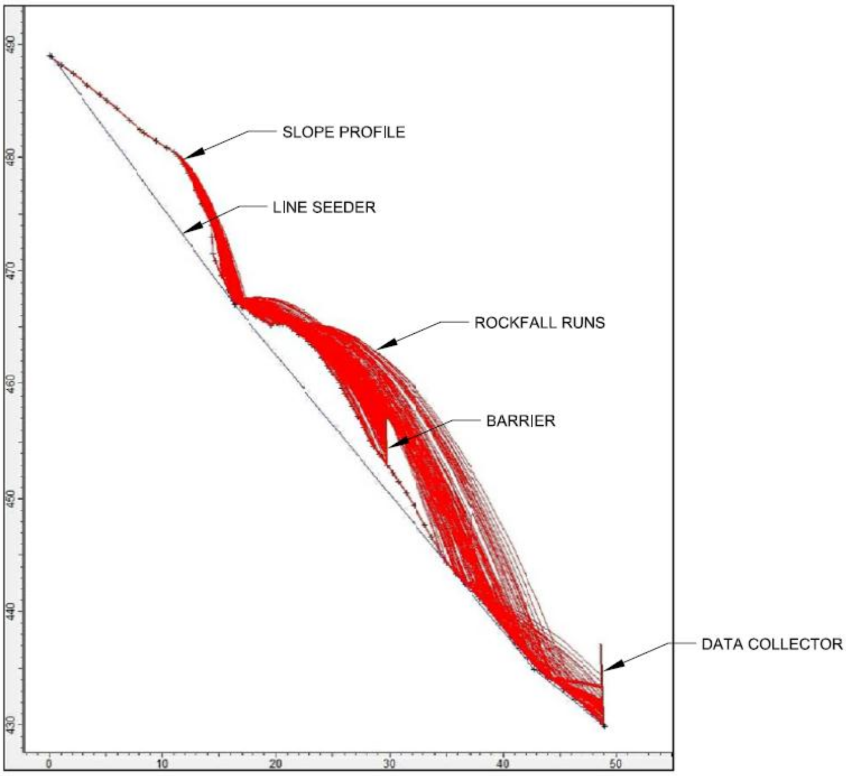


Figure 4.13: Example of a rockfall simulation graphical output

4.3.1 Chapman's Peak Drive

The rockfall simulations were carried out for each of the sections listed in Table 4.1. Their corresponding rockfall simulation graphical output is presented in Appendix B in Figures 1.1 to 1.11. Table 4.4 presents the details of the catch fences as they were installed in 2003. When the original simulations were carried out, the severity of mudslides was not taken into account. Due to excessive rainfall, most of the damage to the catch fences listed below was due to mudslides with rock debris. The simulated mass of the debris was estimated to have breached the catch fences in order to determine how effective the catch fences were. The catch fences are specifically designed to fail when loaded above a given capacity but effectively reduce the energy of the moving object and thereby reducing damage to the area below. The posts of the catch fences are designed to shear off the baseplates to allow for easy re-installation of the catch fence without having the need to re-drill baseplate anchors.

Table 4.4: The details of each of the existing catch fences included in the simulation as installed in 2003.

Catch Fence Number	Capacity (kJ)	Height (m)	Length (m)	Average Elevation of catch fence (MSL) (m)
2A	1500	6	18	160,5
8A	1500	6	35,5	169,2
11	1500	6	70,9	149
15	1500	6	34	159
15B	2000	5	12	137
30	2000	6	38	105

The slope trajectories used for these simulations were completely different from those used in 2003. The 3D simulation was run and two trajectories that intersected the existing locations of each of the catch fences listed in Table 4.4 were selected for 2D modelling.

The estimated volumes that were contained or breached by the catch fences are tabulated in Table 4.5. Table 4.6 shows the results of the 2D modelling for each of the trajectories based on the volume of material in Table 4.5. The number of hits refers to the number of rockfalls that were intercepted by the catch fence after 1000 potential "blocks" or, in this case, debris slides were modelled. Both the kinetic energy and the bounce heights were presented for 100% of the total simulated blocks. It was found that in most instances very little to no change in the bounce heights occurred for the different percentages presented. A negative bounce height indicates that the "block" did not bounce over the fence and this is true because the force of the material breached the fence and did not "jump" the fence. Occasionally when rockfall simulations are run, the results appear to be unrealistic. This is true in the case of trajectory 2a and 15b, where the kinetic energy is excessive. It is most likely that there was a glitch in the 3D trajectory which resulted in very high kinetic energy values. Therefore, it is necessary to run more than one simulation for each area requiring a rockfall mitigation measure.

Table 4.5: The estimated quantity of material that was recorded in the fences and used in the 2D modelling

Catch Fence Number	**Estimated Quantity (m^3)**
2A	8
8A	2
11	10
15	20
15B	20
30	5

During the simulation described for the results presented in Table 4.6, a data collector was placed at the road level to account for any debris and rocks that breached the catch fence and continued into the road as well as those rocks and material that started its journey below the catch fences, the results of which are presented in Table 4.7. As a result, for one set of simulated rockfall graphical outputs, two tables (Table 4.6 and Table 4.7) were produced. Kinetic energy and bounce heights were extracted at the catch fences and then at the data collector at road level for the same simulation. Trajectory 2a and 15b show very high kinetic energies at both the catch fence and at road level. Trajectories 15a, 15b and 30a show that no bouncing has occurred. This could be confirmed for trajectories 15a and 15b as very large rock blocks were intercepted by the catch fence and although the fences were breached, the rock blocks were stopped from reaching the road.

Table 4.6: Summary of the rockfall simulations for the volume of material measured at the catch fence

CHAPMAN'S PEAK DRIVE: SUMMARY OF ROCKFALL SIMULATION RESULTS AT CATCH FENCES			
ROCKFALL INFORMATION		KINETIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)	BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)
TRAJECTORY NO.	NO OF HITS (%)	100%	100%
2a	64	12633	-0.1
2b	75	2610	-6.9
8a	55	222	-4.7
8b	12	659	-6.4
11a	13	3485	-4.9
11b	93	1596	-5.4
11c	89	1308	-0.3
15a	45	6131	-5.9
15b	93	11069	-4.7
30a	81	2735	-5.6
30b	86	2185	-4.9

On average the capacities that the catch fences were designed for along Chapman's Peak Drive appear to have been more than efficient in intercepting rockfalls. A limited number of catch fences which were not designed to withstand debris flows had been breached but contained a large portion of the material. Following this event, an upgrade was carried out in the area of catch fence 15. A number of new catch fences were installed with a capacity of up to 5000kJ. A pinned mesh section was installed behind catch fence 11 to stabilise the loose soil/talus on the slope. Catch fence 2a was upgraded to have a "tail" section of ring nets installed at the bottom of the fence and catch fence 30 was upgraded in capacity. No further upgrades were required to catch fence 8a. This has proven to be effective as no further significant incidents have occurred at the catch fences in recent years.

Table 4.7: Summary of the rockfall simulations for the volume of material measured at road level with catch fence in place

CHAPMAN'S PEAK DRIVE: SUMMARY OF ROCKFALL SIMULATION RESULTS AT DATA COLLECTOR WITH CATCH FENCE IN PLACE			
ROCKFALL INFORMATION		KINETIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)	BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)
TRAJECTORY NO.	NO OF HITS (%)	100%	100%
2a	68	14910	16.4
2b	13	925	0.2
8a	44	379	3.6
8b	3	140	2.4
11a	3	1766	2.9
11b	6	787	3.8
11c	53	904	3.2
15a	47	4307	0.0
15b	81	7624	0.0
30a	14	500	0.0
30b	12	535	1.8

4.3.2 Sir Lowry's Pass

Table 4.8 presents the results of the rockfall simulation for the site before any mitigation measures were put in place. Six locations were identified as potential rockfall hazard zones and 2 sections were modelled for each of these locations. These sections are labelled as "a" and "b" in the tables.

The rockfall simulation was carried out for each of the trajectories tabulated in Table 4.8 for a potential 1m^3 rock block. The rock blocks were simulated to fall down the slopes and data was to be collected with a data collector at road level. In order to determine a good statistical analysis, 1000 rock blocks were modelled.

The simulated graphical output is presented in Appendix B, Figures 2.1 to 2.12. The kinetic energies and bounce heights are relatively low, however, the field evidence for potential rockfalls was overwhelming and had to be taken into consideration when determining if and where to place any mitigation measures.

Table 4.8: Summary of the rockfall simulations for 1m^3 blocks with no catch fences

SIR LOWRY'S PASS: SUMMARY OF ROCKFALL SIMULATION RESULTS FOR THE 1m^3 BLOCKS			
ROCKFALL INFORMATION		KINETIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)	BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)
TRAJECTORY NO.	NO OF HITS (%)	100%	100%
1a	99	132	0.2
1b	99	116	1.1
2a	99	97	0.3
2b	100	132	1.5
3a	99	159	0.1
3b	99	159	0.1
4a	99	610	0.6
4b	23	782	4.3
5a	99	190	0.2
5b	99	117	1.0
6a	99	65	0.1
6b	99	55	0.1

During the site inspection, the locations of the potential catch fences were staked out and surveyed by a land surveyor. The elevation and height of each catch fence (Table 4.9) were then used to re-simulate the rockfall runs but with the catch fence or barrier in place this time. The results of this simulation are presented in Table 4.10. A data collector was placed at road level again and the results of the simulation can be seen in Table 4.11.

Table 4.9: The details of each catch fence simulated

Catch Fence Number	Capacity (kJ)	Height (m)	Length (m)	Average Elevation of catch fence (MSL) (m)
1	1000	3	50	441
2	1000	3	50	434
3	1000	3	40	444
4	1000	4	30	453,5
5	1000	3	30	449
6	1000	3	40	459

An average of 65% of the rocks would be stopped or caught by the catch fences with the exception of Catch Fence 6. Although the rockfall simulation indicates a small percentage of rocks to be stopped or caught by Catch Fence 6, field mapping indicated that the potential for larger rocks to cause a risk to road users was far more significant and, therefore, the decision to install a catch fence in this area was made.

The simulated graphical output is presented in Appendix B, Figures 2.13 to 2.24.

One of the two sections modelled for catch fence 4 appears to have higher bounce heights than the other modelled sections. These values appear to be unrealistic and are mostly likely a digital elevation model error transferred to the 3D software program which indicates higher energies and bounce heights. The negative values are calculated for the bounce heights in relation to the top of the catch fence.

As explained above, catch fence 6 appears to have a small percentage of rocks that are caught by the catch fence, whilst most of these rocks appear to reach the road. Field mapping also indicated the highly weathered rock below the position of the catch fence (at the crest of the cutting). In order to mitigate for the rockfalls below the catch fence, pinned mesh was installed connected to the base of the catch fence. Unfortunately, the rockfall software does not allow for the inclusion of the pinned mesh and, therefore, the interpretation of the results has to be carried out in relation to the field mapping.

Table 4.10: Summary of the rockfall simulations for 1m^3 blocks at the Catch fence

SIR LOWRY'S PASS: SUMMARY OF ROCKFALL SIMULATION RESULTS AT CATCH FENCES FOR THE 1m³ BLOCKS			
ROCKFALL INFORMATION		KINETIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)	BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)
TRAJECTORY NO.	NO OF HITS (%)	100%	100%
1a	66	319	-3.4
1b	78	376	-1.3
2a	77	173	-3.2
2b	74	580	-2.4
3a	35	64	-3.0
3b	65	141	-2.4
4a	66	306	-5.5
4b	42	466	-0.1
5a	69	116	-2.7
5b	71	137	-2.9
6a	14	65	-2.5
6b	16	84	-2.4

Table 4.8 shows lower kinetic energies at road level with no catch fences in place due to the longer slope length the rock blocks have to travel. In most cases, the blocks tend to lose energy the longer distance that it has to travel and this can be seen when comparing the energies in Table 4.8 to Table 4.10. Table 4.10 shows higher kinetic energies recorded by the impact of the rock blocks at the catch fences. This is due to the catch fences being placed higher up on the slope, generally at the crest where the rock block tends to have much higher energies.

Table 4.11: Summary of the rockfall simulations at road level for 1m^3 blocks with Catch fence in place

SIR LOWRY'S PASS: SUMMARY OF ROCKFALL SIMULATION RESULTS AT ROAD LEVEL FOR THE 1m³ BLOCKS WITH CATCH FENCES			
		KINETIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)	BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)
TRAJECTORY NO.	NO OF HITS (%)	100%	100%
1a	33	122	0.2
1b	21	102	1.4
2a	23	78	0.3
2b	26	119	1.5
3a	66	174	0.1
3b	34	118	0.1
4a	34	119	0.3
4b	9	817	4.3
5a	31	101	0.2
5b	29	79	1.0
6a	86	63	0.1
6b	84	57	0.1

The percentage of blocks that reach the road is substantially lower once the catch fence has been installed in place. However, catch fence 6 still shows a large number of blocks reaching the road and this could be as a result of blocks releasing on the face of the slope below the location of the catch fence. This is mitigated by using pinned mesh on the face and connecting the top of the pinned mesh to the bottom of the catch fence. Trajectory 4b shows less than 10% of blocks reaching the road once the catch fence has been installed, however, the energies are still very high. The fence will not be breached with energies lower than 1000 kJ, and any blocks that were to release from the face of the slope has been barred down or in rock bolted in place.

4.3.3 The Cliffs

The table below presents the results of the rockfall simulation for the site which included the existing rockfall mitigation which in this case is a 3m high gabion wall.

There are two sets of rockfall simulations that were carried out. The first set called "CS" covered the study area and modelled 1000 1m^3 rocks per a section and are presented in Table 4.12. The second set called "S" was simulated for specifically identified larger blocks of an estimated volume of 10m^3 and are presented in Table 4.13.

Note that the negative bounce heights indicate that the blocks did not go over the wall. It is calculated as the bounce height of the rock block in relation to the top of the gabion wall.

Table 4.12: Summary of the rockfall simulations at existing gabion wall for 1m^3 blocks

THE CLIFFS: SUMMARY OF ROCKFALL SIMULATION RESULTS FOR THE 1m3 BLOCKS			
ROCKFALL INFORMATION		KINETIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)	BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)
TRAJECTORY NO.	NO OF HITS (%)	100%	100%
CS1	57	1110	-1.0
CS2	59	229	-1.5
CS3	32	430	12.4
CS4	23	268	-0.2
CS5	27	772	0.5
CS6	39	582	6.9
CS7	12	327	0.7
CS8	38	308	0.7
CS9	36	339	0.8
CS10	70	437	-0.7
CS11	98	523	0.4

Interpretation of the rockfall results is very important and needs to be done in conjunction with what was seen on the site. This can be seen for example at trajectory CS3 and CS6 where the bounce height at 100% is more than 12m and almost 7m respectively. This is an unrealistic value based on the bounce heights from the surrounding trajectories as well as the rockfalls that have actually been experienced on site. This once again can be attributed to an error in the digital elevation model in the 3D software program due to outlier points in the topographical survey.

The simulated graphical output is presented in Appendix B, Figures 3.1 to 3.8.

Table 4.13: Summary of the rockfall simulations at existing gabion wall for $10m^3$ blocks

THE CLIFFS: SUMMARY OF KINETIC ENERGY RESULTS FOR THE 10m3 BLOCKS			
ROCKFALL INFORMATION		KINETIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)	BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)
TRAJECTORY NO.	NO OF HITS (%)	100%	100%
S1	46	5320	-0.1
S2	35	1910	-0.2
S3 (doesn't reach wall)	NONE		
S4	43	1360	-0.3
S5	64	2470	-0.1
S6	53	1876	-0.2

The "S" trajectories do not bounce over the wall and trajectory "S3" stops short of the wall and, therefore, no data is presented for that section. Since these larger blocks were found not to bounce over the wall, it was not necessary to re-run the simulation for the upgraded mitigation measure which in this case was to raise the wall by 1,5m. The higher energies that would be experienced by impact from larger blocks can be contained by the gabion wall according to the software analysis. The simulated graphical output is presented in Appendix B, Figures 3.9 to 3.14.

Table 4.14: Summary of the rockfall simulations at upgraded gabion wall for 1m³ blocks

THE CLIFFS: SUMMARY OF KINETIC ENERGY RESULTS FOR THE 1m3 BLOCKS WITH A RAISED WALL			
ROCKFALL INFORMATION		KINETIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)	BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)
TRAJECTORY NO.	NO OF HITS (%)	100%	100%
CS1	-		
CS2	-		
CS3	-		
CS4	24	256	-0.6
CS5	24	781	-0.6
CS6	43	913	4.0
CS7	12	349	-1.3
CS8	43	337	-0.6
CS9	44	326	-0.5
CS10	-		
CS11	98	566	-1.1

For the “CS” trajectories, the rockfall simulation was re-simulated with the gabion wall being raised by 1,5m in height, no rocks bounced over the wall with the exception of CS6 which is explained above as an error in the 3D modelling program carried through by outlier points in the topographical survey. The results are presented in Table 4.14. Trajectories CS 1, 2, 3 and 10 did not have any rocks go over the existing wall and, therefore, the rockfall simulations for the upgraded wall is not presented below as the data would be the same as for the original wall height.

The simulated graphical output is presented in Appendix B, Figures 3.15 to 3.21.

4.4 DISCUSSION

This section of Chapter 4 discusses the outcomes following the detailed results and interpretation of the rockfall simulations and how that information was used to determine the best rockfall engineering solution for each of the study sites.

For any site that requires rockfall mitigation measures, a historical database would be of utmost importance in understanding the behaviour of rockfall within this area. As discussed in the first chapter, this is one of the main limitations of this study, however, it does not prevent an engineer from investigating the site and making an educated and experienced software input estimate to assist in the design solution.

An important factor to consider following rockfall analysis and interpretation of the results is that once on site, adjustments may have to be made to cover potential rockfall areas that were not identified as such by the survey model. Hence in theory, once a rockfall simulation has been run and the results interpreted and used to determine the best engineering solution, then that particular rockfall mitigation type can be surveyed in place. However, practically this is not always the case and on the rare occasion, the rockfall mitigation type may have to be moved completely once all aspects of the site are considered including the budget constraints of the client.

Another limiting factor is the cost of the rockfall mitigation measure. An excellent rockfall analysis may be futile if the cost factor involved is beyond the client's budget. Therefore, the best-engineered solution may not be the most practical one.

4.4.1 Chapman's Peak Drive

Although the lack of a rockfall database is usually a limiting factor on a site, this particular site has a database going back to the inception of the rehabilitated road. Several severe rain events have occurred over the last decade, some which resulted in damage to the road, structures and catch fences whereas other events only triggered the braking mechanisms on the catch fences. These were replaced easily enough and the catch fences were back to optimal performance.

Following the rain damage event that has been modelled in this research study and based on the rockfall database, an upgrade called “Schedule C” was undertaken in 2009. Figure 4.14 shows images of the catch fences as they are today post upgrade. Catch fence 2a experienced a block bouncing below the catch fence and impacting the road structure, this catch fence was upgraded by attaching additional ring nets to the bottom of the catch fence and draping it to cover the gap area. This became locally known as the “trampoline”. Catch fence 8a was found to function as designed and coupled with a detailed site inspection showed no indication requiring an upgrade in fence capacity.

Catch fence 11 didn’t appear to require an upgrade to the fence capacity either, as it was designed to stop rockfalls and not debris flows. However, the site inspection revealed a massive slip above the catch fence and this was pinned in place with mesh and covered with a geotextile to aid vegetation growth. In March 2015, a fire event destroyed this geotextile, although the pinned mesh does not appear to have sustained any damage and no evidence of any movement was present. The winter of 2015 has been relatively dry and the fire damage to the geotextile may pose to be a problem during future wet conditions.

Gulley 15 is what the area is known as where the original catch fence 15 and 15b stood. This was upgraded significantly to increase the capacity of all the catch fences as well as increase the number of catch fences in the area. This gulley has been active since the upgrade, proving that the increased capacity was definitely required.

The gulley area above catch fence 30 has been active in the past. The last field of the fence has constantly filled up and at times even breached it. This fence was upgraded to a 2000kJ fence before the 2007 rain damage event. This area has since appeared to have stabilised.

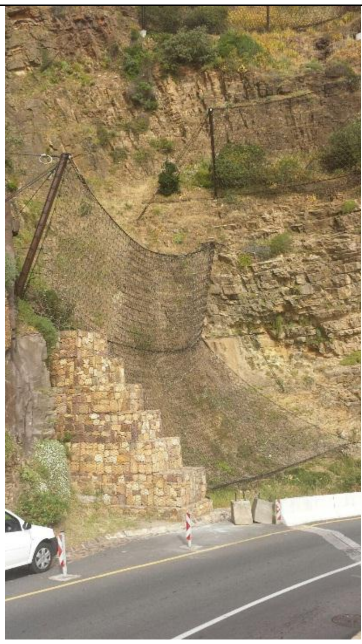
<table>
<tr><th colspan="2">Completed Rockfall Mitigation Measures for Site A</th></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Catch Fence 2a</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Catch Fence 8a</td><td>Catch Fence 11</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Catch Fence 15</td><td>Catch Fence 30</td></tr>
</table>

Figure 4.14: Rockfall mitigation measures for Chapman's Peak Drive (Photos by David Esau, 2015)

4.4.2 Sir Lowry's Pass

Although this pass has been actively experiencing rockfalls over the years, no rockfall database has been created to record any rockfalls that have occurred. Road authorities only reacted after the large wedge that released from higher up on the cutting face landed very close to a vehicle.

The site investigation with detailed geological mapping, coupled with a topographical survey culminated in a rockfall simulation across various sections along the route. The most dominant sections were identified and confirmed on site to be the chosen locations of specific rockfall mitigation type. Catch fences were the main protection measure against rockfalls and this was accompanied by pinned mesh on other cuttings and below some of the catch fences in highly weathered and friable rock faces. Other areas of very poor rock faces were shotcreted and colour coded to match the surrounding rock type. All potentially loose rock that could not be barred down, including the area where the large wedge released from, were rock bolted in place with rock bolts of varying lengths depending on where the release plane was seen or estimated to be.

As mentioned in chapter 2, rainfall plays a significant role in rockfall occurrences, particularly in the Western Cape. Since the completion of this project, one major rainfall event occurred in November 2013, however, no significant rocks were found to be in the catch fences. Since the Western Cape and the rest of South Africa are experiencing a drought in 2015, there is a high probability that when the drought ends, that this area may experience rockfalls of a significant size and the catch fence capacities can be confirmed on site. Figure 4.15 shows the completed catch fences as they were installed in July 2013.

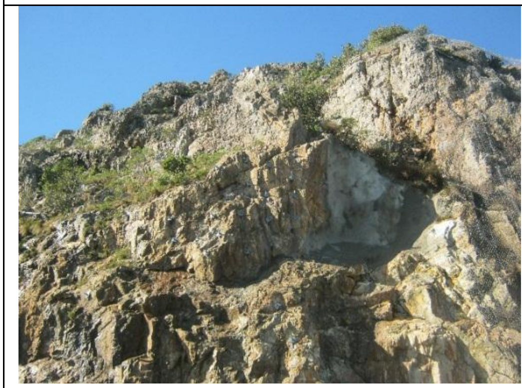
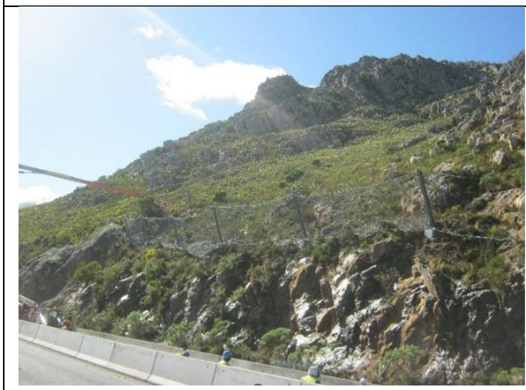
Completed Rockfall Mitigation Measures for Site B	
	
Stabilised Wedge	**Catch Fence 1**
	
Catch Fence 2	**Catch Fence 3**
	
Catch Fence 4	**Catch Fence 5**

Figure 4.15: Rockfall mitigation measure for Site B: Sir Lowry's Pass (Photos by S, Surujbally, 2013)

4.4.3 The Cliffs

This site over the years has undergone barring to remove loose rocks from the face, catch fences have been installed at the most northern face and the area that was investigated for this research study was initially protected by a 3m high gabion wall. The gabion wall has been impacted a number of times and successfully stopped rocks from impacting the building. However, the most recent occurrence caused enough damage to the gabion wall causing it to bulge out towards the building.

