CREATING AN ENGINEERING MODELLING WORKFLOW FOR RAMMS::ROCKFALL, USING THE INPUT PARAMETER SENSITIVITIES.

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Abstract

As the exposure to rockfall increases to both infrastructure and the population of New Zealand. The need for reliable and accurate modelling tools becomes necessary in order to predict, protect and prevent against rockfall.

A rockfall events boulder distributions are largely governed by the terrain properties (slope topography and substrate) and the boulders characteristics (shape, size and density). It is the interactions between these two physical properties that control the boulder’s behaviour as it travels down the slope. Numerical rockfall models such as RAMMS Rockfall account for these physical interactions with a complex algorithm. The purpose of this thesis is to assess the individual input parameters sensitivities to change within this program. Once these were understood they could then be ranked in order of influence on the model.

The greater understanding of these sensitivities would allow the practitioner to confidently use the model in areas that the model has yet to be calibrated for, or in areas where no previous rockfall has been recorded. The location used for the purpose of this analysis was the Heathcote Valley situated within the Port Hills of Christchurch, New Zealand.

After approximately 1000 hours of modelling in this area, it was found that the RAMMS::Rockfall software was most sensitive to changes in surface material, followed by that of boulder characteristics (shape, size and density) and vegetation variations respectively.

These findings were then used to create suggested modelling workflow that could be used to help streamline the modelling process. The workflow makes suggestions for both Greenfield and active rockfall regions and what the primary focus should be for each scenario.

Acknowledgements

This thesis is a culmination of a year's work that was carried out in association with the University of Canterbury and GNS Science. These institutions provided me with the infrastructure, equipment and data to complete this thesis, without their contribution this thesis would not have been possible.

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Table of Contents

List of Figures

List of tables

Chapter One: Introduction

Rockfall is considered to be the rapid movement of boulders down a slope. These boulders travel down the slope through a series of movement processes: free falling, bouncing, rolling and sliding. Rockfall events can vary in size quite dramatically from a few cubic centimetres to a few thousand cubic metres in size. Though typically small in volume, rockfall events have the ability to travel large distances from the source area. During this motion down the slope, the boulder has the added potential to generate large kinetic energies, resulting in a larger probability of doing significant damage to down slope assets. The size of the boulders in these events is controlled by the discontinuities in the source rock while the strength of the source rock as this dictates whether a boulder will break up upon impacts with the slope and. The discontinuities in the rock dictate the size of the initial boulder as well as create planes of weakness where a boulder may fracture during the rockfall process. The interactions between boulders are assumed to be negligible during these events, as boulders tend to move independently of one another (Hungr and Evans, 1988).

Wherever a rock face is exposed on a slope, there is the potential for a rockfall event to occur and potentially damage assets situated down slope from these areas. Trigger events may be due to natural processes such as weathering and earthquakes, or man-made triggers (Machine vibrations, deforestation and under cutting of slopes). Rockfall Hazards are often overlooked in the development of infrastructure and property. This is due to their triggers and severity not being fully understood. This situation occurred in Christchurch, New Zealand 2011 where the potential for coseismic rockfall was not fully understood (Vick, 2015). The risk of rockfall was seen to be low from triggers such as weathering and rainfall, and other possible triggers weren't considered. This meant the possible risk of rockfall damage to properties in the rockfall path was seen to be low. Until an earthquake of unexpected intensity generated a large number of rock fall events in multiple areas of the Port Hills. As a result of this property in this area were damaged and the loss of life.

Seismically induced rockfall is a significant issue to consider in earthquake-prone areas, as earthquakes have the potential to not only generate rockfall but, landslide events as well. The May 2008 Sichuan earthquake is a prime example of this. During this earthquake it is approximated that around 15,000 landslide events were generated, many of which were rockfall events (Dai et al., 2011). This event resulted in ~20,000 people losing their lives in land movement events and contributing to approximately a quarter of the total death toll (estimated at 69,000). The Sichuan earthquake is not the only example of earthquake-induced rockfall around the globe and examples of seismic induced rockfall can be found in regions of Italy (Wasowski and Gaudio, 2000).

Figure1.1 Example of damage to linear infrastructure. Summit Road Canterbury Taken from stuff.co.nz

Understanding the physical processes of rockfall events aids engineers in developing accurate models. This, in turn aids policy makers in making informed decisions on land distributions and risk management processes (Vick, 2015). The distribution of a Rockfall event is largely governed by properties such as the topography of the region, physical properties of the boulder such as shape, size, density and strength (strong or weak), boulder dynamics (velocity, kinetic energy and rotational velocity) and the substrate properties of the impacted slope (Wyllie and Mah, 2004). These properties are what largely control a boulders trajectory and ultimate path. The interactions between these variables is not a simplistic relationship and are continuously changing as the boulder progresses down-slope.

Numerical modelling (2D and 3D) attempts to account for these processes using a complex algorithm to correlate the various variables using site-specific variables. These can then be entered into the program to produce both quantitative and qualitative results that can be examined by the user. The complexity of the interface and input variables various from program to program and an understanding of what each model is sensitive to is crucial in producing an accurate model that can be used with confidence in the real world. As each model behaves differently, it is important to calibrate them with real world examples. This is done to ascertain what variables the model is sensitive to and whether or not the program works within that specific environment (Berger and Dorren, 2006).

1.1 Canterbury Earthquake Sequence (CES)

The Canterbury Earthquake Sequence (CES) spanned from September 2010 to December 2011. During this period the Christchurch and surrounding areas experienced several close to surface ruptures of less than 15Km in depth (Bannister and Gledhill 2012). These ruptures generated unexpectedly large ground accelerations in the area, above 0.5g (Beaven et al. 2011; Fry et al. 2011; Kaiser et al. 2012). Although the region experienced 1000’s of aftershocks, there are four main events that contributed to the damage within the region and generation of rockfall events; these were the following events.

- **September 4, 2010.** This event had a magnitude of 7.1 and occurred at a depth of 9km. The peak ground acceleration was recorded at the epicentre of the event at 1.26 g with the vertical acceleration with the city at ~0.3 g (Cousins et al., 2010). It is thought that topographic amplification in the hills surrounding the city would have increased this by up to an order of magnitude higher than was recorded (Khajavi et al., 2012). There was some localised rockfall to be generated during this event (Massey et al., 2012).
- **February 22, 2011.** This event had a magnitude of 6.2 and occurred at a very shallow depth of 6.3km. The earthquake occurred directly under the Port Hills (Bannister and Gledhill, 2012) and as a result of such intense shaking generating PGA’s (Point Ground Acceleration) of 1.41 g horizontally and 2.21 g vertically (Fry et al., 2011; Holden, 2011; Kaiser et al., 2012), the area experienced widespread rock falls (Massey et al., 2012). A map of the mapped boulders is shown in Figure 1.2 bellow.
- **June 13, 2011.** This event had a magnitude of 6.0. Once again this event generated widespread rockfall in already affected areas (Massey et al., 2012)
- **December 24, 2011.** This event had a magnitude of 5.9 and was situated just offshore of New Brighton. This event caused some localised rockfall in the Christchurch area (Massey et al., 2012)

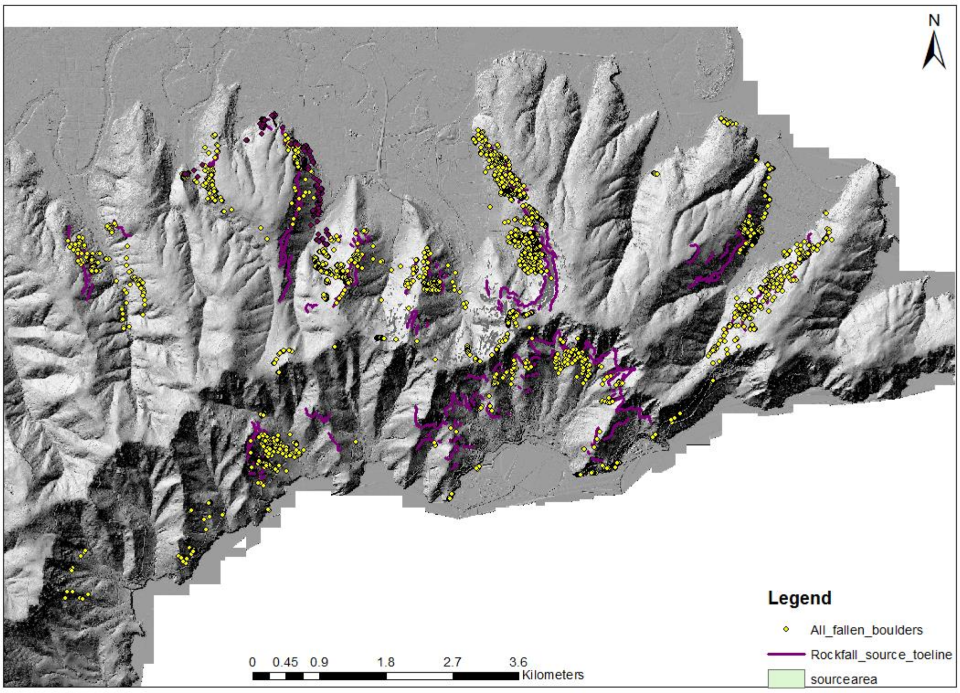


Figure 1.2 Mapped boulders from the Canterbury Earthquake Sequence courtesy of GNS Science

Over the course of these four major events in the CES and subsequent aftershocks over 6000 rockfall boulders were generated. Figure 1.2 shows the 5719 boulders that were mapped by GNS Science and geotechnical engineering firms post-September 4, 2011. As a result of the February 22, 2011, earthquake 181 lives were lost, 5 of these due to rockfall or cliff collapse (Massey et al., 2014). Millions of Dollars in infrastructure was also damaged in the event with parts of the summit road still closed.

1.2 Geological settings

The Port Hills are situated just to the south-east of Christchurch in a volcanic edifice known as the Banks Peninsula. The area was volcanically active during the mid to late Miocene, 11-5.8 Ma (Hampton and Cole, 2009). This volcanic activity comprised mainly of Hawaiian-style eruptions which in turn produced conical basaltic lava flow deposits. These lava deposits radiated outwards from three principle vents (Lyttleton Harbour) and minor associated vents (Brown and Weeber, 1992; Hampton and Cole, 2009; Hampton et al., 2012). Volcanic activity in the region ended in the Mid-Pliocene, 3.6 Ma. This period was followed by a period of tectonic stability that allowed the deposition of Aeolian silts known as the Banks Peninsula loess (Goldwater, 1990).

Figure 1.3 Aerial image of the Banks Peninsula taken from google earth

Figure 1.4 Image showing volcanic deposits within the Port Hills

These basaltic lava deposits along with the Tuffs and ignimbrites within the region are the source material for the cliff collapse and rockfall events. The various layers of volcanic deposits can be seen in Figure 1.4. The top layer in this image is a combination of reworked volcanic materials and loess.

Loess on Banks Peninsula is a product of proglacial fluvial systems originating in the Southern Alps of New Zealand (Davies, 2013). These fine-grained clayey silts were transported by strong winds and deposited on the volcanic's of Banks Peninsula. These deposits are up to 40m thick in some valleys (Jowett, 1995). The New Zealand Geotechnical Database describes loess as: Yellow, brown clayey SILT with some fine sand, dry-moist, firm-stiff, gross layering on a metres scale. The properties of this sediment are important to this project as it covers so much of the region. This is the substrate material that the boulders predominantly come into contact within the Port Hills. The properties of Loess can vary at various times of the year (winter or summer) dependent on moisture content. This has a significant effect on a boulder's run out and trajectory.

1.3 Rockfall in New Zealand

Rockfall in New Zealand is an ever present issue. This is due to the mountainous terrain that is found all over the region. This leaves the potential for a rockfall event to impact on infrastructure resulting in economic loss and potentially loss of life, as has been experienced in the past as recently as December 2016 during the Kaikoura earthquake which resulted in several earth movement events that temporarily cut off the ocean settlement. This kind of isolation is feared the West Coast of the South Island during an Alpine fault rupture. The relationship between seismic events and land movement events has long been recognised (Keefe, 1984) and was highlighted During the CES when the February 22 earthquake generated widespread rockfall within the region. The consequences of this event were the damage to millions of dollars' worth of property and the death of 5 people.

Figure 1.5 Example of a boulder found in the Port Hills taken during a 2D assessment of a proposed bund

The Christchurch event is the largest recent tragedy claiming several lives and resulting in hundreds more being displaced from their homes. However, it is not the only example of rockfall in New Zealand resulting in damage and loss of life. November 9, 2002, a rockfall event occurred near the Ramsay Glacier at the headwaters of the Rakaia River resulting in the death of one tramper and leaving another other unscathed (McSaveny, Davies, Ashby., 2003), July 2011 a woman was struck and killed at Rothesay Bay while out walking her dogs (Davidson 2011). In March 2014 a driver was killed when the vehicle they were travelling in was struck by a boulder (Utiger, 2014). These examples are events that resulted in the loss of life. However, rockfall doesn't just affect human life but can have an economic cost.

1.4 Thesis Objectives

The objectives of this research project are:

1. To analyse and assess the RAMMS:: rockfall model variable sensitivities, using rockfall data collected during the CES.
2. Using the results of this project to generate an engineering workflow chart to aid in the future 3D modelling of other areas using the RAMMS software.

To achieve this:

1. The Heathcote Valley will be examined.
2. In this area, various models are to be run each time accessing a different input variable and noting how changes in this variable affect the model's accuracy from real world data collected from the CES rockfall.
3. The variables assessed in this project are the effects of boulder shape and size, the substrate and how vegetation on the slope affects the boulders runout path.
4. These variables will be ranked in order of most sensitive to least to determine the importance of each.

The outcome from this thesis will be an engineering workflow for 3D rockfall modelling when using the RAMMS rockfall modelling program. Providing a starting point for the various modelling applications.

1.5 Thesis Format

Chapter Two of this thesis outlines the current understanding of the rockfall processes, along with the current available numerical modelling methods, be it 2D or 3D modelling. This was done using a review of the previously published literature on the topic.

Chapter Three outlines the methodology of the field work and data collection done previous to this project and how it was then in turn used to analyse the various input variables In the RAMMS rockfall model. It describes methods and changes made to the model to analyse the changes in boulder shape and size, substrate and vegetation had on the overall model results.

Chapter Four is an analysis of the various models carried out during this project and depicts the changes in the various outputs when a specific input variable are changed and how greatly change in this variable can affect the model's overall accuracy. It compares the model results with known field data and the previous models run.

Chapter Five uses the information gathered during chapters three and four to generate and discuss an engineering workflow; this is then used in further investigations at other sites that are not the initial test site.

Chapter Six presents the discussion and conclusions found in the process of this research project. It then makes recommendations for further research and adaptions that can be made to the model to improve the accuracy of the model.

Chapter Two: Literature Review

2.1 Introduction.

Rockfall can be defined as the movement of a single or groups of rock in a free sliding, rolling, toppling and falling motion down a slope face (Spang 1998). The sizes of these rocks can vary from the size of pebbles to that of houses. The rockfall process is a complex one that is governed by gravity, material properties and the laws of motion (Newton 2005). The rockfall process can be divided into various phases of movement, starting with the detachment from the source, impacts, ballistic trajectory, rolling, sliding and stopping, Figure 2.1. A rockfall process may include all of these phases or a combination of them depending on the influence of external factors acting upon the rock. The primary external factors that control a rock's motion are the slope characteristics: inclination, irregularities and substrate materials (Wyllie 2007).

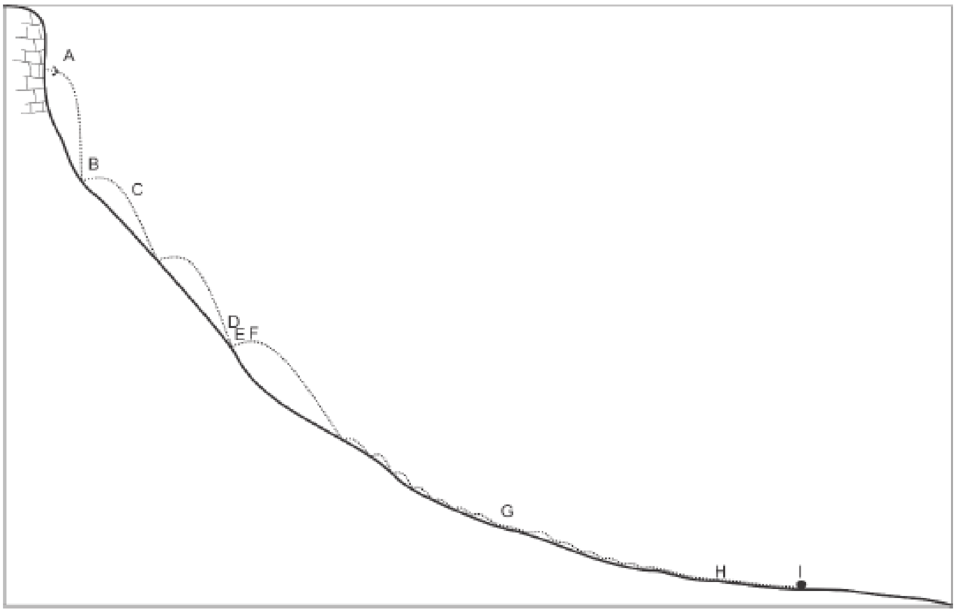


Figure 2.1 A schematic slope profile depicting the rockfall process. A) Detachment, B) Initial impact, C) Ballistic trajectory, D) Impact, E) ground contact and interaction, F) launching, G) Rolling, H) Sliding and I) stopping. Taken from Dorren 2003

2.2 Rockfall Processes

2.2.1 <u>Detachment</u>

The rockfall process is initiated when a block detaches from the source area. Whether a block detaches from a source is dependent on the source materials susceptibility and the triggering mechanism (Doreen 2003). The susceptibility of a rock mass describes whether or not a block will detach from the source. It is a function of the rock mass properties – the rock type, joint roughness, orientation, spacing, aperture, filling and weathering of the rock mass discontinuities control the potential size of the detached block and the mode at which it detaches (Toppling or Sliding).

2.2.2 <u>Triggering mechanisms</u>

The rockfall process can be triggered by a variety of processes either occurring naturally or induced by man-made processes. The natural processes include but are not limited to: rainfall, weathering, freeze-thaw, earthquakes, root wedging, volcanism, snow melt, wind, differential erosion and debuttressing of slopes (Wyllie, 2007). Human induced processes include vibrations from machinery and blasting, deforestation, slope morphology and undercutting of slopes (Dorren, 2003).

2.2.3 <u>Rock mass susceptibility/Characteristics</u>

Whether or not a rock mass will fail and the size of the blocks that can be triggered depends on the rock mass characteristics. These are the variables that control the size and shape of the blocks generated as well as their mass and strength.

All rock outcrops and cut-slopes observed in the field have discontinuities of some form. These were either created during or after the formation of the rock material. Some of these deformations include bedding planes, cooling joints and deformation features such as stress induced fractures, joints and faults (Wyllie and Mah, 2004).

It is the orientation of these discontinuities or sets of discontinuities that control the kinematic feasibility and the manner in which a rock mass may fail. If these sets form in the right orientation, they can form segments of unstable block masses. This is determined using the dip and slip direction of the discontinuity sets relative to the open rock face. Discontinuities dipping out of the face have the potential to generate planar sliding failures, while discontinuities facing into the slope have the potential to generate toppling failures (Wyllie, 2007). This is shown in the diagram below.

Planar and wedge failures in a rock mass are controlled by the upper and lower bounding joints of a rock block, if these joints are dipping out of the face gravitational forces can act upon the block. These forces will allow the block to slide if they overcome the shear strength of the basal plane of the block. Planar failure occurs when the dip angle of the joint is less than that of the slope angle. Thus planar failure becomes more likely the steeper the slope angle becomes. If the joint angle is less than that of the slope angle the potential for sliding failure decreases and the slope is likely to remain stable. Toppling failure is still possible however if the triggering mechanisms such as freeze-thaw and root wedging occur forcing the top of the block out from the slope. Toppling failure is also likely when the discontinuities dip directly into the face of the slope (Wyllie and Mah, 2004).

Another factor to consider in the rock mass characteristics is that of the nature of the discontinuities and how they are formed as this has a large impact on the susceptibility of the rock mass (Wyllie and Mah 2004). The types of rock mass discontinuities are defined by the nature of their formation such as faulting, bedding, foliation, jointing and cleavage. The various natures dictate how easy it is for a block to fail (Wyllie and Mah, 2004). A joint with a low roughness coefficient such as a fault plane requires less shear stress to overcome the joints friction component whereas a discontinuity with a rough joint surface requires more shear stress to overcome the friction component thus making the block more stable and less likely to fail (Wyllie and Mah, 2004).

