POLITECNICO DI TORINO

Department of Structural, Geotechnical and Building Engineering

Master's Degree in Building Engineering

LM-24 Construction Engineering

ROCKFALL ANALYSIS AND MITIGATION STRATEGIES: THE CASE STUDY OF VARALLO (VC)

Supervisor
Prof. Barbero Monica

Student
Ali Haider s314048

Co Supervisors
Eng. Napoli Maria Lia
Dr. Cavagnino Giovanni

Academic year 2022/23

Acknowledgement

I wish to express my sincere gratitude to my esteemed thesis advisor, Professor Monica Barbero. Her unwavering guidance, invaluable support, and encouragement have been pivotal throughout this research journey. Professor Napoli Maria Lia expertise and profound insights have significantly shaped the direction and focus of this study.

I am also indebted to *Polito* for providing the essential resources and state-of-the-art facilities that facilitated the execution of this research. Their commitment to academic excellence has been instrumental in the successful completion of this work.

Furthermore, I extend heartfelt thanks to my colleagues and peers. Their encouragement, stimulating discussions, and unwavering moral support have been a source of inspiration during this scholarly pursuit.

Lastly, my deepest appreciation goes to my family. Their boundless love, understanding, and unwavering encouragement have served as the bedrock of strength during the challenges encountered on this academic voyage.

Abstract

This Thesis deals with the rockfall instability problem and its mitigation. In particular, the case of a slope in Varallo (VC, North-West Italy) prone to rockfall phenomena over the years, with consequences on the road located at its toe, has been analyzed. 2D stochastic analyses have been performed, by using Computer Simulation Tool Rock Science and a strategy to put in safety the road has been suggested. The study starts with the estimation of the rock block volume to be considered for the analyses (the “design block”), by using different methodologies available in literature for assessing the rock block volumes, from the simplest (based on the blocks already fallen at the base of the slope), to a more complex statistical analysis. Then, the parameters involved in the trajectories simulations have been defined by a back analyses, on the event occurred in November 2023. Other simulations have been carried out by considering different scenarios (volumes of the rock block). The study ends with the suggestion and design of two different interventions for the mitigation of the rockfall risk, on the basis of the results obtained from the trajectories analyses.

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION TO ROCKFALL

In regions characterized by rugged landscapes and steep slopes, rockfalls often occur, triggered by the natural processes such as earthquakes, rainfall, erosion and weathering. These events, in which rocks and debris break away from cliffs and slopes, pose a significant risk to both the environment and human structures and infrastructures. The extent of rockfall can vary greatly and is influenced by predisposing factors such as geological composition, slope inclination. One of the main problems associated with rockfalls is that they can disrupt highways, railroads and other major transportation routes often pass through mountainous regions and are therefore susceptible to rock fall hazards. The effects of such disruptions can be far-reaching, causing delays in the transportation of goods, damage to infrastructure and even endangering the lives of travelers.

Figure 1.1.1 *Damage due to RockFall*

In addition, settlements and infrastructure at the foot of steep slopes are also at risk from rock fall. Buildings, bridges and other structures can be endangered by falling rocks, posing a threat to public safety and property. In addition, in industries such as quarrying, where rock formations are extracted on a large scale, there is an increased risk of falling rocks that can endanger workers and equipment.

Comprehensive rock fall mitigation strategies are essential to counter these risks. These include a combination of geological assessments, monitoring systems and technical measures aimed at stabilizing slopes and protecting vulnerable areas. Structural measures such as barriers and retaining walls can help divert falling rocks away from critical infrastructure, reducing the risk of damage and injury.

Despite these efforts, the unpredictable nature of rock falls means that they remain a constant challenge for communities and authorities in mountainous regions. Even minor incidents involving small stones or debris can pose a significant risk to road users and pedestrians. Therefore, constant vigilance and proactive measures are required to minimize the impact of rock falls on human safety and infrastructure resilience.

Rockfalls represent a complex and persistent hazard in mountainous and hilly terrain, with far-reaching implications for both natural ecosystems and human society. By understanding the underlying mechanisms driving rock falls and implementing effective mitigation strategies, we can work towards mitigating their impact and ensuring the safety and sustainability of communities living and working in these challenging environments.

1.1. RockFall Triggering Factors

The behavior of a rockfall is unpredictable and there are many factors that can trigger rockfalls along an excavated and/or a natural slope. The factors causing a rock fall can be divided into two categories: structural and environmental. Of the structural factors, clearly potentially loose rock mass must exist on the surface of the slope. In the case of a pebble or boulder, this will have undergone a previous movement. In the case of a rock mass, it must be sufficiently fissured to produce potentially unstable blocks.

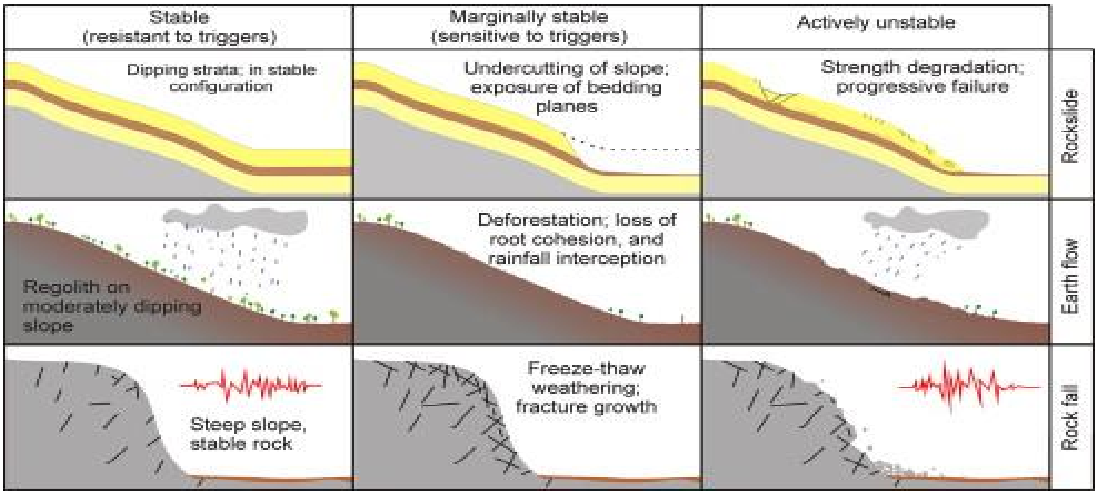


__Figure 1.1.1__ Demonstration of Triggering Factors (https://www.sciencedirect.com/science/article/pii/B9780123964526000021)

The slope on which the rock or boulder is situated must be steep enough to promote instability and to encourage continued movement resulting from this. Environmental factors generally act as triggering forces but may also influence the structure of the surface and hence induce instability. Physical and chemical weathering are the chief agents primarily responsible for rock falls. Joints or discontinuities formed by planes of weakness or previous deformation provide egress for water and vegetation.

This further reduces joint strength by a combination of frost and root wedging, erosion and increased pore water pressures producing a reduction of cohesive strength and frictional resistance to motion. Water pressure acting within joints can have an important effect with similar results.

Heavy rainfall can itself act as a trigger by producing a forceful stream of water or by erosion of stabilizing material. Particularly dangerous is differential weathering in which a weak rock is removed leaving a more resistant rock unsupported as an overhanging ledge. Earthquakes are another common source of environmental trigger but any source of ground borne vibration will suffice. Manmade vibration, due to blasting, operating of construction plant and machinery, the process of excavation itself and passing traffic can all effectively trigger a rock fall. Movement of people and animals on the slope can also act as triggers.

1.2. Factors Affecting Rockfall

Once rock fall has been initiated, its behavior is influenced chiefly by the slop geometry, material and surface cover and the rock geometry and material properties.

Slope geometry can be divided into slope inclination, slope length, surface roughness and lateral variation. The first two factors are very important. The slope inclination defines zones of acceleration and deceleration and the slope length determines the distance over which the rock can be accelerated or decelerated, surface irregularities alter the angle at which a rock impacts the surface and thus are significant in determining the character of the bounce. The effect of lateral variability is usually to channel falling rocks in a certain direction - for example down a gully, which could affect the velocity of the rocks.

The material properties and nature of the covering of the slope influence the behavior of the bounce, which is generally defined in terms of the normal and tangential coefficients of restitution of the rock block on the slope. Rock properties that affect rock fall behavior are its size, friction angle, shape, and mass. Mass and size are important because a larger and heavier rock has greater momentum, is less likely to lodge among irregularities and will therefore travel further downslope. Shape and strength are also important. A spherical rock will obviously travel further than an angular one, as will a rock that does not break apart on impact.

Human-made alterations to the topography, including constructions like roads or retaining walls, can also create new pathways for rock fall or influence the natural flow of rocks down the slope. The integrity of the rocks themselves, their size, angularity, and lithology, further dictate their behavior during descent and impact. Weaker or weathered rocks may break apart more easily upon landing, while larger rocks possess greater kinetic energy and potential for damage.

1.3. Rockfall Failure Mechanism

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 discontinuities include bedding planes, cooling joints and deformation features such as stress induced fractures, joints and faults.

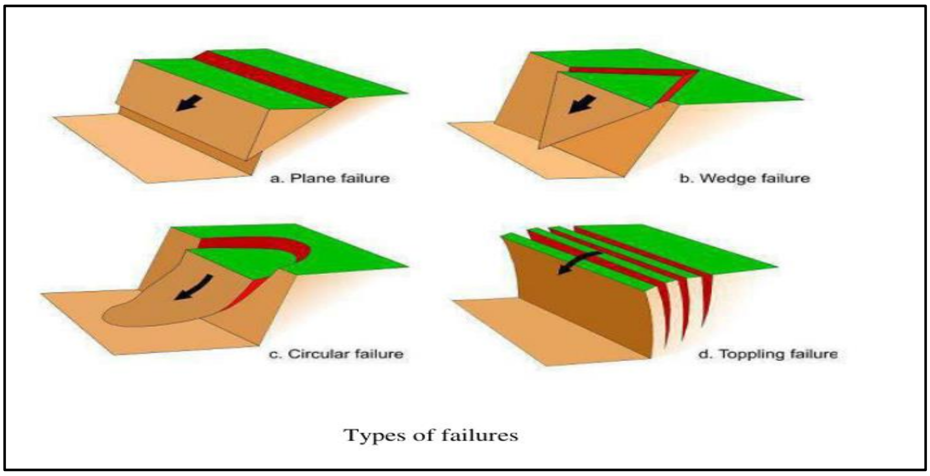


Figure 1.3.1 *Types of RockFall Failures*
Ref. https://slideplayer.com/user/5148433/

It is the orientation of these discontinuities or sets of discontinuities with respect to the slope face that control the kinematic feasibility and the manner in which a rock mass may fail. If these sets are the right orientation, they can form segments of unstable block masses. This is determined using the dip and dip 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. 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.

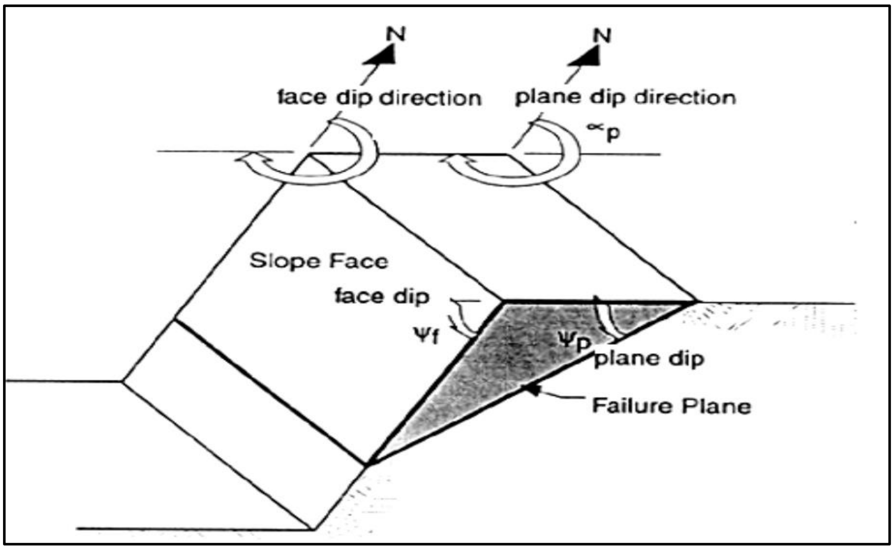


Figure 1.3.2 *Plan Failure with Condition of Failures.*
https://slideplayer.com/user/5148433/

The favorable conditions of plane failure are as follows:

The dip direction of the planar discontinuity must be within (±20°). The dip of the planar discontinuity must be less than the dip of the slope face (Daylight)) of the dip direction of the slope face (Figure 3).The dip of the planar discontinuity must be greater than the angle of friction of the surface.

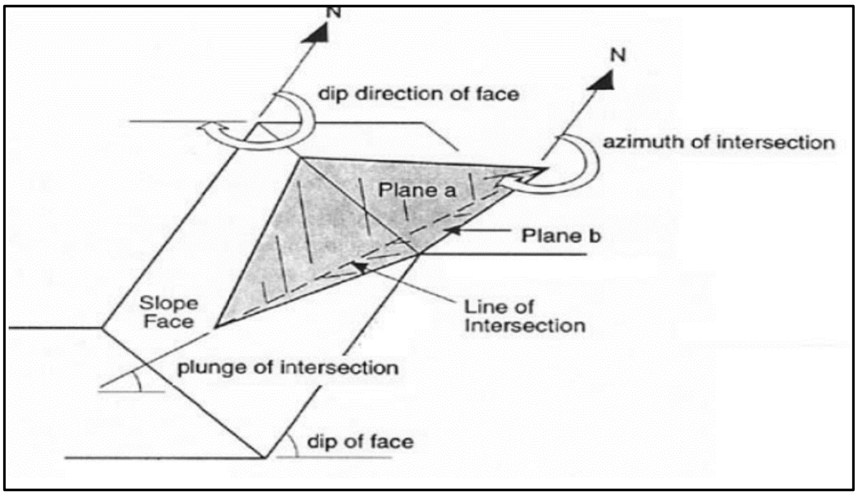


__Figure 1.3.3__ Wedge Failure with Condition of Failures.
https://slideplayer.com/user/5148433/

The structural conditions for this failure shown in **Fig 1.4.1.3**.are summarized as follows: A wedge failure can occur, the line of intersection between two joint planes must approximate the **dip direction** of the slope face because this alignment enables the wedge to move in the same direction as the slope, increasing the likelihood of failure. **The plunge of the line of intersection** must be less than the slope's dip so that the line daylights, meaning the intersection is exposed on the slope surface, making detachment possible. Additionally the plunge must exceed the friction angle of the joint surfaces to overcome frictional resistance allowing the wedge to slide.

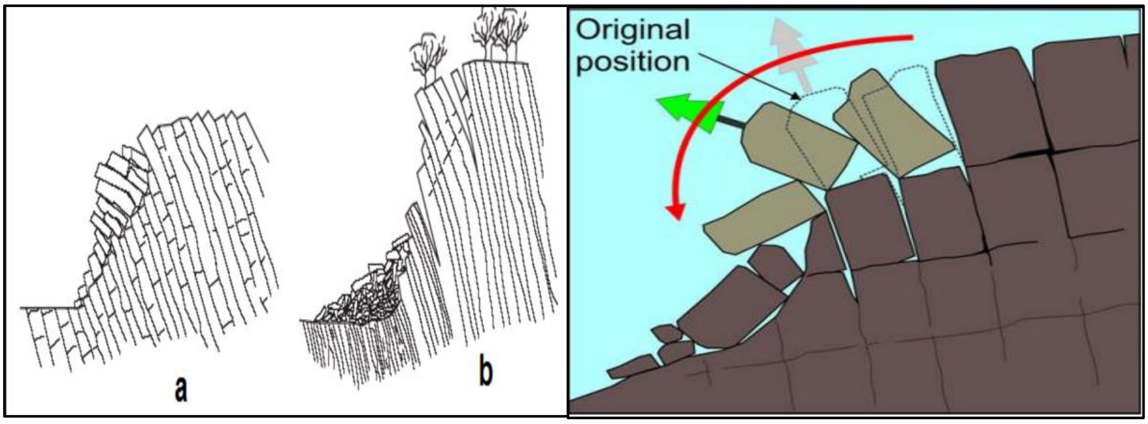


__Figure 1.3.4__ Schematic view of Toppling Failure

Toppling failures occur when columns of rock, formed by steeply dipping discontinuities in the rock rotates about an essentially fixed point at or near the base of the slope followed by slippage between the layers (Figure 6). The center of gravity of the column or slab must fall outside the dimension of its base in toppling failure. Jointed rock mass closely spaced and steeply dipping discontinuity sets that dip away from the slope surface are necessary prerequisites for toppling failure.

1.4. Discontinuity Survey of Rock Mass

A survey is conducted for analyzing the discontinuities in the rock mass. It is really crucial for making a 2D profile rock slope which requires some input parameters obtained from discontinuity survey.