Following this event, a new site inspection and rockfall modelling were done. The rockfall simulation was split into two main scenarios, one with an average block size of $1m^3$ releasing from the crest at various locations and the second scenario with a block size of $10m^3$ releasing from slightly above mid-slope where large blocks precariously lie with the potential to fall. When simulated in the rockfall software these large blocks were found not to reach the gabion wall. The blocks that released from the crest and impacted the gabion wall was found to be contained when the wall was raised by 1,5m. As an additional energy absorption protection against the rockfall, backfill was included behind the gabion wall at 45°. A layer of geotextile was placed in between the gabion wall and the geotextile to prevent the fine portion of the backfill from washing through the gabion wall and landing behind the building. Photographs of the completed gabion wall with the backfill are presented in Figure 4.16.

This project was completed in October 2015 and will also likely experience rockfalls after the next heavy rain event. A maintenance inspection is scheduled for once every quarter of a year as any significant impact on the gabion wall is a major concern for the trustees of the office building that stands directly in front of the wall.

Panorama of the cliff behind the gabion wall looking north

Backfill behind gabion wall

Front of gabion wall

Backfill looking south

Extended section of gabion

Cliff behind gabion wall

Figure 4.16: Rockfall mitigation measure for Site C: The Cliffs (Photos by S, Surujbally, 2015)

4.4.4 Discussion of the Parameters

In an attempt to further analyse the parameters, the researcher has created a number of graphical plots. Some of these parameters show little to no trends or comparison whilst a trend can be identified for other plots.

The slope length in meters was plotted against the maximum kinetic energy for all three of the study sites. No clear trend can be identified between the three sites in Figure 4.17. As the slope length increases, the kinetic energy fluctuates across the various slope trajectories.

The slope length versus the kinetic energy for Chapman's Peak Drive is randomly scattered across the plot. The data for Sir Lowry's Pass lies relatively horizontally. As the slope length increases, the kinetic energy remains within a very small range. Whereas, the data for The Cliffs appears to behave in the opposite manner compared to Sir Lowry's Pass. The slope length appears to have a smaller range whilst the kinetic energy increases and then levels off as the slope length increase.

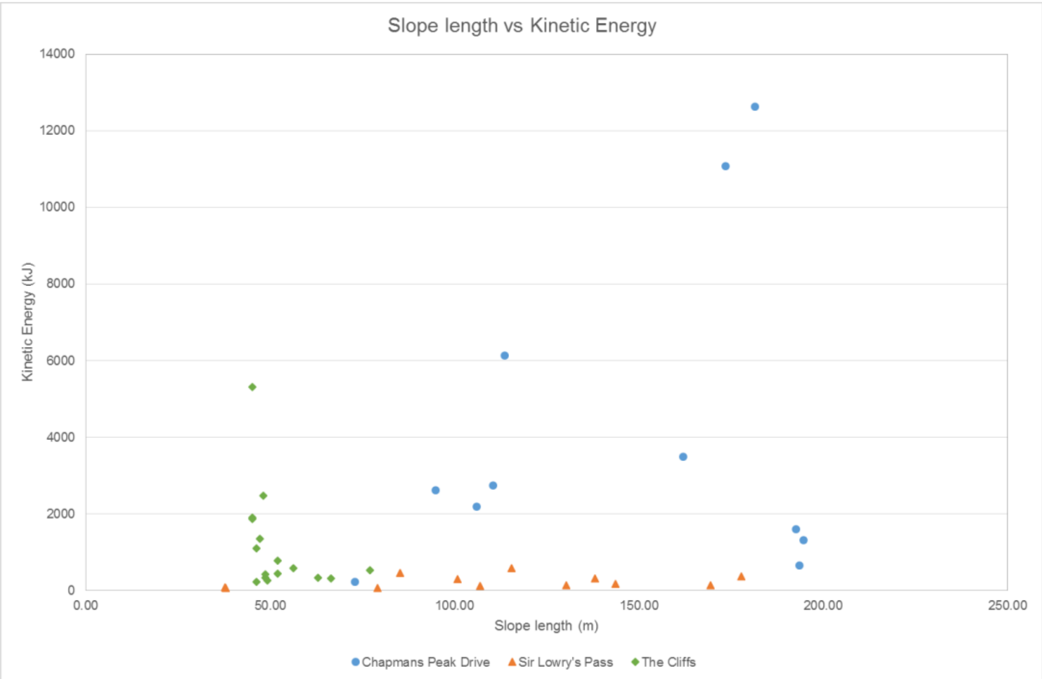


Figure 4.17: The slope length (m) plotted against the kinetic energy (kJ) for all three sites

The slope angle for each of the trajectories of all three sites was also plotted against the kinetic energy (Figure 4.18). Once again no comparison can be made between the three sites. Chapman's peak Drive shows data scattered across the plot, very similar to the plot in Figure 4.17. The data has a somewhat vertical plot, where the slope angle lies within a small range as the kinetic energy increases. The kinetic energy for Sir Lowry's Pass appears to have a very small range as the slope angle increases. The Cliffs starts off with a slight trend, where, as the slope angle increases, the kinetic energy increases. Thereafter, the kinetic energy experiences a drastic decrease with an increase in kinetic energy.

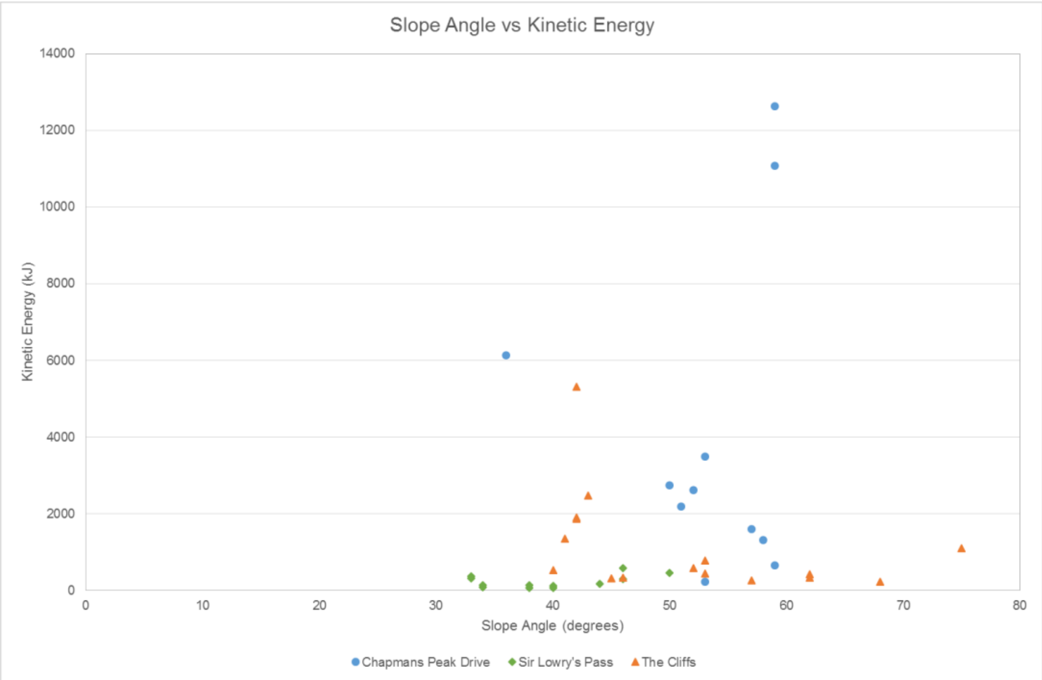


Figure 4.18: The slope angle (degrees) plotted against the kinetic energy (kJ) for all three sites

Table 4.5 shows the estimated quantity of material that was either contained by the catch fences or that had breached the catch fences. The volume of material shown in this table is plotted in Figure 4.19 against the kinetic energy for each of the trajectories that were simulated at Chapman's Peak Drive. The general trend is that as the volume of the material increases so does the kinetic energy. However, trajectory 2a with a volume of approximately 2m^3 appears to have a much higher energy than expected. Trajectory 2a does have a relatively long slope length, however, should not impact the high kinetic energy value to such a large extent. As explain earlier in this chapter, it is most likely as a result of a problem with the digital elevation model.

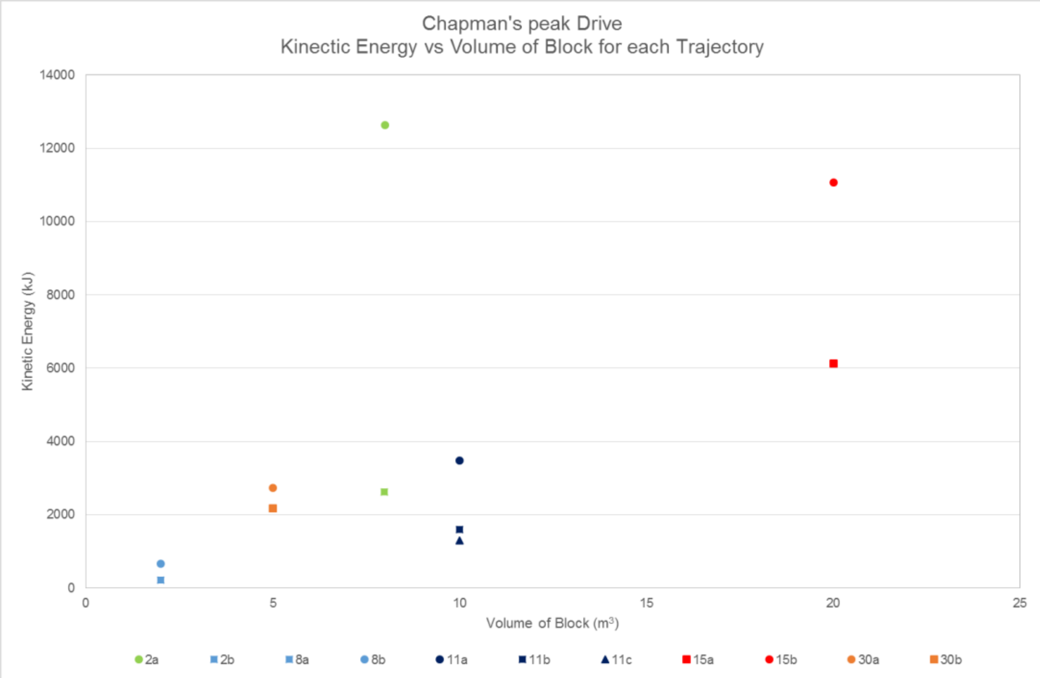


Figure 4.19: Kinetic energy plotted against the Volume of material intercepted in the catch fences at Chapman's Peak Drive

Figure 4.20 graphically represents the data that is presented in Table 4.6 and 4.7. For both the maximum kinetic energy and the maximum bounce heights that were recorded during the simulation at Chapman's Peak Drive. This plot includes both these resulting parameters before and after the rockfall mitigation has been undertaken. In order to clearly differentiate between the kinetic energy and the bounce heights, the researcher has plotted the kinetic energy on the primary y-axis and the bounce height on the secondary y-axis. The kinetic energy has also been plotted as a bar chart, whereas the bounce heights have been plotted as x-y scatter plots. The kinetic energy and the bounce height prior to the mitigation upgrade is plotted in blue, whilst the orange plots show these parameters after the upgrades. Generally, both the kinetic energy and the bounce heights have decreased after the upgrade of the rockfall mitigation has been modelled with the exception of trajectory 2a. The reason for this has been explained previously.

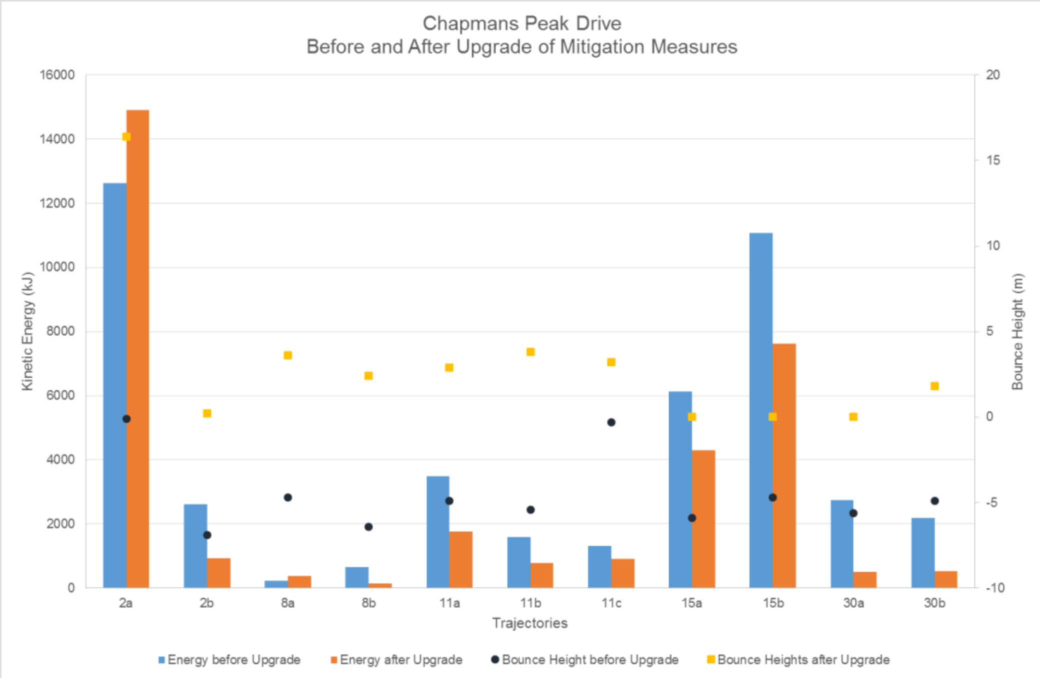


Figure 4.20: Kinetic energy and bounce heights plotted for each trajectory before and after the mitigation upgrade

As explained in Figure 4.20, both Figure 4.21 and 4.22 are presented in the same way. Bar charts present the kinetic energies and the x-y scatter plots present the bounce heights with the colour blue indicating these parameters prior to any mitigation or upgrade and the orange showing the simulation results post upgrades. Figure 4.21 presents the data for Sir Lowry's Pass and shows little change before and after mitigation measures. However, as discussed previously, the visual site investigation identified areas that required rockfall mitigation, particularly as a result of the high degree of weathering experienced by the rock face as well as the massive rockfall incident that had occurred.

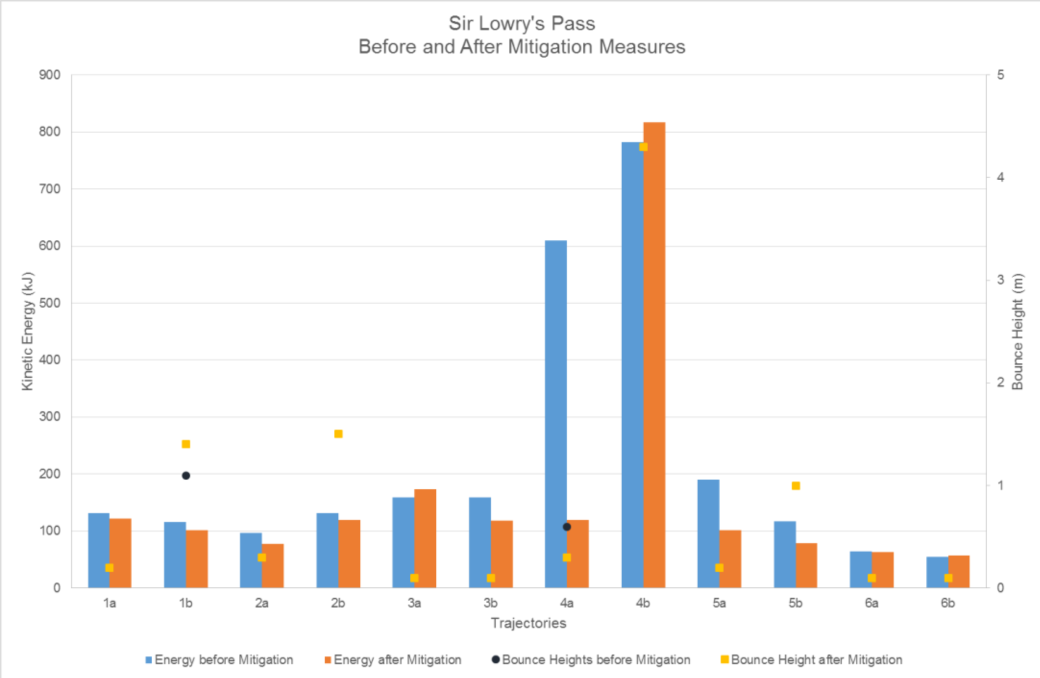


Figure 4.21: Kinetic energy and bounce heights plotted for each trajectory before and after the mitigation

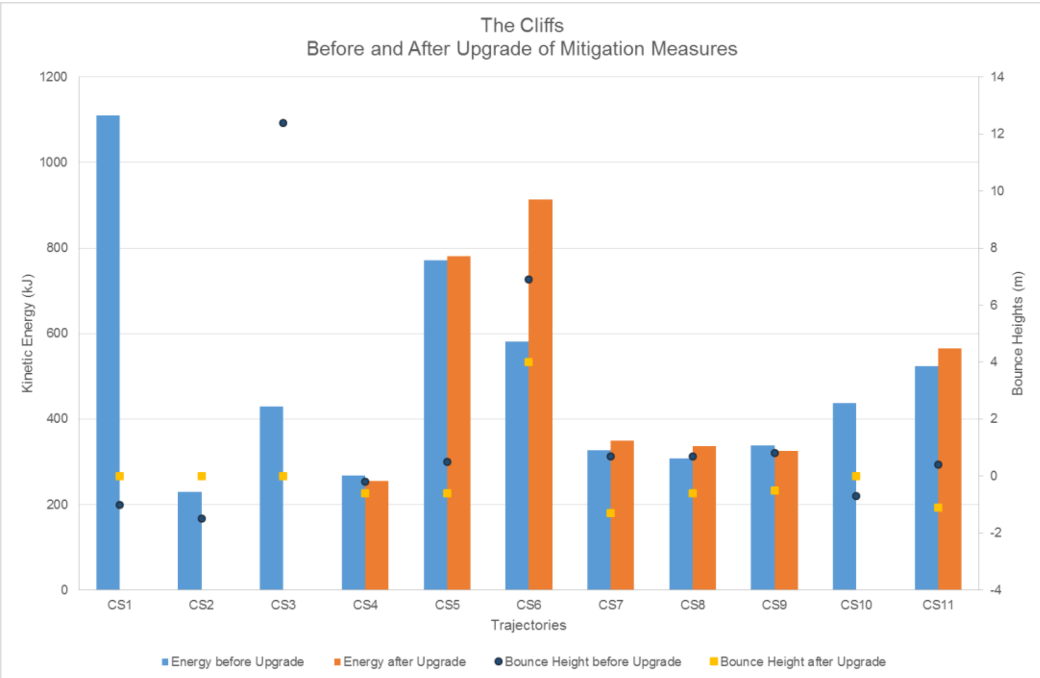


Figure 4.22: Kinetic energy and bounce heights plotted for each trajectory before and after the mitigation upgrade

Only the CS trajectories have been plotted in Figure 4.22 since the S trajectories did not reach the wall after the upgrade at The Cliffs. CS1 to CS3 and CS10 also did not reach the upgraded wall and, therefore, show no kinetic energies or bounce heights after the upgrade. CS6 shows an unusually high kinetic energy post upgrade, whilst CS3 shows a very high bounce height prior to the upgrade. This is most likely as a result of an error in the digital elevation model.

Figures 4.23, 4.24 and 4.25 graphically plot the percentage of blocks that are stopped by the catch fences or wall for each trajectory per site. The plot also shows the percentage of blocks that reach the road with the catch fences in place. Almost all of the trajectories experienced a decrease in the number of blocks reaching the road after the mitigation type had been upgraded at Chapman's peak Drive. The same is true for Sir Lowry's Pass. On almost all of the trajectories, 100% of the blocks reached the road before the rockfall mitigation had been installed. The Cliffs, however, had some conflicting data, whereby there appeared to be more blocks that reached the wall after the upgrade. The wall in the case of The Cliffs represents both the mitigation type and the "road" as it lies at the end of the trajectory path and has not been placed somewhere along the slope like the catch fences have been for the other two sites. Therefore, the number of blocks that reach the wall is purely determined by the rockfall simulation for this site and not the placement of the wall.