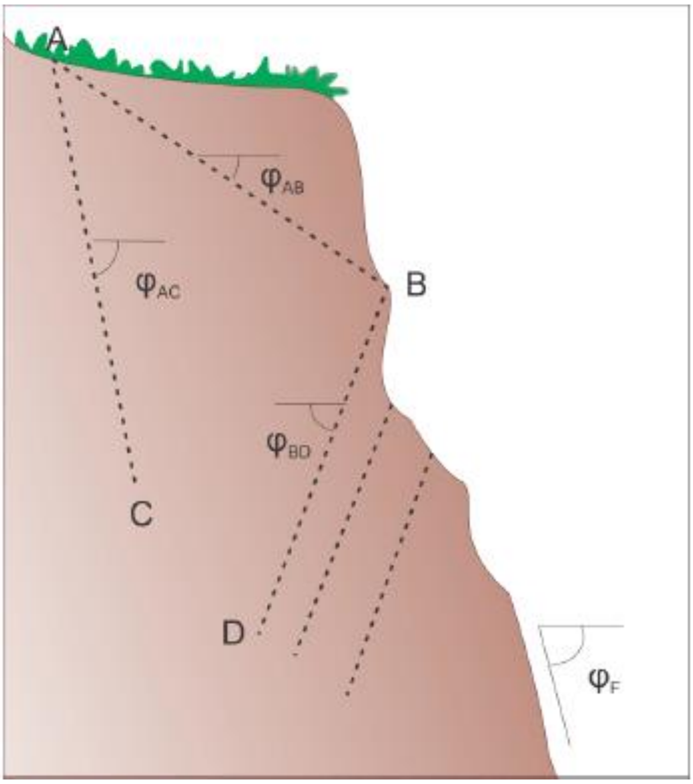


Figure2.2 Schematic of a source area, showing three types of discontinuities. Modified after Wyllie and Mah (2004) taken from L.Vick (2015)

The spacing of the discontinuities in the rock mass dictates the size of the blocks that are released from the outcrop (Palma et al., 2011). A highly fractured rock mass with closely spaced discontinuities will release smaller blocks than that of a rock mass with widely spaced discontinuities which has the potential to release much larger blocks. The orientation of the discontinuities in the rock mass determine the shape of the block that is released in regards to the axis lengths.

While the discontinuities of the rock mass control the size and shape of the block, the properties of the material, such as lithology, density and induration of the rock will have an effect on the shape and size of the block. This is because these properties dictate whether a block will break apart on impact or remain or remain as an intact unit (Vick, 2015)

2.2.4 Initial Impact

After a rock leaves the source, it may enter a period of free fall. This process occurs when the slope angle is more than 70^0 (Dorren, 2003). If the slope angle is less than 70^0, it is likely that the block will travel down the slope in a series bounces, rolling and sliding motions. The initial impact in a blocks trajectory is a crucial one in the rockfall process. If the block is sourced from high above the initial impact zone the potential energy is converted into kinetic energy and the block is likely to run out from the slope. However, if the source is low above the impact area, the block will not have as much kinetic energy and will likely bounce once then stop or stop on the initial impact.

The overall angular momentum of a block increases after the first initial impact and will then continue to increase until it reaches a maximum rotational velocity, following this point the block is affected by each impact (Wyllie 2007).

The ground conditions influence how much kinetic energy is lost upon initial impacts and the following impacts with the slope surface. It has been observed that a block loses between 75-86% of the energy gained in the initial free fall upon initial impact (Dorren, 2003, Evan and Hungr 1993). Hard surface impacts allow the boulder to retain more energy due to the stiffness of the surface. Soft surfaces such as soil deform under the pressure of an impact forming impact scars (Bozzolo and Pamini 1986). This process absorbs some of the block's energy, slowing it down and reducing the runout length of the block. The kinetic energy gained during free fall along with the factors mentioned above will determine whether a block is bouncing, rolling, sliding or even moving at all after the initial interaction with the slope.

Another process to consider during the rockfall process is the interaction with other blocks moving down the slope (Bozzolo and Pamini, 1986). Although this is known to occur in the field, there is limited literature on the influence it has on the block's trajectory. As blocks rarely interact with each other in a rock fall event, the effects of block interaction with each one another are assumed to be negligible. This is an important interaction in rock avalanches as block interaction is a constant in these movements. However, the rockfall process is seen to be fragmental and only contains a few number of blocks (Hungr and Evans 1988b).

2.2.5 **Ballistic trajectory**

After a block's initial impact with the slope it may be launched into a ballistic trajectory, which follows that of a parabolic curve between bounces. This only occurs when the block contains more kinetic energy than what is absorbed during the impact. During this phase of the rockfall process, the block moves with a constant horizontal velocity that is influenced slightly by aerodynamical drag. The block has varying stages of vertical velocity depending on what stage the block is at during this movement. The vertical velocity is controlled by gravity.

The air resistance or drag during this process can be assumed to be negligible as the force and momentum of the block outweighs the resistance force the air has on the moving block (Bozzolo and Pamini, 1986)

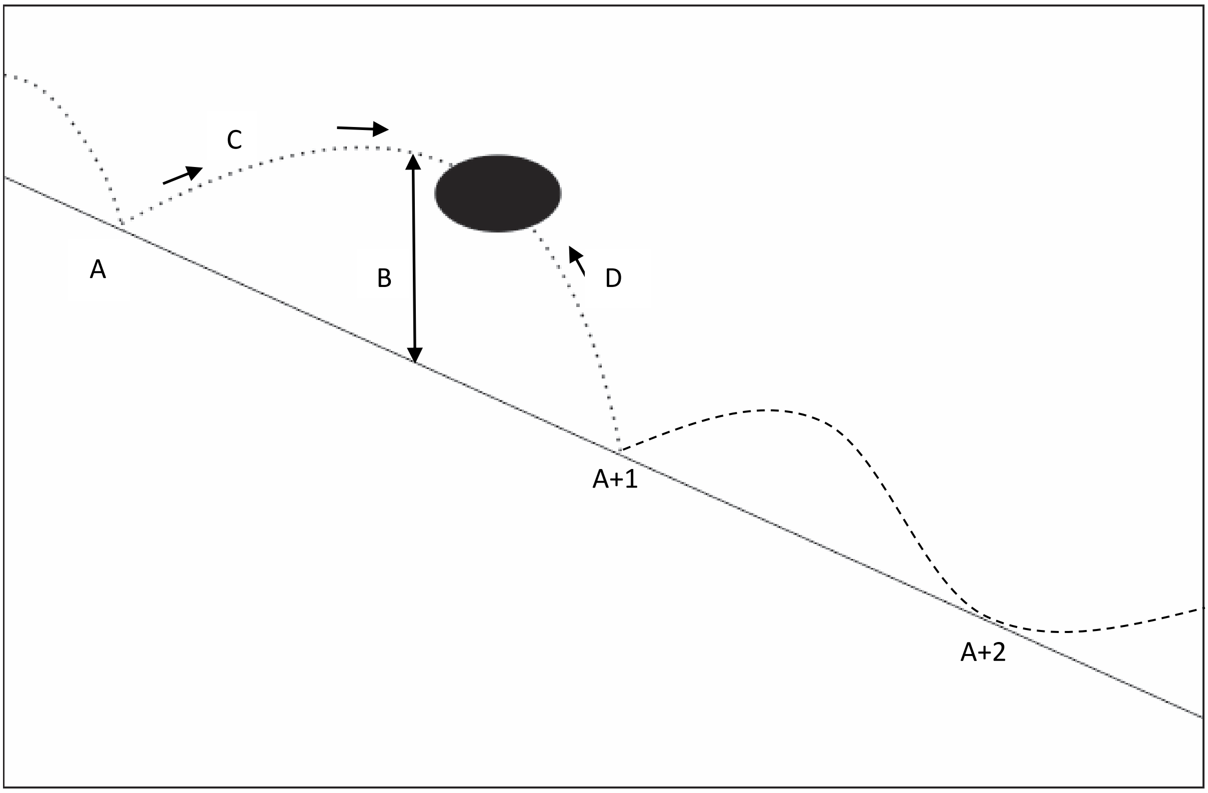


Figure 2.3 Diagram of a ballistic trajectory of a boulder. A) Initial point of contact-inducing bounce, subsequent bounces A+n. B) The maximum vertical height above the slope, C) The ballistic trajectory and D) Drag acting upon the boulder during this trajectory

2.2.6 <u>Block slope interaction</u>

The interaction between a block and the slope as it is travelling along is one of the most complex processes in a rockfall event. It is also one of the most important as these interactions directly control the block's behaviour during the rockfall event. The complexity of this process is due to the dynamic conditions of the block's interactions with the ground and are a function of multiple factors: velocity, impacting angle, angular momentum, soil and rock properties, slope angle, block dimensions, block mass and even that of the weather at the time of impact (wet soils dissipate more energy than that of dry soils). This interaction also controls other rockfall processes such as the launch angle of a block which is controlled by the blocks angular momentum. This is in turn governed by the block dimensions and interaction with the soil properties. The impact angle of the block at the point of contact will determine whether or not a boulder will gain or decrease in rotational momentum. This is shown in the diagram below.

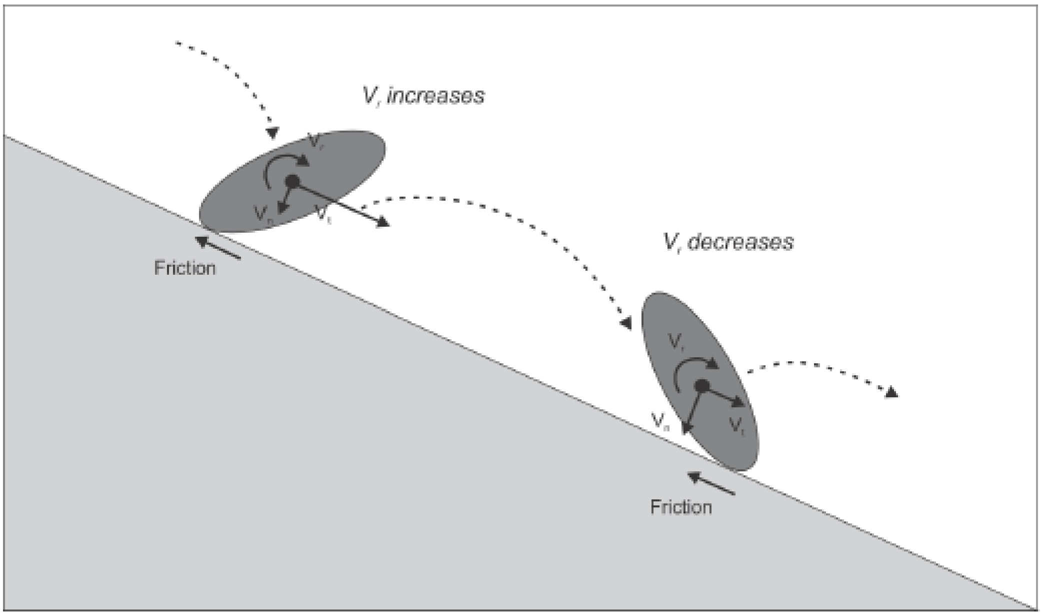


Figure2.4 Rotational velocity and tangential velocity of a block determined by the attitude of the block as it makes contact with the surface. Modified after (Wyllie, 2007) taken from (Vick, 2015).

The ratio of approaching to departing kinetic energies of a block is described using the coefficient of restitution (COR). This ratio is represented by a decimal value, a COR of 1 represents a pure elastic impact where no energy is lost, whereas a COR of less than 1 represents an inelastic impact with energy loss. A COR of 0 describes when the block impacts the surface and is instantly stopped. This surface can be said to be that of a plastic surface (Asteriou et al., 2012). The COR is defined by two components, the normal coefficient of restitution (nCOR) and the tangential coefficient of restitution (tCOR). The nCOR is controlled by the angle of the slope and appears to increase with an increasing slope angle. The tCOR is the reduction in horizontal/tangential energy upon impact. This component is significantly affected by the friction between the block and the slope on impact (Wyllie, 2007). There is no clear relationship between slope angle and the tCOR (Chau et al., 2002).

2.2.7 Transition between rockfall processes

The number of bounces a block undergoes during the rockfall process can be used to describe the number of times a block will have a ballistic trajectory. Other movements a block can undergo in order of decreasing energy, is that of rolling (When at least one surface/point of the block is in contact with the slopes surface at any given point during its rotation around its centre of mass) and sliding (When the block is no longer rotating around its centre of mass, and one surface of the block is in constant contact with the slope surface). The changes between these modes are often attributed to changes in the angle of the slope (Dorren 2003). As the slope decreases in angle the potential energy from the fall distance decreases, the block loses kinetic energy and is no longer able to maintain the phase it is in and thus has to change to the next phase in the process. As the block loses kinetic energy, it also loses rotational momentum and may not be able to sustain a rolling motion thus moves to a sliding movement down the slope.

2.2.8 <u>Slope Vegetation</u>

Vegetation on the rockfall path can affect the block in the same way that substrate material interacts with the block when it comes to grasses and shrubs. This is due to the increased drag exerted on the block from these materials. Other influences are trees that generate large obstacles that a block has to overcome. This either has the potential to stop or slow a boulder. This is a considerable focus for this project as RAMMS:: can take this variance into account and there is significant data from the site areas that can be input into the model.

Tree's that have trunks that are wider than that of the impacting block and are strong enough can potentially deflect a block off its current trajectory. This occurs when the block impacts the tree trunk away from its centre of mass (Bourrier et al., 2009)

2.2.9 <u>Rockfall Run Out</u>

The variables mentioned above all have an impact on the distance that a block will ultimately travel from the source area. One of the largest factors in this equation is the shape of the block and the axis along which it travels (Azzoni et al., 1995).

Spherical blocks of a similar mass and composition travel faster and further than tubular and discoidal blocks. This is due to them having fewer angular edges on the block to generate friction with the surface than that of tubular blocks. A spherical shape is also able to maintain angular momentum a lot easier than shapes such as flat and tubular blocks (Glover, J., 2015). However, this is not always the case. If a tubular block travels along its short axis, it may travel at velocities similar to those of a spherical block. This concept is shown in Figure 2.5.

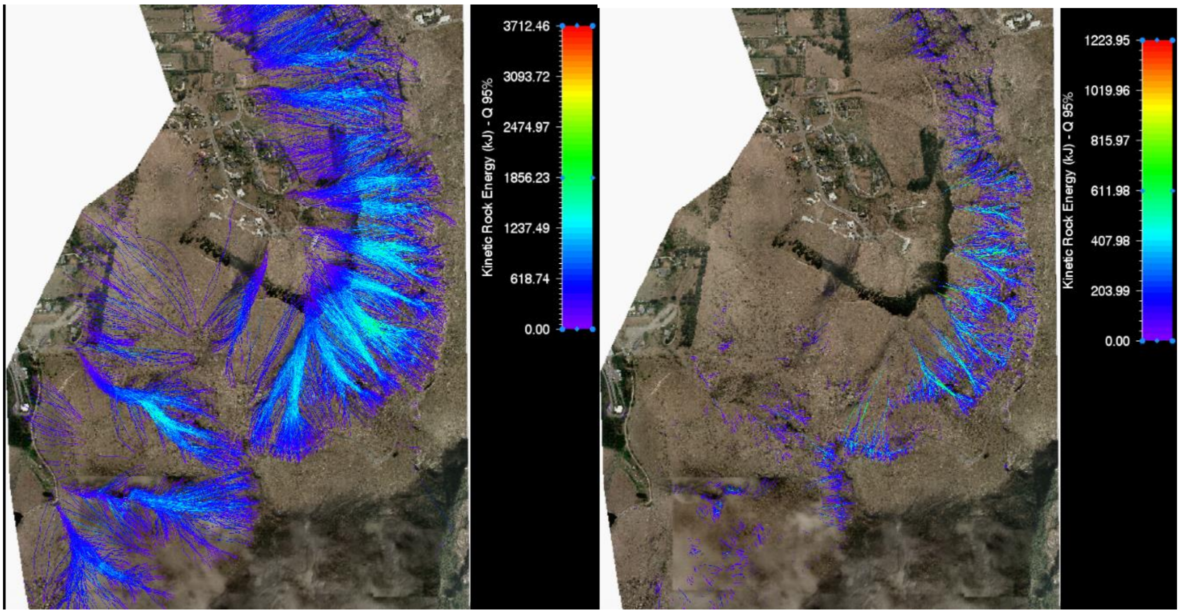


Figure 2.5 Figure showing how block shape can influence rock fall run out

Larger blocks are known to travel further than smaller blocks made up of the same material (Crosta.D, 2004). This is because kinetic energy is a function of mass. The more energy and mass a block has the more momentum it has. Thus it is less likely to be slowed by that of slope irregularities such as vegetation and talus debris.

Even with constant release conditions blocks will end up at different locations as it is a combination of variable factors on the slope that control the final trajectory of a block. However some assumptions can be made based on literature: blocks of greater mass and size will typically travel further than their smaller counterparts and slopes that are longer and constant in their gradient will allow blocks to travel further from the source (Azzoni and de Freitas, 1995). This can be shown using a simple rockfall model using two distinct boulder masses Figure 2.6a and Figure 2.6b

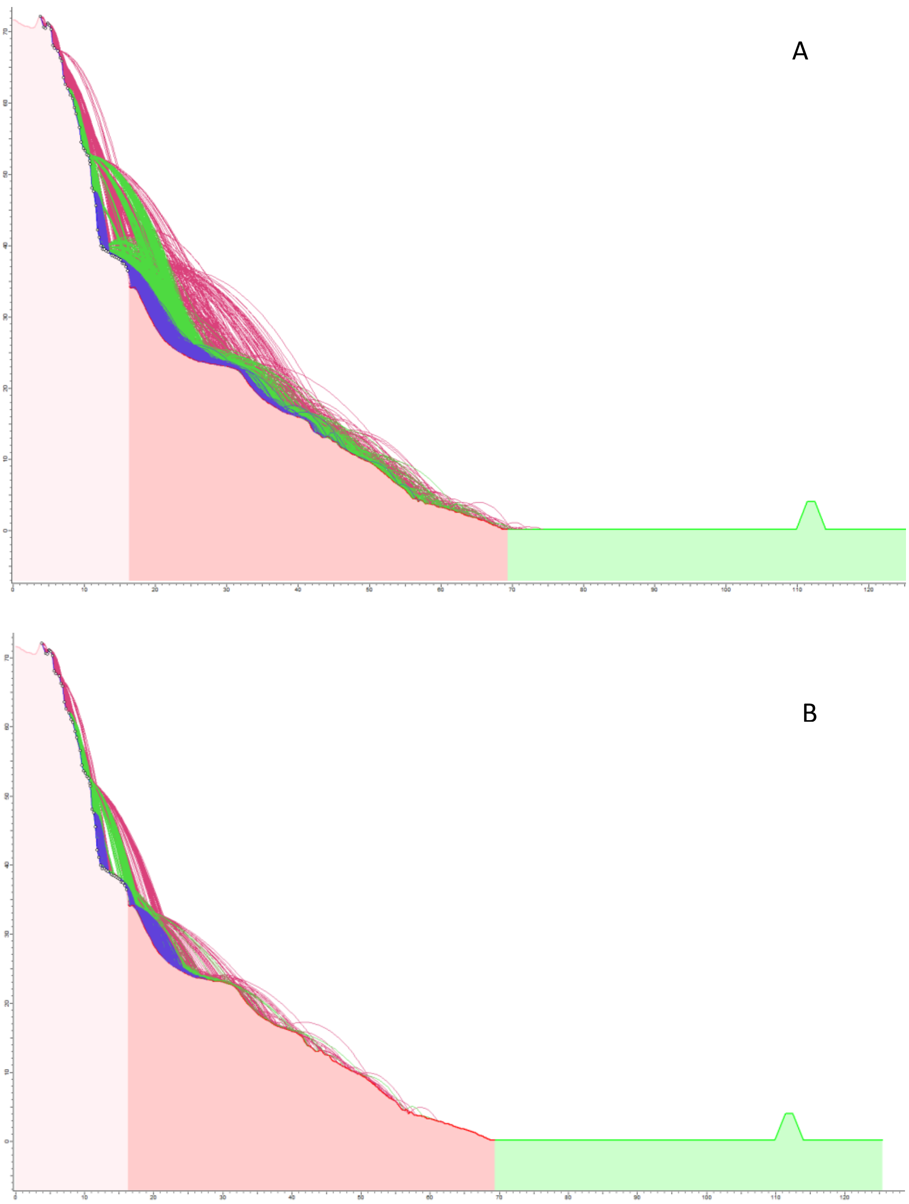


Figure 2.6 A) 5000kg boulder run out compared to B) 500kg run out

2.2.10 <u>Rockfall process conclusions</u>

Rockfall is a complicated process with multiple variables that contribute to the final outcome of a model. The high velocities, energies and unpredictable motion make them a severe hazard to people and assets. The process of assessing the susceptibility of a slope to its rockfall potential is a complex task, and it is much easier to assess rockfall after the fact as is done in this thesis. However understanding certain characteristics and aspects of a boulder's potential trajectory is an important process in considering mitigation methods. This thesis hopes to outline these parameters so that better models can be created to aid in the decision process.

2.3 *Rockfall modelling*

There are two spatial frames that can be used in the construction of rockfall models: two-dimensional model simulates rockfall down a slope in a vertical movement without considering lateral movement within this plane (Dorren 2003). Three-dimensional models are more complex and data hungry, but do take into account non-planar lateral movement down a slope. This thesis looks at the parameters for a three-dimensional model as they are inherently more accurate than that of two-dimensional models.

2.3.1 Two-Dimensional Models

The process of Two-Dimensional (2D) modelling simulates the rockfall in a down slope trajectory. This does not take into account the lateral movement that a boulder may experience during the rockfall process (Dorren, 2003). 2D modelling calculates a boulders behaviour in this vertical field and laterally in a singular plane. It simulates a boulder's movement as distance travelled down a slope, however, fails to produce a specific point laterally on the slope at which the boulder ends. As 2D rockfall models are limited to this plane, it limits the accuracy and reliability of 2D based models. This is due to the tendency of non-spherical boulders to deviate from a linear fall line, and spherical boulders to deviate from this path due to external forces such as topography and barriers such as vegetation (Volkwein et al., 2011).