The first and foremost thing for commencing the survey is to identify the type of discontinuity such as joint fault and cleavage shear Once the type of discontinuity is identified, it is need to measure the Dip that refers to the angle at which a rock layer or geological structure inclines from the horizontal plane. It indicates the steepest angle of descent of the rock layer or structure and dip direction and Dip direction indicates the compass direction in which the steepest angle of descent occurs. It is typically measured clockwise from true north. The next thing to look for is the persistence which shows the length of discontinuity which could be opened or filled with some material such as clay debris etc. in which the thickness of joint opening is measured known as aperture in geological terms. The last two things to measure are Surface roughness and distance between faults line. After obtaining these useful data from sites,

1.4.1. Stereogram diagrams

Stereogram is commonly used in the discontinuity survey of rock masses to understand the orientation and distribution of fractures or discontinuities within the rock. These diagrams provide a graphical representation of the orientation data collected during field surveys, allowing geologists and engineers to visualize the patterns of fractures in three-dimensional space.

Orientation Analysis: Stereograms help in analyzing the orientation of discontinuities within the rock mass. By plotting data points representing the orientation of fractures on the stereogram, geologists can identify dominant fracture sets and their spatial distribution.

Structural Mapping: Stereograms aid in creating structural maps of rock masses, which are essential for assessing the stability of slopes, tunnels, and other engineering structures. Understanding the orientation and spatial arrangement of fractures helps in predicting potential failure mechanisms.

Rockfall Analysis: Stereogram data is used in rock fall analysis to assess the susceptibility of rock slopes to failure and to identify potential failure mechanisms. By incorporating information about fracture orientations and spacing obtained from stereograms, engineers can assess the likelihood of rock fall events occurring in specific areas, as well as their volumes.

1.4.2. Application of Stereogram in RockFall Analysis

Identifying Potential Failure Planes: Stereograms help in identifying discontinuity sets that may act as potential failure planes for rockfall events. By analyzing the distribution of fractures on the stereogram, engineers can identify clusters of fractures that may contribute to rockfall hazards.

Modeling Rockfall Trajectories: The orientation data obtained from stereograms is used to define the geometry of rock slopes in numerical models. By incorporating fracture orientations and spacing information, engineers can simulate rockfall trajectories and assess the potential reach and impact of falling rocks

1.4.3. Parameters Required for Stereogram Construction

Orientation Data: Field measurements of fracture orientations are collected using tools such as a compass or digital clinometer. These measurements include the dip direction (direction) and dip (angle of inclination) of each discontinuity.

Plotting Coordinates: Each orientation measurement is represented as a data point on the stereogram. These points are plotted using spherical coordinates, typically involving azimuth (horizontal angle) and inclination (vertical angle) values.

1.5. Rockfall Hazard Assessment

In rockfall terminology, the rockfall hazard refers to the probability of occurrence of an event (rockfall) of a given magnitude (volume) or intensity (energy) over a predefined period of time and within a given area This definition includes the concepts of location (where a rockfall event will occur), frequency (i.e., its temporal recurrence) and magnitude or intensity (i.e., amount of energy involved). Thus, the simplest rockfall hazard map should describe the probability of occurrence of rock falls of a predefined magnitude within a given area, Because of the high mobility of rockfall events, the propagation (or transit) component must also be taken into account in rockfall hazard assessments. Hence, rockfall hazards are generally recognized to depend on three factors;

Probability of detachment from the rock wall: the probability that a rockfall of a given magnitude (i.e., block size) occurs at a given source location over a Qualitative Rockfall Hazard Assessment: This parameter involves both the spatial probability of occurrence (i.e., **susceptibility**) and the related temporal probability, which is also called the probability of failure (i.e., **frequency**).

Propagation down the slope the trajectory and maximum run out of falling blocks

Rockfall intensity (i.e., kinetic energy).

1.5.1. Susceptibility:

Susceptibility is the likelihood that an event will occur in a specific area based on the local terrain conditions. The susceptibility describes the predisposition of an area to be affected by a given future event and results in an estimate of where rock falls are likely to occur. . Several methods have been proposed in the literature to identify the locations of probable rockfall events.

- Geomorphological mapping using qualitative and direct methods
- Empirical and semi-empirical rating systems
- Statistical analyses
- Deterministic methods

1.5.2. Frequency

In addition to the susceptibility, the temporal probability of failure must be addressed to define the probability of the occurrence of a rockfall event. It can be expressed in terms of the frequency of occurrence or the return period (defined as the inverse of the frequency). The temporal probability of a rockfall with a given volume should be evaluated through the statistical analysis of historical events that have occurred in the study area. The most common approach to estimating the rockfall frequency is the analysis of site-specific rockfall inventories that provide volume and time history information for each rockfall event. A magnitude-cumulative frequency relationship can be constructed from these observations to evaluate the annual frequencies of rockfall events in specified volume classes. If there are no historical rockfall events, the frequency or return period cannot be accurately assessed; hence, only the rockfall susceptibility (and not the hazard) can be evaluated.

1.5.3. Propagation

The propagation of a rockfall event is related to the runout of a falling block and refers to the block's trajectory during its movement down the slope. The trajectory generally depends on the features of both the block and the slope, including the starting location of the block, its mass and shape, the topography of the slope, the outcropping material, the presence of vegetation and the slope roughness. Several methods have been proposed in the scientific literature for evaluating rockfall propagation, and they can be classified into two main categories:

- Empirical method
- Physics-based methods:

2. ROCKFALL DYNAMICS, ANALYSIS AND PROTECTION MEASURES

Rockfall analysis involves assessing the behavior and impact of falling rocks to understand the potential hazards they pose. It's comprised of two main components:

Invasion Area:

This refers to the area where rocks end up after they fall. It's like observing where the rocks roll and come to a stop.

Components:

Trajectories: These are the paths the rocks take as they fall. By tracking these trajectories, we can understand the direction and distance traveled by the falling rocks.

Runout: This refers to how far the rocks travel before they come to a stop. It indicates the extent of the affected area and helps assess the potential reach of rockfall events.

Intensity:

Intensity relates to how severe the rock fall event is. It involves measuring factors such as the velocity of the falling rocks and the kinetic energy they possess upon impact.

Components:

Velocity: This measures how fast the rocks are moving as they fall. Higher velocities indicate greater potential for damage and danger.

Kinetic Energy: This quantifies the energy possessed by the falling rocks due to their motion. It reflects the destructive potential of the rockfall event upon impact.

Understanding Rockfalls:

To gain a better understanding of rockfalls, several questions are posed:

Dynamics of the Falling Block:

This question delves into how rocks move and change as they fall. Understanding the dynamics of falling rocks helps in predicting their behavior and assessing the associated hazards e.g. observing whether rocks tumble, slide, or bounce as they descend can provide insights into their behavior and potential trajectory.

2.1. Phases of Motion

There are several steps and factors to consider when studying how rocks move during a rock fall.

2.1.1. Detachment

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. 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).

The size of the blocks that are released from the outcrop is determined by the spacing between the discontinuities in the rock mass. Smaller blocks will be released from a severely fragmented rock mass with tightly spaced discontinuities than from a rock mass with widely separated discontinuities, which may release significantly bigger chunks because of the closely spaced discontinuities that create many small segments or blocks, as each fracture or joint defines a boundary where the rock can easily separate. When discontinuities are tightly spaced, these planes intersect more frequently, resulting in the formation of smaller blocks. In contrast, widely spaced discontinuities create larger segments of rock, as fewer fractures or joints are present to break the rock into smaller pieces. This means that the rock mass is divided into larger volumes, leading to the release of significantly bigger chunks when failure occurs

2.1.2. Initial Impact (Rock Block Motion in the Air)

A rock may experience free fall once it exits the source. When the slope angle is more than 70 °, this procedure takes place. If the angle of slope be less than 70 °. the block will probably make a sequence of bounces, rolls, and sliding motions as it descends the slope. In the process of rockfall, the first contact on a block's trajectory is quite important. The block is likely to run out of slope if it is sourced from a location that is far above the first impact zone because potential energy is transformed into kinetic energy. The block won't have as much kinetic energy, though, and it will probably bounce once before stopping or stopping on the initial collision if the source is low above the impact area.

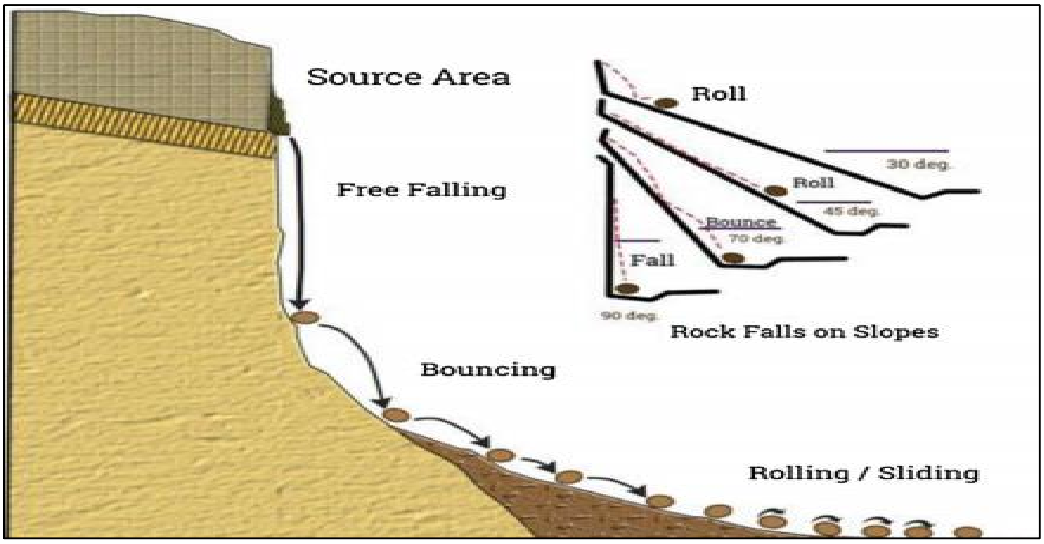


Figure 2.1.1 *General modes of motion of rocks*
(Ritchie AM (1963) Evaluation of rockfall and its control. Highw Res Rec 17:13–28)

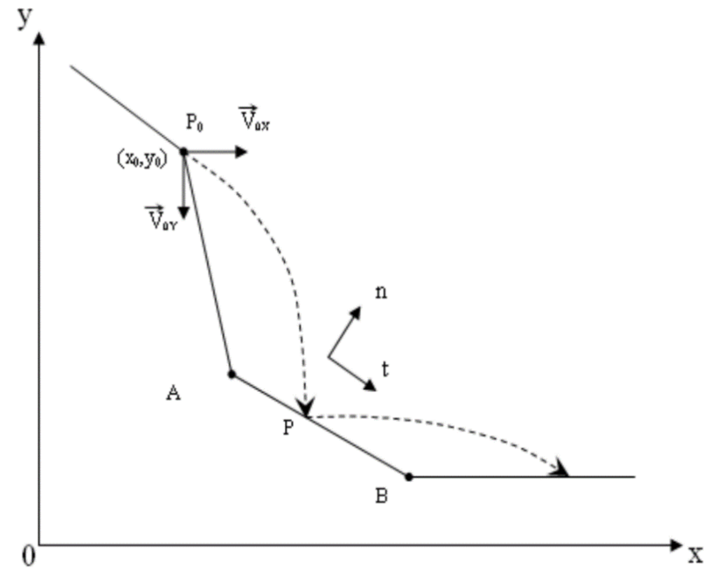
The overall angular momentum of a block increases after the first initial impact and will then continue to increase until it reaches a maximum rotational velocity, following this point the block is affected by each impact.

The ground conditions dictate how much kinetic energy is wasted during the initial impact and subsequent collisions with the slope surface. It has been found that a block loses 75-86% of its original free fall energy upon collision. The rigidity of the hard surface allows the boulder to retain more energy during strikes. Soft surfaces, such as dirt, deform under the pressure of a collision, leaving impact scars. This process consumes some of the block's energy, causing it to slow down and shorten its runout period. The kinetic energy obtained during free fall, together with the characteristics listed above, will decide whether a block is bouncing, rolling, sliding, or even moving at all after the initial encounter at the slope.

Another factor to consider throughout the rockfall process is the interaction with other blocks. Moving down the slope. Although this is known to happen in the field, there is little information on how it affects the block's trajectory. Because blocks seldom contact with one another in a rock fall event, the effects of block interaction on one another are expected to be minimal. This is a significant interaction in rock avalanches since block contact is continual in these motions. However, the rockfall process appears to be fragmented, with just a small number of blocks.

2.1.3. Ballistic Trajectory (Impact of Rock Block on the Slope)

A block may be propelled into a ballistic trajectory following its first collision with the slope; this trajectory resembles a parabolic arc with bounces in between. This only happens when there is more kinetic energy in the block than is absorbed during the collision. The block travels at a steady horizontal velocity during this stage of the rockfall process, with the minimal contribution of aerodynamic drag. Depending on the stage at which the block is in its movement, it has a different vertical velocity. Gravity governs the vertical velocity. 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.



- The graph showing trajectory with a rock starts falling at point P_0.
- The vectors V_{ox} and V_{oy} shows the starting velocity of the rock right when it starts falling.
- Point A is where the rock is at some moment when it is in the air.
- Pont B is where the rock will land if it keeps going on its path.

Figure 2.1.2 Plotting of Rockfall Position, Movement and Direction on 2D Graph.

Starting Position P_o (X_o, Y_o)
This is the spot where rock block detaches and starts to fall with X_o and Y_o being the co-ordinates of the graph.

To find out where the position of the rock will be at any given moment, the equation will be given as,

$X = V_{ox} * t + X_o$ **Eq (1)**

This is for finding out how far along the ground (x-direction), the rock has travelled after a certain amount of time

$Y = ½ * g * t^2 + V_{oy} * t + y_o$ **Eq (2)**

It tells us how high above the ground, the rock is after the same amount of time.
In the graph **n** represents the normal force that acts perpendicular to the surface of the rocks mover over, like an invisible push coming from the ground.

The point where the impact between block and slope occur are obtained by the intersection of the parabola and the lines through two points of the profile A (X_1 , X_2) and B (X_2 , Y_2).
The following system has to be solved

$$Y = -\frac{1}{2}\, g \frac{(X - X_0)^2}{V_{ox}^2} + V_{oy}\frac{X - X_0}{V_{ox}} + Y_0$$ **Eq (3a)**

$$\frac{Y - Y_1}{Y_2 - Y_1} = \frac{X - X_1}{X - X_1}$$ **Eq (3b)**

The solution of the system gives the co-ordinates of the impact point.

2.1.4. Block Slope Interaction

One of the trickiest aspects of a rockfall event is the way a block interacts with the slope as it falls. Since these interactions directly affect how the block behaves during the rockfall event, it is also one of the most significant. The dynamics of the block's interactions with the ground create the complexity of this process, which is influenced by a number of variables including velocity, impacting angle, angular momentum, properties of the soil and rock, slope angle, block dimensions, block mass, and even the weather at the time of impact (wet soils dissipate more energy than that of dry soils). Other rockfall processes are also governed by this interaction, such as the launch angle of a block, which is managed by the block’s 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.

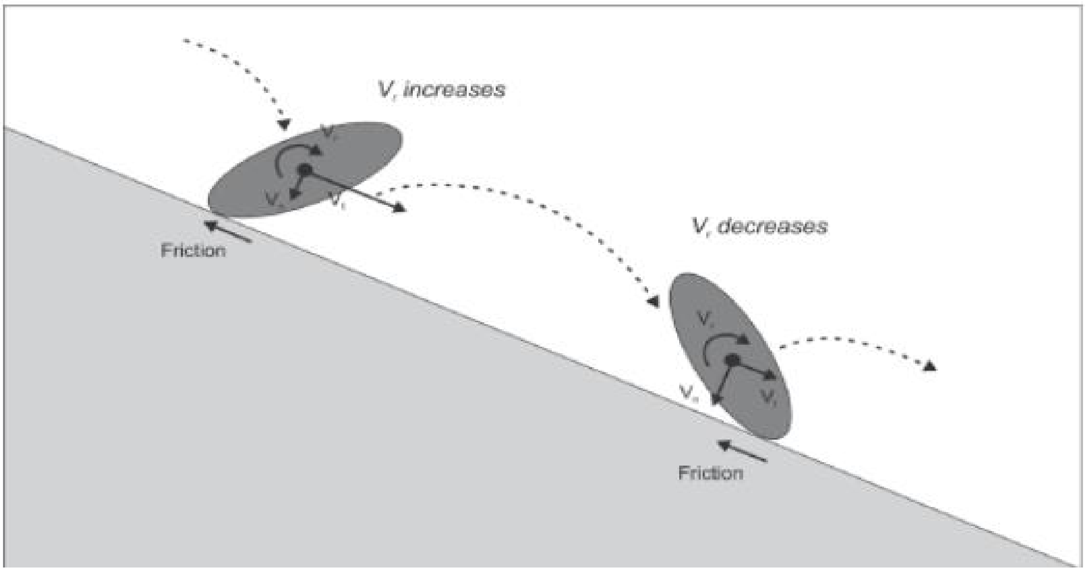


Figure 2.1.3 *Block Slope Interaction*
Anthony Botha, *(April 2017) creating an engineering modelling workflow for ramms:: rockfall, using the input parameter sensitivities.*

2.1.5. Block Motion along the Slope

The number of ballistic trajectory events that a block will experience may be determined by counting the bounces it experiences throughout the rockfall process. A block can also roll (when at least one surface or point of the block is in contact with the slope surface at any given time during its rotation around its center of mass) and slide (when the block is no longer rotating around its center of mass and one surface of the block is in constant contact with the slope surface), which are movements that occur in decreasing order of energy. Variations in the slope's angle are frequently cited as the cause of the shifts between these modes. The block loses kinetic energy and can no longer retain its current phase, forcing it to transition to the next one in the process as the slope's angle falls and the potential energy from the fall distance diminishes. The block slides down the hill as it loses kinetic energy, rotational momentum, and maybe its ability to maintain a rolling motion.