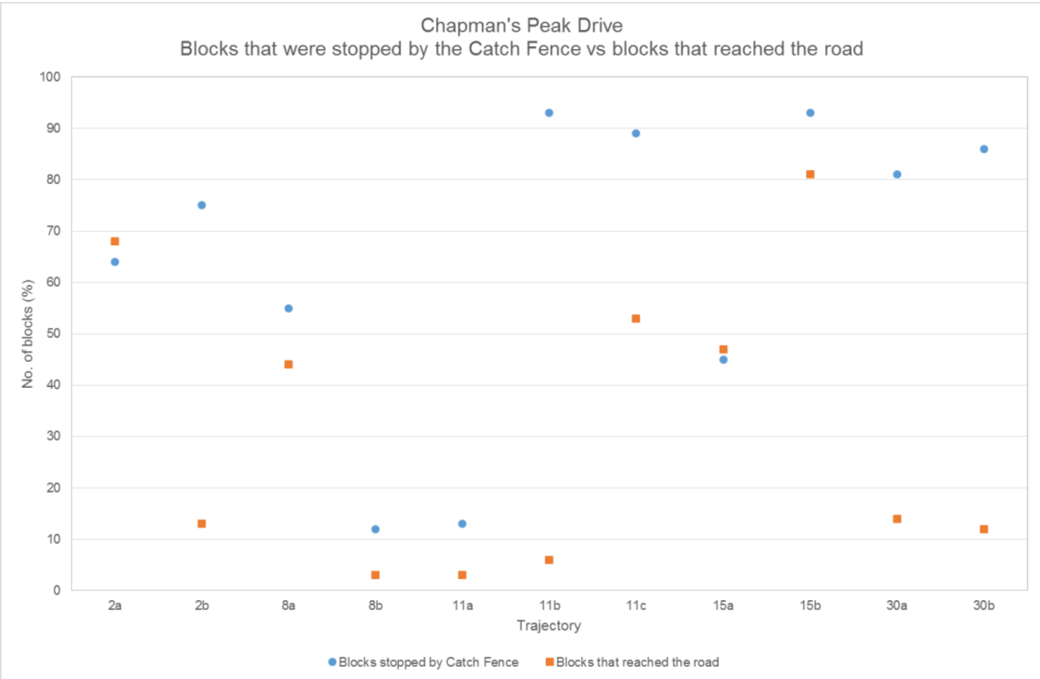


Figure 4.23: Percentage of blocks stopped by the catch fence and those that reach the road for each trajectory at Chapman's Peak Drive

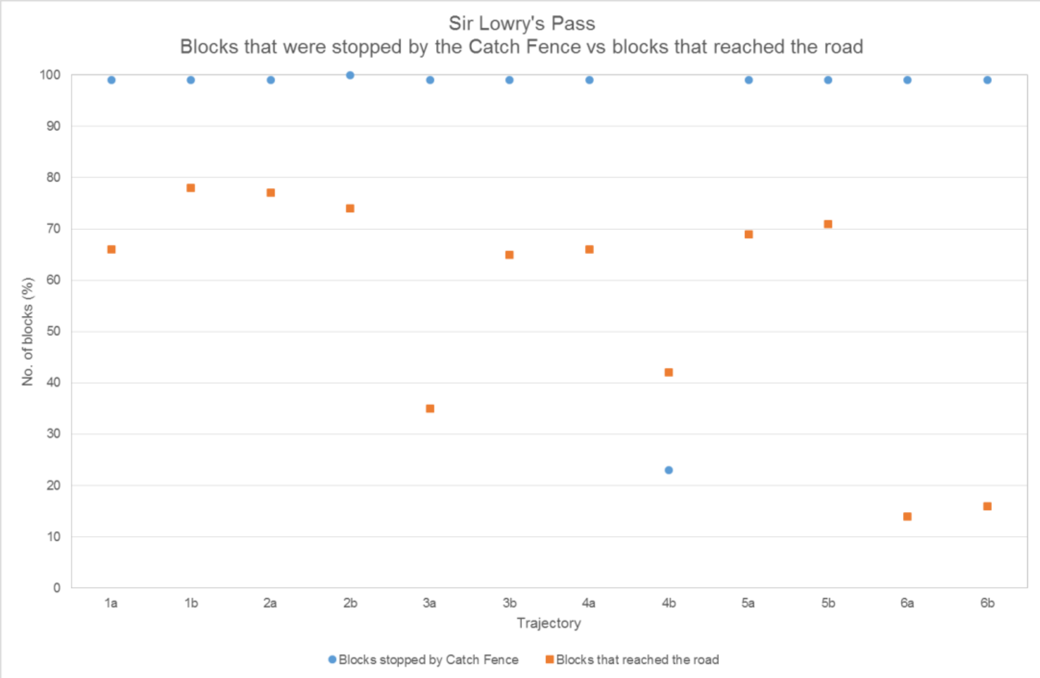


Figure 4.24: Percentage of blocks stopped by the catch fence and those that reach the road for each trajectory at Sir Lowry's Pass

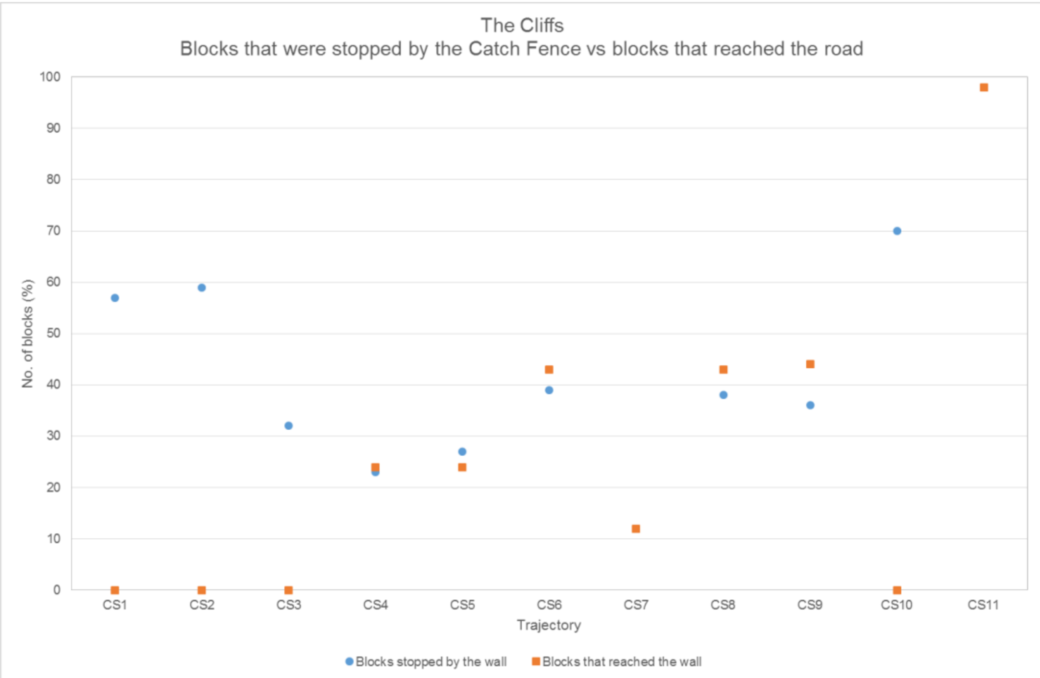


Figure 4.25: Percentage of blocks stopped by the catch fence and those that reach the road for each trajectory at The Cliffs

The output trajectories from the 3D RAMMS software that was used to run the 2D Rocfall software cannot be presented graphically as they are dxf files. They also do not begin at the same elevation or spacing. After much deliberation, the researcher could not find an acceptable manner to present this data since the trajectories are different from each other and the three sites are even more so.

Although two of the three sites comprised the same geological origin, the degree of weathering varied to such a large range that they might as well have been from two completely different geological rock types. The Cliffs was originally a hard rock quarry where blocks were removed as a result of their slight degree of weathering whereas, Sir Lowry's Pass was completely to highly weathered to the extent that the surface layer could be removed by hand. No detailed petrographic analysis was undertaken of the geology for these sites. Therefore, no graphical plot is present for the geology.

This concludes the interpretation and discussion of the parameters and results of the rockfall simulations.

CHAPTER 5 : CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This research study was undertaken to determine the relevance of software programs in assisting an engineer in narrowing down the location of rockfall mitigation measures and thereby reducing risk to lives, vehicles, and property and subsequently eliminating overdesign and thus reducing the cost of the mitigation measures. The aim of the study was achieved by the use of both two-dimensional and three-dimensional software programs in three existing projects. The conclusions and recommendations following the main objective having been reached in this study are discussed below.

5.2 CONCLUSIONS

The conclusions following the analysis of rockfalls using both 2D and 3D programs are highlighted as follows:

- The RAMMS Rockfall software used the survey data presented in an ASCII file to create a grid and thereby create a 3D model of the study area. The point or line of release determines the height at which a rock will fall from. The rock then follows the trajectory based on the topography created by the model.

- The geological material type can be assigned to the study area and this has a significant impact on the trajectory of a rock. Rocks tend to deflect from their original trajectory once a boulder or harder material type is encountered along its path. Therefore determining a rock trajectory without assigning the correct geology to the topography can result in the incorrect final location of the rock.

- The Rocscience Rocfall software was able to determine the kinetic energies and bounce heights of rocks along a specified slope section. It further allowed for the input of a barrier of a given capacity and height at a specified location to determine whether or not the potential rockfalls that were modeled could be stopped or at the very least reduced in energy before impact at its end location.

- Rockfalls generally follow the trajectory dictated by valleys. Although they may release from a spur, depending on the topography of the surrounding area, they normally are inclined by gravity to move towards a valley and follow that trajectory given sufficient energy.

- Geological material type either increases kinetic energy in the case of a hard rock or decreases kinetic energy by absorption in the case of talus or soft soil slopes. This will directly impact the runoff lengths and the impact or final resting location of a rock.

- From information gathered during the site inspections, the input parameters for the software programs were determined such as block mass and initial velocity. The normal and tangential coefficient of restitution was determined from previous literature and work done on some of the sites.

5.2.1 Limitations of the 2D Rocscience RocFall software

It is virtually impossible to accurately predict rockfalls; however the use of software programs can reduce the "guess" factor when designing. With that being said, a number of difficulties can arise when running rockfall simulations. Stevens (1998) explained some of the difficulties such as:

- Slope geometry can be highly variable.
- The initial location of a rockfall is often unknown.
- The slope can be variable or the relevant material properties not well known.
- Calculations used to simulate rockfall events are sensitive to minor changes in these parameters.

However, these difficulties can be overcome by manipulating the input parameters of the software program.

A random distribution can be assigned to the location of each of the slope vertices that model the slope geometry. This assists in simulating the change in slope geometry from one section of the slope to other (Stevens, 1998). Material properties can be taken into account by assigning a large standard deviation for the coefficient of normal restitution (Rn). This should cover a range of different materials should the slope material type differ along the length of the profile. To overcome the uncertainty of the initial location of rocks, a line seeder can be used which allows for random starting points of the rocks along the length of the slope.

5.2.2 General conclusions

It can be concluded that the outcomes of any rockfall analysis are only as good as the input parameters in the software programs. Given the opportunity to field test the rolling of rocks down the slope that requires mitigation measures, it should be done several times. This would allow for actual field parameters input into the software resulting in more accurate results and will not be reliant on assumed parameters.

However in most cases field tests are not possible and, therefore, experience working in the field of rockfall is highly required to ensure that assumed input parameters will result in realistic field conditions.

5.3 RECOMMENDED FUTURE RESEARCH

As a result of the conclusions made above, the recommendations are as follows:

5.3.1 Fieldwork

- It is recommended that the study area is increased to cover a larger area, particularly in areas with a change in geology. This will result in a larger database of both the normal and tangential coefficients of restitutions pertaining to local areas thus resulting in more accurate rockfall analysis.

- Field testing of rockfalls should be done whereby rocks of a specific size and shape are pushed off the slope at a known initial velocity and allowed to follow its natural trajectory down the slope. The setup of high-speed cameras to capture the speed and bounce heights of the rocks should also be undertaken. Although this is an expensive exercise, the data gathered will be used for years to come and will most likely outweigh the cost involved.

- Larger survey areas with increased survey details should be undertaken in order to produce accurate digital elevation models as well as detailed surface profiles.

5.3.2 Software programs

- The spacing of rockfalls (when released in a software program) and trajectories can be increased within the study area to cover more ground which would increase the accuracy of the end locations of the rocks and assist in narrowing down the position of a rockfall mitigation measure.
- The simulations should be re-run in the final version of the 3D software and have the results compared to the proven 2D software.

5.3.3 General recommendations

Modeling rockfalls is definitely an asset to engineers during the design process. One cannot argue the benefits of using a software program to determine trajectories, kinetic energies, bounce heights and end locations of rock blocks. This has been supported by the work done by a company called High Angle Technologies using a rockfall rating system and software programs.

High Angle Technologies (2004) shared their experience in dealing with potential risk in terms of rockfalls. They were of the opinion that the best rockfall analysis is done by skilled engineers, with the assistance of tools such as computer programs. High Angle Technologies stated that “A machine can’t be accurate without the aid of an expert to run it and input the right information, but with the aid of these programs, a skilled geotechnical engineer can make ‘magic’ happen”. They shared their experience on a project in Utah. In order to classify the risk potential, they took an individual look at each component. The components were as follows:

- Determine risk potential: which included whether or not a rock would fall and what was likely to cause such failure. The risk potential was assigned a numerical value between 0 and 10. Zero equating to no fall and 10 means it will definitely fall within a specified time period.

- Determine risk factor: represents the impact of the boulder when it falls. This component is also assigned numerical values of 0 to 10. Zero means that no damage will be done and no one will be hurt, whilst 10 means that serious damage to property or someone could be killed.
- Determine risk exposure: is the product of risk potential multiplied by the risk factor. By reducing the risk potential and the risk factor, the risk exposure can be reduced. A number of 20 or less for risk exposure is reasonable, however, anything over 50 is a serious risk that needs to be changed.

Risk exposure can be determined by establishing a group of evaluators, determining the probability of event or risk potential, entering the evaluators information into a spreadsheet and processing the information (Technologies, 2004). The risk exposure can impact the budget for an area. An example that High Angle Technologies has used is: if County A has 3 hazards, hazard 1, a total risk exposure rating of 79, hazard 2, a total risk exposure rating of 83 and hazard 3, a risk exposure rating of 65. The resulting overall risk exposure for that County is 227.

They had a budget of $100,000 and used the entire amount in their attempt to distribute the budget to reduce the risk exposure rating. Hazard 2 had the highest rating of all. The budget would cover the cost of scaling/barring and a 1,500kJ rockfall fence. Hazard 2 risk exposure rating reduced from an 83 to a 19. The County's overall risk exposure would also decrease. On their second try, they attempted to reduce the risk exposure rating on all 3 hazards to below 50. They budgeted to spend $30,000 on building a catch ditch below hazard 1. This reduced the risk exposure from 79 to 33. At hazard 2, they planned on spending $60,000 to install a 1,000kJ catch fence and some barring. This reduced the number from 83 to 25. For hazard 3, they planned on barring and erecting warning signs with a budget of $10,000 reducing the number from 65 to 39. The County's overall risk was then reduced from 227 to 97.

Although this was a very simple example by High Angle Technologies (2004), they show that by working the numbers, for the same amount of money, they were able to reduce the risk exposure by almost 2. This proved how important rockfall analysis is to a budget and how it can assist in reducing risk and controlling overall costs.

As discussed earlier, more field tests on different types of geological slopes should be conducted to create a local database of input parameters for software programs. All of the programs that are used in South Africa were created in different countries, mainly for areas covered by large vegetation and or in areas that experience significant quantities of snow. Therefore, the field database of input parameters that is created for use in these programs may not be accurate for use in African conditions.

It is recommended that any future studies on rockfall for software programs should include a significant number of field rockfall tests across a range of geological types, with different rock sizes and shapes to create a local database of input parameters.

REFERENCES

Aerial photo 3318_2000_ED7_MD_200003_GEO, Department of National Geo-spatial Information.

Aerial photo 3318DC_13_2010_307_RGB_RECT, Department of National Geo-spatial Information.

Aerial photo 3418AB_03&08_2010_RGB_RECT, Department of National Geo-spatial Information.

Aerial photo 3418BB_14_2010_307_RGB; Department of National Geo-spatial Information.

Andrew, R. D. (1994). The Colorado Rockfall Hazard Rating System. Colorado Springs: University of Colorado.

Arosio, D., Longoni, L., Papini, M., Scaioni, M., Zanzi, L., & Alba, M. (2009, July 15). Towards rockfall forecasting through observing deformations and listening to microseismic emissions. Retrieved from Natural Hazards and Earth System Sciences: www.nat-hazards-earth-syst-sci.net/9/1119/2009.

Avery, M. (2012). Port Hills 3D Rockfall Modelling Christchurch, New Zealand. Christchurch: Geovert Ltd.

Azzoni, A., La Barbera, G., & Zaninetti, A. (1995). Analysis and Prediction of Rockfalls Using a Mathematical Model. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol 32*, 709-724.

Bateman, V. (2010). Developing and Implementing a Rockfall Management System and Mitigation Program for Tennessee. *TR News 266*, 35-37.

Bell, F. G. (2007). Engineering geology. Oxford: Elsevier Ltd.

Brune, J. F. (2010). Extracting the Science: A Century of Mining Research. Colorado: Society for Mining, Metallurgy, and Exploration, Inc. (SME).

Budetta, P., & Nappi, M. (2013). Comparison between qualitative rockfall risk rating systems for a road affected by high traffic intensity. Natural Hazards Earth Syst. Sci.

Berger, F., & Dorren, I. (2006). Objective Comparison of Rockfall Models using Real Size Experimental Data. *Disaster Mitigation of Debris Flows, Slope Failures and Landslides*, 245-252.

Chai, S., Vacoub, T., & Charbonneau, K. (2013). The effect of Rigid Body Impact Mechanics on Tangential Coefficient of Restitution. Geo Montreal. Montreal.

Christen, M., Buhler, Y., Glover, J., Gerber, W., & Bartlet, P. (2015, April 17). RAMMS: Rockfall. Retrieved from RAMMS: Rockfall: www.ramms.slf.ch/ramms.

Coefficient of Restitution. (n.d.). Retrieved from www.rocscience.com: https://www.rocscience.com/help/rocfall/webhelp/rocfall/Coefficient_of_Restitution.htm.

Crosta, G. B., Agliardi, F., Frattini, P., & Lari, S. (2014). Key Issues in rock fall Modelling, Hazard and Risk Assessment for Rockfall. In G. Lollino, D. Giordan, G. B. Crosta, J. Coromina, R. Azzam, J. Wasowski, & N. Sciarra, Engineering Geology for Society and territory - Volume 2: Landslide Processes (p. 54). New York: Springer.

Dorren, L. (2012, September 29). www.ecorisq.org/docs/Rockyfor3D_V5_1_EN.pdf. Retrieved November 27, 2012, from www.ecorisq.org: http://www.ecorisq.org/docs/Rockyfor3D_v5_1_EN.pdf.

Dorren, L. K. (2003). A review of rockfall mechanics and modelling approaches. Progress in Physical Geography 27, 1, pp. 69-87.

Dorren, L., Domaas, U., Kronholm, K., & Labiouse, V. (2011). Methods of predicting rockfall trajectories and run-out zones. In S. Lambert, & F. Nioct, Rockfall engineering (pp. 143-173). John Wiley & Sons Inc.

Dr-Dave. (2011, April 19). The landslide Blog. Retrieved from blogs.aug.org: http://blogs.agu.org/landslideblog/2011/04/19/rockfalls-and-landslides-from-the-february-2011-earthquake-in-christchurch/.

Engineering geology map of Somerset West and Hangkilp area Cape Province, Republic of South Africa, M.J. Mountain & Associates, Jan 1980.

Federal Highway Administration. (2013, 2 28). CRSP-3D. Retrieved from CRSP-3D: http://geotechpedia.com.

Ferrari, F., Giani, G., & Apuani, T. (2013). Towards the comprehension of rockfall motion, with the aid of in situ tests. *Italian Journal of Engineering Geology and Environment*, 163-171.

Geobrugg. (2008, April). Geobrugg Brochure Open Pit Mine Rockfall Protection. Retrieved from Open Pit Mine Rockfall Protection: http://www.edx.co.za/ClientData/www.geobrugg.edx.co.za/data/%7B12%7D%20open_pit_mine%20rockfall.pdf.

Geological map 3318 Cape Town 1990, 1:250 000; Geological Survey.

Geological map 3318DC Bellville 1984, 1:50 000, Geological Survey.

Geological map Kaapse Skiereiland, 1984, 1:50 000, 3418AB and AD.

Govorushko, S. (2012). Natural Processes and Human Impacts: Interaction between Humanity and the Environment. Dordrecht: Springer.

Harber, A. J., Nettleton, I. M., Matheson, G. D., & McMillan, P. A. (2000). Rock engineering guides to good practice: road rock slope excavation. Transport Scotland and Highways Agency.

Haskins, D. (2005). Report on the geotechnical investigation on the stability of quarry slopes and proposed mitigation measures at The Cliffs, Tygerberg Waterfront. Cape Town: Melis & du Plessis.

Haskins, D. (2006). Rockfall event of 03 August 2006 resulting in road closure and the ensuing debris slide of 19 August 2006 whilst repairs were being affected. Cape Town: Melis & du Plessis.

Haughton, S. H. (1969). Geological History of Southern Africa. Cape Town: The Geological Society of South Africa.

Hoek, E. (2007). Practical Rock Engineering. Retrieved from www.rocscience.com on the 30 October 2013.

Hoek, E. and Bray, J.W. (1981). Rock Slope Engineering, Revised 3rd edition, The Institution of Mining and Metallurgy, London.

http://ramms.slf.ch/ramms/index.php?option=com_content&view=article&id=66&Itemid=93. (2015, February 10). Retrieved from http://ramms.slf.ch/ramms.

http://www.news24.com/Travel/South-Africa/PICS-Cape-roads-closed-due-to-mudslides-and-rockfalls-20131117. (2013, 11 17). Retrieved 11 18, 2013, from http://www.news24.com.

Hungr, O., & Evans, S. (1988). Engineering evaluation of fragmental rockfall hazards. 5th International Symposium on Landslides, (pp. 685-690). Balkema, Rotterdam, Lausanne.

Hungr, O., & Evans, S. G. (1989). Engineering aspects of rockfall hazard in Canada. Geological Survey of Canada, Open File 2061, 102pages.

Kumar, K., Subramanya, P., Mathur, S., & S, K. (2010, October 29). Rockfall and Subsidence on Mumbai-Pune Expressway. International Journal of Geoengineering Case Histories, http://casehistories.geoengineer.org, Vol.2, Issue 1, p.24-39. Retrieved from http://casehistories.geoenegineer.org.

Lan, H., & Martin, D. C. (2009). Evaluating the Effect of Topography on Rock Fall Process Using Lidar. International Society for Rock Mechanics.

Massey, C., Hodgson, I., & Petley, D. (2006). A Rockfall Simulation Study for Housing Development in Gibraltar. IAEG, (pp. Paper number 377, 1-7).

Meilhan, P. (2014, February 9). Retrieved from CNN: http://edition.cnn.com/2014/02/08/world/europe/france-train-derailment/.

Melis, L. (2004). Report on the events which occurred during the intense periods of rainfall between 22 July 2003 and 8 August 2004 causing intensive damage to rockfall protection measures and resulting in temporary road closure. Cape Town: Melis & du Plessis.

Melis, L. (2006). Report on the rockfall impacting the road at SV 30 530 on 05 April 2006 causing Vehicular damage. Cape Town: Melis & du Plessis.

Melis, L. (2007). Report on the rockfall events and slope stability which occurred at CPD following the rainfall events of 31 August 2007 causing extensive damage to rockfall protection measures affecting road closure. Cape Town: Melis & du Plessis.

Melis, L. (2013). Chapman's Peak Drive Operations and Maintenance report on the rockfall event at SV 25 180 on 2nd June 2013. Cape Town: Melis & du Plessis.

Moh's Scale. (2015). Retrieved from Rock and Mineral Dictionary: http://www.enchantedlearning.com/geology/rocks/pages/mohsscale.shtml .

Mposo, N. (2012, July 16). http://www.iol.co.za/news/south-africa/western-cape/rockfall-chaos-on-mountain-pass-1.1341835#. Retrieved July 17, 2012, from www.iol.co.za.

Nichol, D. (2006). Rockfall geohazard assessment and protection measures on the highway network, North Wales. IAEG2006, Paper no. 320. Wrexham: Transport Wales, Welsh Assembly Government.

Peckover, F. L. (1975). Treatment of rock falls on railway lines. Am. Railway Assoc. Bulletin 653, 509-513.

Pierson, L. A. (1991). The Rockfall Hazard Rating System. Oregon State Highway Division Engineering Geology Group.

Ritchie, A. M. (1963). Evaluation of Rockfall and Its Control. Highway Research Record.

Saeidi, S., Gratchev, I., Kim, D., & Chung, M. (2014). Evaluation of Restitution Coefficients Concerning Surface Roughness. *23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)* (pp. 1-6). Byron Bay, Australia: S.T Smith.

Saroglou, H., Marinos, V., Marinos, P., & Tsiambos, G. (2012). Rockfall hazard and risk assessment: an example from a high promontory at the historical site of Monemvasia, Greece. Natural Hazards and Earth System Sciences, 12:1823-1836.

Sartori, M., Baillifard, F., Jaboyedoff, M., & J.D, R. (2003). Kinematics of the 1991 Randa rockslides (Valais, Switzerland). Natural Hazards and Earth System Sciences, 3: 423-433.

Singh, R. G., Forbes, C., Chiliza, G, D. S., Musekiwa, C., & D, C. (2011). Landslide Geohazards in South Africa: Landslide susceptibility mapping, socio-economic impacts, mitigation and remediation measures. Pretoria: Council for Geoscience.

Stevens, W. D. (1998). RocFall: A tool for probabilistic analysis, design of remedial measures and prediction of rockfalls. Toronto: University of Toronto.

Technologies, H. A. (2004). Rockfall Risk Evaluation. *RocNews Spring*.

Topographical map 3318DC_2000_ED9_GEO, Department of National Geospatial Information.

Topographical map 3418_2000_ED5_GEO, Department of National Geospatial Information.

Topographically map 3318_2000_ED7; 1:250 000, Department of National Geo-spatial Information.

Topal, T., Akin, M., & Ozden, A. (2006). Analysis and evaluation of rockfall hazard around Afyon Castle, Turkey. IAEG (pp. Paper 439, 1-7). The Geological Society of London.