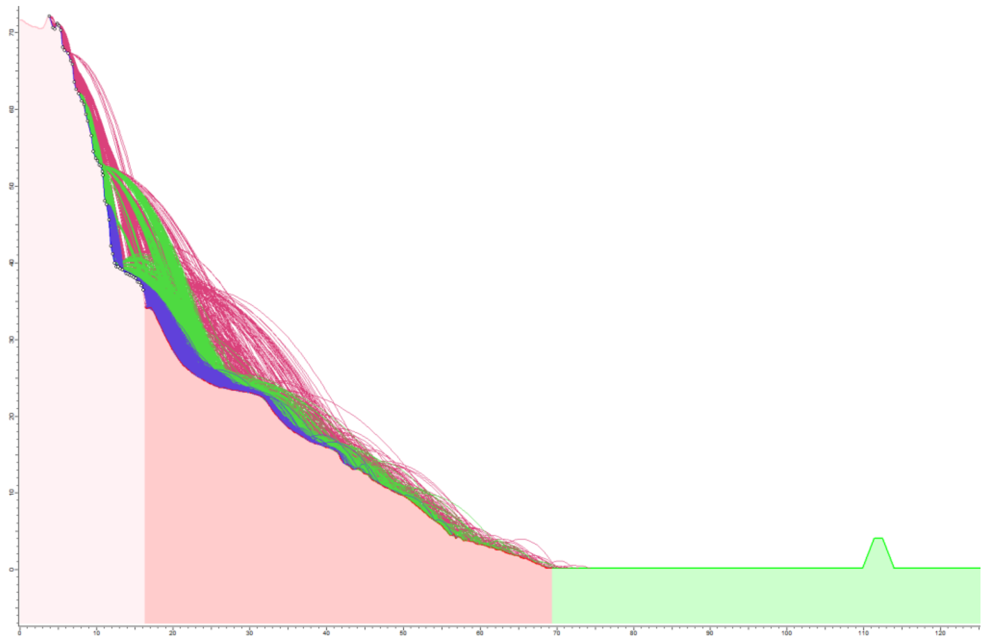


Figure 2.7 Example of a 2D output from the Rocfall software

However 2D modelling is not without its advantages. The simplicity of the 2D model make them user-friendly and thus a time effective way to assess rockfall (Brehaut, 2012).

2.3.2 Three-Dimensional Models

Three-dimensional (3D) models are more complex and thus are more time consuming, data hungry and costly in billable hours and software rights (Bartlet et al., 2013; Dorren, 2003; Lan et al., 2007; Volkwein et al., 2011). However, this method of modelling provides a much greater level of data output from the model. This does require a well-calibrated model in order to do so (Berger and Dorren, 2006). Figure 2.8 Shows an example of a RAMMS 3D model visual output. This model shows that a boulder’s path is not in a singular plane and rarely travels in a linear fashion.

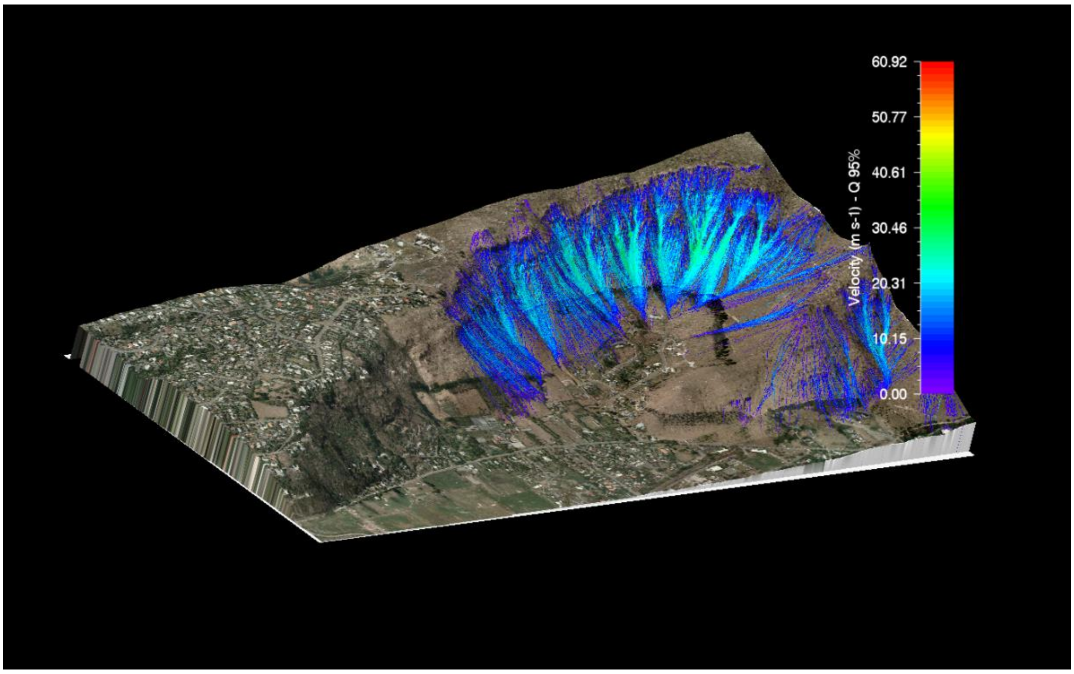


Figure 2.8 Example of a RAMMS visual output of boulder trajectories

Three Dimensional models have an increased accuracy, as they incorporate lateral movement downslope. This is achieved by modelling the interactions between the boulder and the terrain as shown in the digital elevation model (DEM). This allows the user to provide a better estimation of the lateral dispersion as the model's output is as shown in Figure 2.8 and not just a singular slice of the slope. Louise Vick’s thesis provides a detailed description of the various modelling programs available to the practitioner (Vick, 2015).

Chapter Three: Run out data and modelling methodology

3.1 Introduction

A large amount of field mapping and experiments had taken place before this project was undertaken. This meant that very little field work had to be done for this thesis. These data were then in turn used to assess the sensitivity of the various input variables in the RAMMS:: model. The data that were used in this thesis were collected through various methods and from multiple organisations that all collaborated data following the February 2011 earthquake. This thesis incorporates work and data collected from the Port Hills Geotechnical Group, Vick (2015), GNS Science and data collected during this thesis

The purpose of this chapter is to outline the methods used by others in their field work and how these data were then used in this thesis to analyse the sensitivities of the RAMMS 3D model.

3.2 Port Hills Geotechnical Group (PHGG)

Following the February 2011 earthquake and in subsequent events, In CES a geotechnical damage and hazard assessment was undertaken by the PHGG (Vick, 2015). The PHGG consists of several geotechnical companies and research organisations (Aurecon, Bell Geoconsulting limited/University of Canterbury, Geotech Consulting, Opus and AECOM (formerly URS)).

The product of this extensive collaboration is a large ArcGIS database. This database contains the georeferenced position of 5719 boulders within the Port Hills Figure 1.1. Approximately 4000 of these have their x, y and z-axes measured as well as the event in which they were deposited.

It is mainly from this data set that the sensitivity analysis was carried out for the 3D rockfall modelling software RAMMS.

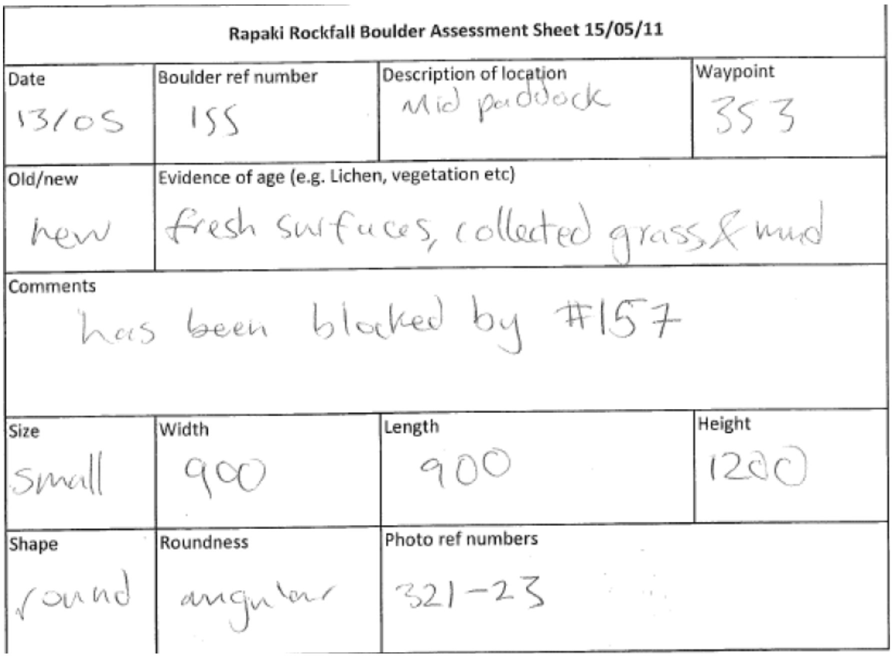
3.3 *Field work and data collection previously done*

Prior to commencing this project, a lot of field work had already been undertaken in the Port Hills regarding rockfall. This meant that very little field work had to be undertaken in order to complete this project. This section is split up into two categories, separating the field work and mapping from the field experiments carried out during previous field work. It is important to understand the methods used, as the majority of this thesis was conducted using data collected previously.

<u>3.3.1 Field work and Mapping</u>

Following the February 2011 earthquake, various groups collected data on the rock fall in the area as mention in the section above. During Louise Vicks thesis more field work was done in order to categorise boulder characteristics in the area. The majority of the field work in Vick (2015) was conducted in the Rapaki Bay region of the Port Hills. This section will focus on the various methods used to map shape, size and location of various boulders.

Field work was largely conducted in the field for the most part by all parties involved. During this time boulders were mapped and measured to be added to the GIS database that was used in this thesis. Figure 3.1 shows the data collected on each individual boulder in the area (L Vick, 2015).



Rapaki Rockfall Boulder Assessment Sheet 15/05/11

Date	Boulder ref number	Description of location	Waypoint
13/05	155	Mid paddock	353

Old/new	Evidence of age (e.g. Lichen, vegetation etc)
new	fresh surfaces, collected grass & mud

Comments
has been blocked by #157

Size	Width	Length	Height
small	900	900	1200

Shape	Roundness	Photo ref numbers
round	angular	321-23

Figure 3.1 example of field notes taken during data collection by L.Vick 2015

Each boulder was mapped using GPS coordinates and the dimensions measured with a measuring tape in the x, y and z-axis.

Following the June 2011 event, data was collected remotely because of ongoing rockfall hazard. This was done using high-resolution imagery taken within a few days of the February earthquake. Historic boulders were distinguished from recent boulders using colour because the lichen on older boulders gave them a whiter appearance. The individual axes could not be measured using this method however the volume could be estimated by using the GIS ArcMap measuring tool and the Sneed and Folk (1958) size classification for boulder size. Boulders are classified into fine (0.25 – 0.4m), medium (0.5 – 0.9m), coarse (1.0 – 1.9m), very coarse (2.0 – 4m) and fine block (4.1 – 8.1m). All the data used in this project was from the above databases and only one trip was required into the field in order to familiarise the area and cross check some of the previous data.

3.3.2 Field experiments

In May 2014 some boulder rolling experiments were carried out by Louise Vick and her team in the completion of her PHD. These experiments were done in order to calibrate the RAMMs model further by comparing the data gathered from these experiments to that of the models. This is a more refined way of doing it as the boulder's exact starting point can be determined and the path it took accurately mapped, along with data collected from sensors attached to the boulder. Thus one would be able to compare exact boulders in the model.

In order to this 20 boulders were selected to be released down the slope. Boulders chosen to be fitted with instrumentation were fitted with accelerometer/gyroscopes to measure the boulders kinetic energy and rotational velocities. Along the boulders potential path, 16 cameras were placed in order to capture the boulder's motion down the slope (L Vick, 2015). This also allowed for comparison between the boulder and the individual impact scars left during the rock fall process. Figure 3.2 shows the placement and recorder impacted scars and boulders form these experiments.

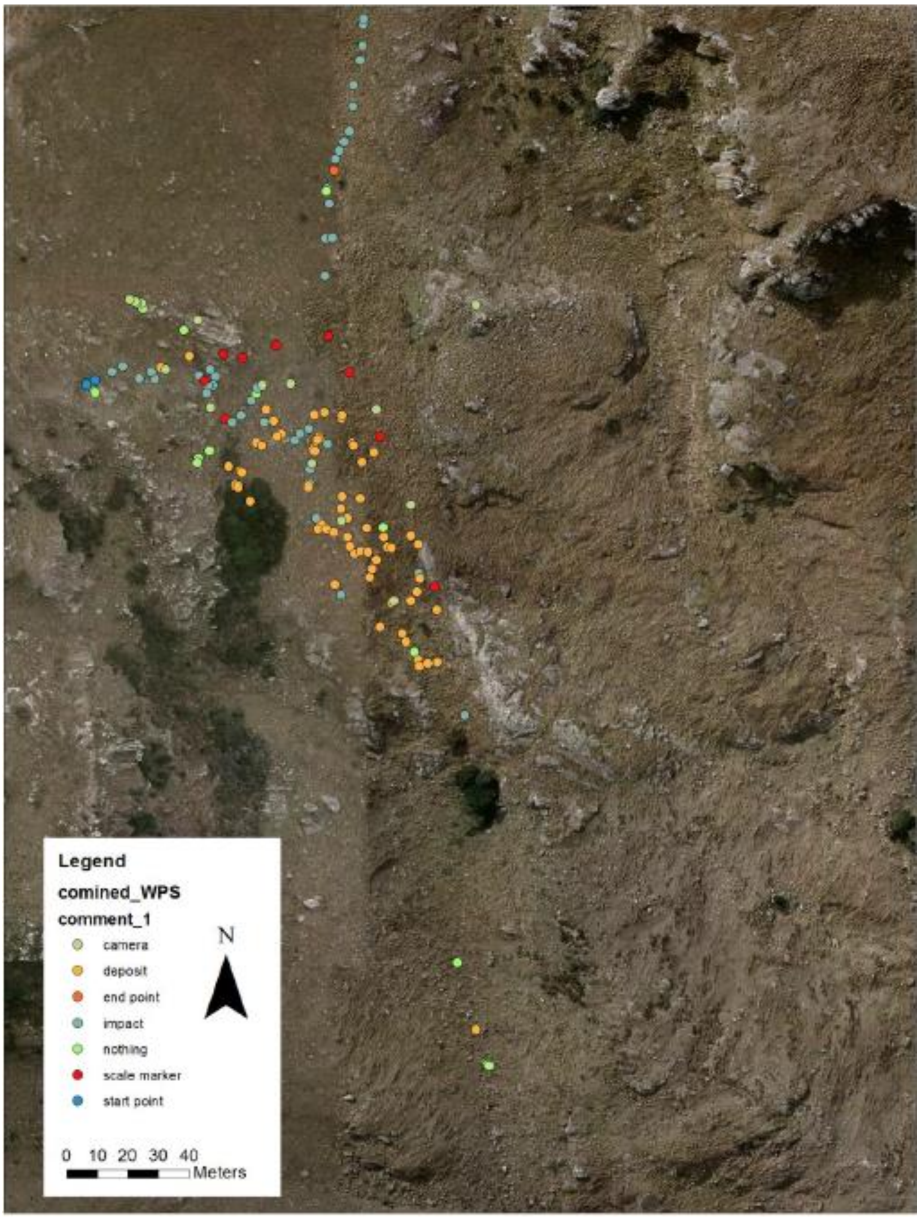


Figure3.2 Image showing camera, scale marker, boulder and bounce position noted during L.Vick field experiments taken from (Vick, 2015)

3.4 Modelling approach for sensitivity analysis

RAMMS gives three main options for parameter changes. These are vegetation, substrate materials and boulder characteristics (shape, size and density). These are the variables one would expect would have the most significant effect on the outcome of a 3D rockfall model (Dorren, 2003). For the purpose of this project, these variables are the predominant focus of the sensitivity analysis. As extensive research has already been undertaken into the sensitivities of DEM resolution this would not be assessed in this sensitivity analysis. It was accepted that the higher the resolution the better the results and the best resolution DEM should always be used.

In order to assess the model's sensitivity to changes in these various parameters, multiple models would have to be run over a number of months. This was due to hardware constraints and the average time it took to run each simulation (around 12 hours; this was later reduced with hardware upgrades). Due to the size of the Port Hills and the amount of data provided for the entire region a single area was chosen to initially run the various simulations and determine the model's sensitivities before selecting other areas to test the determined sensitivities against recorded rockfall events. The initial test area chosen was the Heathcote valley shown in Figure 3.3This area provided a good location to test the various parameter changes as it has a large number of recorded boulders from the CES and all three major variables are present.

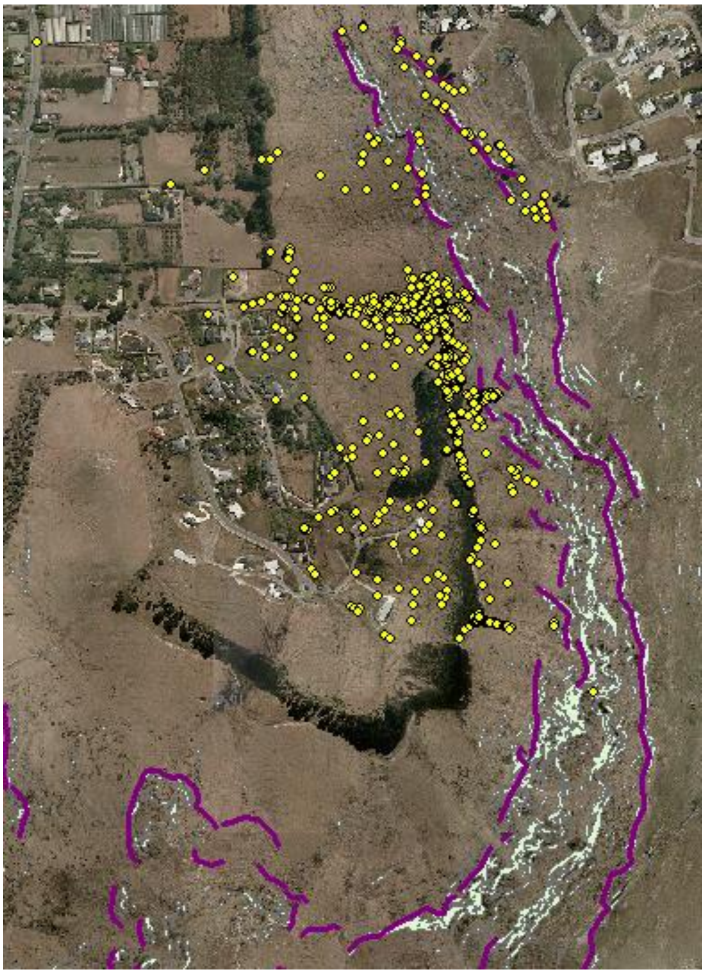


Figure3.3 Image of the Heathcote Valley following the 22/02/2011 earthquake. Yellow dots show final boulder locations Pink lines source toe lines and Lime green areas are the source areas

3.4.1 Substrate variations

Ground conditions act upon a boulder during impact with the ground influencing the boulders velocity, bounce height, kinetic energy and run out distances. Thus how changes in the substrate affect the model's response are important to understand, as inputting the incorrect substrate type could result in a vastly different model output than that of another substrate setting in RAMMS. The RAMMS rockfall program comes with a series of predetermined substrate types ranging from soft to extra hard as well as an option for snow. Table 3-1 shows the various characteristics of each substrate type.

Table 3-1 Pre-defined substrate parameters for the RAMMS::Rockfall program

Terrain	Mu_Min	Mu_Max	Beta	Kappa	Epsilon	Drag
Extra Soft	0.2	2	50	1	0	0.9
Soft	0.25	2	100	1.25	0	0.8
Medium Soft	0.3	2	125	1.5	0	0.7
Medium	0.35	2	150	2	0	0.6
Medium Hard	0.4	2	175	2.5	0	0.5
Hard	0.55	2	185	3	0	0.4
Extra Hard	0.8	2	200	4	0	0.3
Snow	0.1	0.35	150	2	0	0.7

As the purpose of this thesis is to evaluate the model's sensitivities to changes in the various parameters. The Default parameters will be used in order to determine the model's sensitivity to terrain changes. The default parameters were also chosen as the individual parameters for each setting cannot be altered by the user at this stage. In order to explore surface area influences, three boulders were tested all of the same shape but varying sizes and densities. These boulders were 1.1 m^3 at both 1700 and 2700 kg/m^3 and a 2.2 m^3 at 2700 kg/m^3.

3.4.2 Boulder variations

RAMMS rockfall has an inbuilt rock builder tool. This tool has both a library of point clouds that fall into various boulder shape categories and the ability to upload point clouds obtained from the field. The pre-determined database in RAMMS has three major shapes equant, flat and long. These are shown in Figure 3.4.

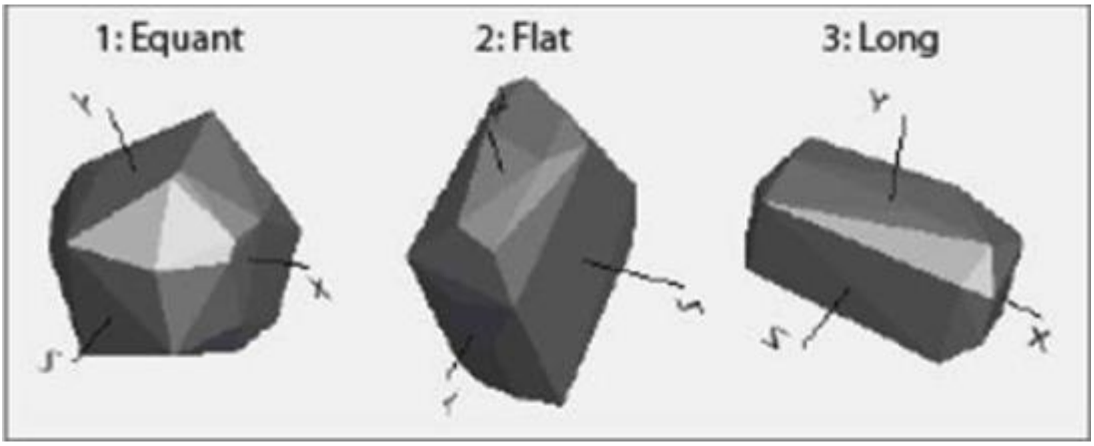


Figure 3.4 Three main shapes for boulder classification in the RAMMS::Rockfall model

The boulders selected for the purpose of this thesis will be drawn from the RAMMS database using all three categories of boulder shape and then varying the size and density in order to determine how these changes affect the outcome and how these results differ from the initial base model run. The boulders chosen for this sensitivity analysis were taken from the CES database using the minimum and maximum sizes along with the overall average for the Heathcote valley. Table 3-2 shows the various boulders that were run in order to assess the model's sensitivity to boulder changes.