2.1.6. Slope Vegetation

Similar to how substrate material interacts with the block in the case of grasses and shrubs, vegetation on the rockfall route can also have an impact on the block motion . This is because these materials cause the block to experience additional drag. Trees are another source of impact; they provide substantial barriers that a block must go through. This might potentially slow down or halt a boulder. Trees with sufficiently robust trunks that are broader than the impacting block have the ability to divert a block off its intended path. When the block strikes the tree trunk distant from its center of mass, something happens.

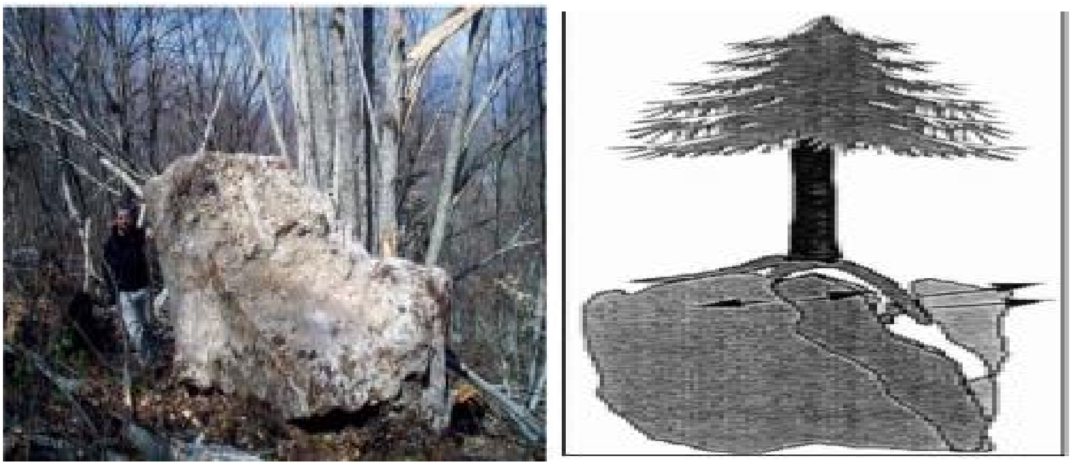


Figure 2.1.4 *RockFall Protection due to Slope Vegetation*

2.1.7. RockFall Runout

The distance a block will eventually move from the source location depends on all of the previously discussed factors. The block's form and the axis it moves along are two of the main variables in this equation. Comparable in mass and composition, spherical blocks move further and quicker than tubular and discoidal pieces. This is because, in comparison to tubular blocks, they have less angular edges on the block to cause friction with the surface. Additionally, a spherical shape may retain angular momentum far more easily than forms like tubular and flat blocks. This isn't always the case, though. A tubular block can move along its short axis, it may travel at velocities similar to those of a spherical block. It is known that larger blocks composed of the same material travel farther than smaller blocks .This is so because mass affects kinetic energy. A block has greater motion the more mass and energy it possesses. Therefore, the likelihood of it being slowed down by talus debris and vegetation or other irregularities in the slope is reduced.

Blocks will ultimately land in different places even under constant release conditions because the final trajectory of a block is determined by a number of variable slope-related elements. On the other hand, several inferences can be drawn from the literature: larger and more massive blocks will usually move farther than their smaller counterparts, and blocks will be able to travel farther from the source on slopes with steeper gradients.

2.1.8. Conclusion on RockFall Dynamics

The movement of rockfall could be unpredictable therefore scientists use stochastic methods to deal with randomness, instead of assuming the block will definitely stop in a given point, they might say there’s a 70% chance that the rock will around this area. Geologists look at what has happened in the past RockFalls and use that information to predict what might happen in future ones. This might be done running computer simulations to see all the different ways the rock could fall and where they might end up. It helps to understand risks and take more informed decisions

A model's final result is influenced by a number of factors in a complex process called rockfall. They pose a serious risk to persons and property because of their tremendous velocities, energy, and unpredictable motion. It is a difficult undertaking to determine a slope's sensitivity to rockfall potential; yet, as this thesis demonstrates, measuring rockfall after the fact is considerably simpler. When thinking about mitigation strategies, it's crucial to comprehend several features and facets of a boulder's possible path. In order to improve models that support decision-making, this thesis aims to delineate these parameters.

2.2. 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 section (without considering lateral movement within this plane). 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 2D Analysis as its aim is to check the reliability of preliminary 3D Analysis.

2.2.1. 2 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 2D modelling calculates a boulders behavior in the 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.

2.2.2. Rockfall Simulation Approaches

Rockfall simulations are done using computer simulation programs. Rockfall models aim to define for a specified "design block", " fall path", "the maximum runout distance", "the envelope of trajectories", velocity and energy distribution along them. The rockfall modeling programs can be simulated into the following categories'

- Lumped Mass Model
- Rigid Body
- Hybrid Approach

2.2.21. Lumped Mass

In this approach, the rockfall is modeled as a collection of discrete particles or masses that interact with the terrain as they fall. Each mass is subjected to gravitational forces and may bounce, roll, or slide upon impact with the ground. This approach is computationally efficient but may not capture the detailed behavior of individual particles. It is suitable for analyzing scenarios where detailed information about the shape or internal structure of the rock is not necessary. It is often used for preliminary assessments or when computational efficiency is a priority.

2.2.22. Rigid Body

In this approach, the rockfall is modeled as a rigid body that interacts with the terrain. The rigid body may rotate, slide, or bounce upon impact, and the simulation considers the conservation of momentum and energy. This approach provides a more detailed representation of the rockfall behavior but is more computationally intensive. The rigid body approach offers greater precision compared to the lumped mass approach, as it accounts for the rock's geometry and structural integrity. It is suitable for simulating scenarios where the behavior of the rock as a solid object needs to be accurately represented, such as in detailed hazard assessments or engineering design studies.

2.2.23. Flexible Approach

The hybrid approach combines elements of both the lumped mass and rigid body models. It utilizes simplified representations for certain aspects of the simulation while incorporating more detailed modeling for others, offering a balance between computational efficiency and accuracy. The hybrid approach provides a compromise between the simplicity of the lumped mass approach and the precision of the rigid body approach. It allows for more flexibility in modeling complex rockfall scenarios by considering both the overall motion of the rock and its structural response to external forces. The hybrid approach is often employed in situations where computational resources are limited, but a more detailed analysis of the rockfall event is required.

2.2.3. Parameters Required for RockFall Modeling

Rockfall analysis requires a substantial amount of information, each of which plays a crucial role in accurately assessing and predicting the potential hazards posed by falling rocks. Some of the key parameters that are required include:

2.2.31. Choice of Detachment Area

In rockfall analysis it refers to the selection of the area from which a rockfall event is initiated. This area is crucial in determining the trajectory and impact of falling rocks. This method involves examining historical rockfall events to identify locations where rocks have previously detached from the slope. By analyzing past occurrences, the areas can be identified that are prone to rockfall and are therefore likely detachment areas physically inspecting the slope to visually identify areas where rocks are likely to come loose. Steep slopes, especially those with a higher dip angle, are more susceptible to rockfall. Observing these areas can provide insights into potential detachment areas. **Line seeder** and **point seeder** are two different methods used in rockfall analysis to simulate the initiation of rockfall events. Line seeder involves defining a line along which rocks are released, while point seeder involves releasing rocks from a single point.

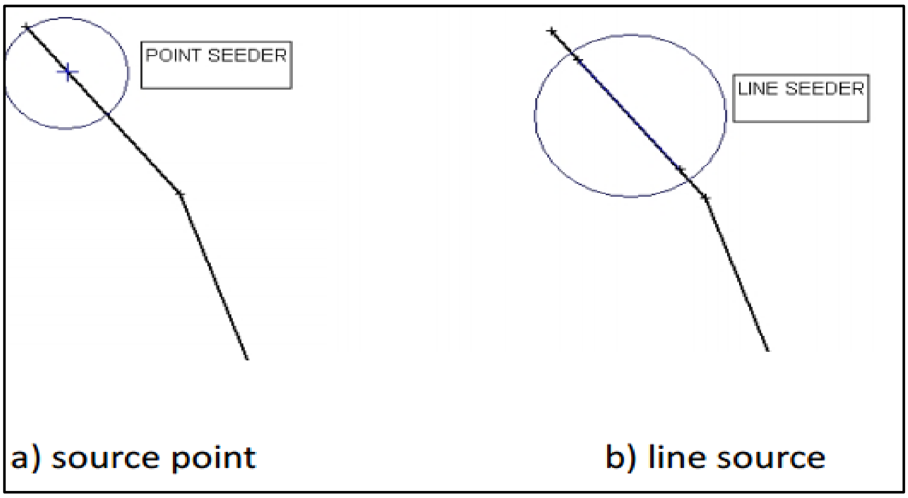


Figure 2.2.1 *Line seeder and point seeder*

In **point seeder**, rocks are assumed to always start falling from the same single spot. This is akin to a cliff where rocks consistently break off from a specific location.
In contrast, the l**ine seeder** assumes that rocks can start falling from any point along a line on the slope. This is comparable to a long stretch of cliff where rocks could detach from anywhere along its length.

2.2.32. Characteristic Design Rock Block Volume

One important aspect of rockfall analysis is determining the volume of rock blocks that could potentially fall. This volume calculation is crucial for understanding the potential impact and risk associated with rockfall events. To calculate rock block volumes in rockfall analysis, one typically needs to consider factors such as past events, field measurements, and structural analysis of discontinuities to estimate the typical size and mass of falling rocks as the size and shape of the rock blocks, the slope of the terrain, and the potential energy of the falling rocks. These calculations can be complex and may require specialized software or expertise. The mass of the rock blocks can be estimated on the basis of the results of geostructural surveys and in-situ measurements of the fallen block volumes (stopped on/close to the rockfall sheltering).

Geostructural survey results provide information on the degree of fracturing of the rock mass, and therefore on the dimensions of the detachable blocks, while the **in - size distribution of the blocks** measured at the foot of a slope provides a clear indication of the already collapsed block volumes, which are likely to detach again and, therefore, can be attributed to the source areas. To estimate the representative unstable volumes on the basis of the survey of the fallen blocks the data related to the block size were first managed by constructing **box plots** from which particularly, the average values can be obtained neglecting outliers. To estimate the representative unstable volumes on the basis of the geostructural survey , the results of the survey could be managed by means of statistical procedures with the software **Dips** (from Rock science)

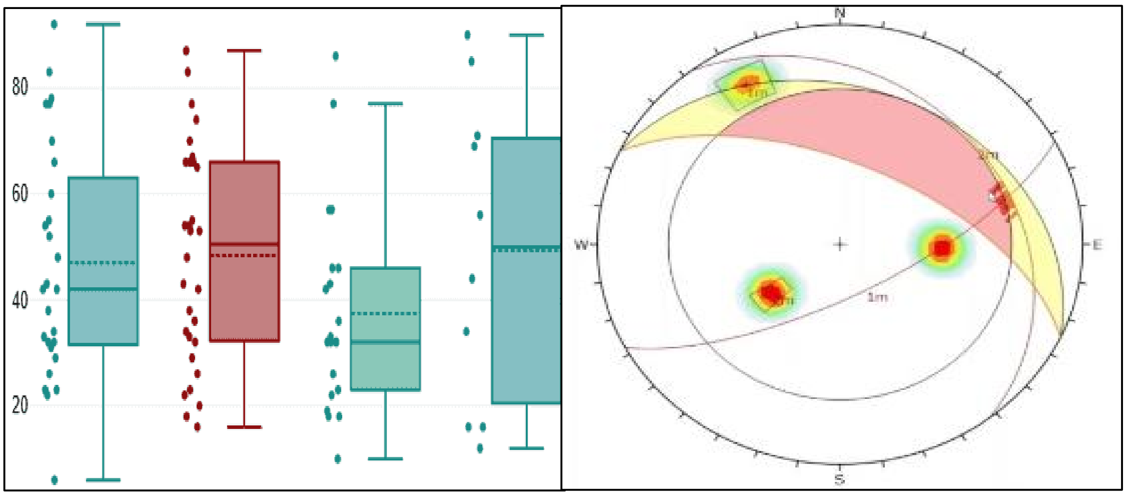


Figure 2.2.2 Example of Box Plots and geostructural survey using (Rock Science Dips)

2.2.33. Initial Velocity of the Blocks

The initial speed at which a rock starts moving when it detaches from the slope is influenced by what we know and don't know (epistemic uncertainty). The velocity depends on how the rock detaches: If it detaches simply due to gravity, like a rock becoming loose and starting to fall, the initial velocity is almost zero because it just starts to move. If the rock is dislodged by some force, like water flow (hydraulic pressure) or an earthquake, it might start with some initial speed but usually not more than 1 meter per second (1 m/s) or up to 1.5 m/s in extreme cases. The initial velocity will be adjusted based on past observations to validate the model, this technique is known as back analysis.

When a model permits the inclusion of both horizontal and vertical velocity components, it allows for a more comprehensive representation of the initial motion of falling rocks. These components provide insight into the speed and direction in which the rocks move at the onset of their descent. The direction of the velocity is derived from the intensity of the two components: horizontal and vertical. In other words, the angle or trajectory at which the rock initially moves is determined by the relative magnitudes of its horizontal and vertical velocities. For instance, if the horizontal velocity component is greater than the vertical component, the rock will predominantly move in a horizontal direction. Conversely, if the vertical velocity component is dominant, the rock's motion will be predominantly vertical.

In 2D probabilistic methods, the initial velocity is introduced with statistical variability. This means that instead of prescribing a single, fixed value for the initial velocity, a distribution of velocities is considered. This distribution accounts for the inherent variability and uncertainty in the initial motion of falling rocks. By incorporating statistical variability, the model can simulate a range of possible initial velocities, reflecting the natural variation observed in real-world scenarios. This approach enhances the accuracy of hazard assessments and enables more reliable predictions of potential rockfall trajectories and impacts.

2.2.34. Restitution Coefficients

This is coefficient is used to identify the intensity of kinetic energy lost when two bodies different materials strikes with each other and bounce. The restitution coefficient in rockfall analysis refers to the ratio of the relative velocity of a falling rock before and after a collision with a surface. It is used to calculate the energy loss during impact and to predict the trajectory of falling rocks. The retarding capability of the slope surface is the most significant parameter affecting the behavior rockfall. Tangential and normal coefficients of restitution are utilized in the analysis of rockfall.

The ratio of approaching to departing kinetic energies of a block is described using the Coefficient of restitution (COR). Which is given as,

$$\mathrm{COR} = \frac{V_1'}{V_1}$$

being V'_1 the block velocity after the impact and V_1 the block velocity before the impact. 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 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 There is no clear relationship between slope angle and the tCOR.

2.2. RockFall Stabilization and Protection Methods

There are two main approaches to overcoming the rock fall problem: protection and stabilization. In both cases the objective is to prevent rocks causing damage to transport routes or buildings and threatening human life but the methods used are very different.
Protective measures are used to deal with rocks that are already in motion. The method of protection must allow for the sizes of rocks involved as the cost of protection increases rapidly with increasing size and the rate at which fallen rock accumulates.
Stabilization involves preventing the rocks moving in the first place. Techniques used include scaling to remove loose rock in a safe manner, and trimming to remove small ragged areas, which would otherwise require repetitive scaling operations. Presplit blasting in the original construction of a cutting or slope leaves a more stable slope..