Vijayakumar, S., Yacoub, T., & Curran, J. (n.d.). Retrieved November 10, 2014 from https://www.rocscience.com/documents/pdfs/library/Effect-of-Rock-Size-on-Rocfall-Analysis.pdf.

Vijayakumar, S., Yacoub, T., Ranjram, M., & Curran, J. (2012, June 24-27). RocFall. Retrieved January 12, 2015, from www.rocscience.com/products/12/papers.

Western Oregon University. (2005). Retrieved from Western Oregon University: https://www.wou.edu/las/physci/taylor/g473/rockprop.pdf.

www.news24.com (2013, November 17). http://www.news24.com/Travel/South-Africa/PICS-Cape-roads-closed-due-to-mudslides-and-rockfalls-20131117.

Wyllie, D. C. (2015). Rock Fall Engineering. Florida: CRC Press Taylor & Francis Group.

Wyllie, D., & Mah C, W. (2005). Rock Slope Engineering Civil and Mining. Taylor & Francis e-Library.

APPENDIX A

ROCKFALL RESULTS

Appendix A: Rockfall Results

A.1. Chapman's Peak Drive

Table 1: Summary of the rockfall simulations for the volume of material measured at the catch fence

CHAPMAN'S PEAK DRIVE: SUMMARY OF ROCKFALL SIMULATION RESULTS AT CATCH FENCES											
ROCKFALL INFORMATION		KINECTIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)					BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)				
TRAJECT-ORY NO.	NO OF HITS (%)	100%	98%	95%	75%	50%	100%	98%	95%	75%	50%
2a	64.3	12633	11866	11606	4600	2112	-0.067	-0.286	-0.726	-3.348	-4.955
2b	75.4	2610	1392	1275	994	809	-6.85	-6.85	-6.85	-6.85	-6.85
8a	55	222	195	191	181	169	-4.668	-4.679	-4.686	-4.724	-4.776
8b	12.4	659	446	367	191	130	-6.381	-6.381	-6.381	-6.381	-6.381
11a	12.9	3485	3322	3214	1066	338	-4.866	-5.018	-5.105	-5.467	-5.478
11b	93.2	1596	1865	1822	1236	1141	-5.417	-5.417	-5.417	-5.417	-5.417
11c	89.3	1308	1121	1034	362	199	-0.262	-1.726	-2.82	-5.726	-5.944
15a	45.2	6131	1556	1409	1262	1168	-5.868	-5.952	-5.952	-5.952	-5.952
15b	92.8	11069	5526	5109	4596	4225	-4.652	-4.652	-4.652	-4.652	-4.652
30a	80.8	2735	818	786	677	481	-5.641	-6.186	-6.197	-6.216	-6.22
30b	86.2	2185	1682	1544	1234	1037	-4.945	-4.945	-4.945	-4.945	-4.945

Table 2: Summary of the rockfall simulations for the volume of material measured at road level with catch fence in place

CHAPMAN'S PEAK DRIVE: SUMMARY OF ROCKFALL SIMULATION RESULTS AT DATA COLLECTOR WITH CATCH FENCE IN PLACE											
ROCKFALL INFORMATION		KINECTIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)					BOUNCE HEIGHT IN RELATION TO THE ROAD (m)				
TRAJECT -ORY NO.	NO OF HITS (%)	100%	98%	95%	75%	50%	100%	98%	95%	75%	50%
2a	67.7	14910	12582	8110	4844	2695	16.414	9.187	8.457	5.295	3.512
2b	13.1	925	736	651	514	368	0.183	0.183	0.183	0.183	0.183
8a	44	379	284	268	106	81	3.584	3.556	3.547	3.519	3.519
8b	3.4	140	134	119	69	35	2.383	2.383	2.383	2.383	2.383
11a	2.7	1766	1056	782	450	300	2.849	2.849	2.849	2.849	2.849
11b	6.4	787	764	749	623	465	3.766	3.766	3.766	3.766	3.766
11c	52.7	904	782	720	136	112	3.218	2.814	2.577	1.37	1.37
15a	46.8	4307	3749	3594	3230	2885	0	0	0	0	0
15b	81.4	7624	4299	4010	3613	3325	0	0	0	0	0
30a	13.9	500	475	456	395	344	0	0	0	0	0
30b	11.9	535	514	454	388	290	1.777	1.777	1.777	1.777	1.777

A.2 Sir Lowry's Pass

Table 3: Summary of the rockfall simulations for 1m³ blocks

SIR LOWRY'S PASS: SUMMARY OF ROCKFALL SIMULATION RESULTS FOR THE 1m³ BLOCKS											
ROCKFALL INFORMATION		KINECTIC ENERGY DISTRIBUTION OF ROCKS HITTING ROAD (kJ)					BOUNCE HEIGHT IN RELATION TO ROAD LEVEL (m)				
TRAJECT-ORY NO.	NO OF HITS %	100%	98%	95%	75%	50%	100%	98%	95%	75%	50%
1a	99.1	132	117	111	96	87	0.155	0.155	0.155	0.155	0.155
1b	99.5	116	100	95	86	80	1.142	1.142	1.142	1.142	1.142
2a	99.6	97	77	73	66	59	0.27	0.27	0.27	0.27	0.27
2b	100	132	118	113	101	93	1.468	1.468	1.468	1.468	1.468
3a	99.5	159	147	141	129	120	0.09	0.09	0.09	0.09	0.09
3b	99	159	107	101	89	82	0.116	0.116	0.116	0.116	0.116
4a	99.7	610	124	114	105	98	0.613	0.261	0.255	0.247	0.24
4b	23.2	782	766	710	611	522	4.291	3.587	2.931	1.902	1.263
5a	99.8	190	159	147	123	964	0.231	0.231	0.231	0.231	0.231
5b	99.6	117	98	88	71	64	0.998	0.998	0.998	0.998	0.998
6a	99.1	65	54	52	46	42	0.107	0.107	0.107	0.107	0.107
6b	99.8	55	50	49	43	39	0.109	0.109	0.109	0.109	0.109

Table 4: Summary of the rockfall simulations for 1m^3 blocks at the Catch fence

SIR LOWRY'S PASS: SUMMARY OF ROCKFALL SIMULATION RESULTS AT CATCH FENCES FOR THE 1m3 BLOCKS											
ROCKFALL INFORMATION		KINECTIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)					BOUNCE HEIGHT IN RELATION TO TOP OF FENCE (m)				
TRAJECT-ORY NO.	NO OF HITS %	100%	98%	95%	75%	50%	100%	98%	95%	75%	50%
1a	65.8	319	296	252	190	168	-3.435	-3.502	-3.517	-3.537	-3.537
1b	78.1	376	299	262	193	159	-1.311	-1.641	-1.726	-2.035	-2.169
2a	76.7	173	122	93	68	60	-3.17	-3.183	-3.185	-3.185	-3.185
2b	73.6	580	205	183	87	65	-2.441	-2.678	-2.685	-2.687	-2.687
3a	34.7	64	59	56	50	44	-3.008	-3.008	-3.008	-3.008	-3.008
3b	65.2	141	124	114	97	81	-2.449	-2.449	-2.449	-2.449	-2.449
4a	65.9	306	132	95	83	77	-5.507	-5.594	-5.627	-5.647	-5.658
4b	41.5	466	458	453	404	94	-0.138	-0.394	-0.555	-2.034	-4.546
5a	68.8	116	104	96	81	73	-2.707	-2.707	-2.707	-2.707	-2.707
5b	70.8	137	120	110	80	71	-2.973	-2.895	-2.992	-2.994	-2.994
6a	13.5	65	61	60	52	37	-2.531	-2.531	-2.531	-2.531	-2.531
6b	16.1	84	81	77	68	57	-2.424	-2.424	-2.424	-2.424	-2.424

Table 4.6: Summary of the rockfall simulations at road level for 1m^3 blocks with Catch fence in place

SIR LOWRY'S PASS: SUMMARY OF ROCKFALL SIMULATION RESULTS AT ROAD LEVEL FOR THE 1m3 BLOCKS WITH CATCH FENCES											
ROCKFALL INFORMATION		KINECTIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)					BOUNCE HEIGHT IN RELATION TO TOP OF WALL (m)				
TRAJECT-ORY NO.	NO OF HITS (%)	100%	98%	95%	75%	50%	100%	98%	95%	75%	50%
1a	33.2	122	107	101	87	76	0.155	0.155	0.155	0.155	0.155
1b	21.4	102	95	87	80	71	1.412	1.412	1.412	1.412	1.412
2a	23.2	78	71	68	60	55	0.27	0.27	0.27	0.27	0.27
2b	26.3	119	102	99	90	78	1.477	1.468	1.468	1.468	1.468
3a	65.8	174	147	142	127	117	0.09	0.09	0.09	0.09	0.09
3b	33.7	118	107	100	87	78	0.116	0.116	0.116	0.116	0.116
4a	33.8	119	114	109	100	92	0.3	0.256	0.251	0.242	0.231
4b	9	817	717	679	581	519	4.326	3.712	3.293	1.944	1.523
5a	30.9	101	81	75	64	54	0.231	0.231	0.231	0.231	0.231
5b	28.8	79	68	65	57	51	0.998	0.998	0.998	0.998	0.998
6a	85.8	63	55	52	46	41	0.107	0.107	0.107	0.107	0.107
6b	83.8	57	51	48	42	39	0.109	0.109	0.109	0.109	0.109

A3. The Cliffs

Table 6: Summary of the rockfall simulations at existing gabion wall for 1m³ blocks

THE CLIFFS: SUMMARY OF ROCKFALL SIMULATION RESULTS FOR THE 1m³ BLOCKS												
ROCKFALL INFORMATION			KINECTIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)					BOUNCE HEIGHT IN RELATION TO TOP OF WALL (m)				
TRAJECTORY NO.	HITS ON THE WALL %	BLOCKS OVER THE WALL %	100%	98%	95%	75%	50%	100%	98%	95%	75%	50%
CS1	57.3	0	1110	93	89	77	20	-1.05	-1.28	-1.44	-2.34	-2.42
CS2	59.5	0	229	148	117	65	40	-1.53	-1.69	-1.72	-1.79	-1.83
CS3	32.2	1.0	430	181	127	59	32	12.38	-1.82	-1.85	-1.91	-1.95
CS4	23.2	0.2	268	247	232	111	59	-0.21	-0.5	-1.07	-1.45	-1.57
CS5	27.3	0.2	772	280	229	89	16	0.45	-0.2	-0.49	-1.17	-1.44
CS6	39.9	2.8	582	303	276	170	69	6.91	6.8	-0.39	-0.92	-1.04
CS7	12.2	0.8	327	326	317	290	162	0.65	-0.08	-0.22	-0.68	-1
CS8	38.2	2.8	308	293	277	61	17	0.74	0.73	-0.39	-1.17	-1.45
CS9	36.6	2.2	339	302	282	55	16	0.78	0.75	-0.33	-1.19	-1.44
CS10	69.9	0	437	134	118	71	31	-0.66	-0.81	-0.85	-1	-1.04
CS11	97.5	0.8	523	288	245	158	92	0.44	-0.2	-0.39	-0.99	-1.29

Table 7: Summary of the rockfall simulations at existing gabion wall for 10m^3 blocks

THE CLIFFS: SUMMARY OF ROCKFALL SIMULATION RESULTS FOR THE 10m^3 BLOCKS												
ROCKFALL INFORMATION			KINECTIC ENERGY DISTRIBUTION OF ROCKS HITTING WALL (kJ)					BOUNCE HEIGHT IN RELATION TO TOP OF WALL (m)				
TRAJECT-ORY NO.	HITS ON THE WALL %	BLOCKS OVER THE WALL %	100%	98%	95%	75%	50%	100%	98%	95%	75%	50%
S1	46	0	5320	2380	1290	705	449	-0.09	-0.3	-0.36	-0.66	-0.8
S2	35.4	0	1910	1520	1440	1230	1030	-0.2	-0.36	-0.45	-0.53	-0.65
S3 (doesn't reach wall)	NONE											
S4	42.6	0	1360	913	730	261	183	-0.31	-0.46	-0.7	-0.91	-0.94
S5	63.5	0	2470	1340	1160	617	466	-0.07	-0.27	-0.4	-0.79	-1.15
S6	52.9	0	1876	1609	1517	580	313	-0.21	-0.95	-1.11	-1.31	-1.34

Table 8: Summary of the rockfall simulations at upgraded gabion wall for 1m³ blocks

THE CLIFFS: SUMMARY OF ROCKFALL SIMULATION RESULTS FOR THE 1m3 BLOCKS WITH A RAISED WALL												
ROCKFALL INFORMATION			KINECTIC ENERGY DISTRIBUTION OF ROCKS HITING WALL (kJ)					BOUNCE HEIGHT IN RELATION TO TOP OF WALL (m)				
TRAJECT-ORY NO.	HITS ON THE WALL %	BLOCKS OVER THE WALL %	100%	98%	95%	75%	50%	100%	98%	95%	75%	50%
CS1	-											
CS2	-											
CS3	-											
CS4	23.7	0	256	238	225	118	70	-0.6	-1.82	-2.21	-2.94	-3.07
CS5	24.3	0	781	288	259	101	12	-0.56	-1.27	-1.84	-2.56	-2.93
CS6	42.5	8	913	560	333	156	71	4	-1.2	-1.74	-2.42	-2.52
CS7	12.4	0	349	345	319	292	247	-1.27	-1.37	-1.5	-2.14	-2.5
CS8	42.5	0	337	297	274	51	18	-0.57	-1.11	-1.44	-2.51	-2.94
CS9	44	0	326	291	272	63	34	-0.47	-1.04	-1.21	-2.07	-2.93
CS10	-											
CS11	97.6	0	566	302	254	162	101	-1.12	-1.67	-1.88	-2.43	-2.79

APPENDIX B

ROCKFALL GRAPHICAL OUTPUT

APPENDIX B: ROCKFALL GRAPHICAL OUTPUT

B1: Rocscience RocFall

B1.1 Chapman's Peak Drive

a) Images of the results of rockfall simulation: With existing mitigation measures in place