Table 3-2 selection of rock characteristics chosen for sensitivity analysis

RAMMS Shape Classification	Volume (m^3)	Density (kg/m^3)	Weight (kg)
Real Equant	1.1	2700	2970
	1.1	1700	1870
	2.2	2700	5940
	2.2	1700	3740
	0.6	2700	1620
	0.6	1700	1020
Real Long	1.1	2700	2970
	1.1	1700	1870
	2.2	2700	5940
	2.2	1700	3740
	0.6	2700	1620
	0.6	1700	1020
Real flat	1.1	2700	2970
	1.1	1700	1870
	2.2	2700	5940
	2.2	1700	3740
	0.6	2700	1620
	0.6	1700	1020

3.4.3 Vegetation variations

If modelled correctly vegetation can have a significant impact on the outcome of a model. This is due to the ability of vegetation to alter the trajectory of a boulder, slow it down or stop it completely. RAMMS approaches vegetation by increasing the drag coefficient in that area. RAMMS has three different forest types implemented into the software at the moment:

- Open forest – $20m^2/ha$ – forest drag = 250kg/s
- Medium Forest – $35m^2/ha$ – forest drag = 500kg/s
- Dense Forest – $50m^2/ha$ – forest drag = 750kg/s

For the majority of this vegetation will remain constant at the median setting unless the effects of vegetation are being considered at which point this setting will be changed. This is to keep vegetation constant for other parameter changes within the model. Figure 3.5 shows how the drag is applied to the boulder during its motion down the slope.

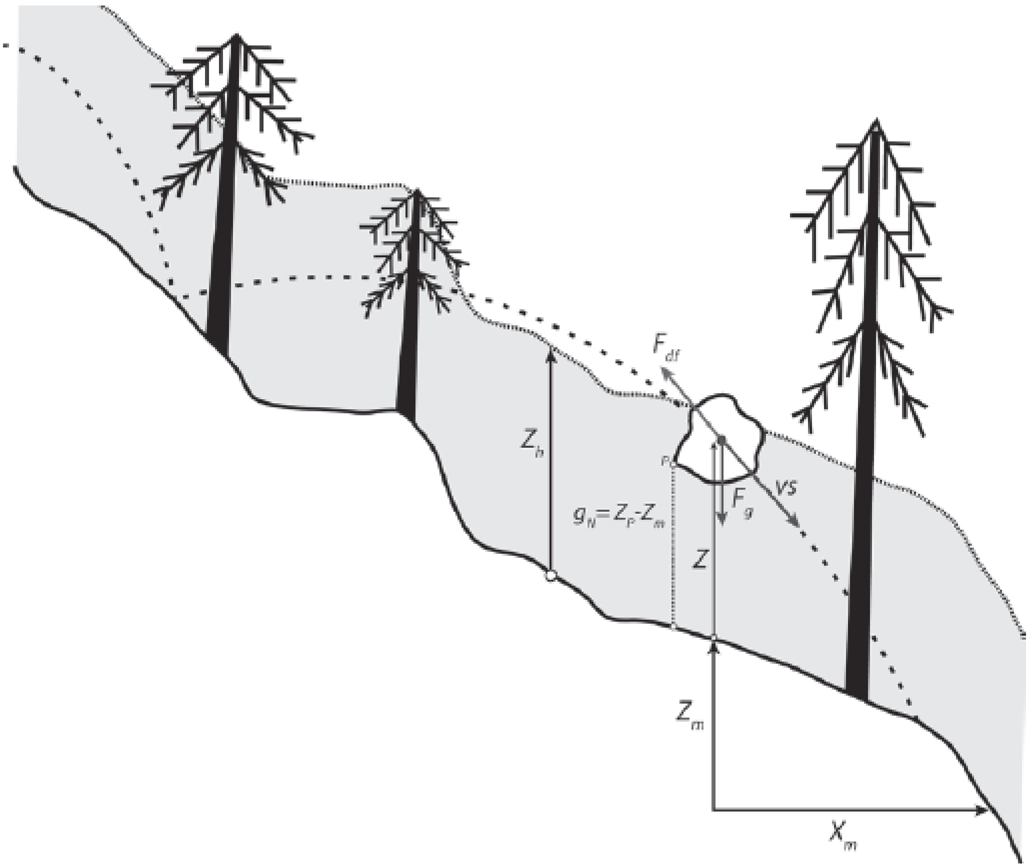


Figure3.5 Application of vegetation drag in the RAMMS::Rockfall model taken from RAMMS::Rockfall manual

3.4.4 <u>Assessing Runout</u>

RAMMS::Rockfall modelling software does not give an average runout distance for the boulder's trajectory. As this could be confused with distance travelled. A boulder does not always travel in a direct linear path source to final resting place and may travel down a gully rolling/bouncing from side to side. This would then give a false representation of the linear distance travelled. In order to assess the boulders runout a barrier plot was set up and the number of boulders to reach this point for each of the input changes would be recorded. Figure 3.6 shows the placement on this barrier plot. As boulder size is known to effect runout a 2.2m^3 was used for all assessments.

Figure3.6 Barrier plot location for runout assessment shown as red line

3.5 Model assemblage and simulations

The above data were then entered into RAMMS along with the geometrical data (DEM) required run a 3D numerical simulation. Using ArcGIS, the geometric data provided by GNS Science was created for easier input into the RAMMS modelling software. The geometrical data inputted into the model comprised of the following data:

- A 1m LiDAR Digital elevation model (DEM), cropped to the Heathcote valley and converted to *ascii* format.
- An aerial image of the Initial site in a georeferenced *tiff* format.
- Polygon source areas were generated by subtracting the post-CES LiDAR from pre-CES LiDAR.
- Polygon of various terrain types to be assigned terrain types.
- Vegetation polygons to be assigned various vegetation density's

The above geometric data was imported into the RAMMS directory for easy access and then compiled into a 3D image of the Heathcote Valley. From here it is up to the user what parameters are entered for the various variables required to generate a numerical model. A base model was generated for the area using the lowest value for each input parameter. This was in order to see how much the overall outcome of the model changed when altering a specific input parameter. A baseline model was established within the RAMMS program for each of the tested parameters. Each parameter was then varied as stated in sections 3.4.1.1-3.4.1.3. These were then compared to the baseline model for each parameter assessing how much each measured output changed when altering one input variable. The inbuilt statistics tool also allows the user to view the statistics of any measured output such as velocity, kinetic energy, bounce height, rotational velocity and reach probability (the probability that an object will reach a determined point within the model) at any given point in the scenario. Figure 3.7 shows the barrier plot used to determine entry statistics into the vegetation. Figure 3.8 shows the statistical output for this plot.

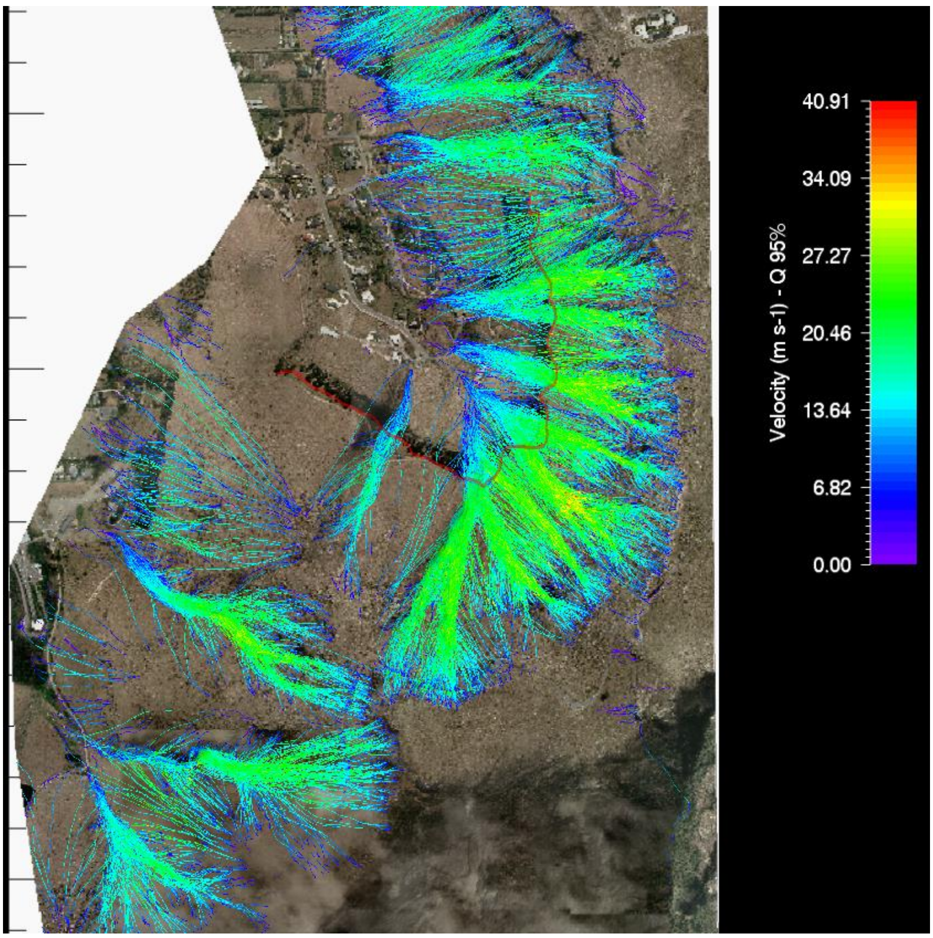


Figure3.7 Vegetation start barrier location shown as red line

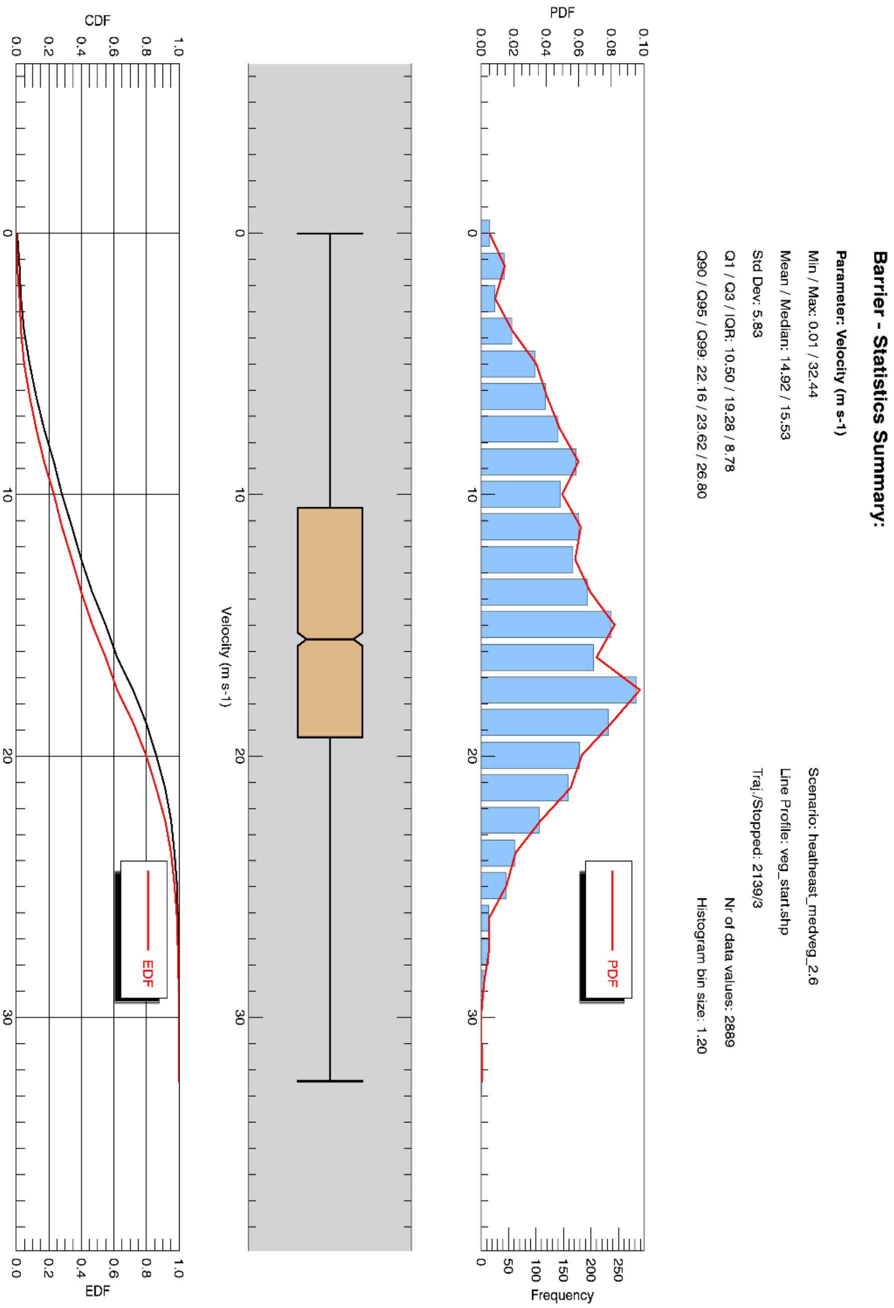


Figure 3.8 RAMMS::Rockfall visual output for velocity redline shows were vegetation start barrier plot was taken from.

Chapter Four: Sensitivity analysis

4.1 Introduction

In order to assess the sensitivity of the individual input parameters in the RAMMS::Rockfall model, multiple simulations were run within the test area of the Heathcote valley. Each simulation was run in order to test the sensitivity of the 3 major input parameters in RAMMS::Rockfall (Boulder variations, Terrain variations and changes in vegetation). These parameters were chosen for this project as they are the three main features that can be changed within the model and are also a large factor in any rockfall fall numerical model.

This chapter includes the data obtained from the numerical modelling done in the Heathcote Valley; this is so it can be discussed in later chapters. The process of validating a numerical model is vital to any assessment as it provides further confidence that a model's output is a realistic and accurate one. The test site was chosen for its characteristics as it contained all the necessary variables for a complex sensitivity analysis. Therefore allowing a workflow to be generated in later chapters.

4.2 Boulder Variations sensitivity analysis

Discontinuities in a rock mass vary depending on the source material and locality. Thus it was important to consider the three different shape classifications in RAMMS. The real flat, long and equant boulders were used as they best represent boulder shapes found in the field. It is already known from the previous literature that equant boulders will travel further and faster than that of long boulders. The data from each simulation confirms this, but how sensitive is the model to individual changes within these shapes and how do they affect the overall outcome of the measured parameters within the RAMMS model. The individual data for each of the 18 various models run for boulder shape can be found in Appendix A, Table 8-1.

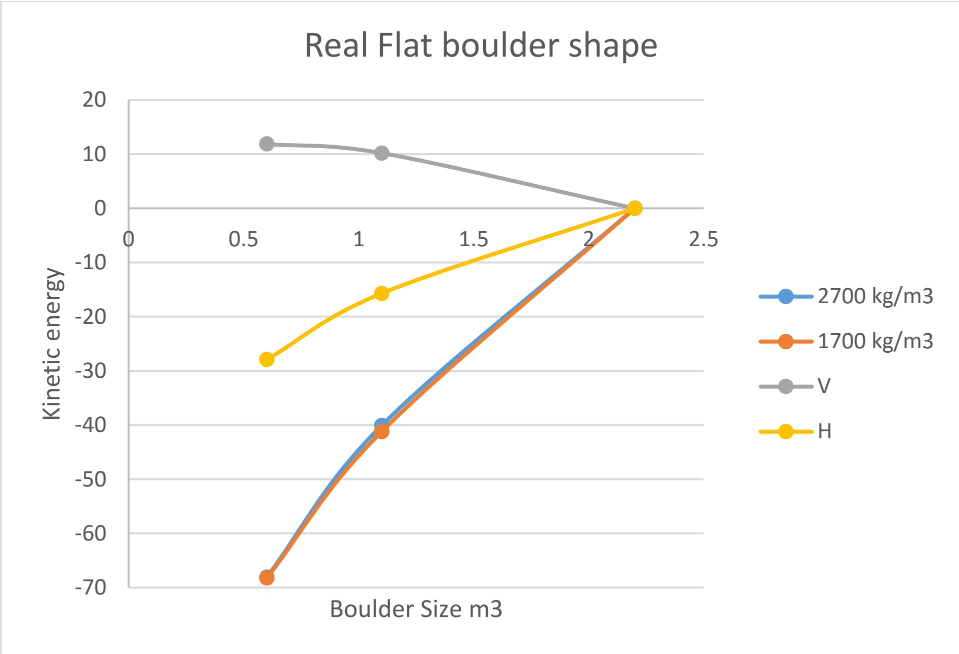


Figure 4.1 RAMMS::Rockfall model outputs for the Real Flat boulder shape

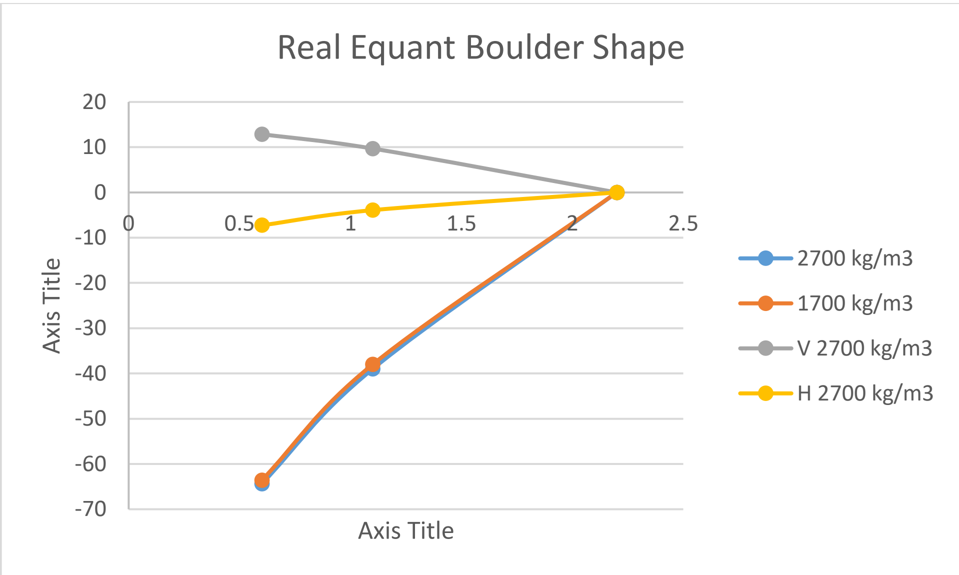


Figure 4.2 RAMMS::Rockfall model outputs for the Real equant boulder shape

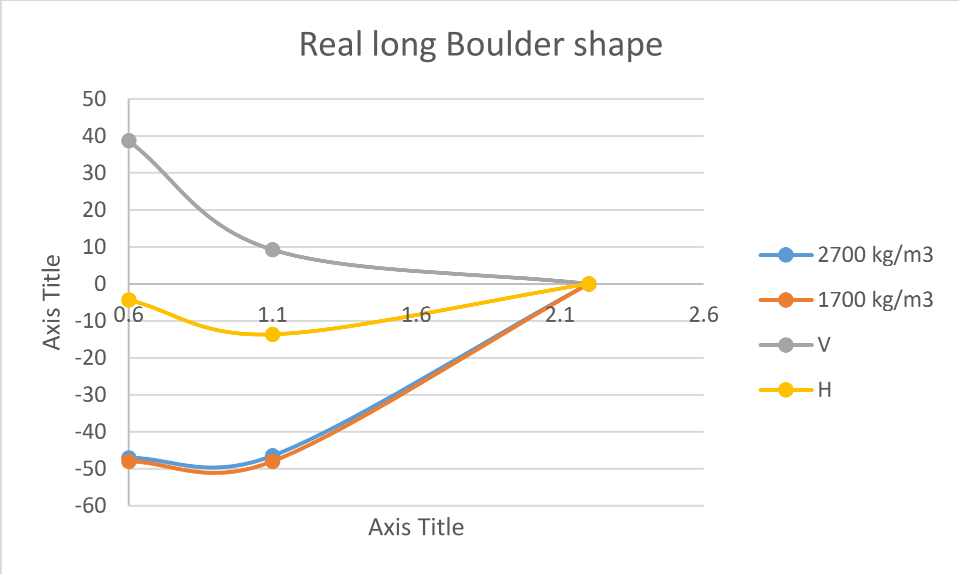


Figure 4.3 RAMMS::Rockfall model outputs for the real long boulder shape

Figures 4.1, 4.2 and 4.3 show the percentage change for each of the measured model outputs for each boulder shape and varying density. The modelling began at the largest boulder size and density (2.2 m3 at 2700 kg/m3) and worked down from there to the smallest (0.6 m3 at 1700 kg/m3). The percentage changes in kinetic energy for the two densities showed little to no difference and were indistinguishable on the plot itself. Therefore the higher density was plotted for the other two variables as there was no discernible difference.

From this data, we can determine that the kinetic energy of a model is most sensitive to changes in size and shape as it shows the greatest percentage of change from one size to the next. This is constant over the three shapes. However, the long boulder does behave differently at smaller volumes than that of the flat and equant boulders which continues in a decreasing fashion all though at an increased rate. The long boulder flattens off and approaches a constant change. This could be due to the shapes interaction with the DEM at smaller volumes. Being smaller than the resolution of the DEM could suggest less interference between boulder and substrate and thus remain at a constant change. The model's response in regards to velocity seems to be independent of shape as all three shapes follow the same trend for the most part.