Other stabilization methods include drainage, to prevent the buildup of water pressure, and the prevention of weathering by the application of shotcrete finally individual rocks and rock masses can be prevented from moving by the use of rock bolts, dowels, anchors and buttresses. Ten common methods of stabilization and six methods of protection are illustrated in Figure 2.2.3

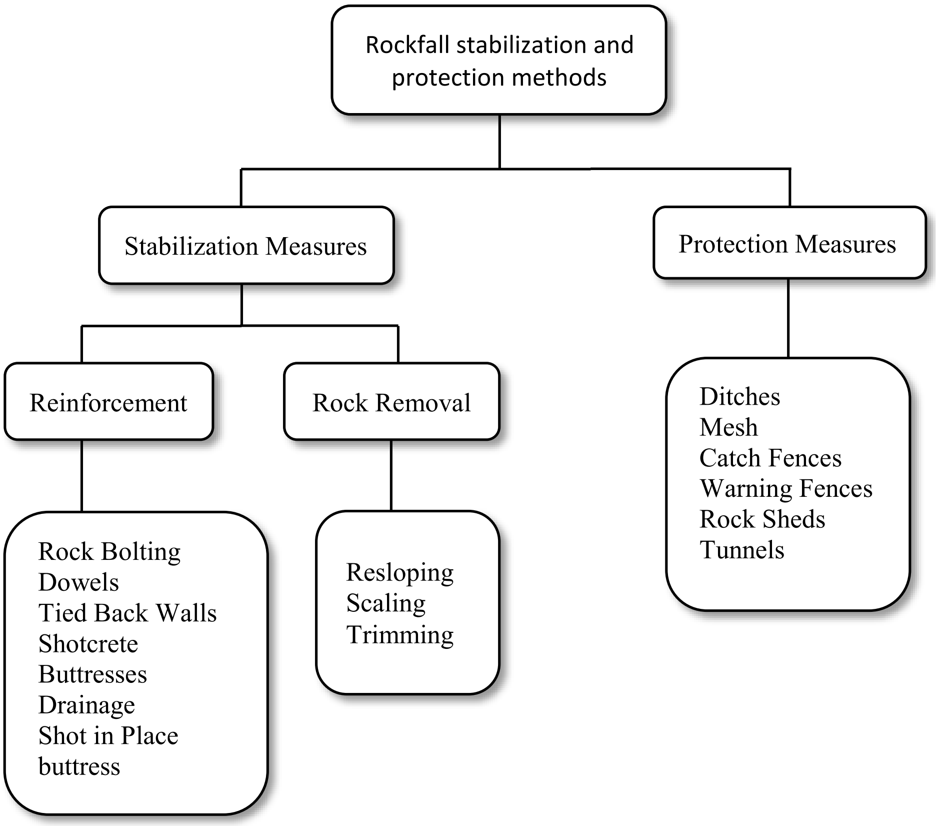


Figure 2.2.3 *Flow Chart for Slope Stabilization and RockFall Protection Measures*
Slope stabilization and protection methods (Wyllie and Nortish, 1996).

2.2.4. Methods of Slope Stabilization

Stabilization methods fall into two categories, reinforcement and rock removal. Figure 14 lists some of the more common stabilization methods. It is important that the appropriate method is used for the particular conditions at each site.

2.2.41. Rock Bolts

A rock bolt consists of a steel rod, which is inserted into a pre-drilled hole in the rock mass. It is fixed either by grouting or by an expansion bolt. The exposed end passes through a steel plate designed to spread the compressive force caused by the tensioning of the rod. Rock bolts are installed across potential failure surfaces and anchored in the sound rock beyond the surface. The application of a tensile force in the bolt, which is transmitted into the rock by a reaction plate at the rock surface, produces compression in the rock mass and modifies the normal and shear stresses across the potential failure surface.

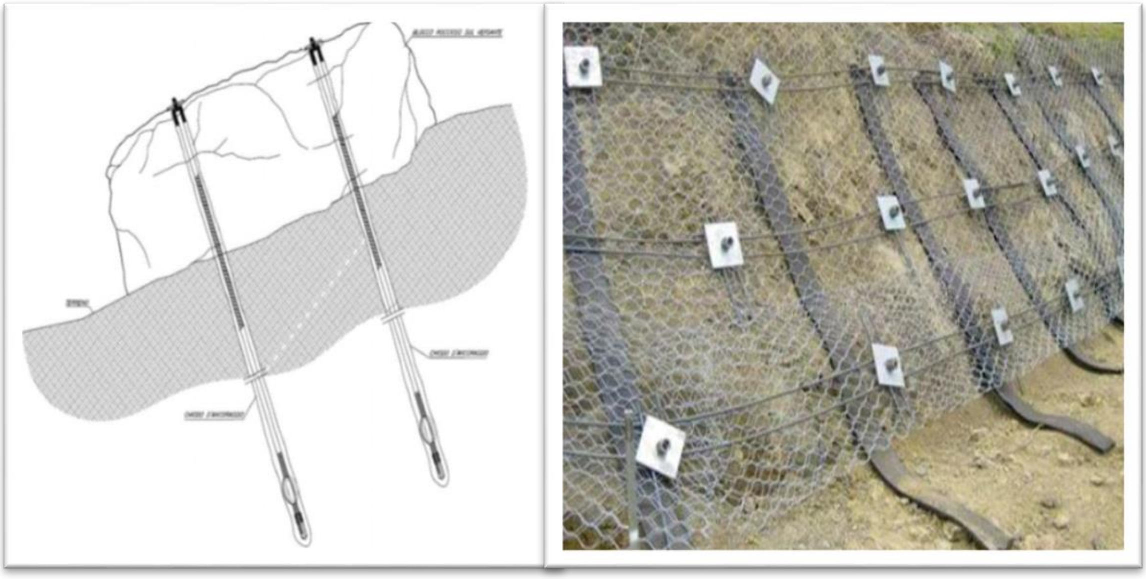


Figure 2.2.4 *Rock Bolt Installation into Slope*

2.2.42. Dowels

These are essentially rods or cylindrical pieces made of reinforcing steel. They are crucial in providing stability and strength to structures, particularly when concrete needs to be anchored to rock surfaces. It's typically made of carbon steel and is designed to enhance the tensile strength of concrete structures, which involves filling the holes drilled into the rock with a special mixture called grout. Grout is a fluid form of cement that solidifies over time, effectively bonding the dowels to the rock substrate. The exposed steel is then encased in reinforced concrete to provide additional strength and protection. These dowels are usually around 25mm in diameter, embedded approximately 0.5 meters (or roughly 1.5 feet) into the sound rock. Spaced approximately 0.5 to 0.8 meters apart

2.2.43. Shotcrete

Shotcrete is a specialized material, a fine aggregate mortar that is applied pneumatically, meaning it's sprayed onto a surface under pressure. Typically, it's layered between 75 to 100mm thick. This application method makes it particularly useful for protecting zones or beds of closely fractured or degradable rock faces. When applied, shotcrete acts as a shield, effectively preventing the fall of small rock blocks and controlling the gradual movement of larger sections of rock that could potentially form unstable overhangs. It's important to note that while shotcrete offers surface protection, it doesn't provide significant support against the sliding of the overall slope. Its primary function lies in surface reinforcement and stabilization. To ensure its effectiveness and longevity, drainage holes are drilled through the shotcrete. These holes serve a critical purpose by preventing the buildup of water pressure behind the shotcrete face, which could potentially compromise its integrity. Overall, shotcrete serves as a versatile solution for protecting vulnerable rock surfaces, enhancing safety in areas prone to rockfall or instability.

2.2.44. Resloping

When there is overburden or weathered rock in the upper portion of a cut, it's crucial to employ specific strategies to mitigate the risk of rockfall events. One common approach is to cut this material at an angle flatter than that of the more competent rock below. The cutting of the overburden or weathered rock at a flatter angle, reduces the likelihood of rock detachment and destabilization. Steeper angles are more prone to rockfall due to gravity and weathering processes. Flattening the slope angle helps minimize the potential for large rock masses or debris to dislodge and fall. Since, Overburden or weathered rock layers can vary significantly in thickness and properties over short distances. Therefore it's essential to conduct thorough investigations of the site conditions before implementing this strategy.

2.2.45. Trimming

One commonly employed method to mitigate this risk is trimming, which involves a series of steps aimed at safely removing the dangerous overhanging blocks. A thorough assessment of the rock slope is conducted to identify areas of instability and potential overhangs before undertaking any trimming activities. The trimming process typically begins with drilling holes into the overhanging rock mass. These holes are strategically placed to weaken the structure of the rock and facilitate its controlled removal. Once the holes are drilled, controlled blasting techniques may be employed to break up the overhanging rock into smaller, more manageable pieces. The blasting is carefully controlled to minimize the risk of collateral damage and ensure the safety of workers and surrounding areas.

2.2.46. Scaling

Scaling describes the removal of loose rock, soil, and vegetation on the face of a slope using hand tools such as scaling bars, shovels, and circular saws. On steep slopes workers are usually supported by ropes anchored at the crest of the slope and tied to a climbing harness.

2.2.47. RockFall Protection Measures

An effective method of minimizing the hazard of rock falls is to let the rock falls occur and to control their distance and direction of travel. Several methods of rock fall control and protection are listed in Figure 14. These include catchment ditches and barriers, wire mesh fences, mesh hung on the face of the slope and rock sheds. A common feature of these protection structures is their energy absorbing characteristics, which either stop the rock fall over some distance or deflect it away from the facility that is being protected. It is possible to control rocks with diameters as large as 2 to 3m falling from heights of several hundred meters and striking with energies as high as Rigid structures such as reinforced concrete walls or fences with stiff attachments to fixed supports are rarely appropriate for stopping a falling rock.

2.2.48. Ditches

Ditches are designed to intercept and capture rocks that dislodge from higher elevations, preventing them from reaching vulnerable areas below. The basic principle behind catch ditches is to provide a barrier that redirects the trajectory of falling rocks, thereby reducing their velocity and dispersing their kinetic energy. This is typically achieved by excavating a trench or channel along the toe of the slope, creating a physical barrier that intercepts and traps falling debris. The dimensions of the ditch, including its height and width, are crucial factors in determining its effectiveness. When rocks impact the catch ditch, they either come to rest within the ditch itself or are deflected away from vulnerable areas, minimizing the potential for damage and injury. Additionally, catch ditches can also serve to channel debris away from infrastructure or property, further enhancing their protective function.

2.2.49. Meshes

This method involves installing a wire mesh directly onto the face of a rock slope, creating a barrier that helps contain falling rocks and prevents them from bouncing onto roads or other vulnerable areas below. One of the significant advantages of using draped mesh is that it reduces the required dimensions of any catch ditch at the toe of the slope. Since the mesh itself absorbs a portion of the energy from falling rocks, the need for extensive ditching to capture and contain rocks is considerably reduced. This can be particularly beneficial in areas where space constraints or terrain challenges make traditional ditch construction difficult or impractical. Different types of mesh materials may be utilized depending on the specific requirements of the site. Chain link mesh, for example, is suitable for controlling smaller rock falls with dimensions less than about 0.6 meters on steep faces. Woven wire rope mesh may be employed for larger rocks with dimensions up to 1 meter. For even larger blocks, specialized ring nets can be utilized to provide effective containment.

2.2.50. Meshes

Nets and fences are integral components of rockfall protection systems, designed to mitigate the impact of falling rocks on steep rock faces, ditches, and talus run-out zones. When a rock collides with a net or fence, the mesh or barrier undergoes deformation, activating energy-absorbing components over an extended collision time. This gradual dissipation of energy significantly enhances the structures' ability to stop rolling rocks, allowing for the use of lighter and more cost-effective materials in their construction.

The capacity to absorb energy effectively reduces the force transmitted to foundations and surrounding structures, minimizing potential damage.

The angular velocity of the impacting rock is a critical factor in determining the extent of damage at the point of impact. Careful attention must be paid to the assembly of these structures, particularly in ensuring correct torque on the bolts of friction brakes. Incorrect torque can lead to structural failure, highlighting the importance of precise assembly instructions.

Figure 2.2.5 *Geobrugg ring net shown restraining a boulder. These nets can be designed with energy absorbing capacities of up to 2500 kNm which is equivalent to a 6 tonne Boulder moving at 20 m per second*

3. Case Study of Varallo (VC)

3.1. Introduction

Varallo is a small town located in the Piedmont region of northern Italy, within the province of Vercelli (VC). It lies at the foot of the Italian Alps, making it a town surrounded by dramatic mountainous landscapes. It is situated along the Sesia River, which is a vital waterway flowing through the valley. Varallo's proximity to the Alps gives it a unique terrain with steep slopes and rocky formations, making it susceptible to natural hazards such as rockfalls. The town is approximately 450 meters (about 1,476 feet) above sea level and is surrounded by dense forests, rivers, and cliffs, adding to its scenic beauty but also presenting challenges for infrastructure development, particularly the roads that traverse this rugged terrain.

As can be seen from the map, it is a slope with little vertical development of about 200 m very steep. In the upper part it is made up of outcropping rock (Figure 2.2.1), while in the lower part lower from around 550 m above sea level is characterized by an extensive layer of debris with blocks also of considerable size and dense tree and shrub cover

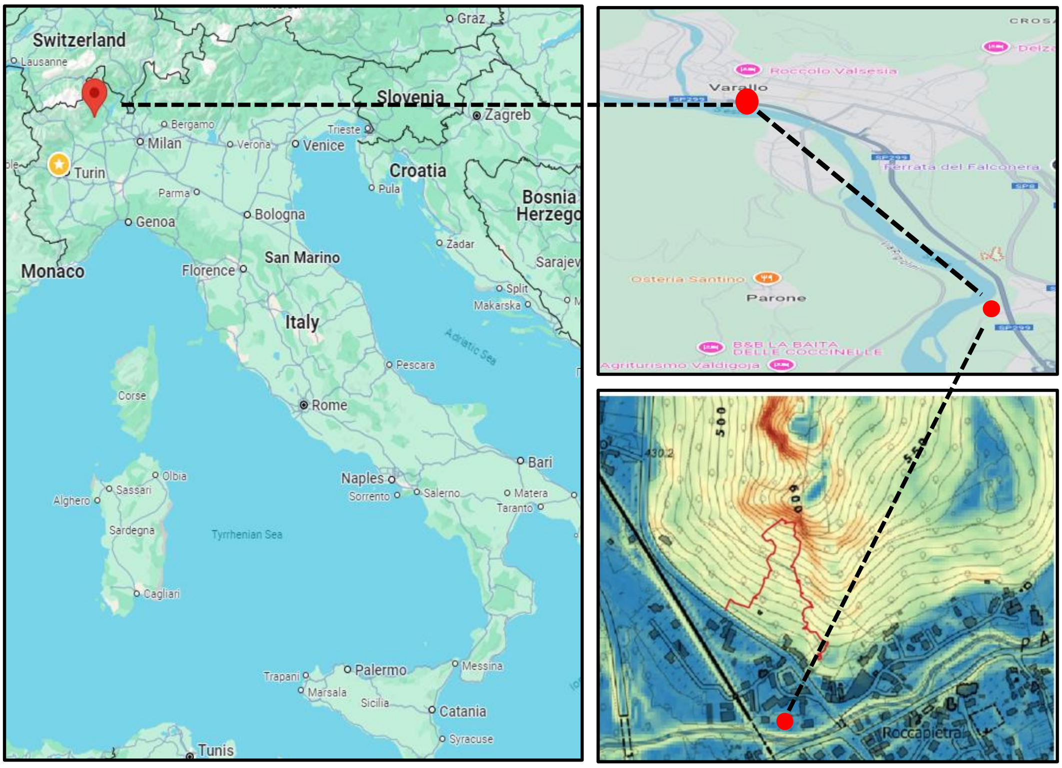


Figure 3.1.1 Route Map of Case Study Location near Varallo province Vercelli (VC)

3.1.1. Geographical Location of Case Study

Our case study is focused on a location near Via Gamberaro, connected to Via Fratelli Varalli Road, which experiences heavy vehicle traffic. Due to the high traffic flow, the risk of rockfalls and landslides in this area posed a serious threat to human life. Therefore, it was necessary to install a rockfall protection system in the form of mesh in order to mitigate these risks and ensure the safety of those traveling through this route.

Varallo is located near some of the most significant peaks in the Alps, most notably Monte Rosa, which lies to the north of the town. Monte Rosa is part of the Pennine Alps and is the second-highest mountain in Europe, with its massif providing a dramatic backdrop to Varallo. The surrounding mountains are heavily forested at lower elevations, transitioning to rocky outcrops and bare cliffs at higher altitudes.

Varallo's location in the Sesia Valley, surrounded by steep alpine slopes and rocky formations, places it in a geologically active zone. The proximity to the Alps, combined with the effects of weathering, erosion, and natural watercourses, makes managing the risk of rockfalls a key concern for the town's infrastructure and residents.

3.1.2. Historical Significance

Varallo is historically significant for its religious and cultural heritage. It is most famously known for the **Sacred Mount of Varallo (Sacro Monte di Varallo)**, a UNESCO World Heritage site. This sacred complex, founded in 1491 by the Franciscan friar Bernardino Caimi, features 45 chapels with life-sized figures depicting scenes from the Bible. The Sacro Monte became a pilgrimage site and is considered one of the most important religious landmarks in Italy.

The town has a long history dating back to medieval times and has been a vital part of the religious, cultural, and economic development of the region. Its strategic location in the Sesia Valley has historically made it a hub for trade and travel between northern Italy and Switzerland.

3.1.3. Inspection of RockFall Case Study Location

A severe rockfall event occurred on November 2023 at location shown in Figure 3.1.2 , and block volume was found to be 3 cubic meters. A large boulder, detached from the walls of the Barbavara Castle which are located immediately upstream of the municipal road network, it reached the road surface of Via Fratelli Varalli, causing damage to the asphalt itself. The two mounds of earth are observed while survey which derive from the continuous unloading of the earth present in the detachment niche, which in contact with the air dries out and as it dries it loses cohesion.