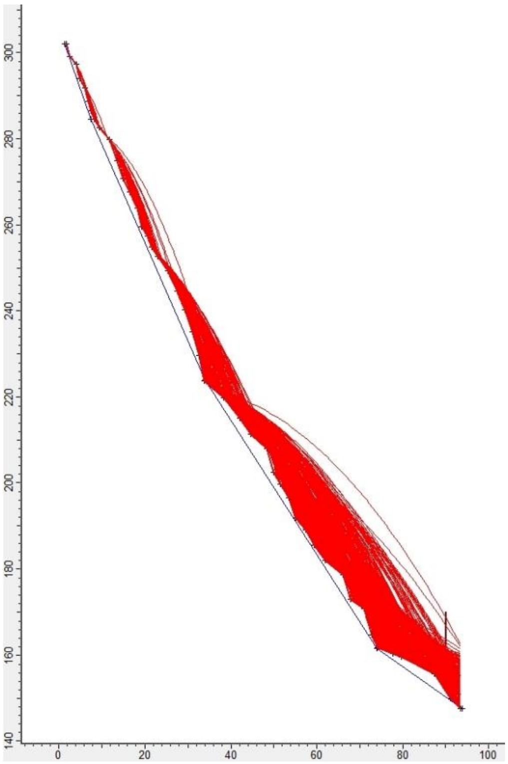


FIGURE 1.1: Rockfall simulation trajectories along 2A

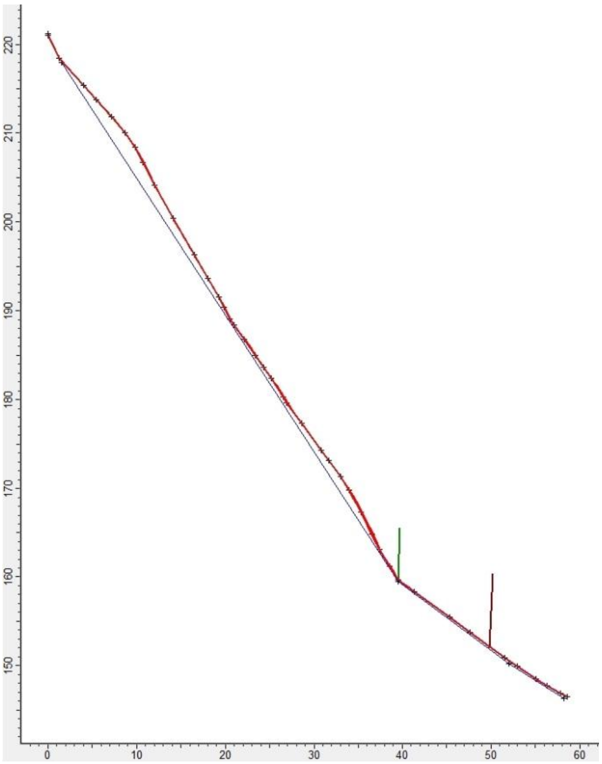


FIGURE 1.2: Rockfall simulation trajectories along 2B

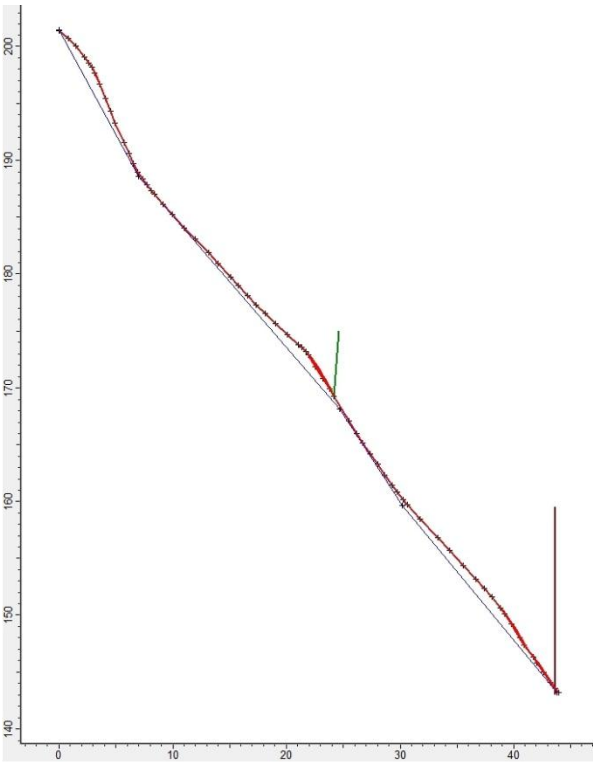


FIGURE 1.3: Rockfall simulation trajectories along 8A

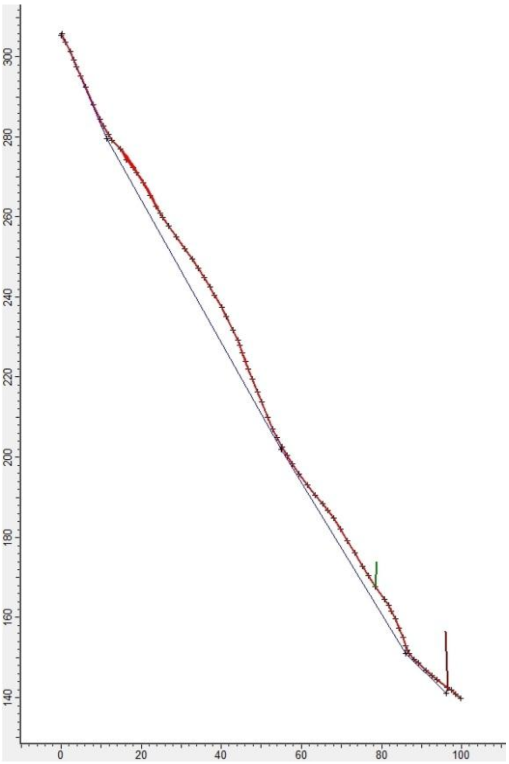


FIGURE 1.4: Rockfall simulation trajectories along 8B

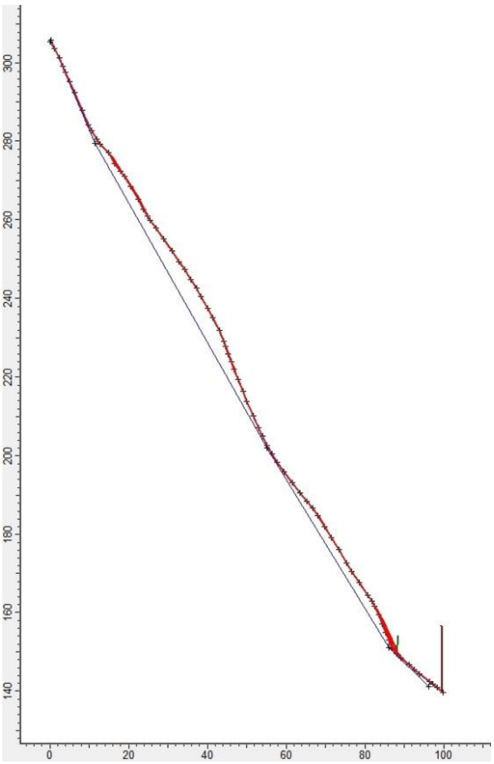


FIGURE 1.5: Rockfall simulation trajectories along 11A

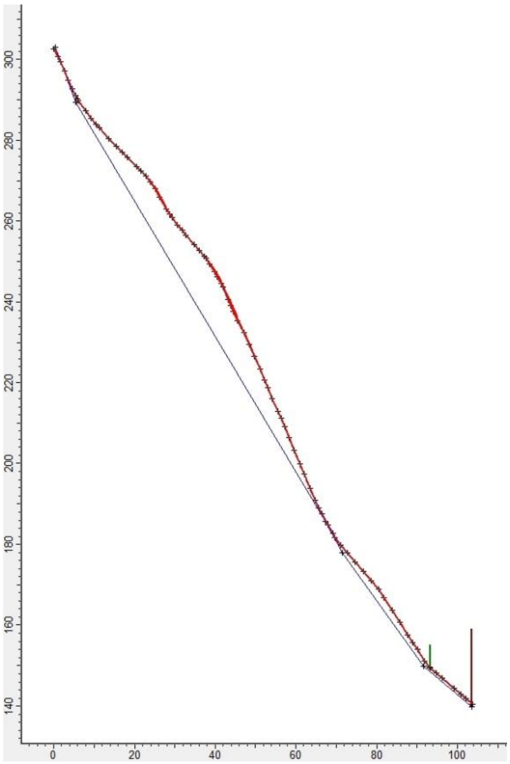


FIGURE 1.6: Rockfall simulation trajectories along 11B

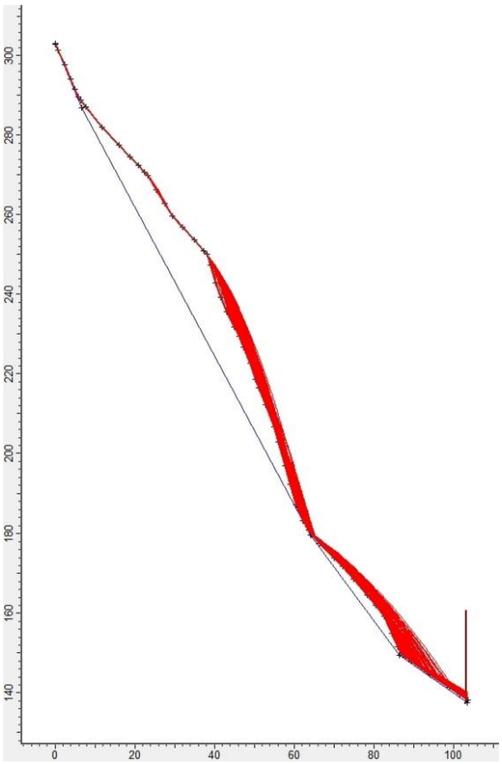


FIGURE 1.7: Rockfall simulation trajectories along 11C

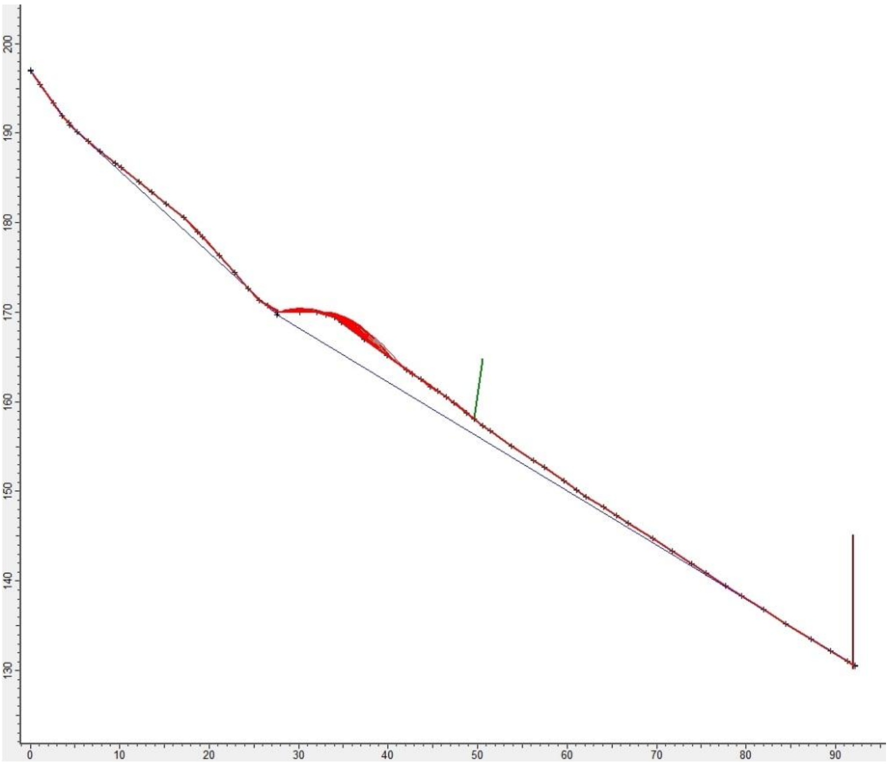


FIGURE 1.8: Rockfall simulation trajectories along 15A

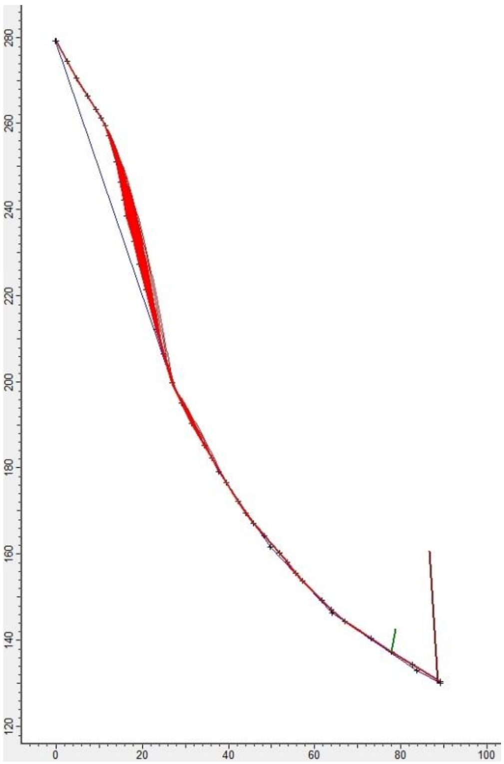


FIGURE 1.9: Rockfall simulation trajectories along 15B

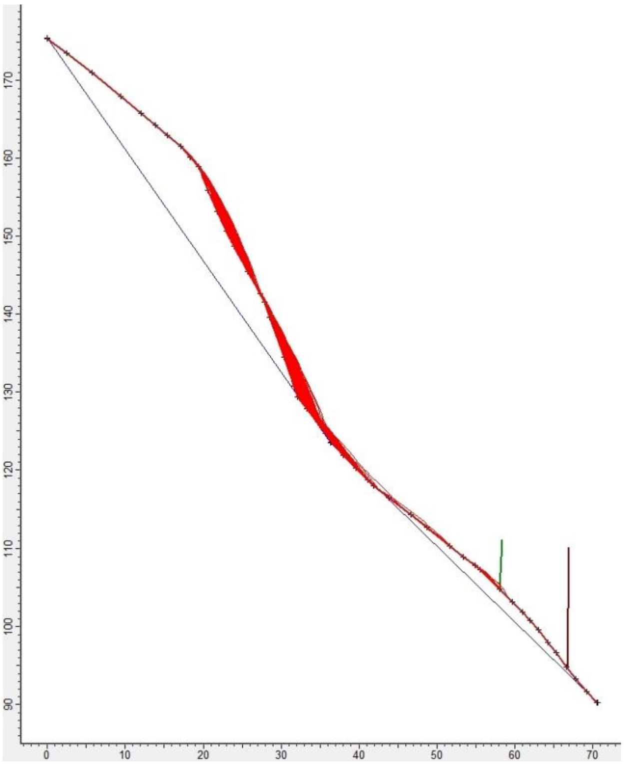


FIGURE 1.10: Rockfall simulation trajectories along 30A

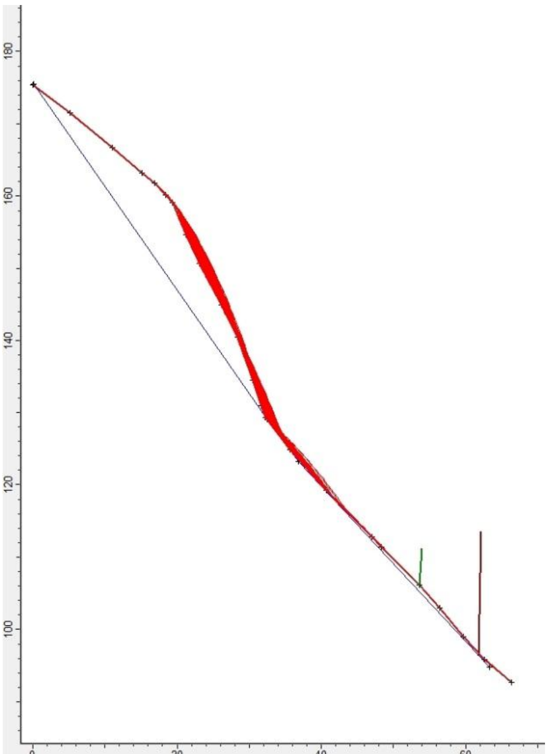


FIGURE 1.11: Rockfall simulation trajectories along 30B

B.2 Sir Lowry's Pass

a) Images of the results of rockfall simulation: Without any mitigation measure

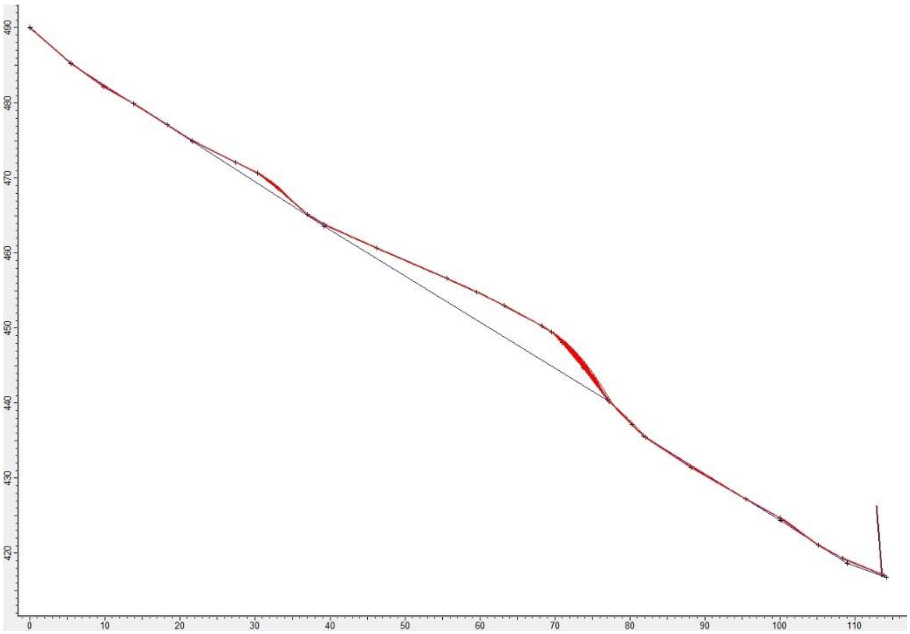


FIGURE 2.1:Rockfall simulation trajectories along 1A

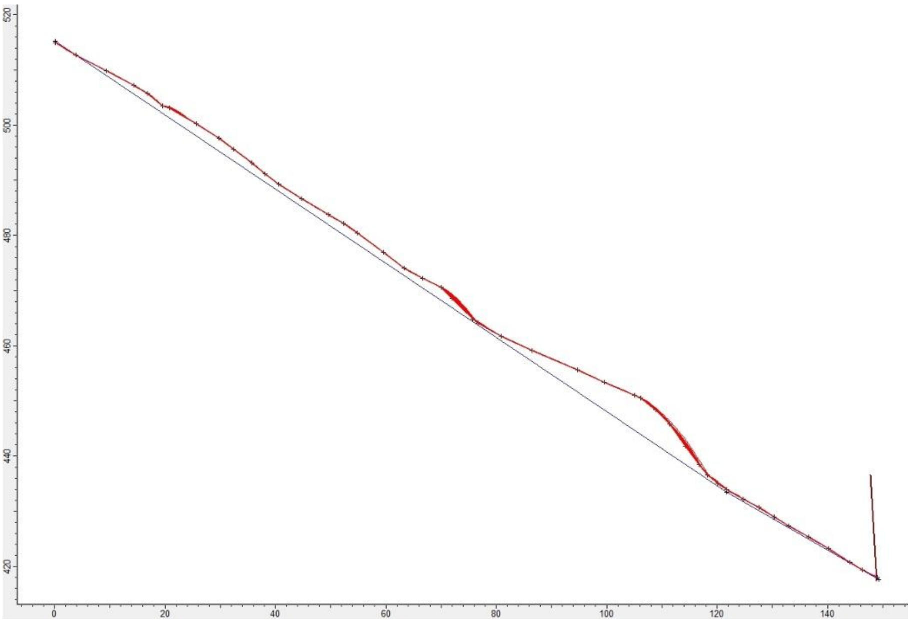


FIGURE 2.2: Rockfall simulation trajectories along 1B

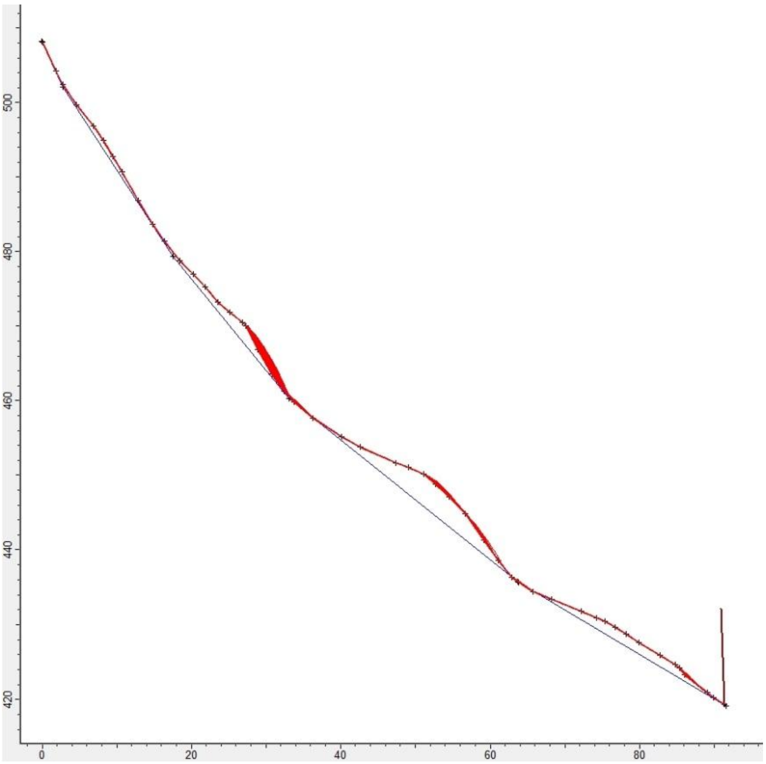


FIGURE 2.3: Rockfall simulation trajectories along 2A

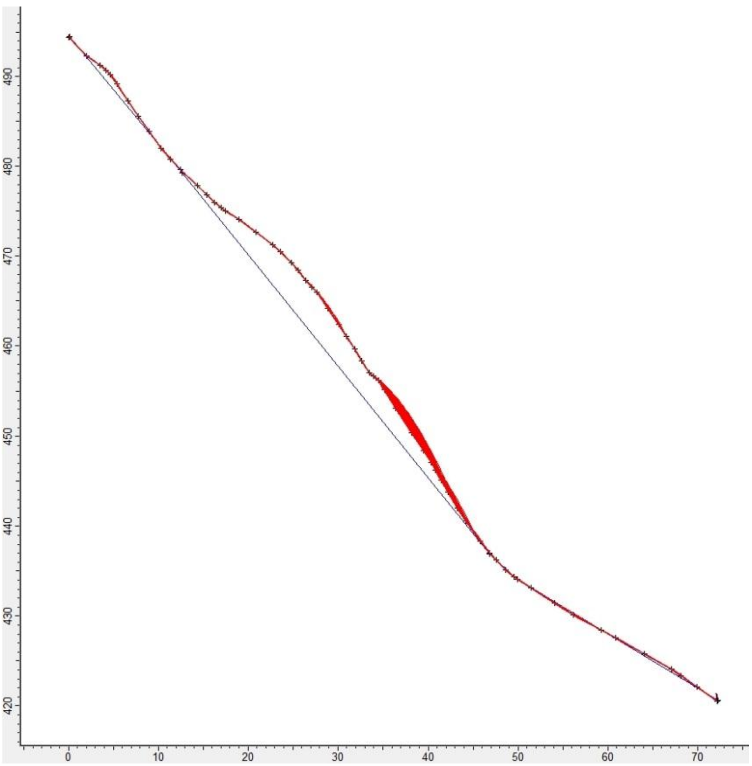