This is not the case for the Bounce height across the three boulder shapes. The percentage change between each size boulder is different across all three shapes. The greatest change is with regards to change in size with the real flat boulder shape. This shape has up to a 30% change in height over the three sizes. This is compared to that of the Equant and long boulder shapes that have a maximum percentage change of approximately 10%. Although minor in change with regards to the kinetic energy changes, the bounce height is most affected by a change in shape and size compared to that of the velocity and kinetic energy which appear to be sensitive to size.

As RAMMS::Rockfall does not measure the distance a boulder travels from the source area to rest, but instead provides a visual output of the boulder's trajectory. Figure 4.4 shows how the changes in a boulder shape effect this trajectory. From this we can see that boulder shape has a direct impact on the distance a boulder will travel. The equant boulder travels the furthest with 210 making it past the barrier plot (Appendix A, Figure 8.2). While the real flat travels the least amount of distance with 7 boulders making it past the barrier plot (Appendix A, Figure 8.1).

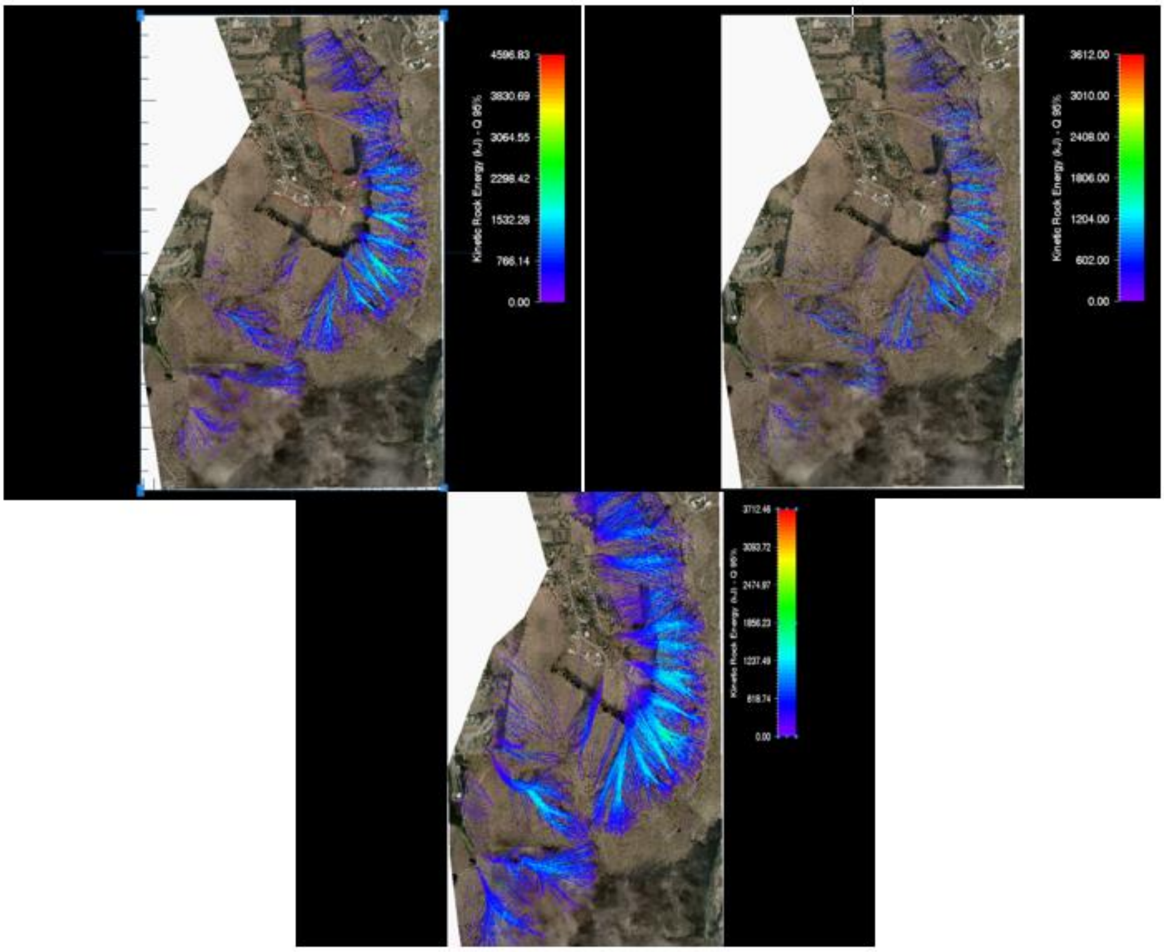


Figure 4.4 Top left Kinetic energy output Real long, Top Right Kinetic energy output Real flat and Bottom Kinetic energy trajectory real equant

4.3 Substrate Variation sensitivities

Substrate variations refer to the changes in soil and rock properties along the slope. These are predefined within the RAMMS rockfall model from extra-soft to extra-hard. In order to test the model's sensitivity to changes in this parameter 7 of the RAMMS::Rockfall pre-sets were tested with three varying boulder characteristics all of the same size. The real equant shape was chosen as it is the most consistant in its trajectory. The snow option was not assessed in this sensitivity analysis due to lack of snow in the area. The Tabulated Results from each of these simulations can be found in Appendix B, Table 8-2. Using the RAMMS statistical outputs the sensitivity of each substrate setting was assessed in relation to change in boulder size and density. The results of this are represented in figures 4.5, 4.6 and 4.7.

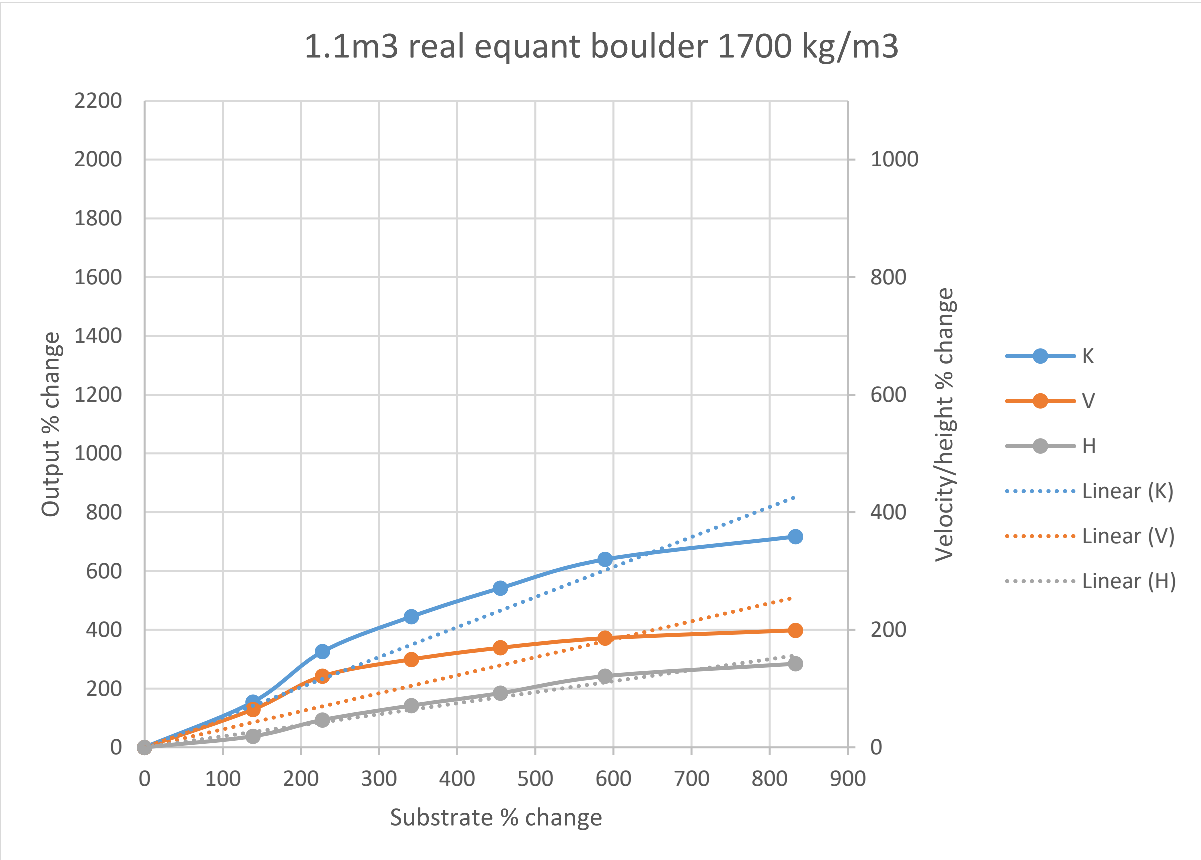


Figure 4.5 Kinetic energy, Velocity and Height outputs for a 1.1m3 real equant boulder at 1700 kg/m3. Substrate selections from extra-soft to extra hard.

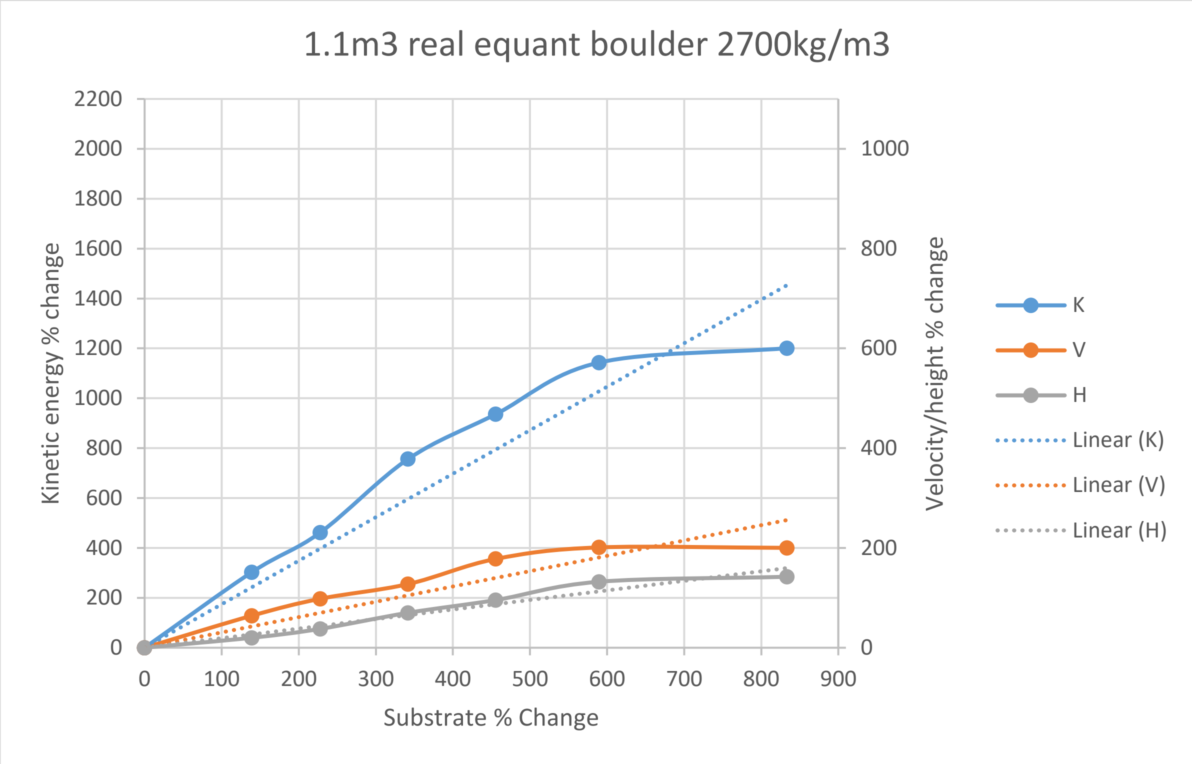


Figure 4.6 Kinetic energy, Velocity and Height outputs for a 1.1m3 real equant boulder at 2700 kg/m3. Substrate selections from extra-soft to extra hard.

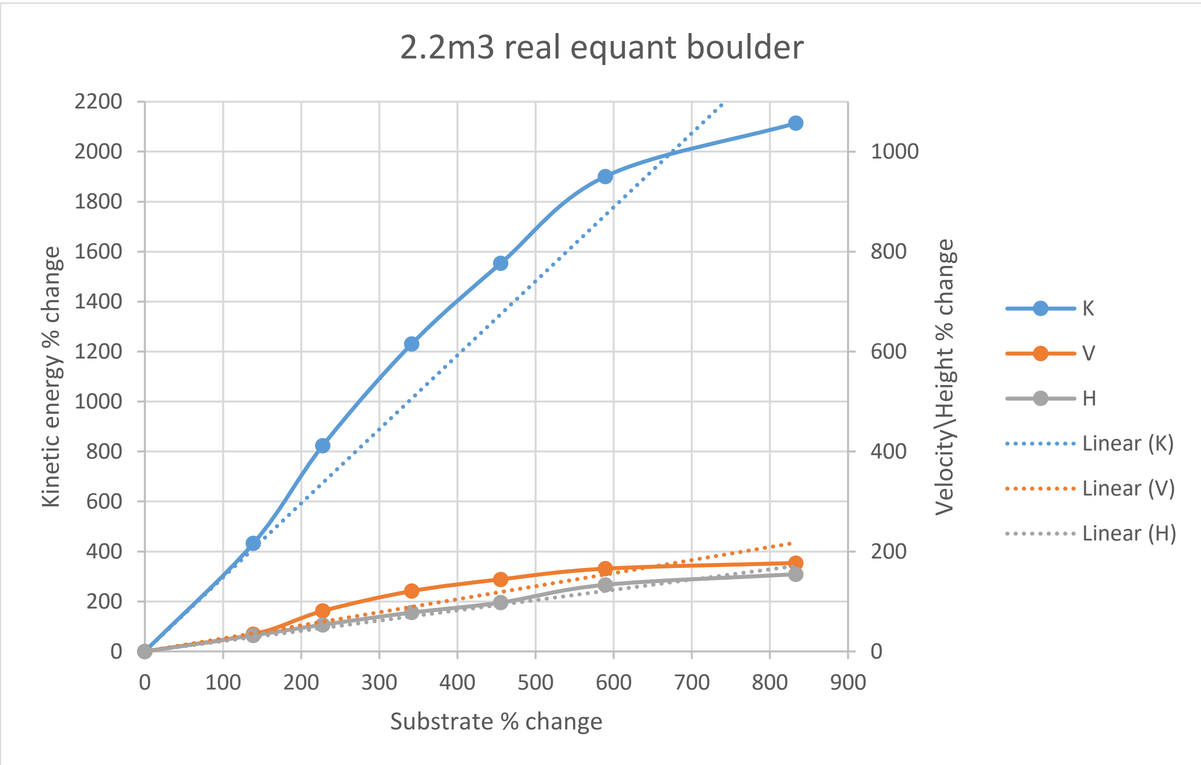


Figure 4.7 Kinetic energy, Velocity and Height outputs for a 2.2m3 real equant boulder at 2700 kg/m3. Substrate selections from extra-soft to extra hard.

Once this data was graphed, it was evident that one of the measured parameters was significantly more sensitive to changes in the substrate material, as the kinetic energy had percentage increases of between 154.64-7.7.42%, 302.49-1200.72% and 432.71-2113.95% respectively over the three boulder changes. This was greater than those witnessed in the percentage changes in velocity and bounce height. The overall percentage changes in velocity and bounce height remain relatively constant over the three boulder variations at approximately 40-200% over the three boulder variations. The percentage changes in kinetic energy increased with the increasing boulder size and mass. This is due to the increase in kinetic energy with the increasing boulder mass. As the mass of a boulder increases so does that of the kinetic energy. As the changes in velocity over the three various sizes remain relatively similar and a greater increase in kinetic energy is witnessed

Along with the sensitivities to the overall mass of the boulder the model displays greater sensitivities to changes between certain substrate types. This is evident in Figures 4.5, 4.6 and 4.7 as the Kinetic energy, velocity and bounce heights do not trend linearly compared to that of the substrate percentage changes. The model appears to be more sensitive to changes from soft to medium-soft where the percentage changes are seen to increase from a relatively linear progression for both Kinetic energies and velocity. This is seen more so in the denser boulder classifications. The trend then progresses back to a linear fashion until the changes between hard and extra-hard where the trends flatten out and drop below the trend line. The bounce heights over the three boulder variations remain fairly constant and only begins to show sensitivities from hard to extra-hard substrate changes.

As was done with boulder characteristics the runout was assessed using the predetermined barrier plot. The effects of the chosen substrate were significant with the first two settings of ex-soft and soft resulting in zero boulders making it two the barrier plot this can be seen in figure 4.8. As the surface settings got harder more and more boulders made it to the barrier plot with extra-hard allowing 580 boulders to reach the barrier plot (Appendix B, Figure 8.5).

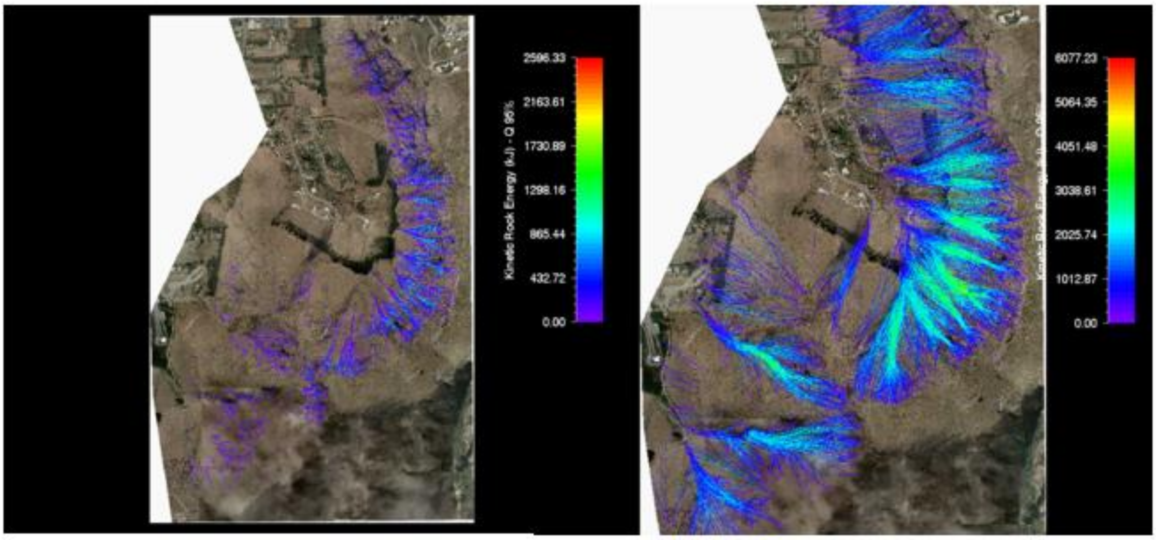


Figure 4.8 Left Extra-soft boulder trajectories Right Extra-hard boulder trajectories

In conclusion, we can determine that when changing a boulders mass and the substrate classifications, the model's kinetic energy output is the most sensitive to these parameter changes. Kinetic energy showed the greatest percentage change overall compared to that of the velocity and bounce height; these remained relatively constant over all the simulations run.

4.4 Vegetation Changes

In order to assess the sensitivity and effectiveness of vegetation on the model, 12 simulations were run in the area using varying densities of vegetation and varying boulder characteristics. The real equant boulder shape was chosen for these simulations as these travel the furthest and are the least affected by other parameters within the model. The outputs for these can be found in Appendix C, Table 8-3. It shows the parameters used and how these affected the; kinetic energies, bounce height and velocity of the boulder within the vegetation space. The effects of vegetation were only measured from the point that vegetation impacts on the on the boulder itself and stopped at the end of the vegetation. The initial no vegetation models were run in order to determine the effects of the other parameters in the model and would be subtracted in order to ascertain the true effects of the vegetation in this area. The vegetation effects have been modelled in three variations open forest, medium forest and dense forest.

Figure 4.9 shows the effects that vegetation has on the overall Kinetic energy within the vegetated area for each boulder. The amount that vegetation impacts on the Kinetic energy of a boulder depend on three parameters: The density and area of the vegetation (This corresponds to the amount of additional drag applied to the boulder and the period it is applied for) and the boulder's physical properties (shape, size and density). The difference in percentage change in kinetic energy for a 2.2 m^3 equant boulder is between 14.15% and 22.41% less than that of a 0.6 m^3 boulder of the same shape.

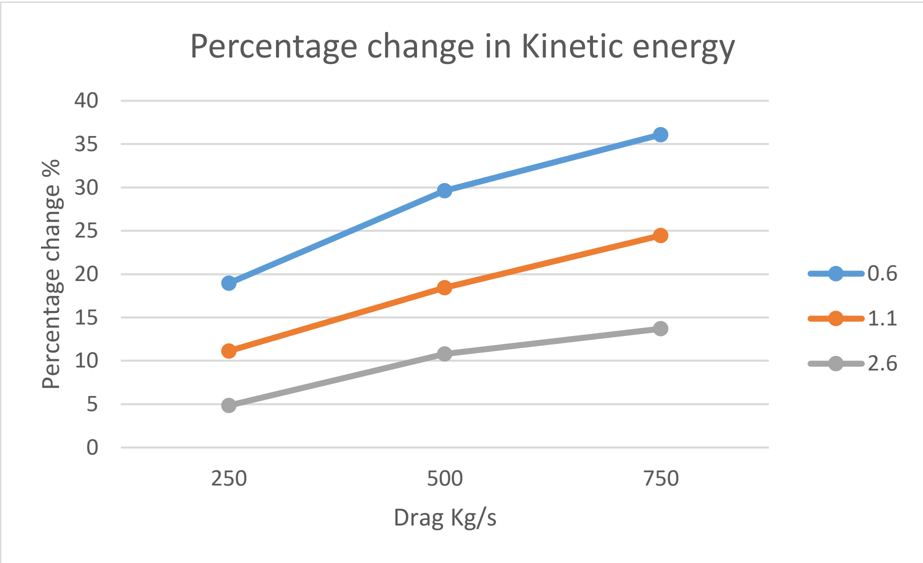


Figure 4.9. Graph showing the average percentage change in kinetic energy for three boulder sizes 0.6, 1.1 and 2.2 m3

This can be attributed to the boulders physical momentum and inertia. Once a larger boulder gets going the kinetic energy, and momentum is increased. This, in turn increases the amount of energy required to stop or slow the boulder. A larger boulder's kinetic energy is less affected by vegetation than that of a smaller boulder.