***Figure 3.1.3 3** m^3 Block stopped on the municipal road Via Fratelli Varalli.*

***Figure 3.1.4** damage to the road surface by rockfall*

The presence of numerous blocks, some related to recent collapses, in the tree cover at the base of the rock walls confirms that these rock faces are active and subject to "widespread collapses and overturnings." Therefore, it is reiterated that the risk of falling boulders affecting the underlying **municipal road** and residential buildings remains high.

Figure 3.1.5** rocky spur is located in the vicinity of a historic residence situated below **Via F.lli Varalli

As shown in Figure 3.1.6 an entire rocky spur is located in the vicinity of a historic residence situated below Via F.lli Varalli. This demonstrates the possibility of large-scale collapses, for which it is difficult to conceive of effective and realistically feasible safety measures. Therefore, it is more appropriate to speak of risk mitigation interventions rather than complete prevention.

Given the complexity of the slope and the geological risk of the area—considering that the sector near Via F.lli Varalli spans approximately **200 meters** (see Figure 3.1.7 Route Map) it was deemed essential to conduct a **geological, geomorphological, geomechanical, and ballistic study** .This study begins with fetching out slope profile from DTM using QGIS and further goes on for conducting the back analysis and forecasting from which safety barriers are designed.

3.2. Rockfall Back Analysis for Model Validation

Back analysis is a methodology used to calibrate and validate rockfall simulations. It involves using data from previous rockfall events to adjust and refine the simulations parameters until the model accurately replicates the observed outcomes of these events. Validation builds confidence in the model's predictive capabilities and helps identify and correct any discrepancies. Accurate model validation is essential for reliable risk assessment and effective mitigation planning.

Back analysis is not just about matching past events; it is also about learning from discrepancies between observed and modeled results. These discrepancies can highlight limitations in the current understanding or gaps in the data. By systematically investigating these differences, researchers can refine their models and improve the predictive accuracy for future events

The analysis conducted in this thesis focuses on a specific site that has experienced past rockfall events. Before beginning the rockfall analysis of the recent event, it is important to accurately determine key parameters such as friction angle, initial volume, and initial position of rock movement, and material properties, which can be challenging.

The data from past rockfall events is collected for conducting a robust back analysis. This process involves gathering comprehensive and detailed information about previous incidents to inform the calibration of simulations. It serves as a benchmark against which the accuracy of the model's predictions can be assessed. Below are the key aspects of data collection.

The block Volume from past event is considered and then computer simulations were performed using the trial-and-error method. Parameters were iteratively adjusted until the simulation results matched the observed outcomes of the past event, specifically the final resting position of the rock on the road. This alignment of simulated and real-world data confirms that the selected parameters are suitable for rockfall analysis. This allows for the calculation of the kinetic energy of the recent rockfall event, Runout & some other valuable information.

3.2.1. Model Setup

To conduct a 2D back analysis of rockfall, the first crucial step is to extract the coordinates of the slope to generate a 2D profile in the RocScience software "Rockfall 2". This process begins with the use of QGIS, a powerful open-source Geographic Information System (GIS). In QGIS, a contour map of the Digital Terrain Model (DTM) for the specific site, in this case, Varallo (VC), is used to draw sections representing the slope.

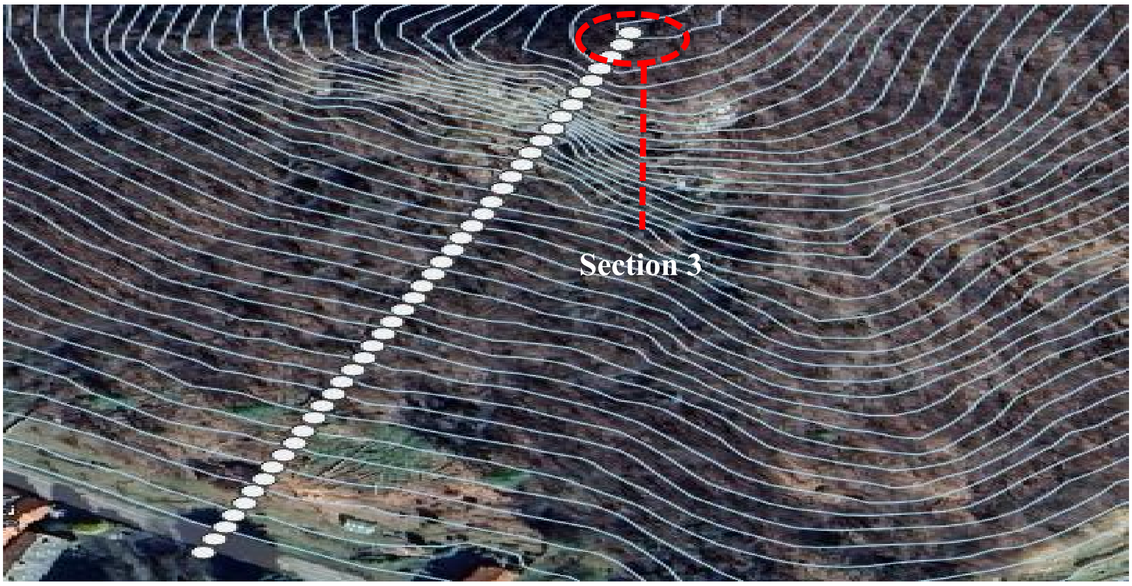


Figure 3.2.1 Section drawn from DTM of Varallo (VC) Site of Rockfall occurred in November 2023

A Digital Terrain Model (DTM) is a digital representation of a terrain's surface topography, stripped of all objects like trees and buildings, showing the bare earth's surface. It is crucial for various geospatial analyses, including hydrological modeling, slope stability studies, and, notably, rockfall analysis.

The coordinates along these sections are extracted meticulously. These coordinates are essential for accurately modeling the terrain in the simulation software. Once the sections are drawn on the contour map, the next step involves extracting these coordinates into a usable format. This is achieved by saving the coordinates as a CSV file using Excel. The CSV file organizes the extracted data into two columns: one for the x-coordinates (distance along the slope) and one for the z-coordinates (elevation).

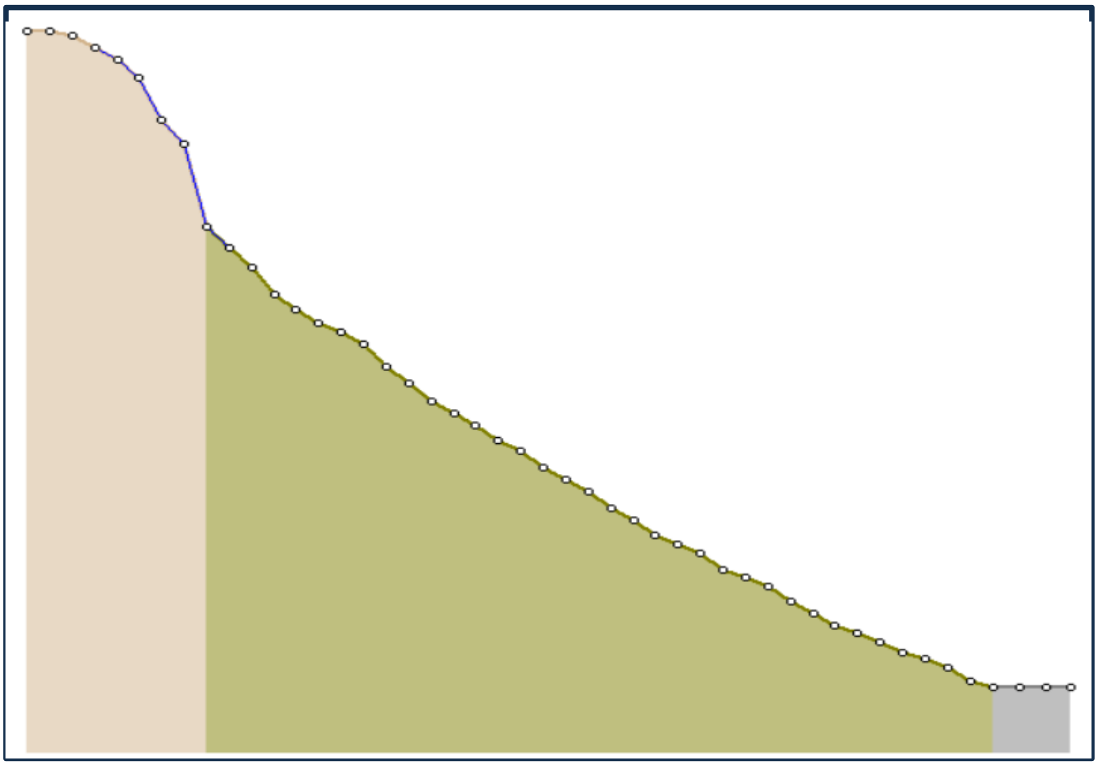


Figure 3.2.12 *Profile of slope drawn in Rockfall 2 by extracting co-ordinates from QGIS DTM Model*

These coordinates are then imported into Rockfall 2. In Rockfall 2, the 2D profile of the slope is created using the imported coordinates, which now accurately represent the slope's terrain based on the DTM data from QGIS. The simulation process begins by inputting these coordinates into Rockfall 2 and running simulations with various parameters, such as initial velocity, restitution coefficient, and friction angle, as detailed in the following Section.

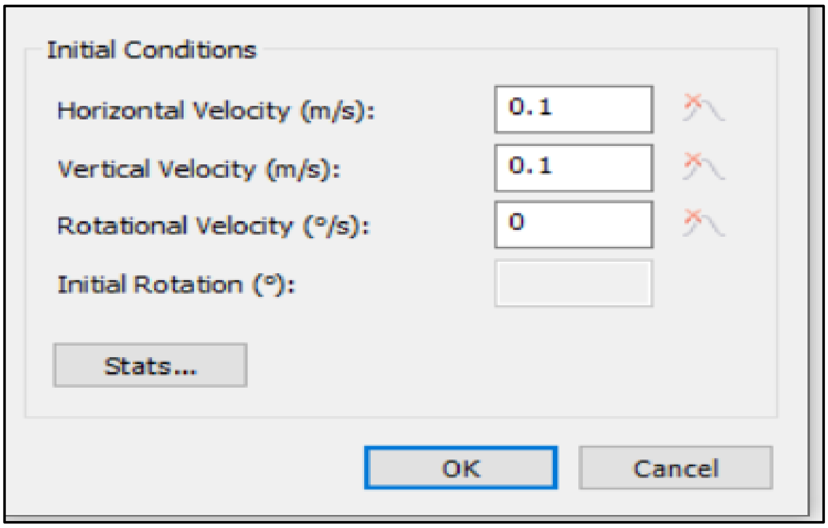
3.2.2. Initial Parameter Selection

The Initial parameters influence the rockfall analysis results, and the accuracy of the predictions made by the simulation models. The only fixed parameter that we will maintain as a constant and use as a reference point is the block size, which is 3 cubic meters, according to the rockfall event occurred in 2023 in the area of interest. This block, having detached from the hillside, ultimately came to rest on the asphalt road. The chosen values are often based on a combination of literature review, empirical data, and site-specific conditions. here, we elaborate on the key parameters typically considered and the rationale behind their initial selection.

3.2.3. Initial Velocity

Velocity is often challenging due to epistemic uncertainty, which arises from a lack of precise knowledge about the conditions leading to the rockfall. The initial velocity can vary significantly depending on the mechanism triggering the detachment and the physical conditions at the site.

When a rock block detaches purely under the influence of gravity, the initial velocity is typically close to zero. The block then begins to move with an initial velocity that is minimal, as there is no additional force propelling it at the onset. In contrast, if the detachment is triggered by external forces, the initial velocity can be greater than zero. In our case study, we considered that the rock detaches and moves solely under the influence of gravity. The Rockfall 2 software allows to add both horizontal and vertical velocity of the bock, therefore we have started with 0.1m/s and do several trial-and-error methods until and unless we got desired results. In more sophisticated analyses, particularly those employing 2D probabilistic methods, the initial velocity is treated as a variable parameter with statistical variability, but in this case study we didn't assume any standard deviation and kept zero in the values of coordinates. The X-Coordinates in figure 3.12 shows distance and Y-cordinates shows elevation of terrain model.s


Initial Conditions

Horizontal Velocity (m/s): 0.1

Vertical Velocity (m/s): 0.1

Rotational Velocity (°/s): 0

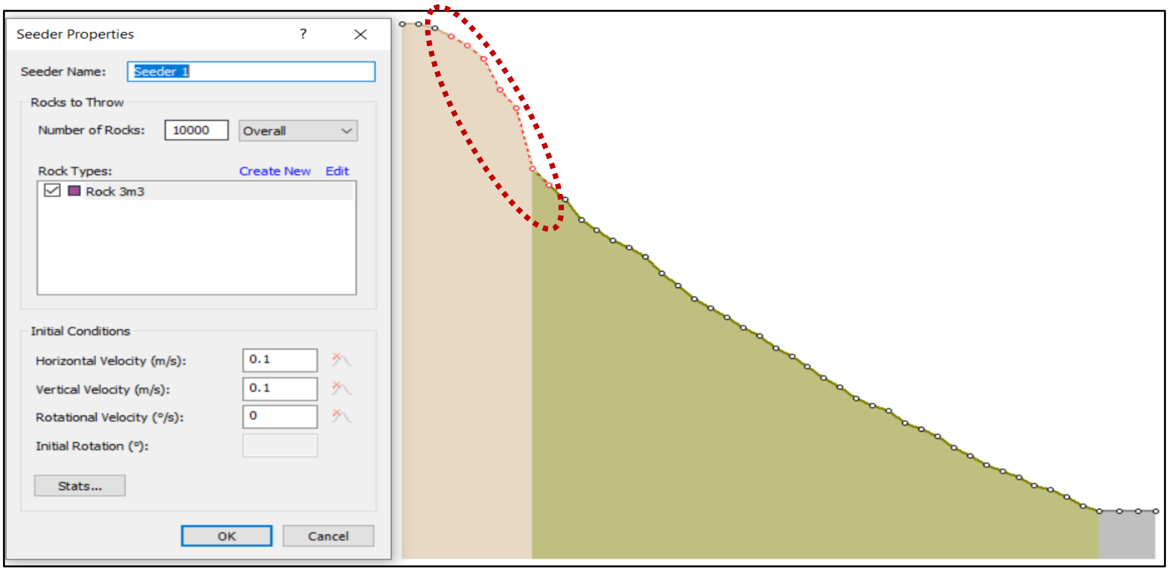
Initial Rotation (°):

Figure 3.2.3 Demonstration of Adding initial velocity values in Rockfall 2 for developing 2D Profile of Slope

3.2.5. Starting Location of Rockfall

The beginning point for the rocks can be set anywhere on or above the slope surface. Rockfall 2 is a sophisticated tool that allows us to specify the beginning place using either a single point in space (referred to as a **"point seeder"** in the application) or a polyline (referred to as a **"line seeder").** Each rock's initial position is selected by producing a random location anywhere along the polyline. This "line seeding" strategy is beneficial when the engineer is unsure of where the rockfall will begin but wants to designate a plausible range of starting sites (for example, along one of the slope's higher segments).

In this case study, line seeder has been employed because the exact location of the initial rockfall is unknown, although it is most likely on the upper range of the hill, and the rock mass is fractured . The **line seeder** function gives us the option to add the **number of rocks** that will fall in the simulation from the start position. **10000** rock blocks have chosen so to obtain a good statistical validity of the results, that is such a number for which with a higher number of simulations the results do not change anymore Line seeder can be defined manually on the slope or by entering the values of coordinates. Typically, areas at the top of the hill are chosen because the rocks that form there have the highest potential energy and are likely to be the most prone to detachments.



Seeder Name: Seeder 1

Rocks to Throw

Number of Rocks: 10000 Overall

Rock Types:

☑ Rock 3m3

Initial Conditions

Horizontal Velocity (m/s): 0.1

Vertical Velocity (m/s): 0.1

Rotational Velocity (°/s): 0

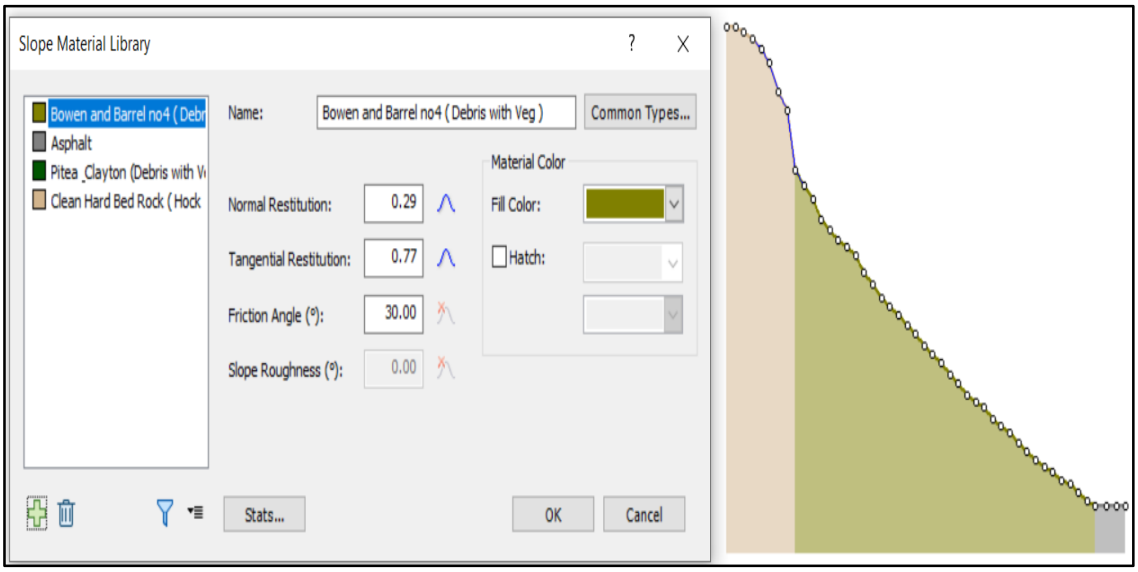
Initial Rotation (°):

Figure 3.2.5 Location of Line seeder in the slope profile made in Rockfall 2

3.2.6. Assigning Material Properties

The slope's materials might change greatly from the crest down the toe, as well as across different cross sections. Even when the material is homogenous, the material parameters that are important for rockfall analysis (the coefficients of restitution) may be unknown. The Slope Material library dialogue in Rockfall 2 allows us to design our own materials or pick established materials from the library. The most significant factors to assign to slope materials are friction angle and restitution coefficients.