FIGURE 2.4: Rockfall simulation trajectories along 2B

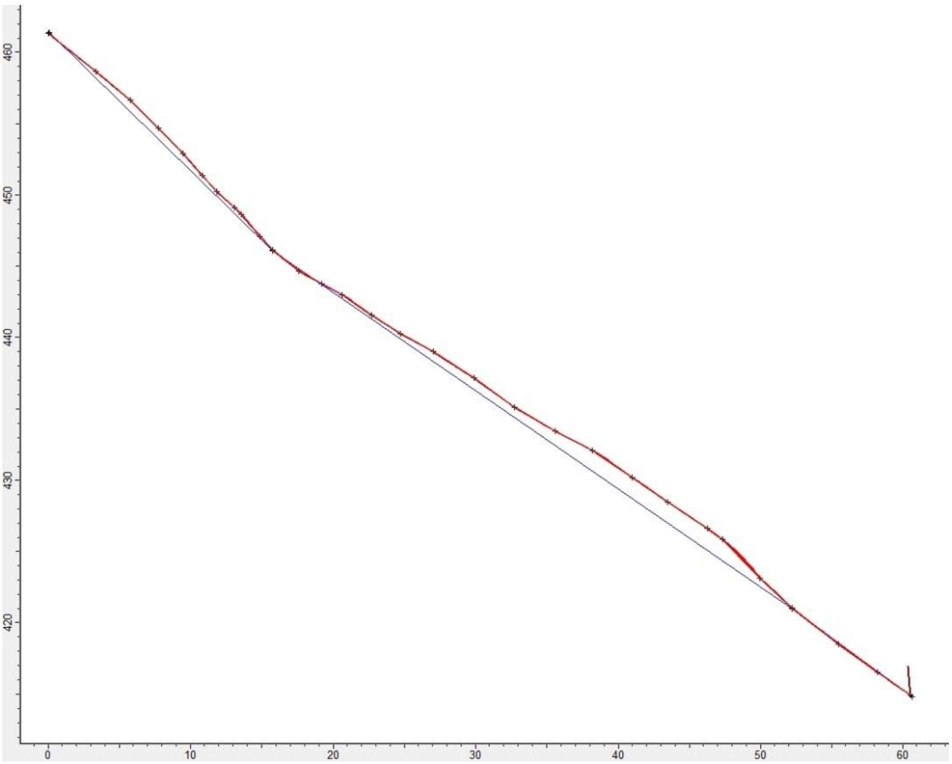


FIGURE 2.5: Rockfall simulation trajectories along 3A

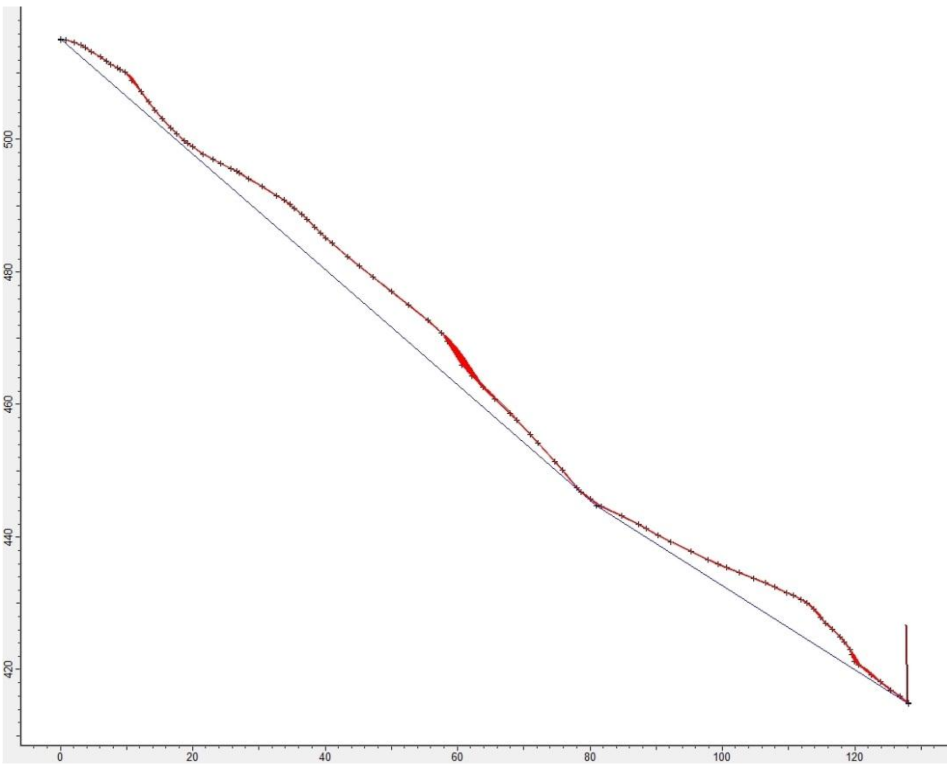


FIGURE 2.6: Rockfall simulation trajectories along 3B

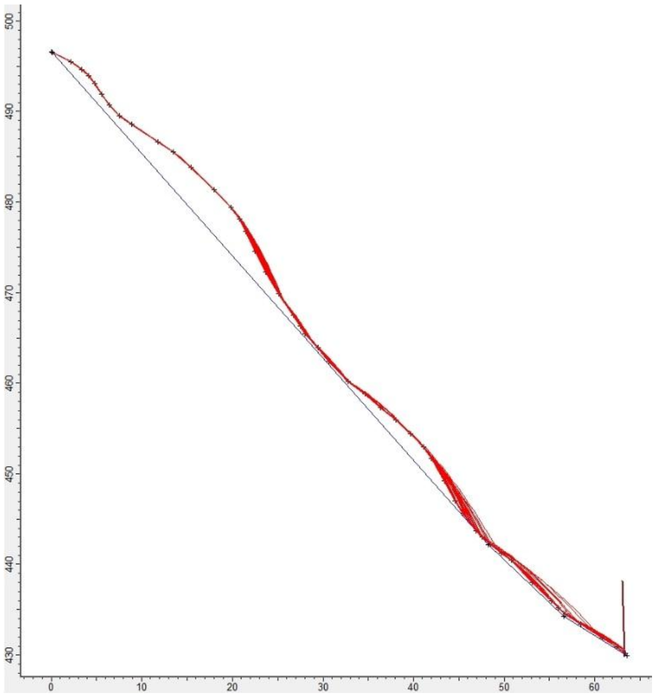


FIGURE 2.7: Rockfall simulation trajectories along 4A

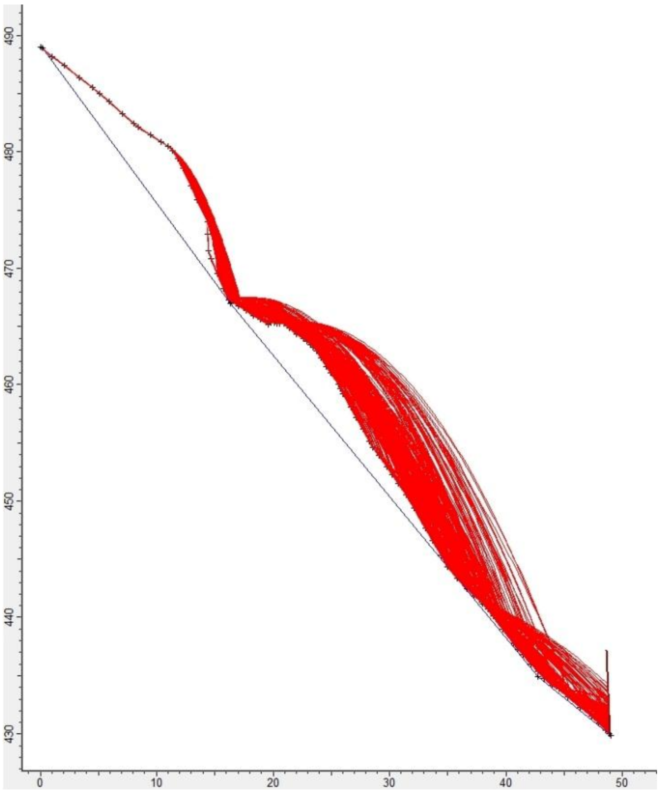


FIGURE 2.8: Rockfall simulation trajectories along 4B

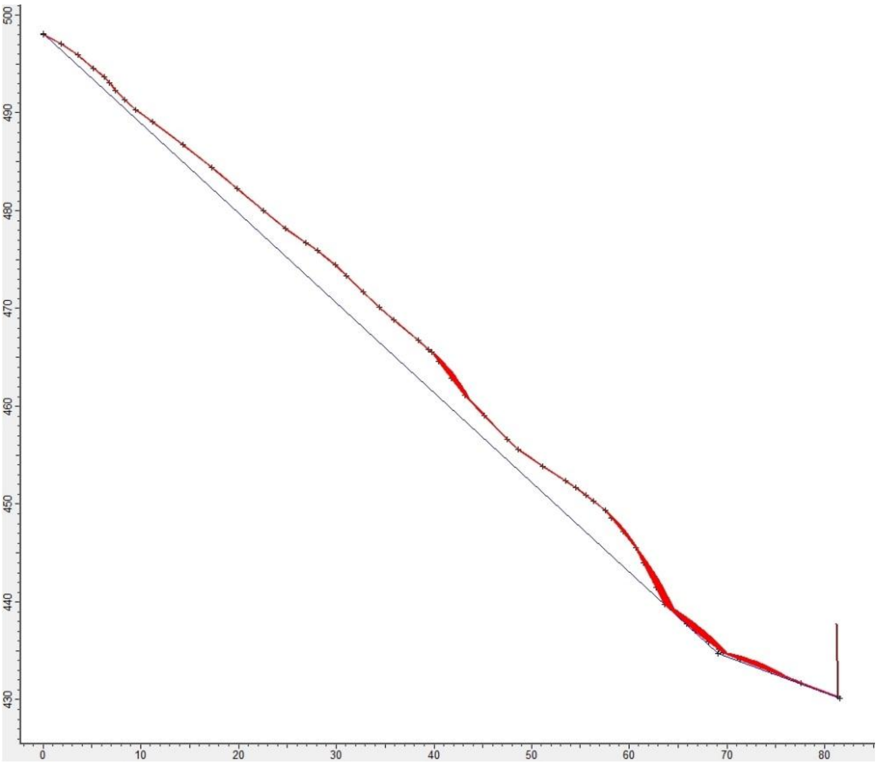


FIGURE 2.9: Rockfall simulation trajectories along 5A

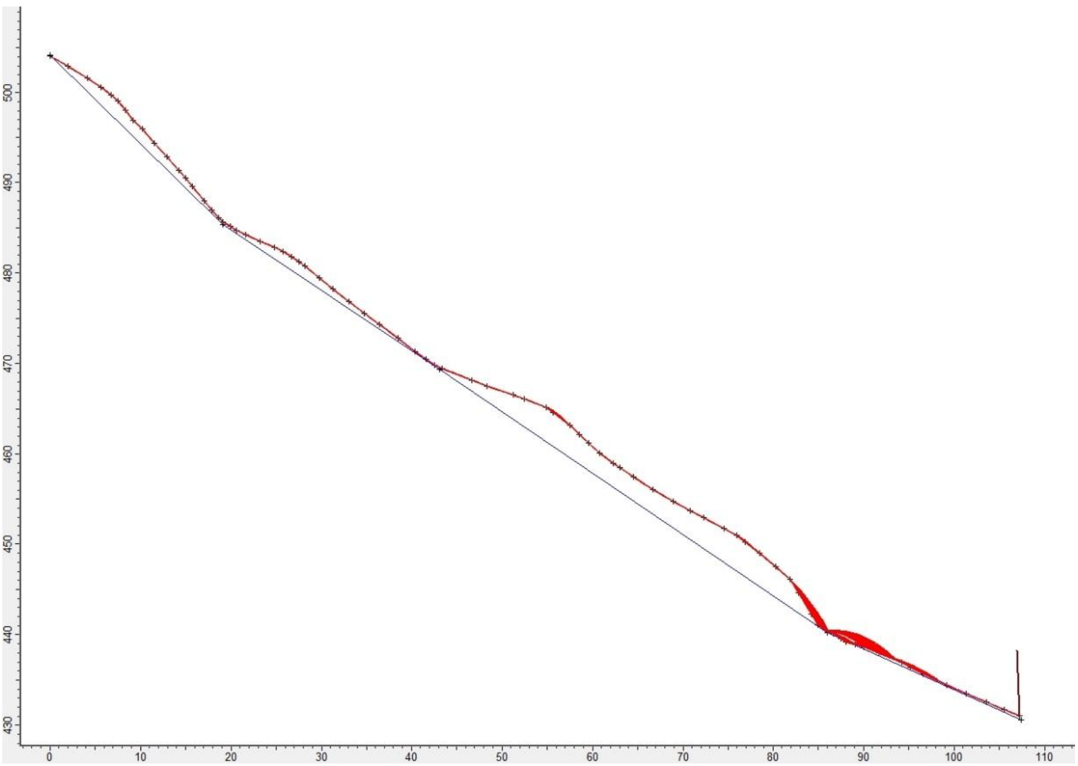


FIGURE 2.10: Rockfall simulation trajectories along 5B

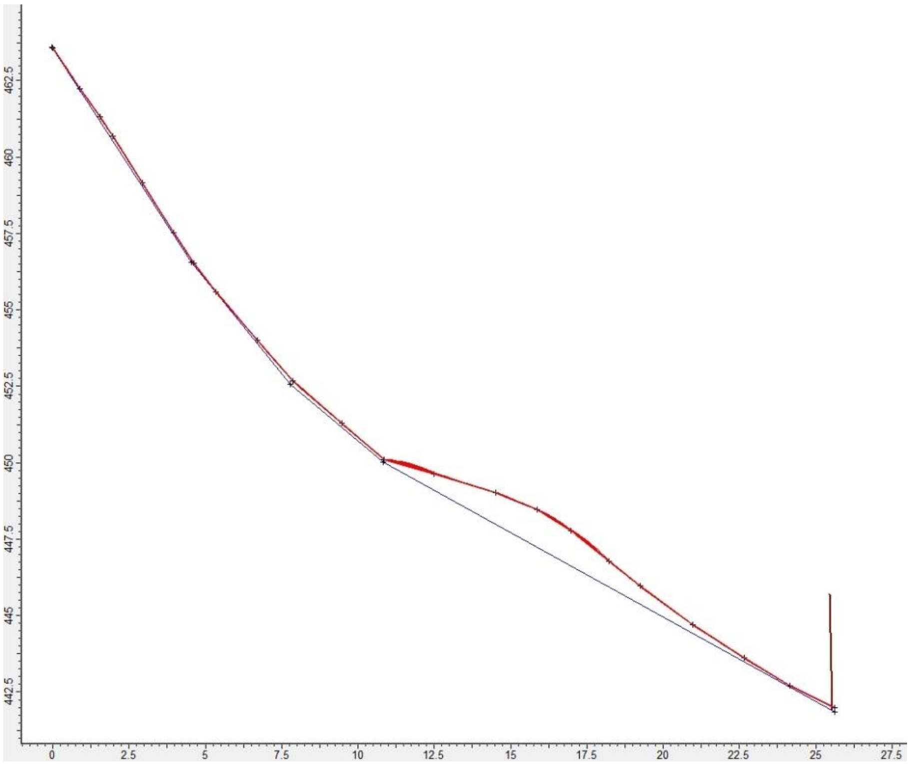


FIGURE 2.11: Rockfall simulation trajectories along 6A

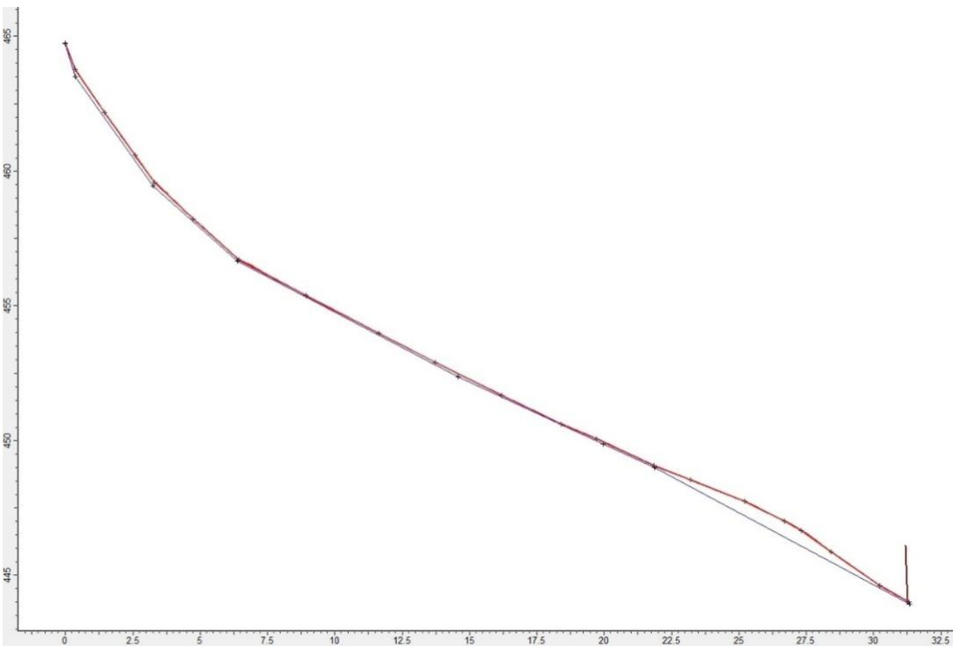


FIGURE 2.12: Rockfall simulation trajectories along 6B

b) Images of the results of rockfall simulation: Catch Fences in Place

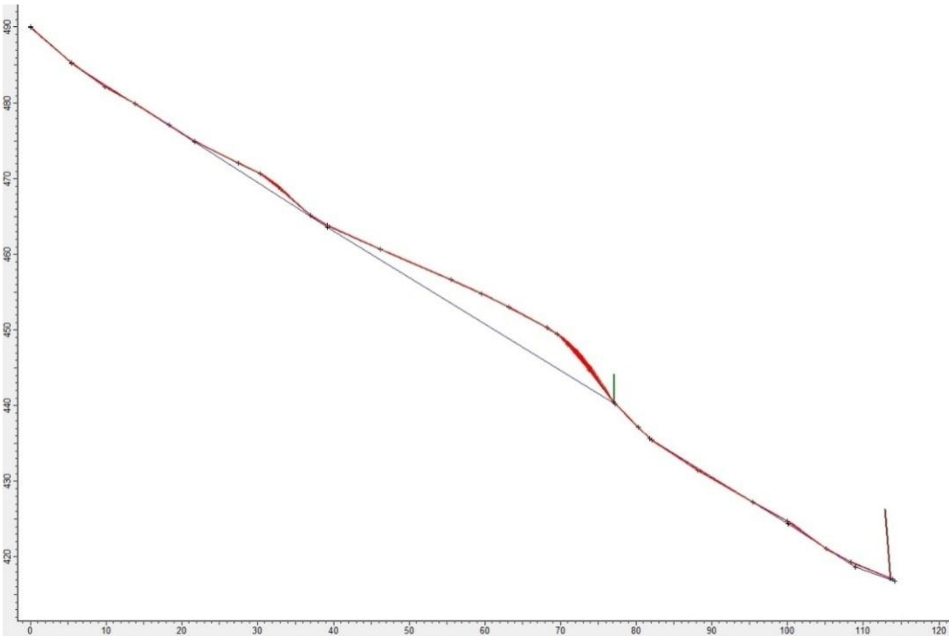


FIGURE 2.13: Rockfall simulation trajectories with Catch Fence 1 along 1A

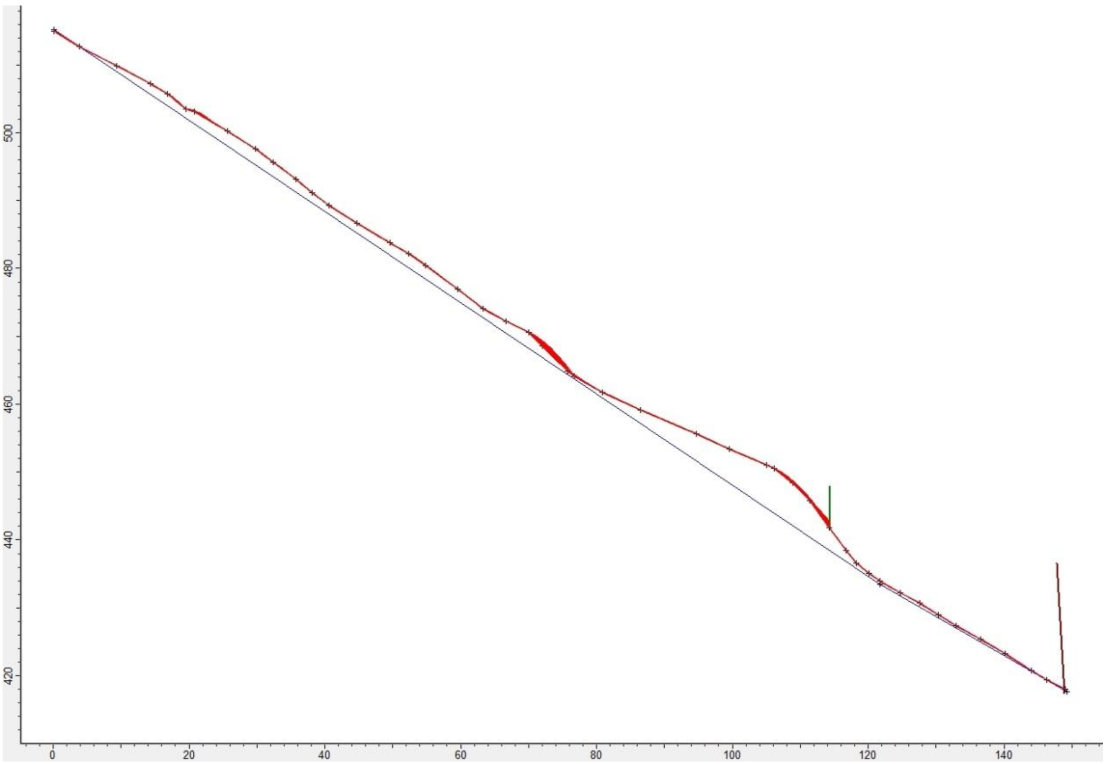


FIGURE 2.14: Rockfall simulation trajectories with Catch Fence 1 along 1B

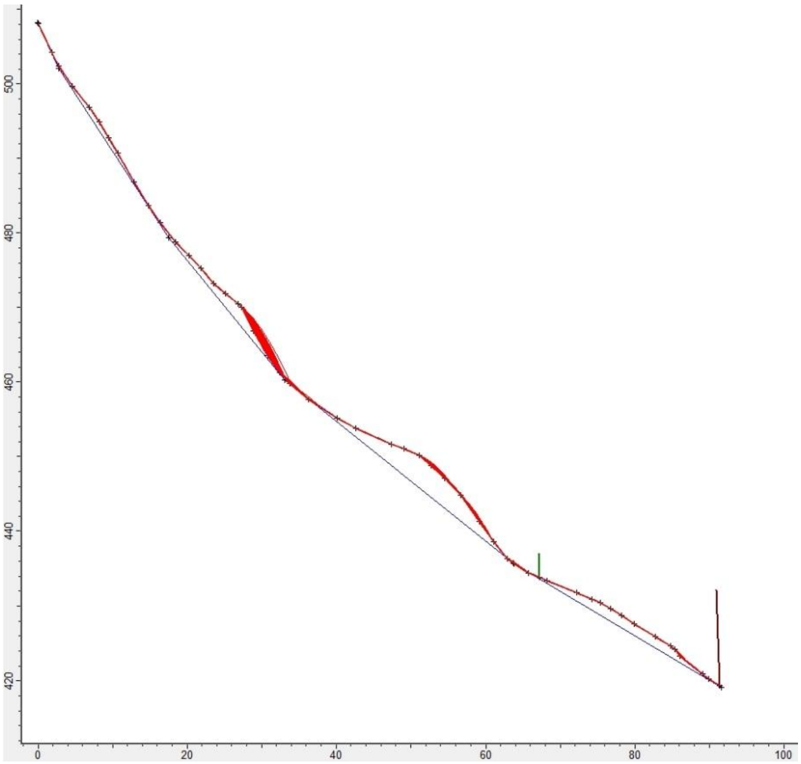


FIGURE 2.15: Rockfall simulation trajectories with Catch Fence 2 along 2A

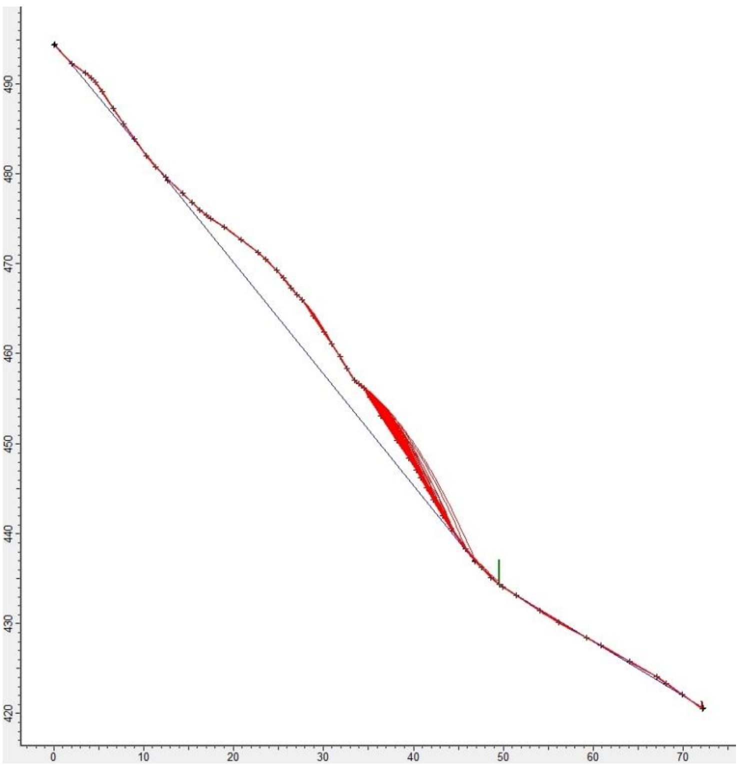


FIGURE 2.16: Rockfall simulation trajectories with Catch Fence 2 along 2B

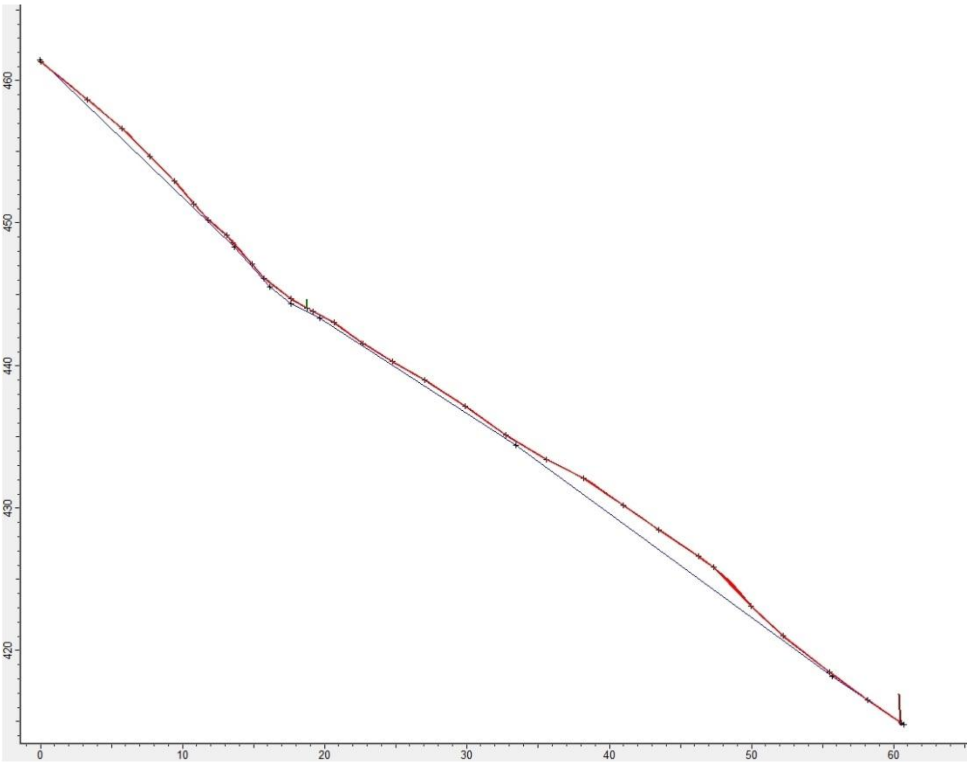


FIGURE 2.17: Rockfall simulation trajectories with Catch Fence 3 along 3A

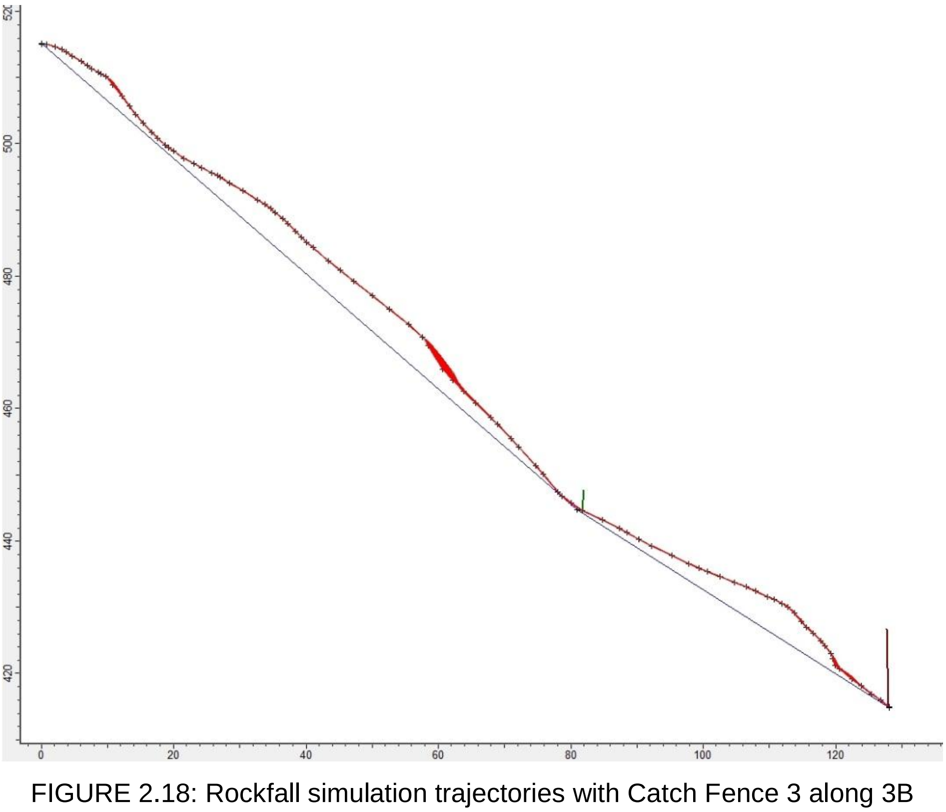