The overall effects of vegetation on the various boulders velocity can be seen in figure 4.10. This figure shows similar trends to those seen in Kinetic energy with the average difference in the change in velocity between that of a 2.2 m^3 boulder and that of a 0.6 m^3 boulder being between 12.71 and 22.77% reduction within the vegetated area. This suggests that the vegetation effects on a boulders velocity directly correlates to the boulder's physical characteristics as larger boulders are less affected by vegetation than that of smaller boulders of the same shape. As was seen with kinetic energy.

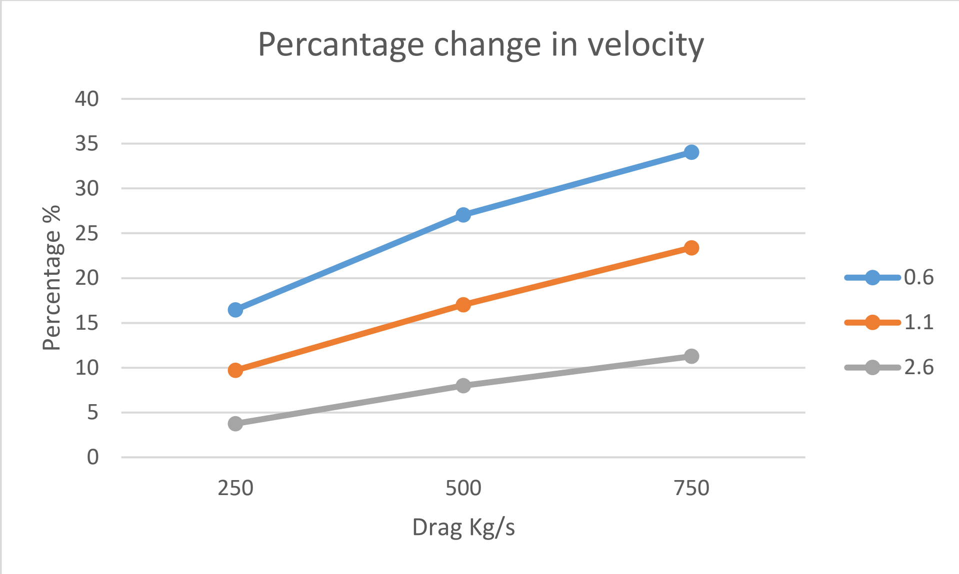


Figure 4.10. Graph showing the average percentage change in Velocity for three boulder sizes 0.6, 1.1 and 2.2 m3

The effects of vegetation on a boulder's velocity is easily compared to that of kinetic energy as all three boulder variations entered the vegetated area at approximately the same velocity of 14 ms^{-1} (Appendix C) this is not the case for kinetic energy as the various boulders all entered the vegetated area at varying magnitudes of kinetic energy (265.69 – 1227.18 Kj).

The third variable measured in regards to the effects of vegetation was that of bounce height. The results of which can be seen in Figure 4.11. This again shows a similar trend to that of kinetic energy and velocity with the smaller boulder sizes being affected more than that of, the larger boulders and a decrease in bounce height as the vegetation density increases. The average difference in the percentage of change between that of a 0.6 m^3 and a 2.2 m^3 was 10.35 – 22.78 %.

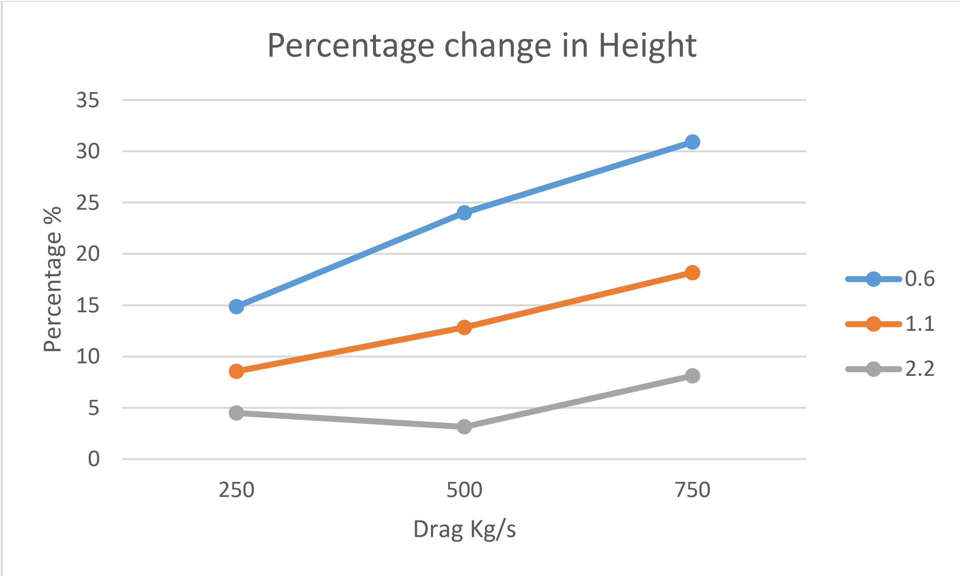


Figure 4.11 Graph showing the average percentage change in bounce height for three boulder sizes 0.6, 1.1 and 2.2 m3

The effects of vegetation on the boulder's runout were also assessed and was found that for the area of vegetation used in this sensitivity analysis, vegetation had very little effect with the overall runout as seen in figure 4.12. With no vegetation acting upon the boulder 1699 made it to the barrier plot this was compared to that of maximum density where 710 made it to the barrier plot (Appendix C). This compared to the effects of the other input parameters.

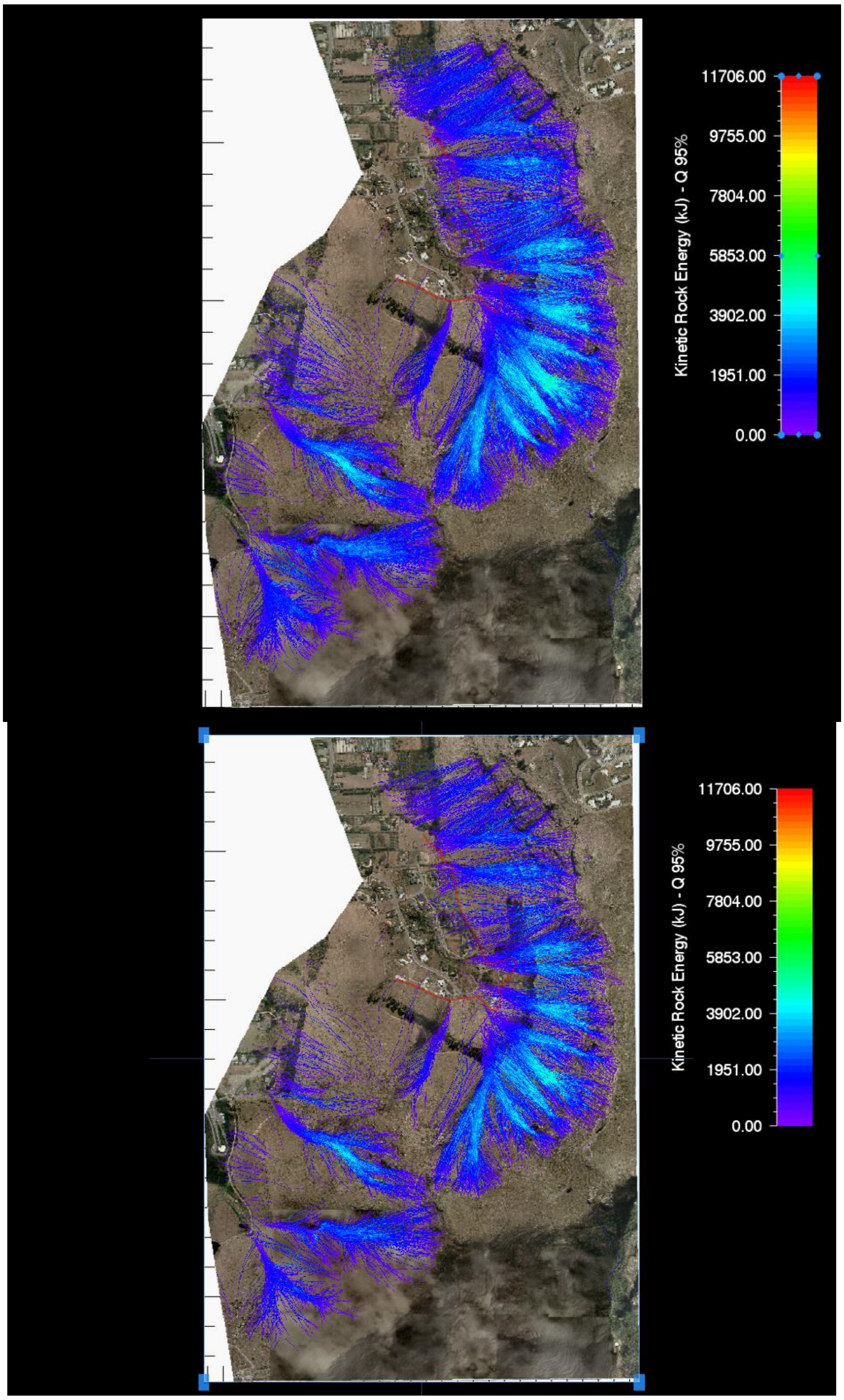


Figure 4.12. Top no veg boulder trajectories, Bottom max Vegetation boulder trajectories

Overall the effects of vegetation in this specific area all showed similar patterns in the changes in the measured variables. Kinetic energy, velocity and bounce height are all affected by a similar magnitude of change of 4.8-36.1%, 3.75-34.03% and 4.5-30.89% respectively when interacting with vegetation within this area. This data suggests that a boulder's Kinetic energy is most sensitive to vegetation changes followed by velocity and bounce height is least affected by that of vegetation in the RAMMS::Rockfall modelling process.

4.5 Conclusions

Overall over the 61 models run for this sensitivity analysis of the RAMMS 3D rockfall model, Kinetic energy was the most sensitive model output variable to changes. When compared to changing variables such as boulder characteristics (shape, size and density), substrate materials and vegetation the kinetic energy had the greatest percentage change for each of the changeable parameters. The kinetic energy was greatly influenced by boulder size and substrate properties with a percentage change of between 154.64% and 2113.95%. This was compared to a maximum percentage change of 200% for velocity and 154% when considering substrate changes. These changes were not always linear as was seen in the substrate variations. The RAMMS model had a larger response to change when going from a soft to the medium-soft environment and again when going from a hard to extra-hard environment.

Chapter Five: Modelling work Flow

5.1 Introduction

When beginning any modelling project be it 2D or 3D modelling, it is important for the practitioner to understand what the model is being used for. Is the model being used to aid in land use planning and assess where it is best to place vital infrastructure or is the model being used to assess a previously unknown rockfall risk in order to determine the best mitigation methods and the specifications required for the selection. Each of these uses requires different output accuracies in order to determine. For example, when determining the location of a school the potential runout/reach of the boulders needs to be determined with a higher accuracy that energy at which it will impact the structure. Whereas the kinetic energy and bounce height are of importance when considering the location and type of mitigation method to be used. Once this is understood the practitioner can go about collect the relevant data to most accurately represent the situation within the time and costs that are afforded to them. Time and money are of concern when generating an accurate model and are not always available in the scope of the project being undertaken, thus, it is important to understand what data to focus on to obtain the most accurate model for the situation required.

5.2 Input variable importance according to sensitivity analysis

Using the data from the previous chapters sensitivity analysis, it was possible to assign a rank to each input parameter in terms of how they affected the overall percentage change in each measured output. The ranking system chosen for this was a simple numerical value system, 1 being the variable that results in the largest percentage change and 5 being the least. This allows the practitioner to determine what input variables are important to focus on for the desired output, e.g., Kinetic energy for barrier type selection. The practitioner will focus on substrate classification and boulder size and density. These are outlined in Table 5-1.

Table 5-1 Variable importance according to sensitivity

Input parameter	Kinetic energy	Velocity	Bounce height	Run out
shape	4	3	3	2
Size	2	2	2	3
density	3	4	4	4
Substrate	1	1	1	1
Vegetation	5	5	5	5

5.3 Model approach

When approaching any engineering modelling problem, there are some questions that need to be answered before commencing modelling of that area. These questions include; is there any evidence of a previous rockfall in the area or are they dealing with a Greenfield (An area with no evidence of historical rockfall i.e. no boulders or impact scars) location, what kind of access is available in the area and is there access to the source area. The answers to each of these questions will determine how the practitioner will proceed when analysing an area for the purpose of modelling rockfall behaviour. Suggestions are made on how to approach these scenarios in this chapter. It is important to remember that the practitioner considers input parameters according to the desired output of the model.

5.3.1 Greenfield

The first step in any 3D modelling process is obtaining the highest resolution DEM as possible. This has the greatest influence on any model run. Getting a DEM that has a smaller grid size than your smallest potential boulder is important as the model behaves differently with certain boulder shapes when the grid size is larger than that of the boulder being run.

- *No Physical access*

  When no physical access is available to the site, the practitioner has to rely on published data and imagery of the area in order to run a model of the area. This imagery will more than likely give no indication of boulder characteristics in the way of shape and size.

  A practitioner's primary focus should be in determining the substrate type and running models around variations in this parameter, as this has the most effect on any parameter in the RAMMS model. RAMMS gives a simple description for each of the substrate types, and these can be used in order to determine substrate selection from a visual classification (Schweizer. R., 2016). Care should be taken when choosing between soft and medium-soft as well as between hard and extra-hard. This is because the model's reaction to changes between these substrates is greater than that of transitions between other substrate types.

Accurately determining the boulder’s characteristics in this situation is extremely difficult without a large budget that can be used for Arial footage (Drone or helicopter) in order to obtain source area rock mass characteristics and even then this would still leave some uncertainty. Depending on the intended use of the model the primary boulder characteristic (Shape, size and density) focus will change and should refer to Table 5-1 to determine what parameters to focus on. In order to reduce the uncertainty a wider array of varying boulder characteristics will need to be run. These should fall on either side of the assumed most likely characteristics.

Vegetation, for the most part, should be considered last as there are only three main settings for it. Making it easily changed and run multiple times in order to minimise uncertainty. This should only really be considered if there are blocks of vegetation/trees larger than 5000 m^2. Less than this and the effects of vegetation are negligible.

- *Physical access available*

When there is physical access to the model area, another question needs to be asked about the location. Is there access to the potential source area and can the boulder characteristics be determined from the source area.

  - *Source area inaccessible*

  This location type has moderate levels of uncertainty, and although some variables are able to be constrained, some assumptions still have to be made leaving some uncertainty in the model's overall accuracy.

  As Table 5-1 shows the substrate has the greatest effect on the model's output. With access to the site, the classification of the substrate can be narrowed down further, and a narrower range of parameters have to be considered. As RAMMS uses variables defined during a boulder’s contact with the soil such as scar length and contact time, these cannot be used to define the substrate type in a Greenfield location. Thus tests such as soil depth and surface strength can be used to determine substrate classification. Therefore the practitioner should focus on pinpointing the changes in detailed mapping of the area, keeping in mind the uses of the model and the descriptions in the RAMMS manual.

As the source area is not accessible the same methods and focuses should be undertaken as when the area is not accessible for a selection of boulder characteristics. Again taking into consideration, the models use and using the model's sensitivity to the various parameters into consideration.

If significant vegetation is present within the area an estimation of the vegetation in density per hector should be taken. However, as effects from vegetation in the model are minor unless in areas larger than 5000 m^2.

- *Source area accessible*

Of the three Greenfield scenarios discussed in this workflow, this scenario has the lowest uncertainty. This is because the input variables can be constrained down the most to what is actually observed in the field. This means that a smaller range of parameters have to be considered and fewer models have to be run.

The process for this scenario only changes with respect to obtaining the potential boulder characteristics from that of the previous scenario. The primary focus is still on substrate classification as the model's reaction to changes in this are the greatest. It is here the practitioner again needs to consider what they are trying to achieve the model and what they are trying to measure (potential kinetic energy, velocity, bounce height or boulder reach). The assessment of vegetation within the area remains the same as in the previous scenario.

As these areas have no discernible record of previous rockfall events, one should consider all potential scenarios and run a variety of models that fall on either side of what is thought to be probable. Always keeping in mind what the final use of the model. Figure 5.1 is a simplified workflow for Greenfield areas and should only be used as a guideline. The more information that can be determined and entered into the model the more confidence in the accuracy of the model's output.

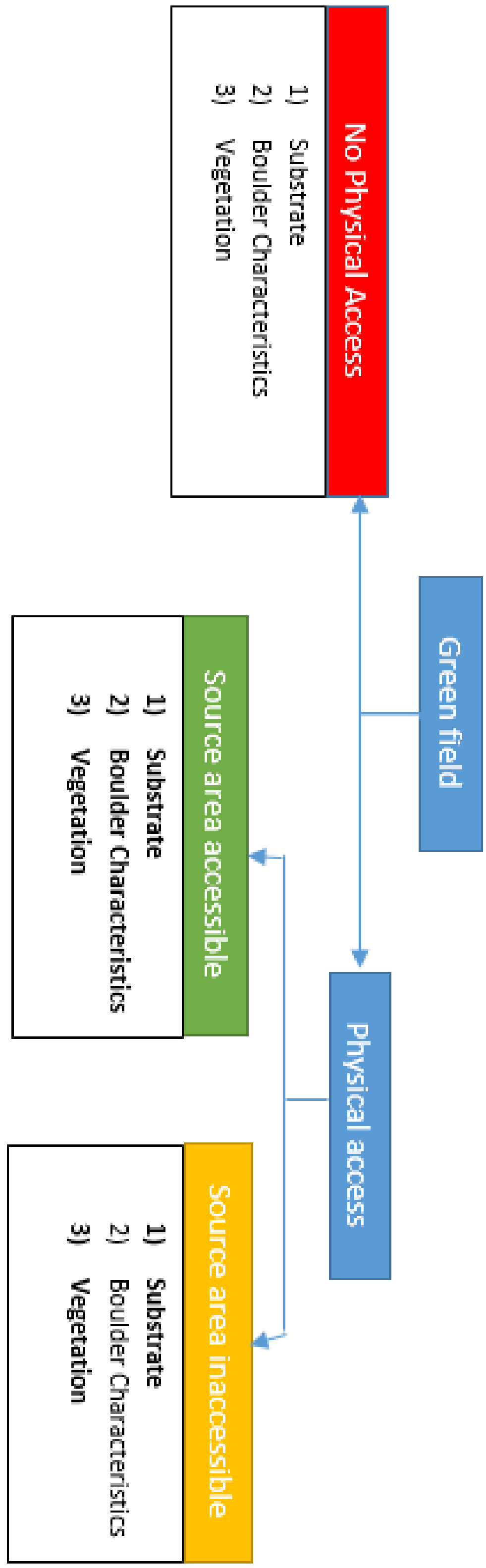


Figure 5.1 suggested workflow for Greenfield scenarios

5.3.2 **Previously/currently active**

Unlike a Greenfield location, these areas have some previous rockfall data that can be used in order to further refine the input parameters and increase the model's accuracy. This also allows reducing the number of scenarios needed in order to increase the accuracy. Like in the Greenfield locations the highest resolution DEM is recommended for the best level of accuracy. Just as with Greenfield locations the workflow can be split into two location types, Physical access and no physical access to the site.

- *No Physical access*

  This category can again be split into two categories for modelling, locations with imagery after the event and locations without any imagery of the rock fall event. The lack of imagery can be a result of an immediate response to the event where there hasn't been enough time for high-resolution imagery, or the project's budget did not cover the expense.

  - *No imagery of the rockfall*

    This scenario can be treated much the same as a Greenfield location with no access to the location and limited information. The steps and sensitivities for this have already been outlined in section 5.3.1 of this thesis under the title No physical access.

  - *Post-event imagery available*

    As the site has no available access, similar steps to those suggested when dealing with a Greenfield site can be followed. Unlike a Greenfield site, some boulder information can be obtained using imagery. As size and shape can potentially be determined depending on resolution, the range of variance needed to be modelled within this parameter are reduced. This increases the potential accuracy of the model as the change in shape and size of a boulder effect the most change in the final measured model outputs (Kinetic energy, velocity, bounce height and run out).

- *Physical Access*

  - *Source area inaccessible*

    This scenario can be treated as a Greenfield location, and substrate data should still be the primary focus as it has the greatest effect on the outcome of the model. With the addition of fallen boulders and impact scars means these parameters can be further refined. As size and shape of a boulder have the larger effect on the model's response time should be spent mapping and describing fallen boulders within the modelling area. Some uncertainty still remains as the source area cannot be examined in order to determine what boulders are probable in future events.