In rockfall studies, the coefficient of normal restitution (RN) often has values between 0.3 and 0.5. The coefficient of tangential restitution (RT) typically has values between 0.8 and 0.95. The lower part of the mountains is covered with vegetation and soft soils, while the upper end is made up of bedrock and asphalt. Regrettably, slight variations in the coefficients of restitution can cause significant changes in the rockfall simulation technique. A slope section having RN = 0.4, for instance, will behave substantially differently from the identical slope segment with RN = 0.5. Most engineers are familiar with the concept of "friction angle" and would be able to specify the friction angle of each slope segment with a good degree of reliability.



- Bowen and Barrel no4 (Debr
- Asphalt
- Pitea _Clayton (Debris with V
- Clean Hard Bed Rock (Hock

Name: Bowen and Barrel no4 (Debris with Veg)

Normal Restitution: 0.29

Tangential Restitution: 0.77

Friction Angle (°): 30.00

Slope Roughness (°): 0.00

Fill Color:

☐ Hatch:

Figure 3.2.6 *Assignment of Slope Materials and its properties in rockfall material library.*

Figure 3.2.3 above illustrates how the four distinct materials have been assigned to the slope based on the most likely real-world situations that are similar to our site. **Asphalt** material is already accessible in the material library, and the physical properties of the three materials—**Bowen & Bewel**, **Pitea & Clayton**, and **Clean Hard bed rock (Hock)**—are derived from established tables based on the materials that most likely fit the actual site circumstances. These numbers were utilized in an initial study, but they were later calibrated using a retrospective analysis of an earlier occurrence. When the outcome roughly matches 80% of the actual event in terms of trajectories, runout, bounce, and total kinetic energy, the back analysis's quality is deemed adequate.

3.2.7. Results and Discussions

Rockfall 2 generates a variety of outputs to aid in statistical studies and the creation of corrective actions. Rockfall 2 generates plots that show , among the others, the **maximum velocity, kinetic energy**, and **bounce height of the boulders** throughout the whole slope profile (referred to as "envelopes" in the application). These envelopes are important for determining where mitigation measures should be implemented. The application also generates histograms that show the distribution of the velocity, kinetic energy, and bounce-height of the rocks at each point along the slope profile.

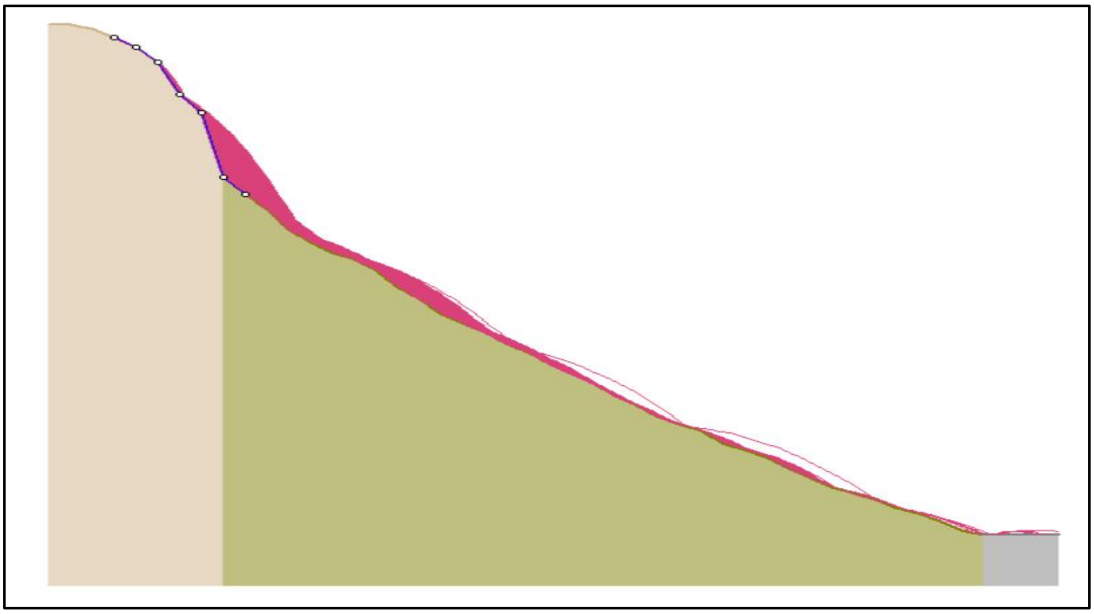


Figure 3.2.7. *Simulated Model IN Rockfall 2*

The most important data for knowing the validation of back analysis model is **rock endpoints Graph**, which is arguably, the most important single piece of output from the program. This is considered an essential piece of output because it is usually the final location of the rocks that determines whether the parameters used were adequate according to past events or not. The location of the rock endpoints is presented as a distribution. The distribution can either be displayed graphically in the program. As we have used past rockfall event occurred in November 2023 as a reference for back analysis in which 3m^3 of rock fell from the hill and stopped at asphalt road, therefore, It was necessary for the validation of the back-analysis model to have at least some blocks out of the 10,000 that would come to rest on the asphalt road upon running the simulation. It has been observed that the parameters selected for the model validation exhibited a degree of similarity to past events, as detailed in the graph 3.2.4 below.

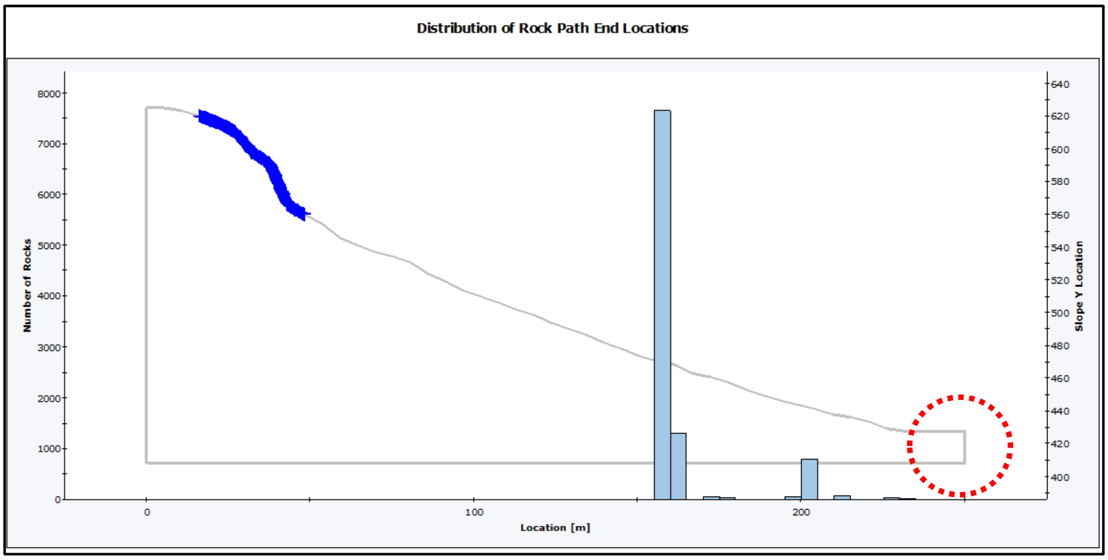


Figure 3.2.7 *Statistical distribution of the end points along the slope in Rockfall 2*

The graph, which was created with the Rockfall 2 program, shows the statistical distribution of rockfall endpoints down the slope. The horizontal positions in meters are shown by the X-axis, and the proportion of rocks that halt at each coordinate is indicated by the left Y-axis. A significant zone for prospective mitigation measures is highlighted by the fact that most rocks terminate around 100 meters from the detachement, as evidenced by the tallest bar and steepest beginning drop in the cumulative curve. About 18 to 22 blocks are captured by the asphalt road zone, therefore we can conclude that the data are sufficient to adjust the parameters shown in **Table 3.2.7-**1 below for rockfall forecasting in relation to the most recent rockfall occurrence.

S.No	Parameters	Values
1	No. of Rocks for simulation	10000
2	Horizontal Velocity	0.1 m/s
3	Vertical Velocity	0.1 m/s
4	Density of Rock	2358 Kg/m^3
5	Mass of Rock	7664 Kg
6	**Material Properties of debris with vegetation**	
6.1	Normal Restitution	0.35
6.2	Tangential Restitution	0.77
6.3	Friction Angle	30°
7	**Material Properties of Clean Hard bed Rock**	
7.1	Normal Restitution	0.53
7.2	Tangential Restitution	0.99
7.3	Friction Angle	30°
8	**Material Properties of Asphalt**	
8.1	Normal Restitution	0.40
8.2	Tangential Restitution	0.75
8.3	Friction Angle	33°

Table 3.2.7-2 Final parameters determined through Back Analysis used for forecasting rockfall.

4. ROCKFALL FORECASTING

After completing the back analysis and validating the model with preset parameters based on the 3m^3 rock volume (e.g. velocity, friction angle, restitution coefficient, and line seeder), the parameters are utilized to estimate future rockfalls. The most important need is the design rock volume, which is calculated using two different approaches. The first technique uses a simple statistical methodology to create a box plot of section 3 based on data provided by geologists from in-situ surveys to obtain the first design volume V_1.

The second method employs a complex statistical approach (on section 3) "**preliminary assessment of the volume-return time relationship**" to determine rock block sizes before and after scaling. For the simulation, we selected three five sections within the geologist-defined zone and performed analyses using the design rock block volumes from both methods. The three different rock volumes will be assigned on each section and then results from these simulations, including kinetic energy and rock movement end locations, were then compared to check the compatibility of the design rock volumes from both methods.

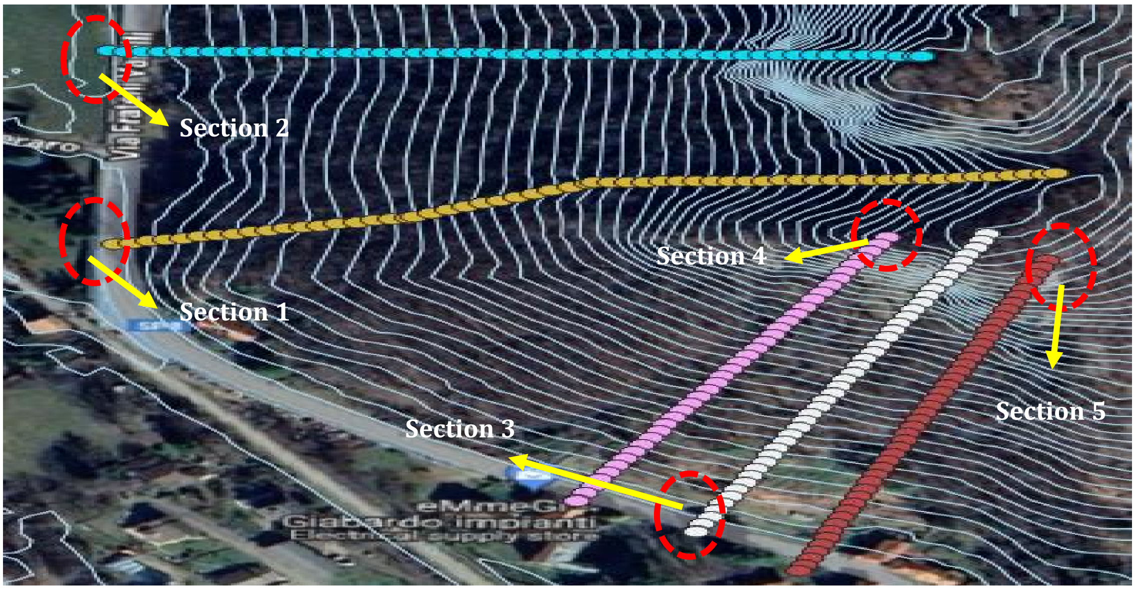


Figure 3.2.1 *Five different sections of Slope extracted from QGIS DEM Model of Varallo VC*

Rockfall barriers will be designed using the information gleaned from the analysis, specifically with regard to the kinetic energy and the ultimate resting places of the rocks. This all-encompassing strategy guarantees that the foundation of our next forecasts and barrier design will be solid, verified parameters. Numerous output formats are produced by Rockfall 2 to support statistical analysis and the development of corrective action plans. Plots created by Rockfall show the maximum rock velocity, kinetic energy, and bounce height across the course of the full slope profile, or "envelopes" as the software refers to them. These envelopes are helpful in determining the best locations for corrective actions. Additionally, the application generates histograms showing the distribution of the pebbles' kinetic energy, bounce height, and velocity. These envelopes are useful when deciding where remedial measures should be placed. The program also produces histograms displaying the distribution of the velocity, kinetic energy and bounce-height of the rocks at selected locations along the slope profile (referred to as “data collectors” in the program). The data collectors are useful when designing the remedial measures (e.g. deciding the capacity of a barrier).

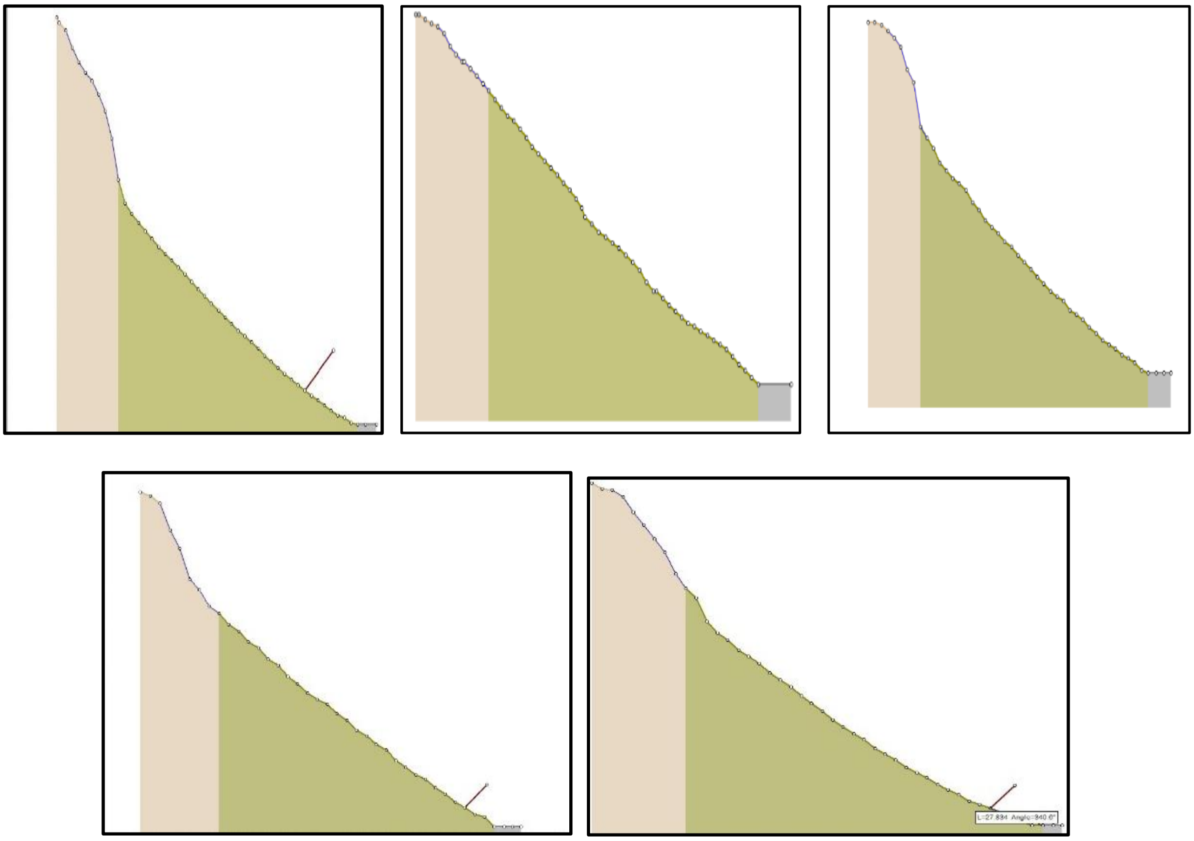
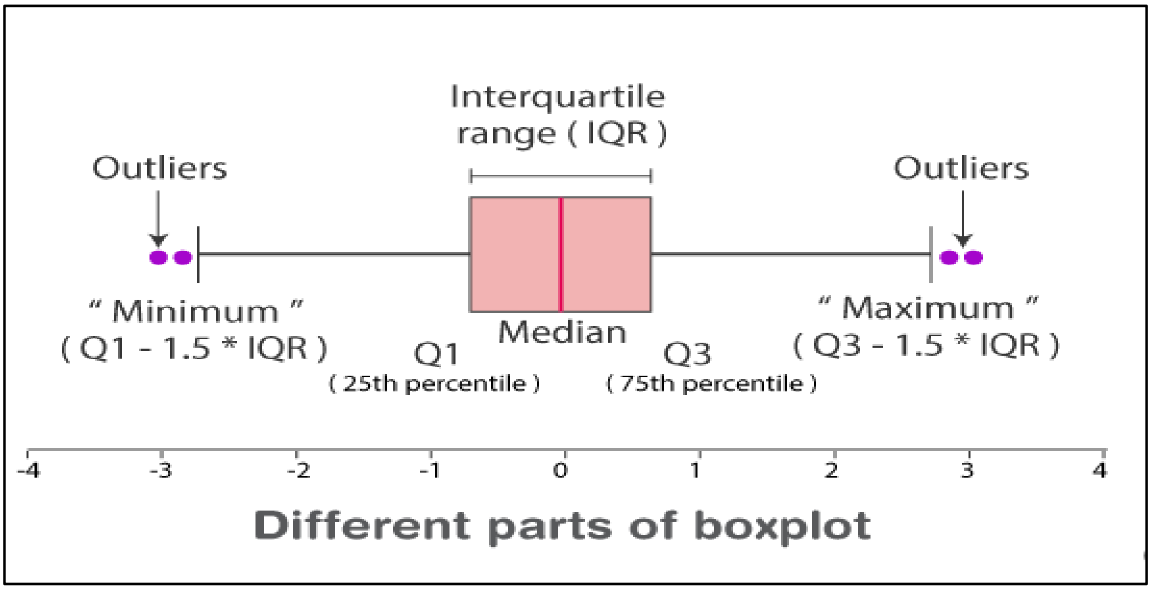