FIGURE 2.18: Rockfall simulation trajectories with Catch Fence 3 along 3B

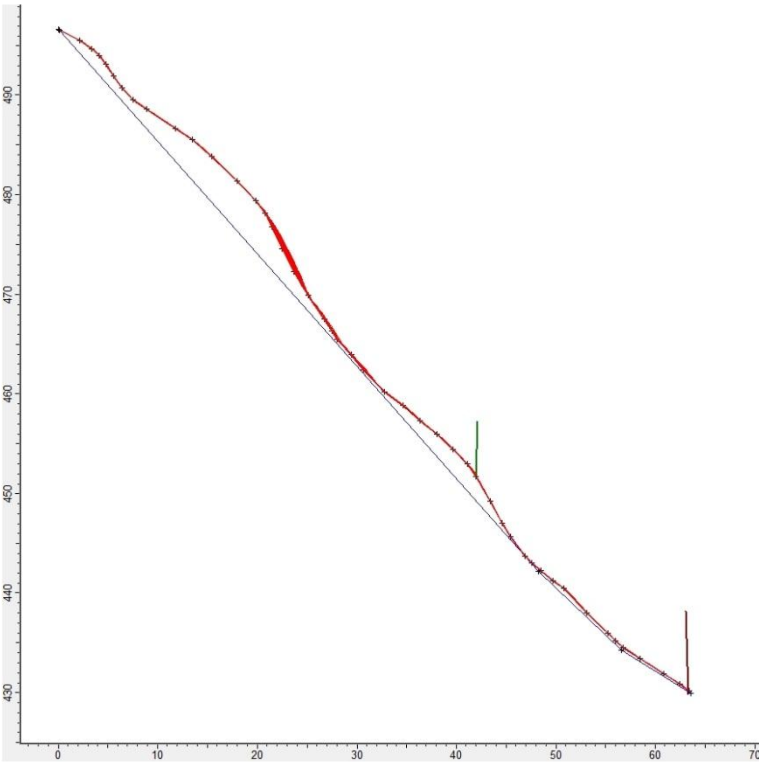


FIGURE 2.19: Rockfall simulation trajectories with Catch Fence 4 along 4A

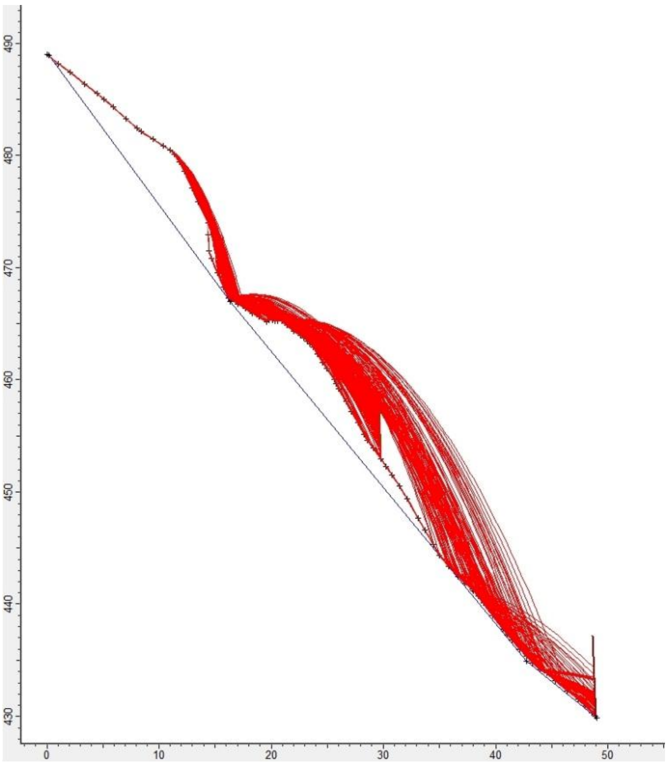


FIGURE 2.20: Rockfall simulation trajectories with Catch Fence 4 along 4B

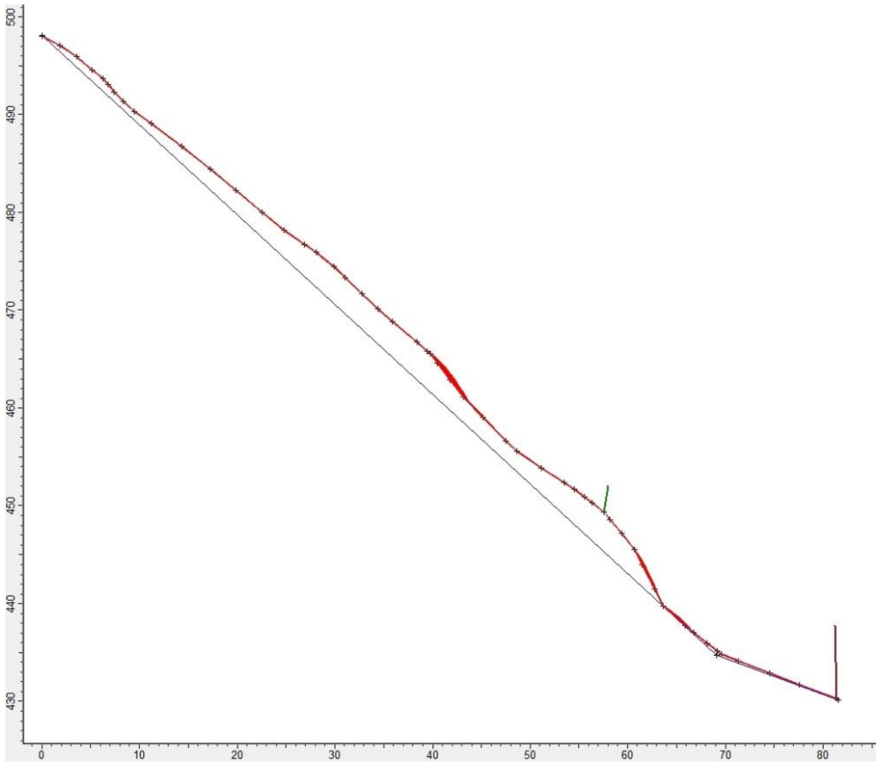


FIGURE 2.21: Rockfall simulation trajectories with Catch Fence 5 along 5A

FIGURE 2.22: Rockfall simulation trajectories with Catch Fence 5 along 5B

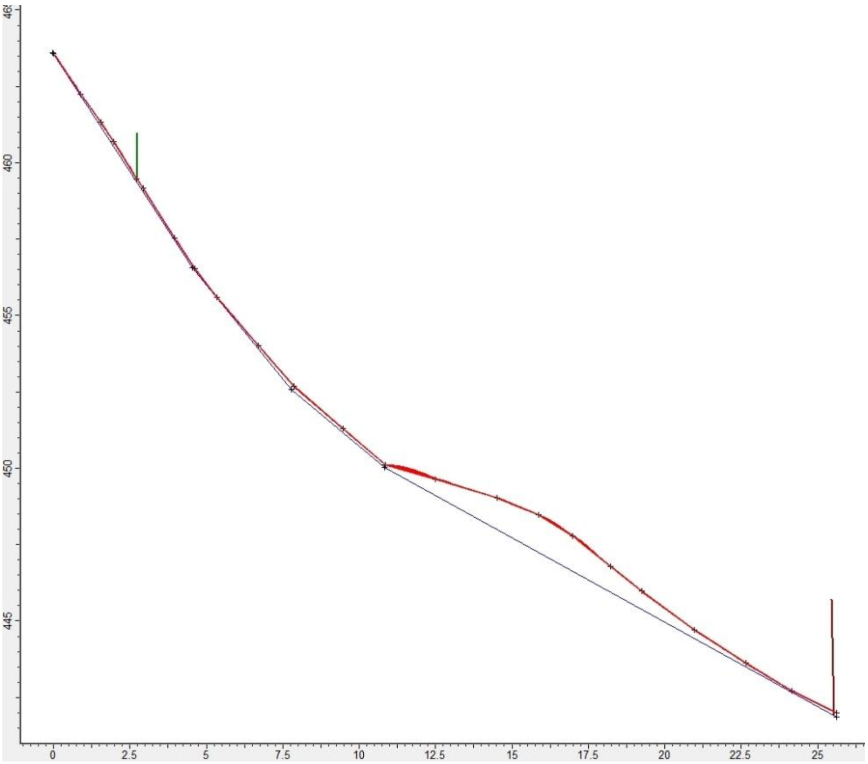


FIGURE 2.23: Rockfall simulation trajectories with Catch Fence 6 along 6A

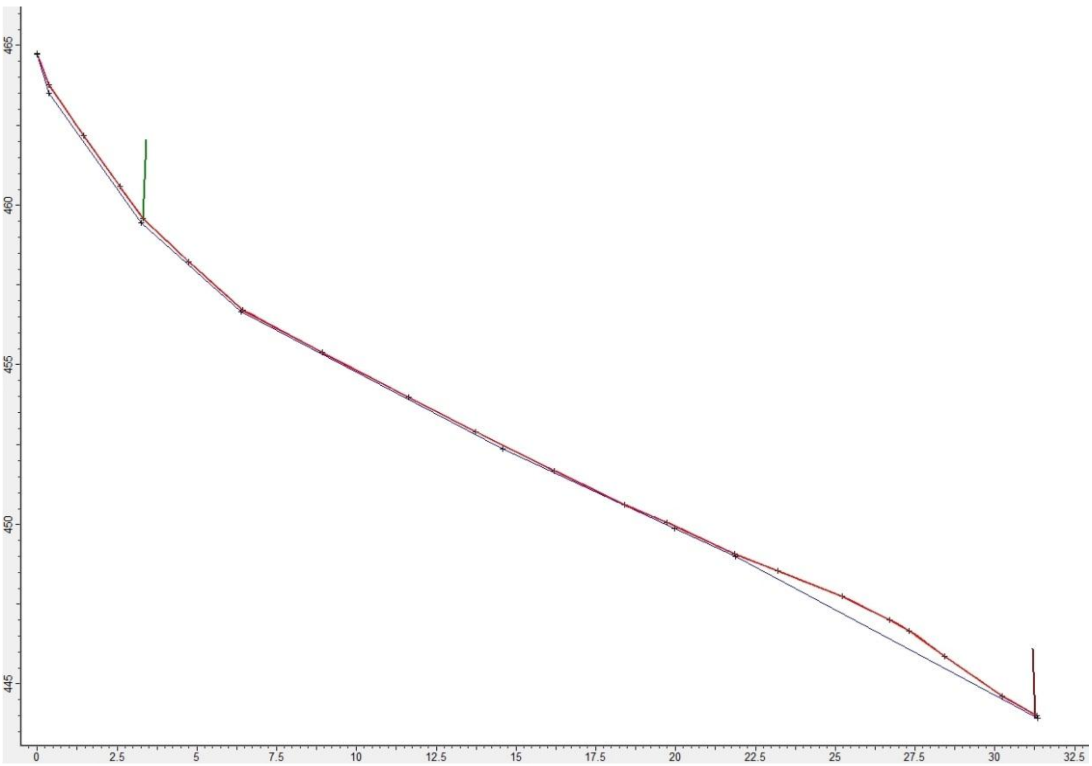


FIGURE 2.24: Rockfall simulation trajectories with Catch Fence 6 along 6B

B2.3 Cliffs Data

a) Images of the results of rockfall simulation: Existing Wall

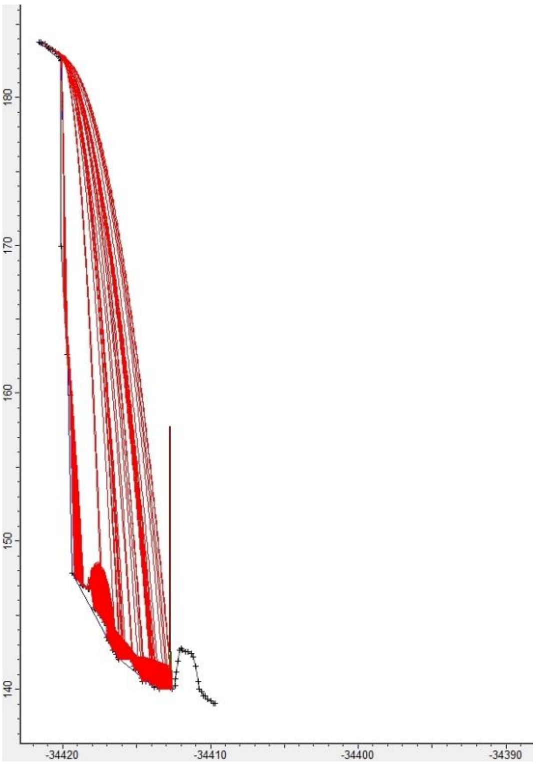


FIGURE 3.1: Rockfall simulation trajectories along CS1

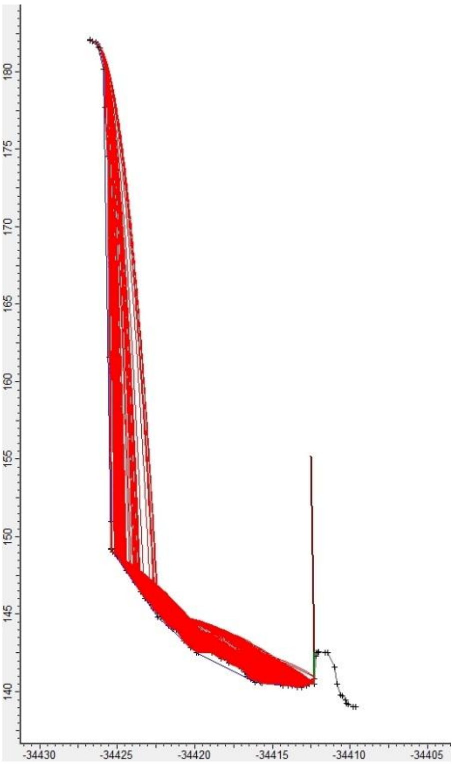


FIGURE 3.2: Rockfall simulation trajectories along CS2

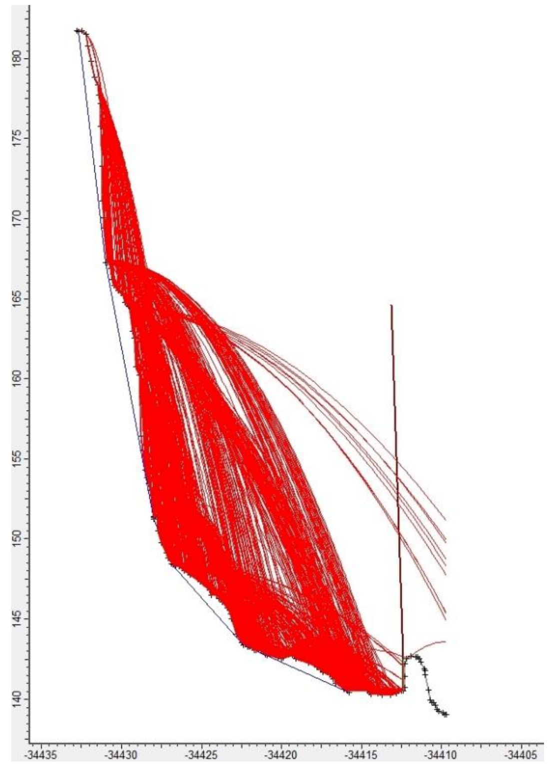


FIGURE 3.3: Rockfall simulation trajectories along CS3

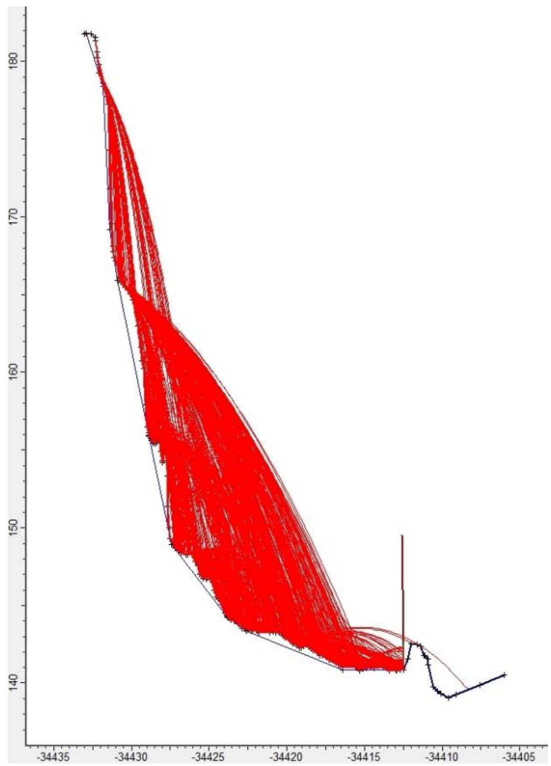


FIGURE 3.4: Rockfall simulation trajectories along CS4

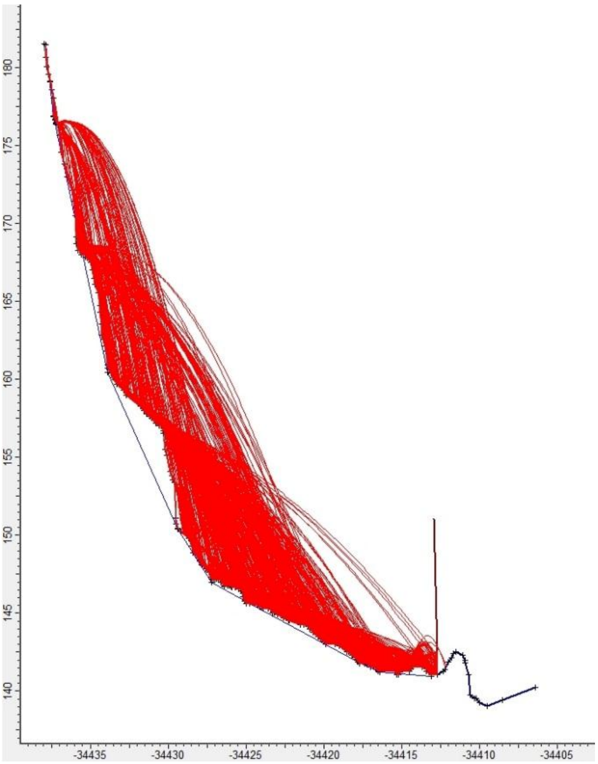


FIGURE 3.5: Rockfall simulation trajectories along CS 5

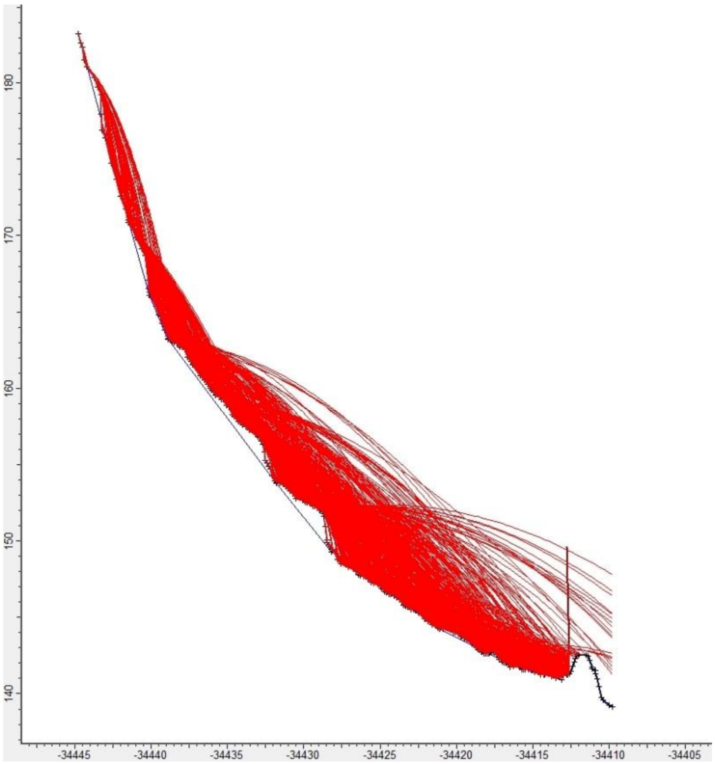


FIGURE 3.6: Rockfall simulation trajectories along CS6

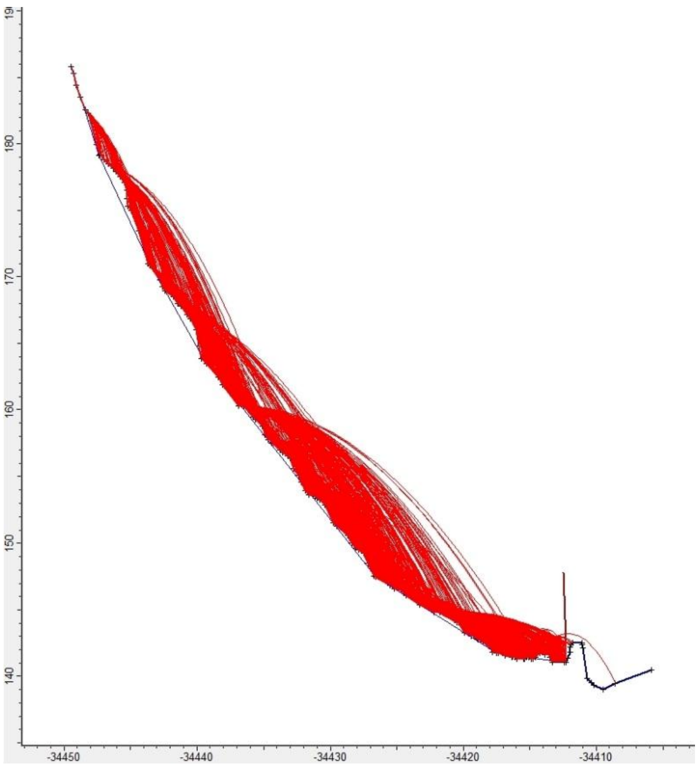


FIGURE 3.7: Rockfall simulation trajectories along CS7

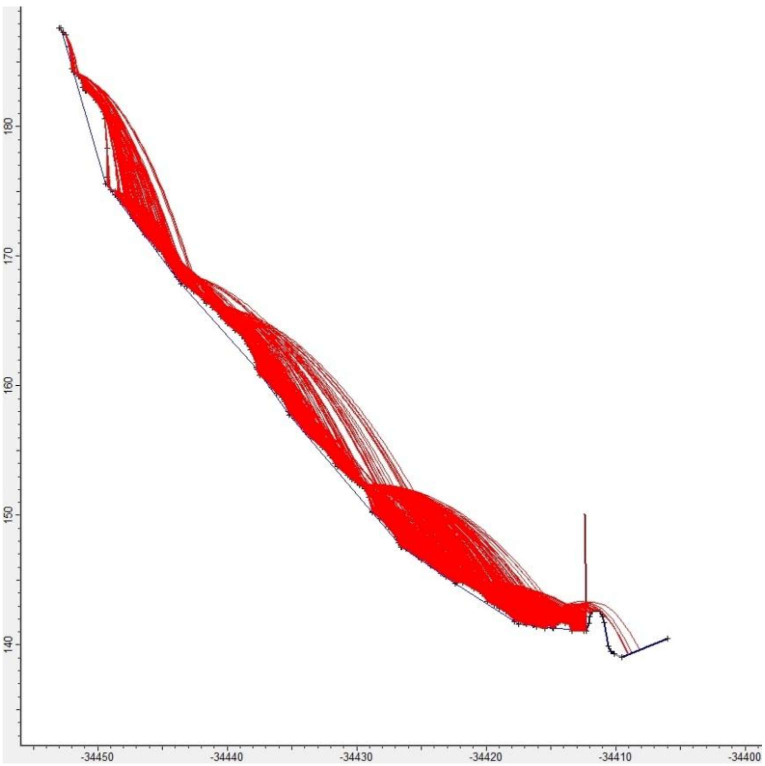