- *Access to the source area*

  Out of all the probable modelling scenarios described within this thesis, this scenario has the lowest level of uncertainty. This is due to the amount of data available to the practitioner in the field. The primary focus as with all scenarios remains with the substrate selection and is the only parameter that cannot be fully determined. This is due to how RAMMS classifies the substrate numerically in the model. Kappa can be determined from the impact scar using the equation 1/k=scar length. This can help determine one of the four variables used in the substrate interaction with the boulder. Boulder shape and size can be classified increasing the accuracy of the model and reducing the range of required variations to increase accuracy. The fallen boulders can be compared to the source area, and potential boulders from the area identified.

Although the uncertainty in already active rockfall areas in regards to modelling is significantly lower, some assumptions are required in some cases. Therefore it is important to consider how changes in each input parameter will affect the final result, as large changes in substrate type could increase the Kinetic energy output by up to approximately 2000%. Figure 5.2 shows a summarised suggested workflow for modelling within an active rockfall area.

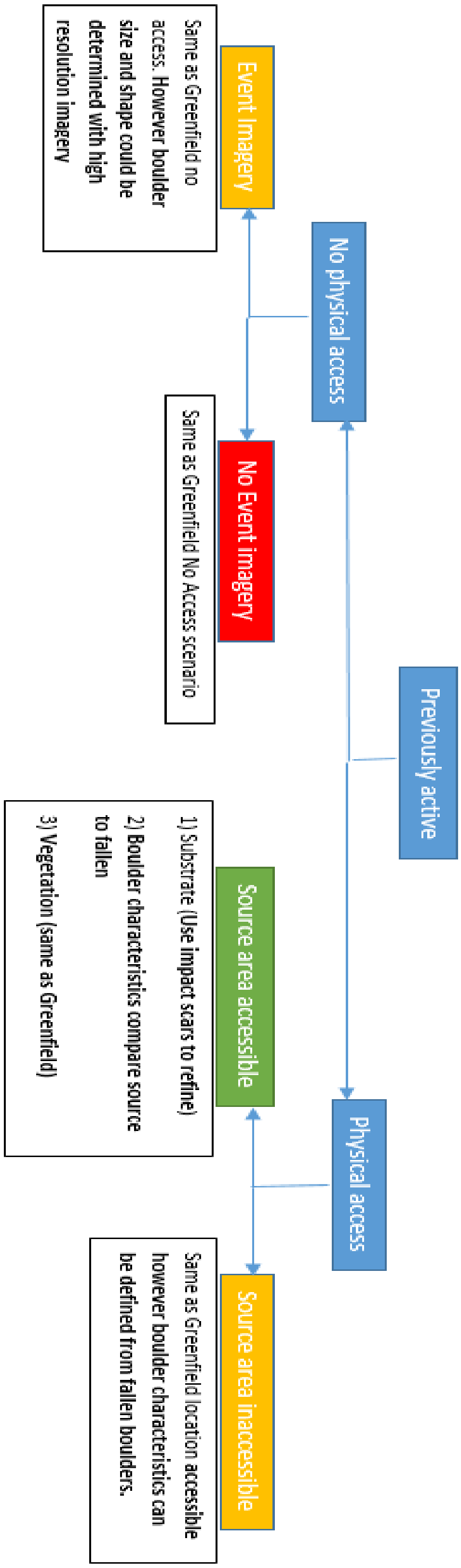


Figure 5.2 suggested workflow for active rockfall areas

5.4 Conclusion

The purpose of this chapter was to build and describe the workflow process for both Greenfield and active rockfall locations. This is presented in two separate workflow charts in figures 5.1 and 5.2. It is important to remember that this is just a guideline and only serves to make suggestions on the modelling process. These charts should be used in conjunction with the Variable importance table (Table 5-1) as the focus of the project may change depending on the desired output from the model.

Chapter Six: Conclusion

6.1 Introduction

The understanding of the physical rockfall process assists engineers, scientists and policy makers in the creation of reliable models that have the ability to assess the rockfall as a hazard to infrastructure and people (Hungr, 2005). These numerical models are a reliable tool when well calibrated to the scenario. This is not always possible and thus understanding the model's individual sensitivities is required. This allows practitioners to develop models with increased confidence for areas that have yet to be calibrated for. The need for this arose because the calibration of a model often requires an experienced user and in field verifications (Berger and Dorren, 2006). However, this is not always possible in Greenfield scenarios.

This project focussed on the modelling of a single area in the Port Hills in order to assess the RAMMS 3D rockfall modelling software's sensitivity to changes in the three changeable parameters. These parameters included the areas substrate, boulder characteristics and vegetation coverage in a specific area. The percentage change in each of the models measured outputs was then evaluated.

6.2 Applications

Once a model's sensitivities are understood the applications of the model do not change, but the confidence in the results generated are increased. Practitioners can use this sensitivity analysis to tackle any one of the following scenarios:

- L**and use planning.** Where ever there is a slope with exposed rock there is a potential for rockfall to occur. Therefore before any damage can occur to the infrastructure be it existing or future development, it is possible to assess the area. In doing so, the practitioner can provide the best estimate in regards to whether the area is at risk to rockfall and proceed from there (Vick, 2015). Avoidance is the best countermeasure when it comes to rockfall hazards.
- **Demolition and scaling.** Following the Christchurch earthquakes and more recently the Kaikoura earthquake property and infrastructure had to be either demolished or repaired. The likely hood of further rockfall in these areas is high. This makes entry

into these locations dangerous. Understanding the rockfall within the area will help determine areas that are not safe for personal entry and determine rockfall safe zones where boulder impact is unlikely.

- **Rockfall mitigation design.** In situations where avoidance is not an option, rockfall mitigation has to be considered. The understanding of a model's sensitivity here is paramount as slight changes can result in large changes in kinetic energy and bounce height. As the boulder has to be stopped before impact with the protected structure, these parameters are important to understand going into an area that is not calibrated for the model.

6.3 Limitations of the model/sensitivity analysis

Any Rockfall model is an approximation of a complex natural process. As we don't yet fully understand the rockfall process. However, there are limitations that are pertinent to this thesis and should be considered when undertaking a model using RAMMS:

- The sensitivity analysis in this thesis was run in a targeted area and due to the time constraints have not been verified in other locations that may have differing slope geometries to that of the tested site in this thesis. Although the analysis was comprehensive at this site, the fact that the data could not be verified in an area that is not the Port Hills should be taken into consideration when using elsewhere.
- The model at this stage does not have an option to enter custom substrate types, and modelling has to be done using one of the RAMMS predefined options. This generates uncertainty in the model as the substrate is one of the largest controls on a boulders behaviour.
- The Vegetation modelled in this thesis was done using one vegetation block in the Heathcote Valley, and therefore a full understanding of the effects on vegetation has not been reached. The RAMMS vegetation model works by applying a drag force to the boulder and does not take the tree to boulder interactions into consideration. Therefore it was assumed that the larger the vegetation area, the greater the effect. These interactions have the potential to alter a boulders trajectory; this is not considered in the RAMMS model.

Practitioners using this model need to consider the limitations of this sensitivity analysis as well as the limitations of the model itself. The workflow suggestions were made with these limitations in mind, though every scenario should be considered different to the next and evaluated individually.

6.4 *Contributions and future research*

As result of this thesis, questions regarding the individual parameter sensitivities in the Port Hills region for the RAMMS::Rockfall model have been determined. During this thesis, further questions were raised about the sensitivities of the RAMMS::Rockfall model and this research would benefit in answering these questions. The contributions and questions raised are outlined below:

6.4.1 Contributions

How does understanding a models sensitivities to various parameters help the practitioner make decisions when using the RAMMS software?

1) When the user understands how the model will react to changes in various parameters and how these will affect the output of the model in terms of the kinetic energy, velocity, bounce height and runout potential. Then the practitioner can then tailor their time into focussing on these parameters so that the model is as accurate as possible with the available time and data.

2) A simple and easy to follow workflow that practitioners can follow and adapt to their situation was created. As each of the input parameters has been ranked in importance from highest percentage change for a parameter to the lowest. This is shown in Table 5-1 this aims to eliminate the time that the user has to spend defining parameters that will not add to the overall value of the model. This reduces the number of models that need to be run allowing for more comprehensive models that include good quality input data.

6.4.2 Further Research

During the completion of this thesis and the sensitivity analysis for the Port Hills some questions were raised by the sensitivity analysis and the RAMMS rockfall model itself:

1) The model's sensitivities in other locations.
   This thesis provides an engineering workflow for approaching a 3D modelling scenario using the sensitivities assessed during this thesis. Due to time constraints, these sensitivities were unable to be tested in other locations around New Zealand and

abroad. This is in the pipeline for post thesis work with a site in Canada. However for the time being this work focusses solely on the Christchurch Port Hills.

2) The overall effects of vegetation on the RAMMS model.
   Vegetation is used globally as a form of rockfall mitigation (Jancke et al., 2009). Therefore, it is important to understand how interactions with this environment affect the boulder. The RAMMS rockfall model assesses this interaction by increasing the drag the boulder experiences in a vegetated area. As has been noted in the field the interaction between trees and boulders is not that simple. A boulder may miss the trees altogether and therefore not be affected by this parameter; it may also experience a glancing blow and be directed away from the boulder's current trajectory. These two events have the potential to generate a model using RAMMS that gives a false output to what may actually occur in this area.

As a result of this thesis the sensitivities within the RAMMSS::Rockfall to changes in the input parameters have been determined. The model was found to be most sensitive to changes in the substrate settings with regards to percentage changes in kinetic energy. This allowed the input parameters to be ranked from most influential to least. The sensitivities of the model were found to be respectively substrate choice, boulder characteristics and vegetation respectively. From this information, an engineering workflow was generated for both Greenfield and active sites.

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8 Appendix

8.1 Appendix A – Boulder Characteristics Results

Table 8-1 Tabulated results from the boulder sensitivity analysis for Kinetic energy, velocity and bounce heights

Size	Shape	Density	Kinetic energy	% change (density)	% change (size)	Velocity	% change (density)	% change (size)	Height	% change (density)	% change (size)
2.2	Real flat	2700 kg/m3	368.12		0	9.02		0	1.72		0
		1700 kg/m3	234.04	-36	0	9.06	0	0	1.73	1	0
	Real long	2700 kg/m3	384.12		0	9.21		0	1.61		0
		1700 kg/m3	249.43	-35	0	9.19	0	0	1.61	0	0
	Real equant	2700 kg/m3	623.28		0	11.65		0	1.79		0
		1700 kg/m3	390.41	-37	0	11.62	0	0	1.8	1	0
1.1	Real flat	2700 kg/m3	220.58		-40	9.94		10	1.45		-16
		1700 kg/m3	137.63	-38	-41	9.87	-1	9	1.41	-3	-18
	Real long	2700 kg/m3	205.52		-46	10.06		9	1.39		-14
		1700 kg/m3	129.71	-37	-48	9.89	-2	8	1.37	-1	-15
	Real equant	2700 kg/m3	380.26		-39	12.78		10	1.72		-4
		1700 kg/m3	242.04	-36	-38	12.85	1	11	1.73	1	-4
0.6	Real flat	2700 kg/m3	117.53		-68	10.09		12	1.24		-28
		1700 kg/m3	74.35	-37	-68	10.1	0	11	1.25	1	-28
	Real long	2700 kg/m3	203.48		-47	12.77		39	1.54		-4
		1700 kg/m3	129.71	-36	-48	12.84	1	40	1.56	1	-3
	Real equant	2700 kg/m3	222.05		-64	13.15		13	1.66		-7
		1700 kg/m3	142.11	-36	-64	13.24	1	14	1.67	1	-7

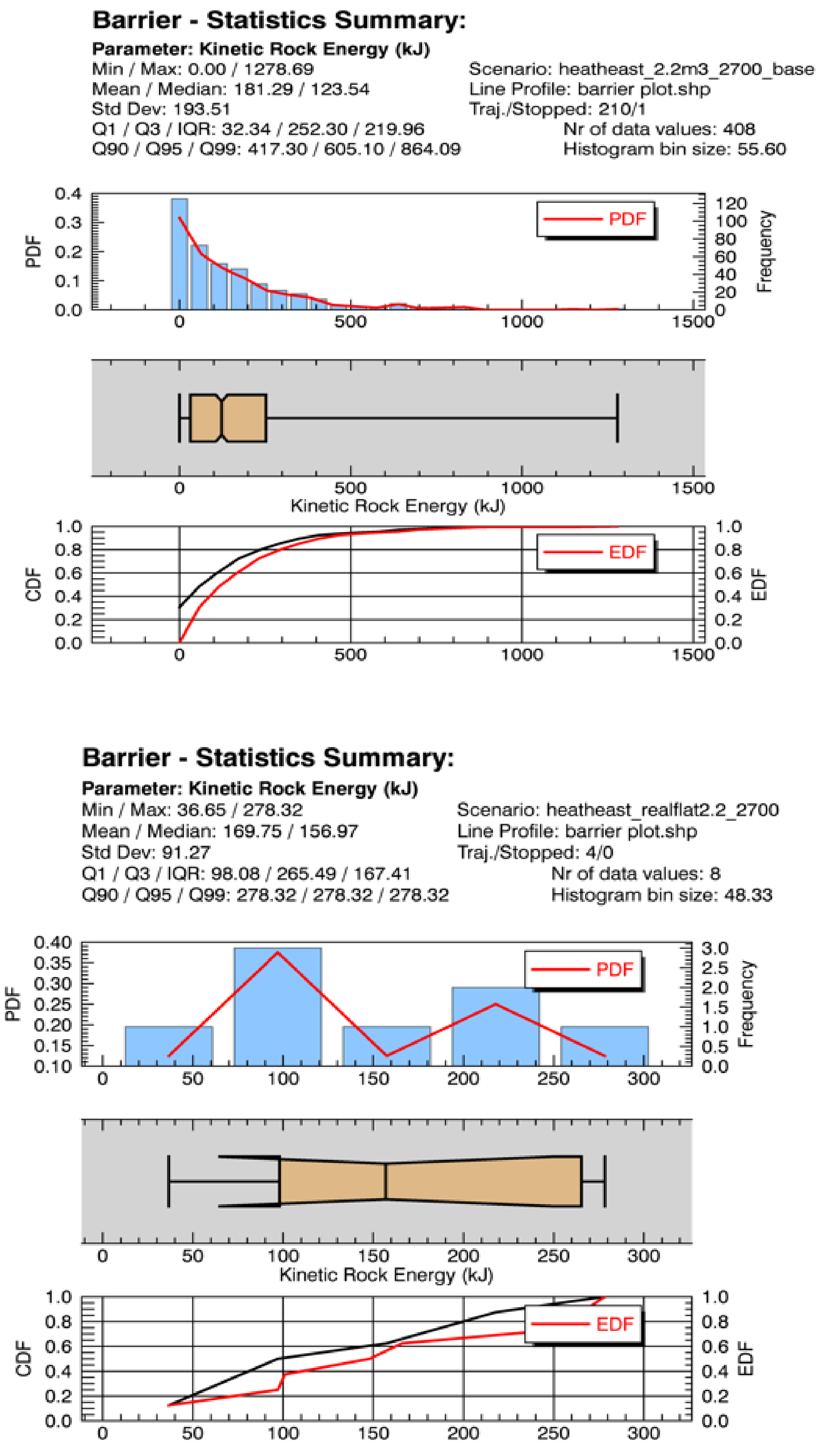
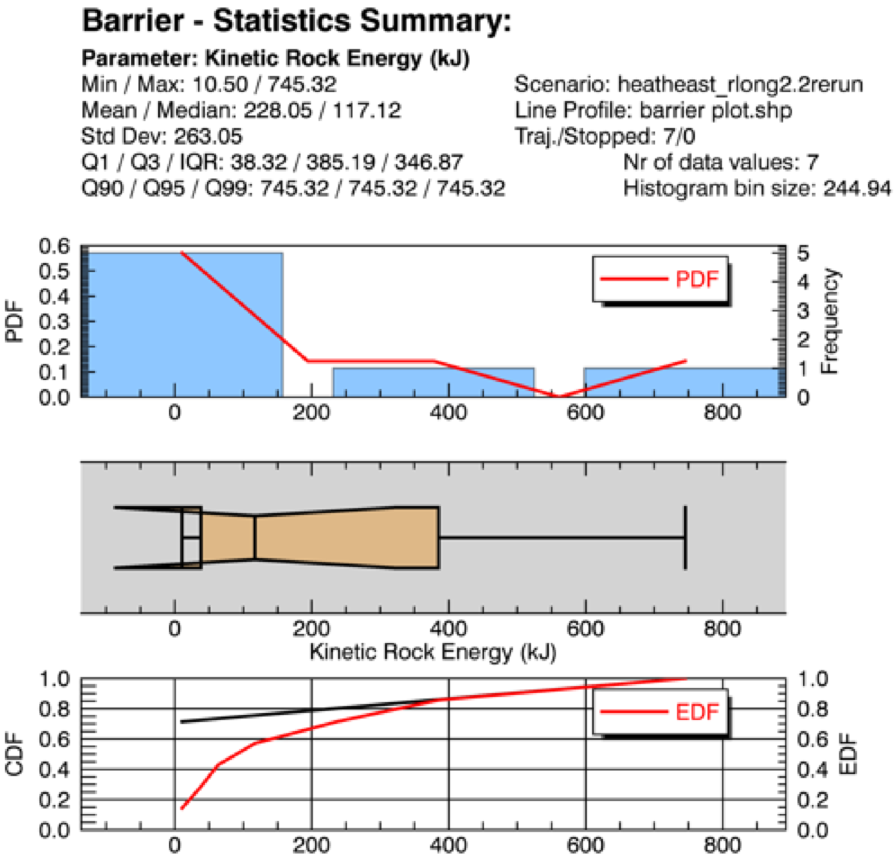


Figure8.1 Top real equant barrier plot results. Bottom Real flat barrier plot results for runout



Figur8.2 Real long barrier plot results for runout

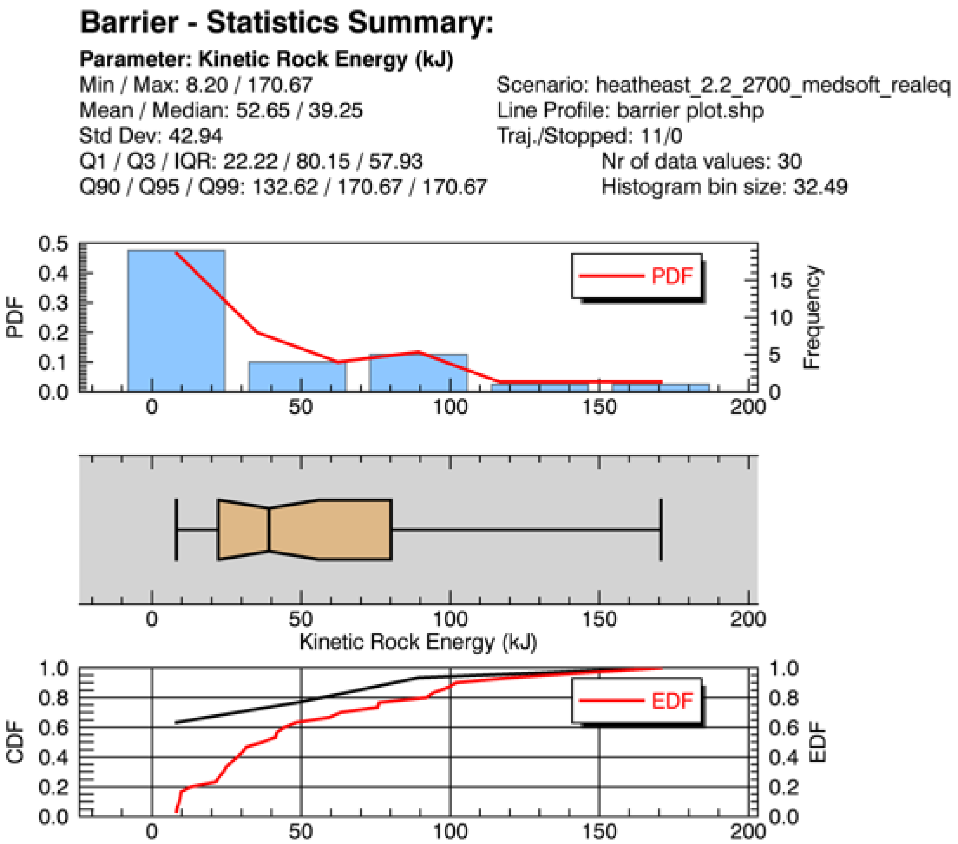
8.2 Appendix B substrate variation results

Table 8-2a Substrate sensitivity analysis results for Kinetic energy, velocity and bounce height (Data for 1.1 m^3)

Boulder Selection	**Substrate Setting**				**Individual substrate parameters**								**Output Variables**			
1.1 1700 Equant		MU min	%change	Beta	%change	Kappa	%change	Drag	%change	sum%change	Kinetic E	%change	Velocity	%change	Height	%change
	ex soft	0.2	0	50	0	1	0	0.9	0	0	37.7	0	4.77	0	0.9	0
	soft	0.25	25	100	100	1.25	25	0.8	-11	139	96	155	7.85	65	1.07	19
	med soft	0.3	50	125	150	1.5	50	0.7	-22	228	160.54	326	10.55	121	1.32	47
	medium	0.35	75	150	200	2	100	0.6	-33	342	205.45	445	11.91	150	1.54	71
	med hard	0.4	100	175	250	2.5	150	0.5	-44	456	242.04	542	12.85	169	1.73	92
	hard	0.55	175	185	270	3	200	0.4	-56	589	278.77	639	13.63	186	1.99	121
	extra hard	0.8	300	200	300	4	300	0.3	-67	833	308.17	717	14.27	199	2.18	142
1.1 2700 Equant	Substrate Setting	MU min	%change	Beta	%change	Kappa	%change	Drag	%change	sum%change	Kinetic E	%change	Velocity	%change	Height	%change
	ex soft	0.2	0	50	0	1	0	0.9	0	0	33.64	0	3.54	0	0.87	0
	soft	0.25	25	100	100	1.25	25	0.8	-11	139	151.74	302	7.83	64	1.08	20
	med soft	0.3	50	125	150	1.5	50	0.7	-22	228	211.7	462	9.45	98	1.24	38
	medium	0.35	75	150	200	2	100	0.6	-33	342	322.77	756	10.85	127	1.53	70
	med hard	0.4	100	175	250	2.5	150	0.5	-44	456	390.64	936	13.26	178	1.76	96
	hard	0.55	175	185	270	3	200	0.4	-56	589	468.64	1143	14.36	201	2.09	132
	extra hard	0.8	300	200	300	4	300	0.3	-67	833	490.37	1201	14.32	200	2.18	142