Figure 3.2.2 *Slope Profile of Five different sections drawn in Rockfall 2 for Forecasting of Rockfall Model*

4.2. Design Block Volume by Box Plot

A box plot, also known as a box-and-whisker plot, is a statistical tool used to summarize the distribution of a dataset by displaying its central tendency, dispersion, and skewness. It consists of a rectangular box that represents the interquartile range (IQR), encompassing the middle 50% of the data, with the lower quartile (Q1) marking the 25th percentile and the upper quartile (Q3) marking the 75th percentile. The line inside the box indicates the median (Q2), or the 50th percentile. Whiskers extend from the box to the smallest and largest values within 1.5 times the IQR from the quartiles, while data points outside this range are considered outliers and are plotted individually. In rockfall forecasting,

It provides a clear and straightforward visualization of the data distribution. This simplicity makes it easier to understand and interpret the data.



4.2.5. Application of Box Plot in estimating Design Block Volume

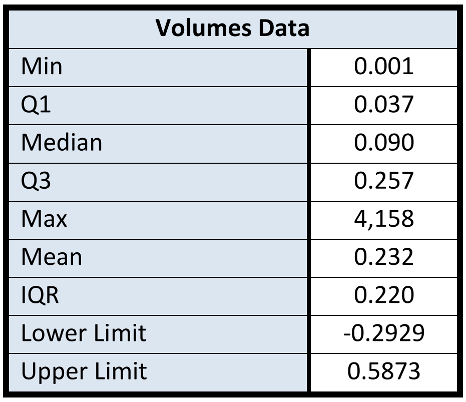
A box plot can be used to analyze the distribution of rock sizes from past landslide events, allowing for the identification of typical and extreme values. By constructing a box plot from collected rock size data, the maximum rock size within the whiskers or significant outliers can be determined and used as the design block volume for future simulations and barrier design, ensuring that mitigation measures are robust against both common and worst-case scenarios.

In the context of rockfall analysis for forecasting design block volumes, box plots are particularly beneficial. They provide a clear visual summary of rock size distributions, helping to identify the central tendency, variability, and presence of outliers within the data collected from past landslide events. By plotting the sizes of rocks that have fallen previously, the typical rock sizes and the extreme values can be determined. This information is crucial in deciding the design block volume.

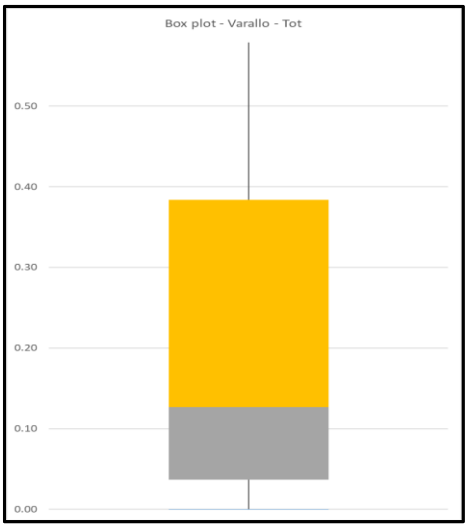
Compared to other statistical methods, box plots are advantageous because they are simple to interpret and provide immediate insights into the data's spread and outliers. They are less affected by non-normal distributions and do not assume any specific data distribution, making them robust for varied rockfall data sets. Additionally, the visual nature of box plots aids in communicating findings to stakeholders who may not be familiar with complex statistical methods, thereby enhancing decision-making in rockfall mitigation and barrier design.

In this case study of **Varallo (VC)**, the estimation of the representative unstable volumes on the basis of the survey of the rockfall, occurred in April 2024, the data related to the block size were first managed by constructing box plots. The data of rock volumes, measured in cubic meters, is collected and organized. A box plot is then created using excel, displaying the minimum, quartiles, median, and maximum values, as well as any outliers. The upper whisker or significant outliers are considered to determine the maximum rock size, ensuring that mitigation measures account for the largest potential rockfall events.

Based on the volumes reported in excel ("total" sheet), the following box-plot was obtained.



Volumes Data	
Min	0.001
Q1	0.037
Median	0.090
Q3	0.257
Max	4,158
Mean	0.232
IQR	0.220
Lower Limit	-0.2929
Upper Limit	0.5873



The block distribution is not symmetrical

For the different areas, the box plots shown in the following figure were found, where the points represent the **outliers** (volumes greater than approximately **0.58 m3**).

The table represents statistical summaries for four sets of rock volume data (V1, V2, V3, and V4) which are likely used in rockfall analysis to identify design block volumes.

In particular, by excluding the outliers, the average values obtained for four different locations are 0.090 m³, 0.066 m³, 0.074 m³ and 0.090 m³.

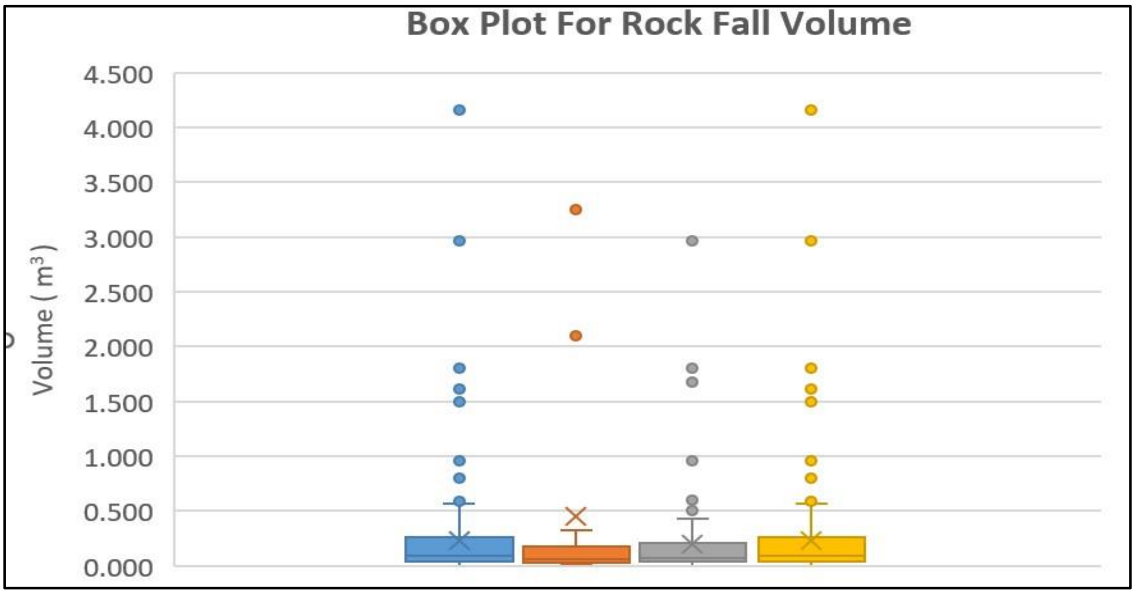


Figure 4.2.5. Volume of Rock Blocks fallen at different locations in Varallo VC

For instance, while the mean values are quite similar across the volumes, therefore the maximum values indicate significant variability, due to which maximum value of volume V1 **4.2** from table is considered in design to ensure safety, the last three volumes pertain to various locales that is not in our interest.

4.2.6. Results of Forecasting using Design Block Volume by Box Plot:

Following results are achieved after performing rockfall simulation using design block volume from box plot of the date related land sliding of April 2024. The following three sections are used to estimate the kinetic energy envelope, end location of block and velocity profile of simulation. The results are given below,

Simulation Results of Section 1 with Design Block 4.2 m^3

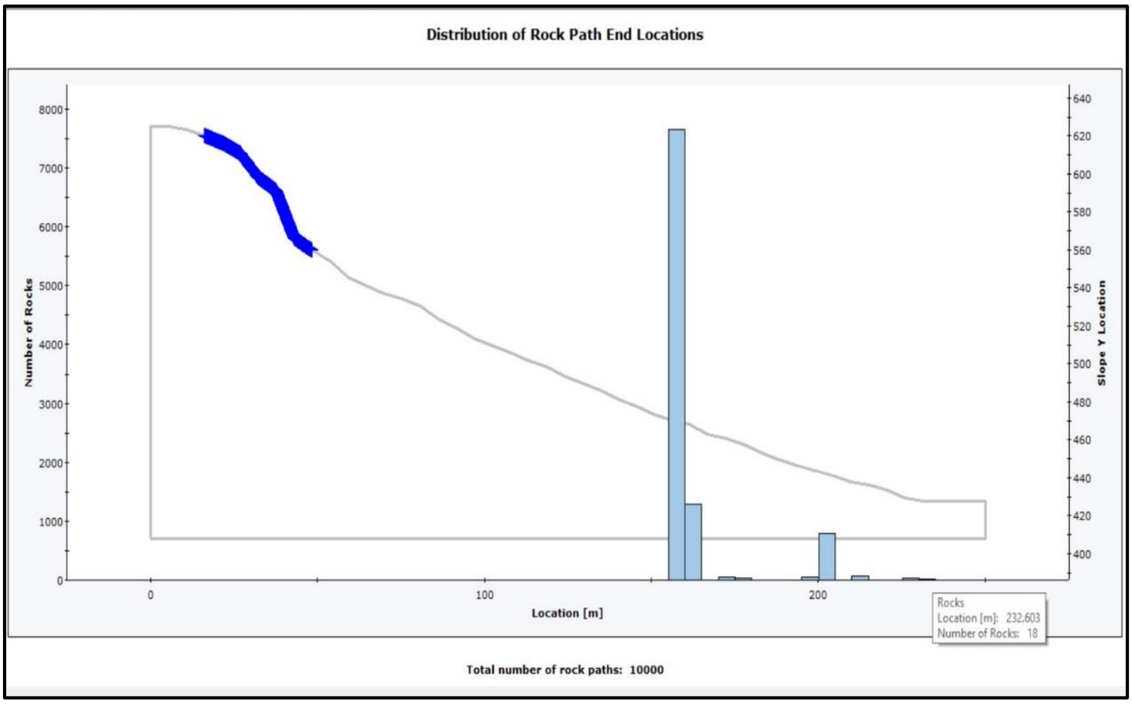


Figure 4.2.1 *Number of blocks stopped at end location of Asphalt Road out of 10000 Blocks*

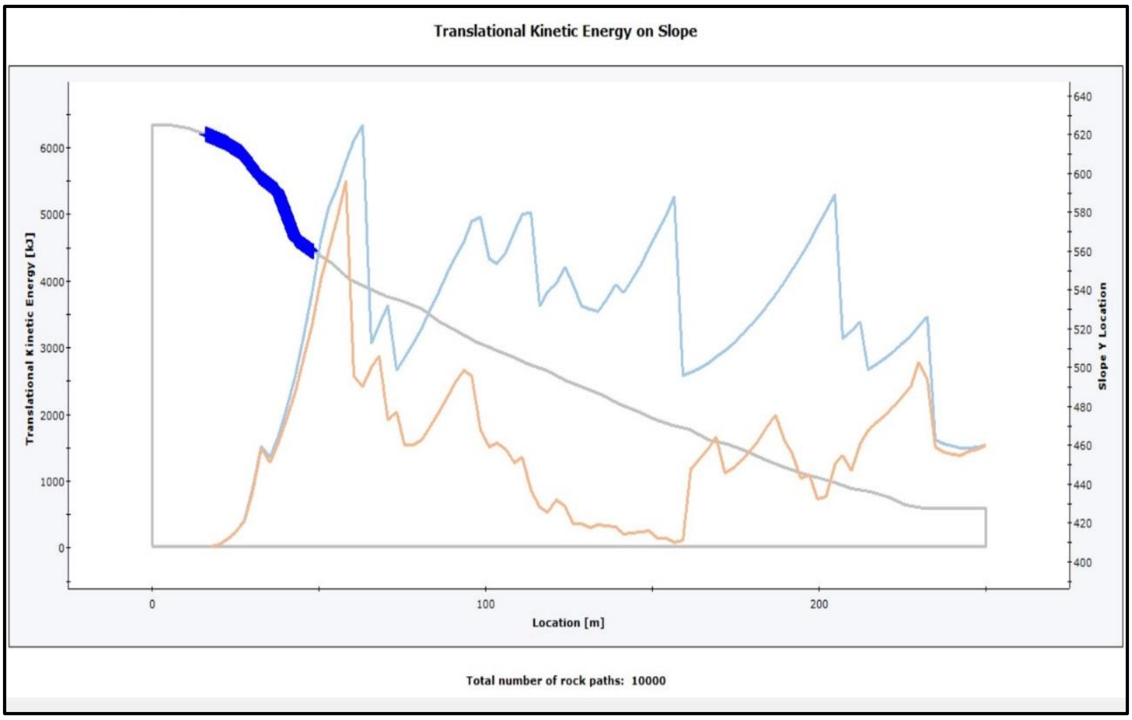


Figure 4.2.2 *Maximum and 95% of Maximum velocity of Design block volume at different Locations of slope*

A collector is inserted in the model at position x = 224.914 m and y = 460.640 m which is placed in the location of the future rockfall barrier. From the Collector we obtain the statistical trend of **translational velocity** and **impact along height** as seen in **Figure 4.1.2.3) and Figure 4.1.2.4),**

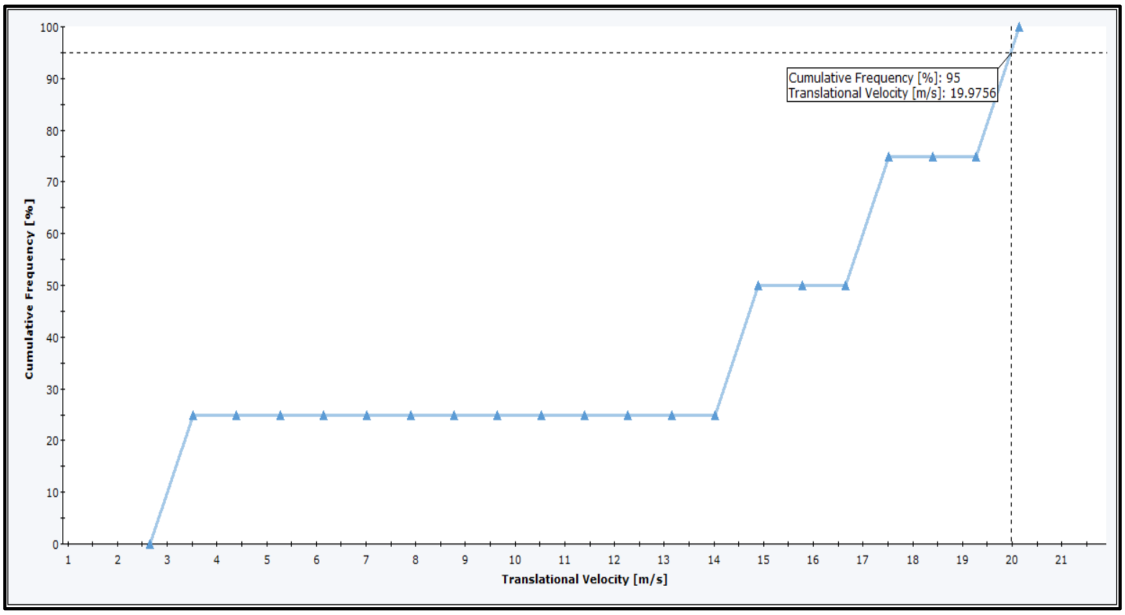


Figure 4.2.3 *Translational velocity using design block volume obtained from Box Plot method*