FIGURE 3.8: Rockfall simulation trajectories along CS8

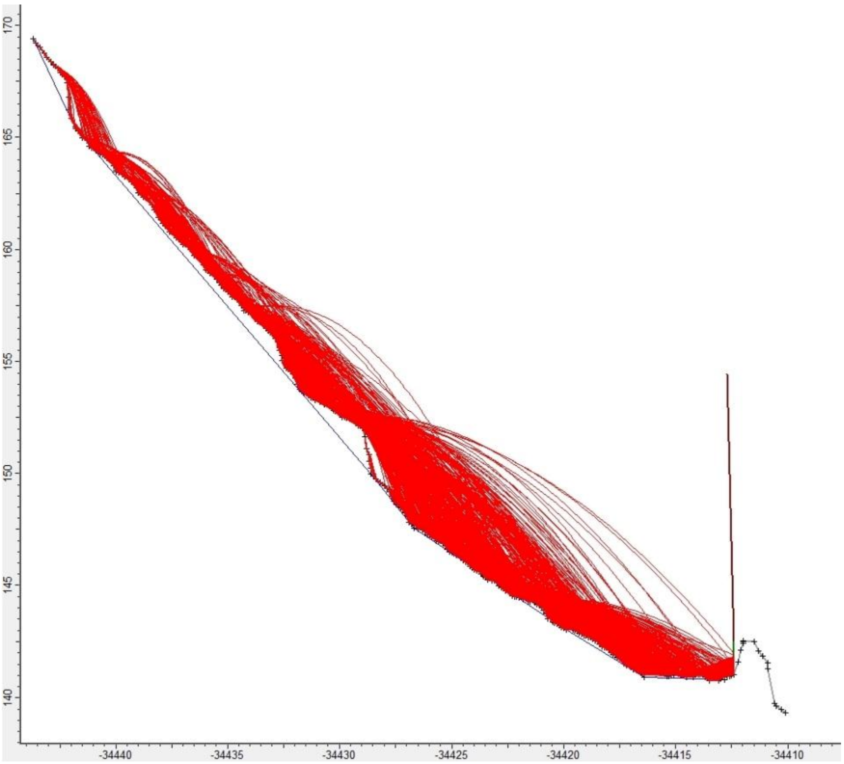


FIGURE 3.9: Rockfall simulation trajectories along S1

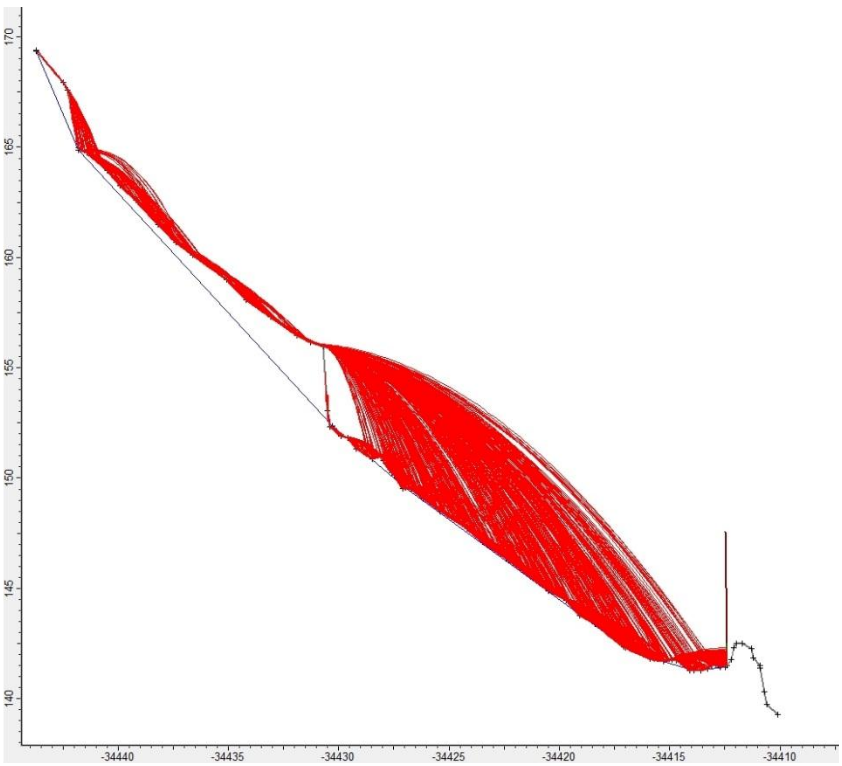


FIGURE 3.10: Rockfall simulation trajectories along S2

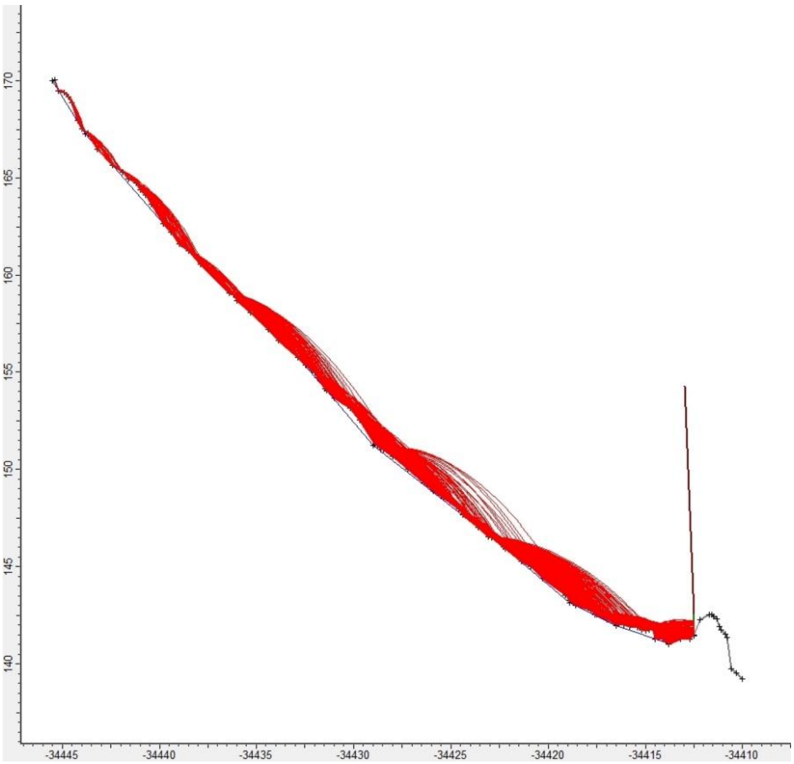


FIGURE 3.11: Rockfall simulation trajectories along S3

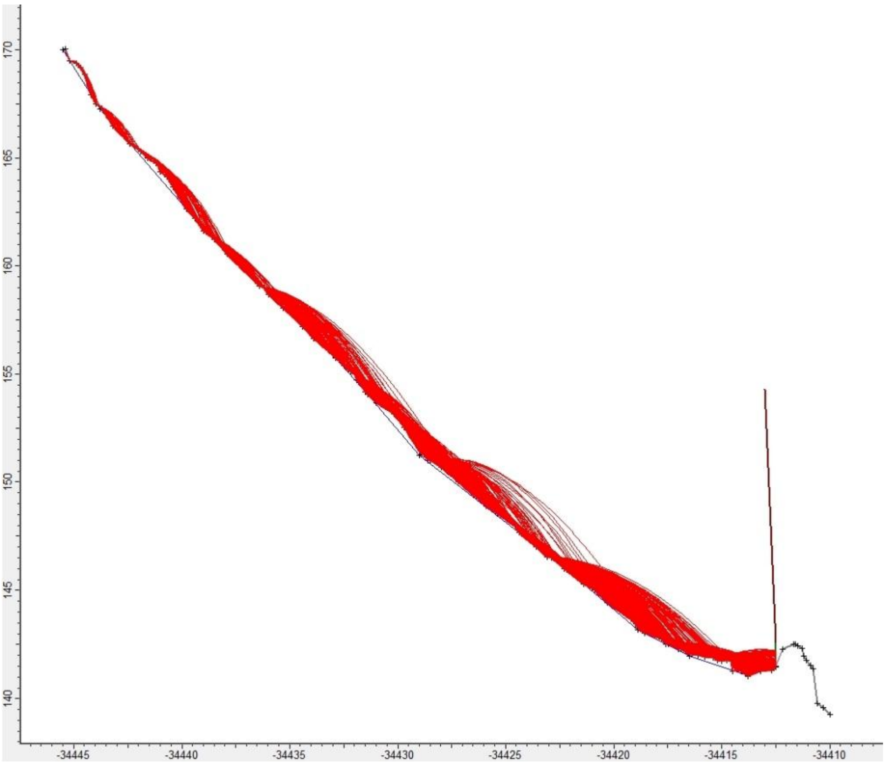


FIGURE 3.12: Rockfall simulation trajectories along S4

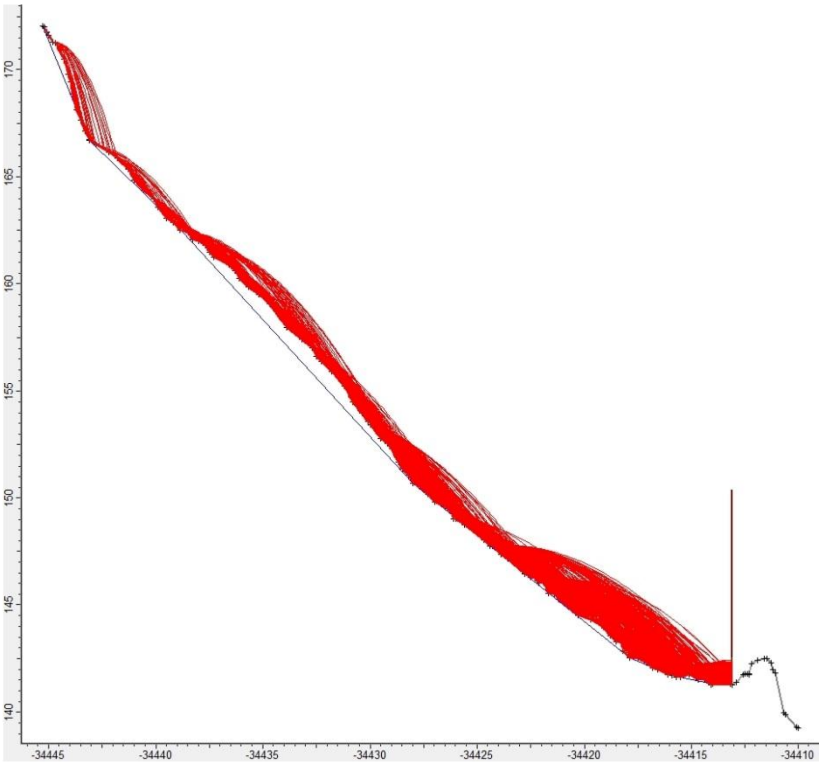


FIGURE 3.13: Rockfall simulation trajectories along S5

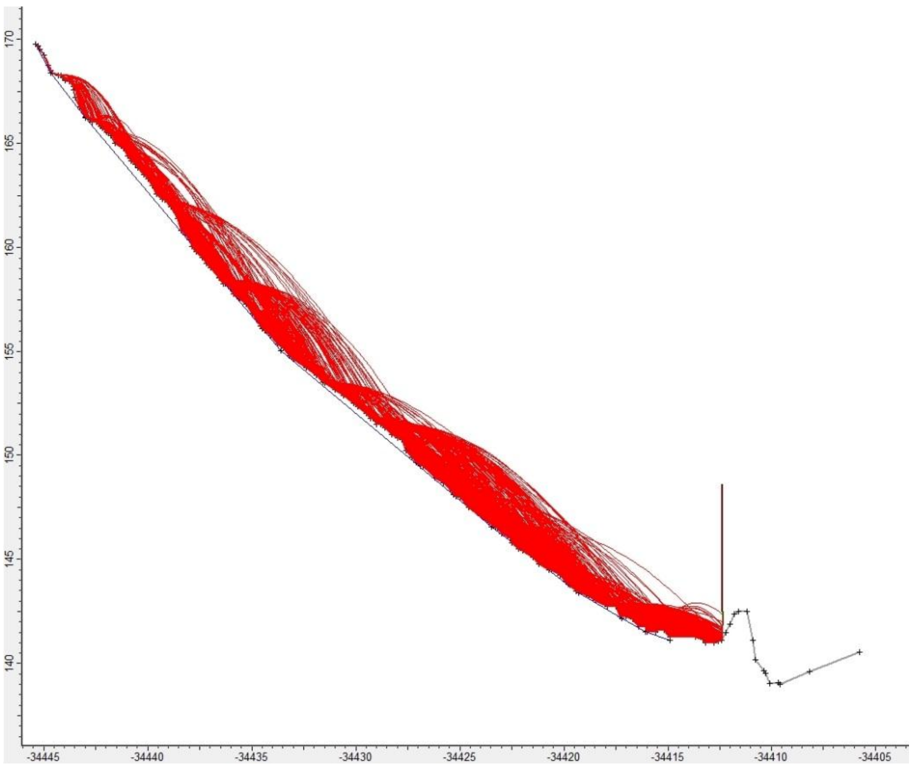


FIGURE 3.14: Rockfall simulation trajectories along S6

b) Images of the results of rockfall simulation: Upgrade of wall

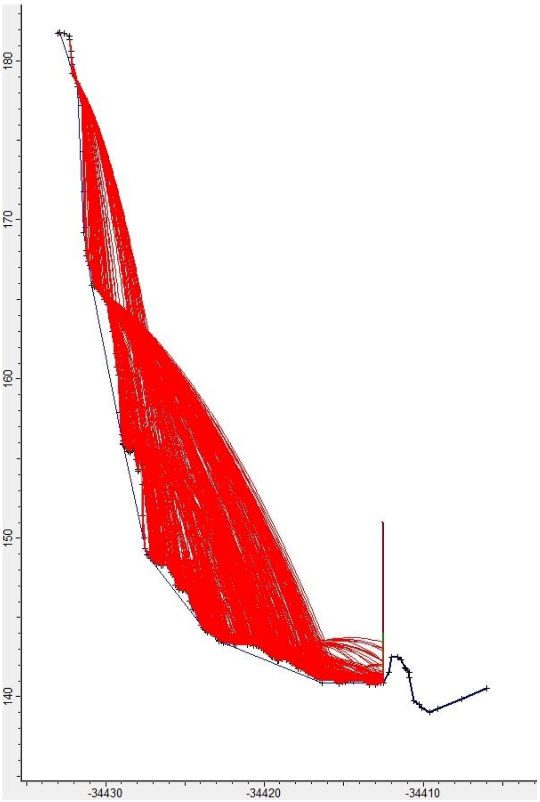


FIGURE 3.15: Rockfall simulation trajectory with raised wall along CS4

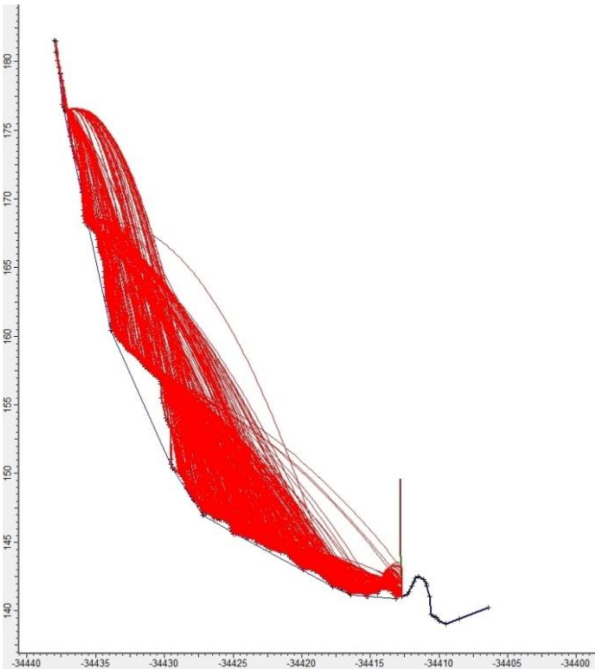


FIGURE 3.16: Rockfall simulation trajectory with raised wall alongCS5

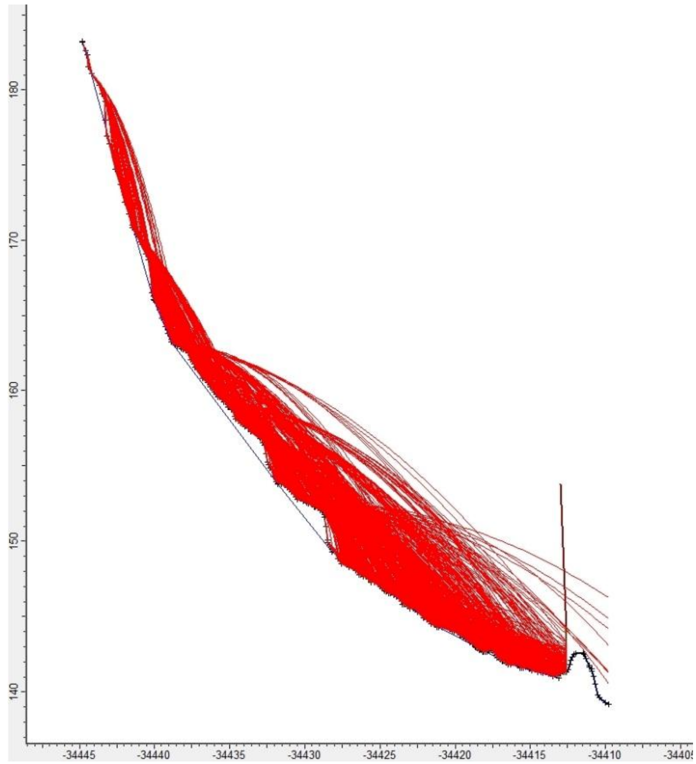


FIGURE 3.17: Rockfall simulation trajectory with raised wall along CS6

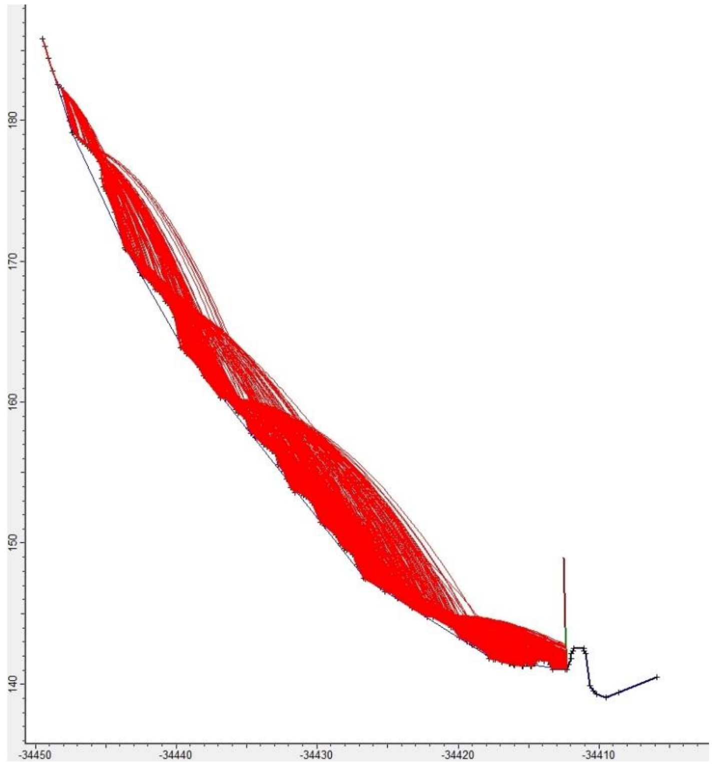


FIGURE 3.18: Rockfall simulation trajectory with raised wall along CS7

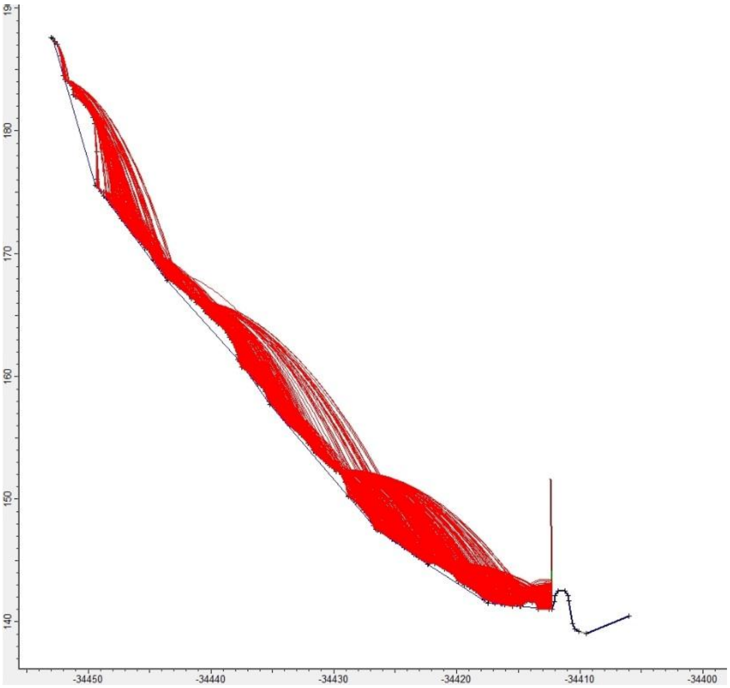


FIGURE 3.19: Rockfall simulation trajectory with raised wall along CS8

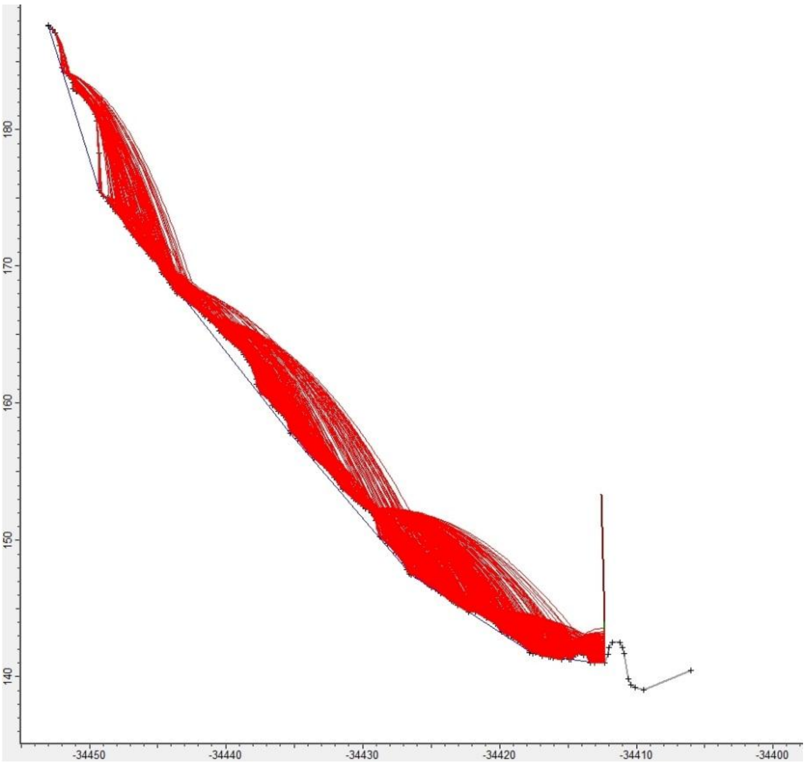


FIGURE 3.20: Rockfall simulation trajectory with raised wall along CS9

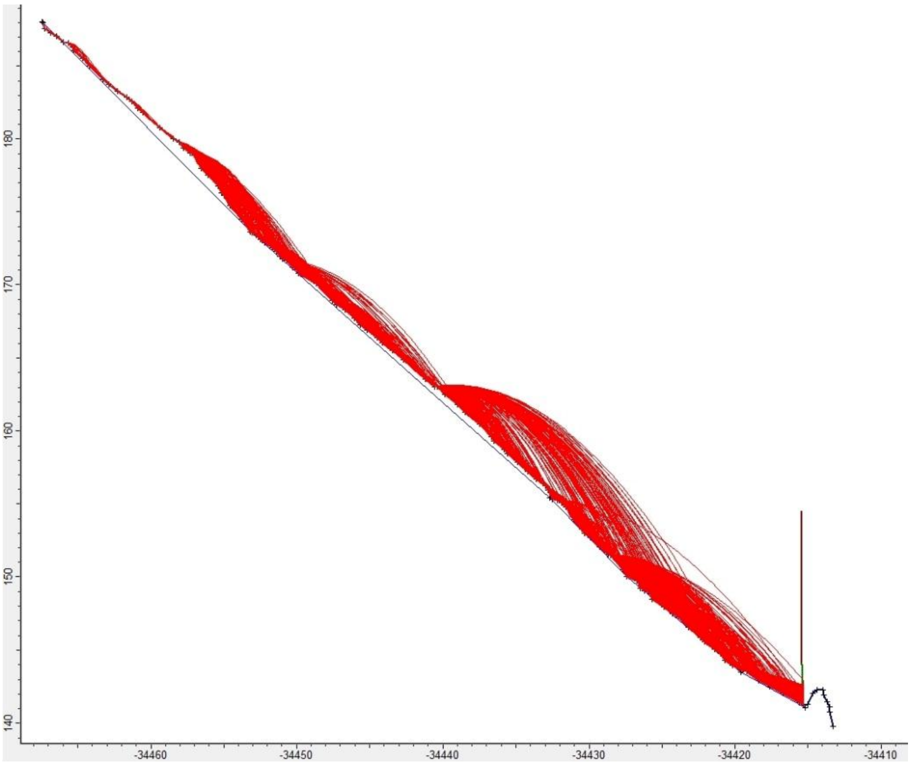


FIGURE 3.21: Rockfall simulation trajectory with raised wall along CS11