Table 8-2b substrate sensitivity analysis results for kinetic energy, velocity and bounce heights for 2.2 m³

Boulder Selection	**Substrate Setting**	**Individual substrate parameters**								**Output Variables**						
2.2 2700 Equant	Substrate Setting	MU min	%change	Beta	%change	Kappa	%change	Drag	%change	sum%change	Kinetic E	%change	Velocity	%change	Height	%change
	ex soft	0.2	0	50	0	1	0	0.9	0	0	102.4	0	4.58	0	1.09	0
	soft	0.25	25	100	100	1.25	25	0.8	-11	139	200.83	433	6.4	34	1.19	32
	med soft	0.3	50	125	150	1.5	50	0.7	-22	228	348.34	824	8.63	81	1.38	53
	medium	0.35	75	150	200	2	100	0.6	-33	342	501.81	1231	10.53	121	1.6	78
	med hard	0.4	100	175	250	2.5	150	0.5	-44	456	623.28	1553	11.65	144	1.78	98
	hard	0.55	175	185	270	3	200	0.4	-56	589	754.37	1901	12.67	166	2.1	133
	extra hard	0.8	300	200	300	4	300	0.3	-67	833	834.66	2114	13.21	177	2.29	154



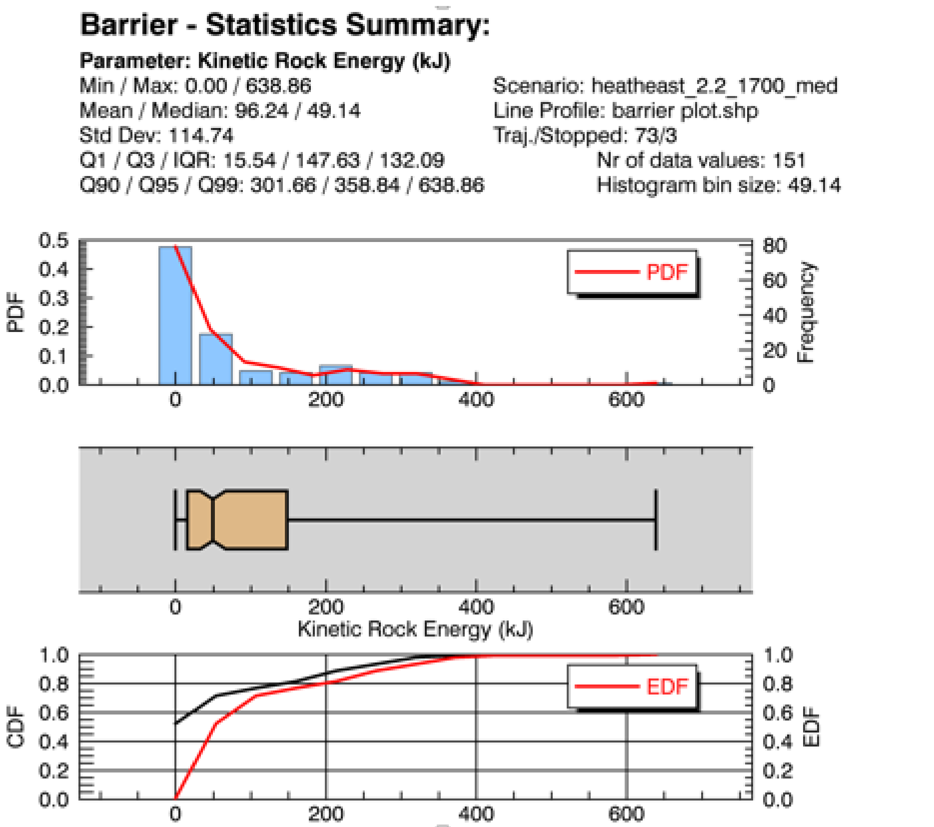


Figure 8.3 Top Med-Soft barrier plot results for runout Bottom Medium barrier plot results for runout

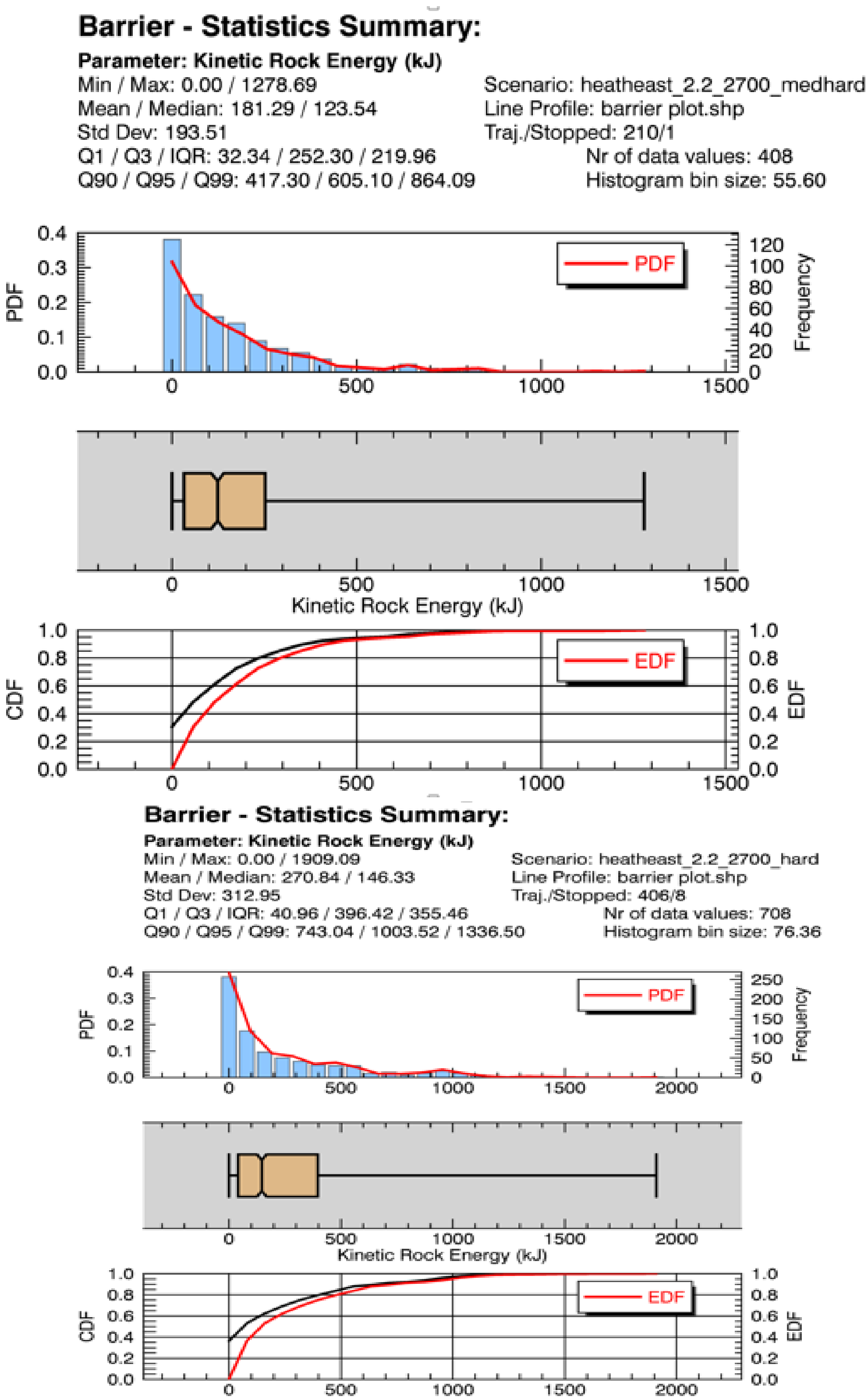


Figure 84 Top Med-hard barrier plot results for runout Bottom Hard barrier plot results for runout

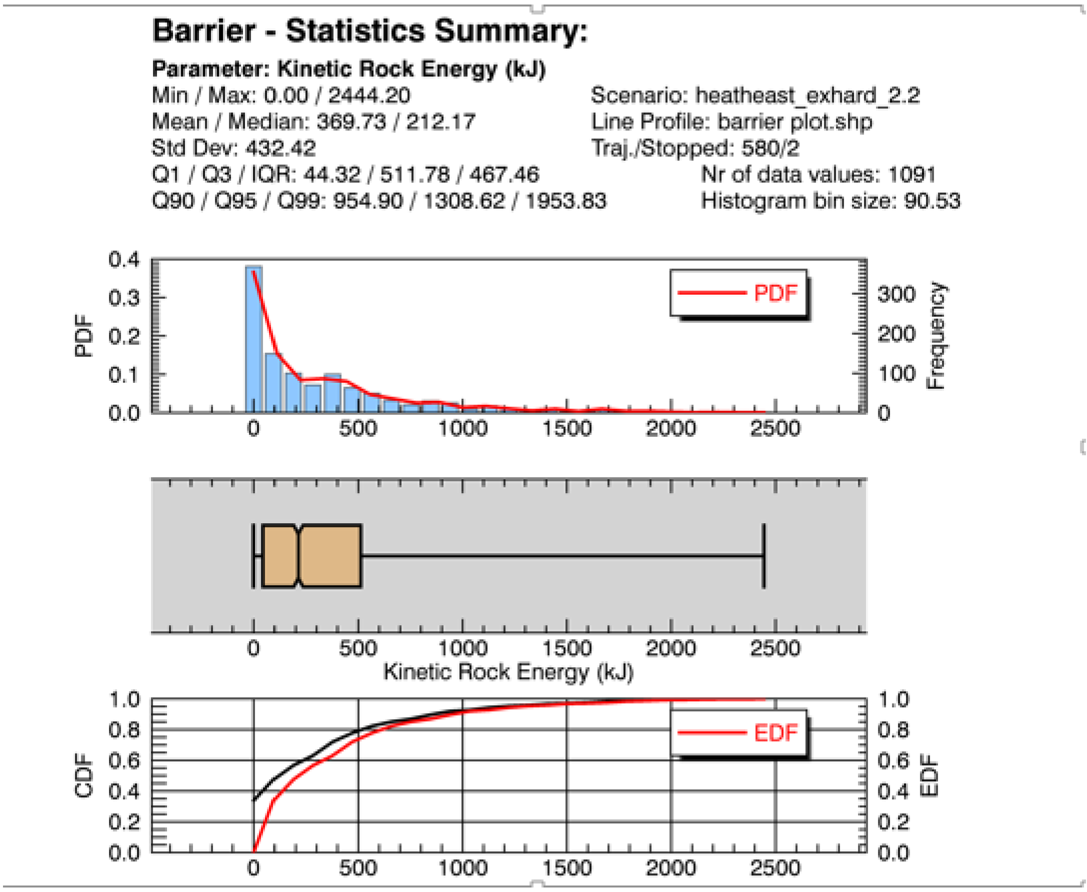


Figure 8.5 Extra-Hard barrier plot results for runout

8.3 Appendix C – Vegetation Results

Table 8-3 Vegetation sensitivity results for kinetic energy, velocity and bounce height

Drag		Kinetic eng				Velocity				Height		
None	start	end	diff	%change	start	end	diff	%change	start	end	diff	%change
0.6	265.87	145.32	**120.55**	**45.34171**	14.58	10.28	**4.3**	**29.49246**	1.75	1.36	**0.39**	22.28571
1.1	448.5	218.53	**229.97**	**51.27536**	14.03	9.23	**4.8**	**34.2124**	1.87	1.34	**0.53**	28.34225
2.2	1253.1	730.94	**522.16**	**41.66946**	14.82	10.76	**4.06**	**27.39541**	2.23	1.75	**0.48**	21.52466
250		Kinetic eng				Velocity				Height		
0.6	265.69	94.78	**50.36**	**18.95442**	14.58	7.88	**2.4**	**16.46091**	1.75	1.1	**0.26**	14.85714
1.1	448.42	168.54	**49.91**	**11.13019**	14.02	7.86	**1.36**	**9.700428**	1.87	1.18	**0.16**	8.55615
2.2	1227.96	646.31	**59.49**	**4.84462**	14.66	10.05	**0.55**	**3.751705**	2.22	1.64	**0.1**	4.504505
500		Kinetic eng				Velocity				Height		
0.6	265.52	66.32	**78.65**	**29.62112**	14.57	6.33	**3.94**	**27.04187**	1.75	0.94	**0.42**	24
1.1	448.51	135.82	**82.72**	**18.44329**	14.03	6.84	**2.39**	**17.03493**	1.87	1.1	**0.24**	12.83422
2.2	1267.31	608.35	**136.8**	**10.79452**	14.92	9.67	**1.19**	**7.975871**	2.23	1.68	**0.07**	3.139013
750		Kinetic eng				Velocity				Height		
0.6	265.53	49.12	**95.86**	**36.10138**	14.69	5.39	**5**	**34.03676**	1.78	0.84	**0.55**	30.89888
1.1	448.58	108.88	**109.73**	**24.46163**	14.03	5.95	**3.28**	**23.37847**	1.87	1	**0.34**	18.18182
2.2	1227.18	536.91	**168.11**	**13.69889**	14.65	8.94	**1.65**	**11.2628**	2.22	1.56	**0.18**	8.108108

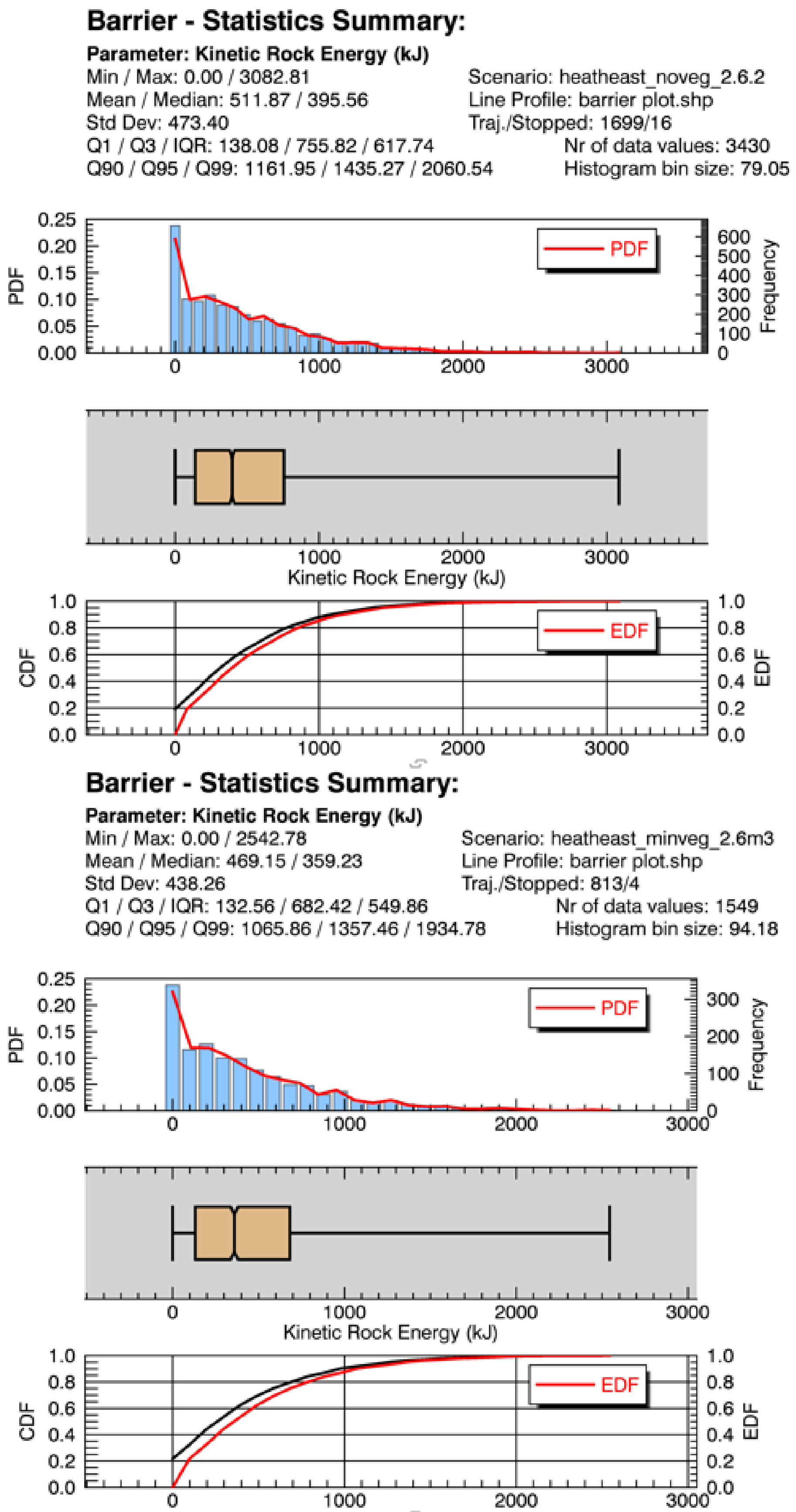
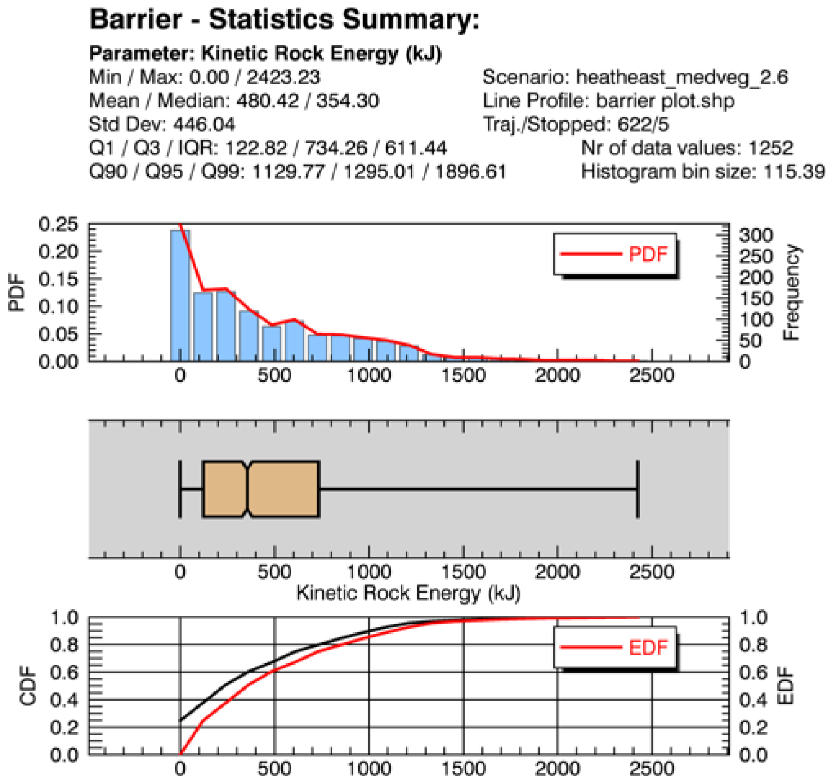


Figure 8.6 Top no veg barrier plot results for runout. Bottom Min vegetation barrier plot results for runout



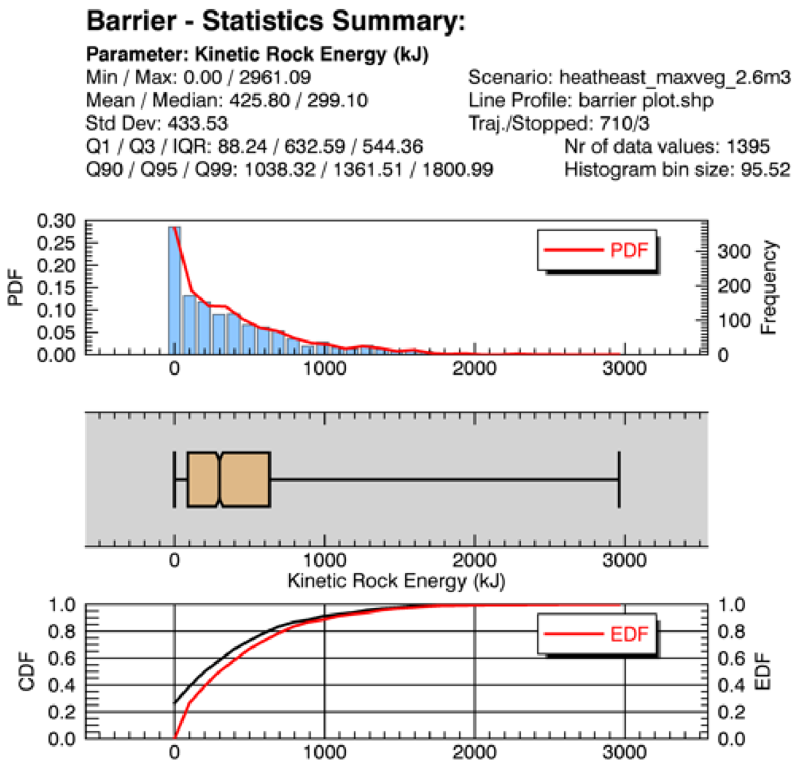


Figure 8.7 Top medium vegetation barrier plot results for runout. Bottom max vegetation barrier plot results for runout