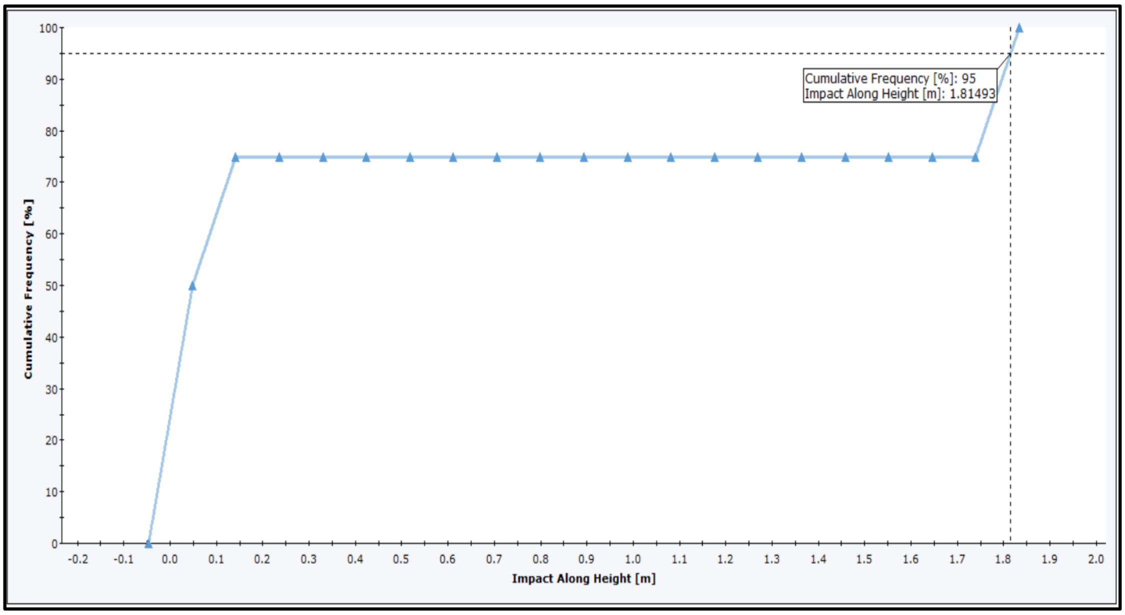


Figure 4.2.4 *Impact Height using design block volume obtained from Box Plot method*

4.3. Estimation of Design Block Volume by Volume Frequency Relationship

The **Volume Frequency** relation is based on both historical data and surveys of blocks that have previously detached from the slope and gathered near its base. Rockfall is notoriously difficult to study because to its intrinsic unpredictability and the effects of both variability (natural randomness) and epistemic uncertainty (limited knowledge). Given the complications, probabilistic approaches are well suited for simulating rockfall occurrences.

Modern design practices, especially in building construction, the need to ensure structural safety over the building's expected lifetime. This is already established in design codes for common natural hazards like extreme winds or earthquakes, where the magnitude of external forces is linked to the probability of occurrence within the structure's design life. A similar approach is used for rockfall protection design, where the design block's size should be related to its probability of occurrence

Despite the importance of this relationship, traditional methods for determining the design block size in rockfall protection lack a direct connection to its return period. Typically, the size is selected based on an analysis of previously fallen blocks and surveys of the slope, but this approach often lacks a rigorous probabilistic basis. To address this, there is a methodology that introduces a **volume-frequency** relationship that correlates the size of fallen blocks with their return periods, derived from extensive rockfall event data. However, the challenge remains that detailed and extensive records of rockfall events are rare, often only covering a few decades. As a result, current design practices are often based on subjective engineering judgment, leading to potential biases.

To overcome these limitations, a methodology was introduced by ***de Biagi et al 2017*** for estimating the volume-frequency relationship that underpins the selection of the design block volume. This approach, if sufficient data on previous rockfalls are available, allows for a more objective and statistically sound determination of the design block size, ensuring that it is appropriately matched to the expected return period.

4.3.5. Methodology

A three-step procedure for deriving a volume–frequency relationship for blocks with a reduced amount of available data is built up and discussed in the following. Some aspects of the proposed methodology result from hydrological approaches in flood-frequency analyses (see Claps and Laio, 2003). The main hypothesis of the procedure is that the temporal occurrences (i.e. the events) are considered separately from the deposit volumes distribution in a representative area where the rockfall occurs. A representative area is defined as the portion of deposit beyond a defined line, in which the hazard is computed. We consider the foot of the slope as a representative area deriving a volume–frequency relationship as follows.

1- Collection and Filtration of Data

- Start by collecting data on rockfall events in a specific area. Each event in **catalogue C** includes an estimate of the rockfall volume.

- Define a **threshold volume, V_t** to focus on significant rockfalls. This threshold helps filter out smaller, less relevant events.

- Filter the original catalogue C to create a reduced **catalogue C^*** This new catalogue only includes events where the volume V (e) of the event e is equal to or greater than V_t

  $$C^* = \{e: e \in C \text{ and } V(e) \geq V_t\} \quad (1)$$

  It means any event with a volume smaller than V_t is excluded.

- Create a similar list, F, which includes all measured volumes that could have fallen at any time, even if they weren't observed.

- Apply the same threshold V_t to list F to create F^*:

  $$F^* = \{s: s \in F \text{ and } V(s) \geq V_t\}$$

  Again, only volumes equal to or larger than V_t are kept.

2- Apply Probabilistic Models

Temporal Occurrences (Poisson distribution):

Since large rockfall events are rare, the timing of these events can be modeled using a Poisson distribution. This model assumes that the events occur independently and the probability of an event occurring is constant over time.

The Poisson distribution is used to describe the number of events happening in a fixed period.

Block Volume Distribution (Generalized Pareto Distribution - GPD):

The sizes of the blocks in the filtered list F∗ are modeled using the Generalized Pareto Distribution (GPD). This distribution is suitable for modeling extreme values, which is appropriate for large rockfall.

The GPD has two parameters that control its shape, allowing it to fit the distribution of block sizes well.

- **Temporal Frequency λ**
  λ represents the average number of significant rockfall events per year (those with volumes larger than V_T.

- **Cumulative Distribution Function (CDF) FV(*v*)**

  The CDF FV (*v*) gives the probability that a rockfall volume is less than or equal to a particular value ***v*.** For calculating the frequency of rockfalls larger than a certain volume *v*, use the equation:

  $$\lambda \, [\, 1 - F_V \,(v)\,] = \frac{1}{T}$$

  Here, T is the return period, which is the average time between events that have a volume larger than *v*.

- **Volume for Specific Return Period V_T:**
  To find the rockfall volume corresponding to a specific return period T, invert the CDF:

  $$V_T = F_V^{-1} \;\; (1 - \frac{1}{\lambda T})$$

  This equation tells you what volume V_T of rockfall to expect given return period T

3- Estimation of Parameters

- The catalogue C^* provides data to estimate λ, the average frequency of significant rockfall events.
- The list F^* provides data to estimate the parameters of the GPD, which describe the distribution of rockfall sizes.
- Once we have λ and the GPD parameters, we can use them to predict how often large rockfalls will occur and how large they are likely to be.

4- Defining the Threshold Volume

To accurately analyze rockfall events, it's essential to set a **threshold volume (V_t)**. This threshold represents the smallest block size that is consistently observed and recorded. By establishing V_t, we focus on significant events and mitigate inconsistencies in data recording, especially for smaller, often overlooked rockfalls.

Consider a catalogue of events, **C**, compiled over a period **t**. Not all small events are reliably recorded, so we can create a **reduced catalogue (C^*)** that includes only events where the block volume **V(e)** meets or exceeds V_t:

$$C^* = \{ e : e \in C \text{ and } V(e) \geq Vt \} \; C^*$$

The number of events in C* is denoted as **n***. To account for potential gaps in recording, especially before monitoring began, we adjust the effective observation period to:

$$t^* = \tau (C^*) = t + \frac{t}{2n^*}.$$

This ensures a more accurate representation of the time frame during which significant events were captured.

5- Modeling Temporal Occurrence with the Poisson distribution:

Assuming that significant rockfall events occur independently and randomly over time, we can model their occurrence using a **Poisson distribution**. The probability of observing **n** events in the period **t*** is given by:

$$p(n) = \frac{e^{-\lambda t*} \, (\lambda t^{*})^{n}}{n!} ,$$

Here, **λ** represents the average rate of occurrence (events per year) for rockfalls exceeding V_t.

This model allows us to relate the probability of block sizes to their annual occurrence. Specifically, the probability that a block smaller than volume **v** occurs in a year is:

$$G_V(v) = e^{-\lambda} [\, 1 - F_V(v) \,]$$

Where **$F_V(v)$** is the cumulative distribution function (CDF) representing the probability that a block is smaller than ***v***.

6- Modeling Block Volume Distribution with Generalized Pareto Distribution:

To describe the distribution of rockfall block sizes above the threshold V_t, we employ the **Generalized Pareto Distribution (GPD)**. The CDF of the GPD is:

$$FV(v) = 1 - (1 + \xi \frac{v - \mu}{\sigma})^{-1/\xi} ,$$

μ is the location parameter, set equal to V_t.
σ (scale) and **ξ** (shape) are parameters estimated from the data.

Since the volumes smaller than V_t are not considered, the location parameter is equal to threshold volume, i.e. $\mu = V_t$. The inverse of Eq. (10), to be used in Eq. (6), is equal to;

$$v(F_V) = F_V^{-1}(F_V) = \mu + [\, (1 - F_V)^{-\xi} - 1 \,] \frac{\sigma}{\xi} .$$

Using the GPD, we can determine the block volume corresponding to a specific **return period (T)**, which is the expected time between events of that size or larger:

$$v(T) = \mu + [\, (\lambda T)^{\xi} - 1] \frac{\sigma}{\xi}$$

Conversely, for a given block volume **v**, the return period **T** is:

$$T(v) = \frac{1}{\lambda}\left(1 + \xi \frac{v - \mu}{\sigma}\right)^{1/\xi}.$$

As a consequence, the annual frequency of occurrence, which is the reciprocal of the return period, is

$$\frac{1}{T} = \lambda\left(1 + \xi \frac{v - \mu}{\sigma}\right)^{-1/\xi}.$$

To utilize these models effectively, we need to estimate their parameters:

Poisson Rate λ is estimated using the reduced catalogue C*, as:

This represents the average number of significant events per years

GPD Parameters **σ** and **ξ** are determined through statistical methods, typically using the maximum likelihood estimation (MLE) technique, based on the block sizes in the dataset exceeding $\mathbf{V_t}$ The location parameter **μ** is set to $\mathbf{V_t}$.

4.3.6. Application Of Volume-Return Time Relationship In Case Study Varallo (Vc) :

Several assumptions were made to estimate the V-Tr relationship.

Historical Data

The historical data were interpreted as indicated below, and using a Poisson distribution:

Case A (the threshold volume was set equal to 0.3 m^3, and the number of collapse events was considered slightly reduced to take into account some events with volumes lower than the threshold volume)

No. of sampling years (2000-2024) t = 25 years

Threshold volume, **Vs = 0.3 $\mathbf{m^3}$**

No. collapse events with V>Vs (2000-2024) **n* =24**

With reference to the Poisson distribution:

$t^* = t + (t/(2\,n^*)) = 25.52 \rightarrow \lambda = (n^*/t^*) = 0.94$

Case B (the threshold volume was reduced, and the number of collapse events was slightly increased)

No. of sampling years (2000-2024) t = 25 years

Threshold volume, Vs = 0.15÷0.2 m^3

No. collapse events with V>Vs (2000-2024) $n^* = 28$

With reference to the Poisson distribution:

$t^* = t + (t/(2\,n^*)) = 25.45 \rightarrow \lambda = (n^*/t^*) = 1.10$

Relief On The Foot

since we did not have sufficient data relating to the volumes of collapses that occurred in the past, the volumes relating to the rockfalls that had collapsed were also considered and various hypotheses have been analysed.

taking into account the removal using a hydraulic jack, the larger blocks removed manually were only considered in some cases.

below are the details and the related volume (v) – expected return time (tr) graphs, based on the generalized pareto distribution, whose parameters ξ and σ were obtained using **Matlab**

$$\frac{1}{T} = \lambda\left(1 + \xi\,\frac{v - \mu}{\sigma}\right)^{-1/\xi}.$$

HP 1 – CASE A

Volumes considered: all those $\geq 0.3\ m^3$

tail index (shape) parameter, ξ	0.99
scale factor, σ	0.21
Vs = μ	0.3
λ	0.94

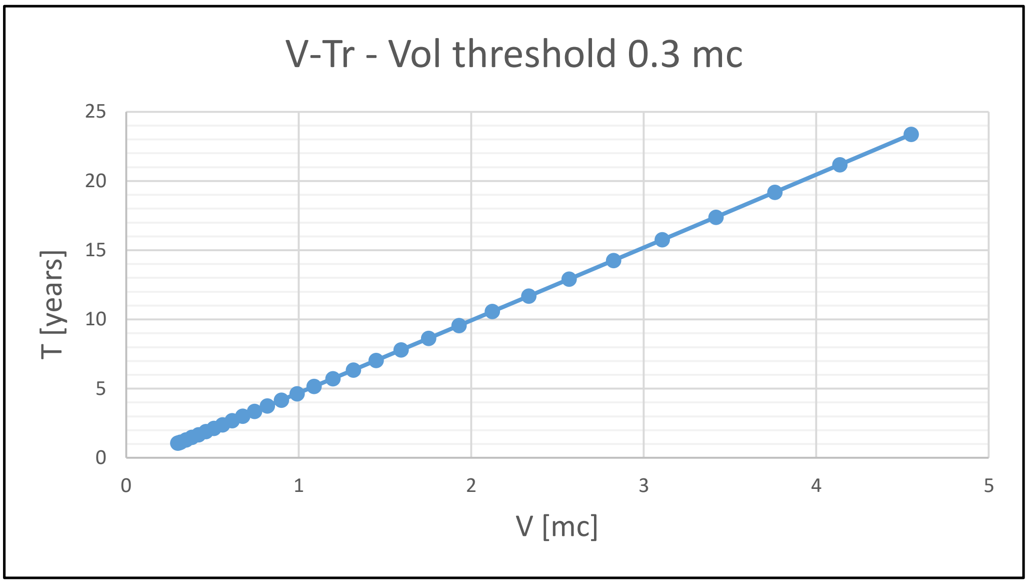


Figure 4.3.1 *NB. For a Tr=25 years approximately the Volume would be approximately 5 m* ^{3}

HP 2 – CASE B

Volumes considered: all those ≥ 0.2 m ^{3}

tail index (shape) parameter, ξ	0.68
scale factor, σ	0.24
Vs = μ	0.2
λ	1.10

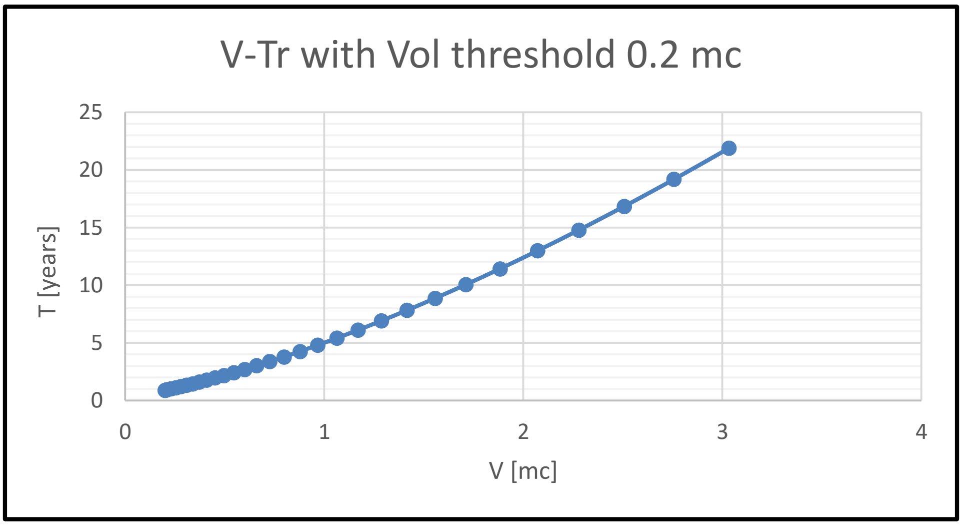


Figure 4.3.2 *NB. For a Tr=25 years approximately the Volume would be approximately 3.3 m* ^{3}

HP 3 – CASE B

volumes considered: all those ≥ 0.2m ^{3}, excluding the following volumes (from scaling) in m ^{3}:

1.496
1.680
1.800
2.100
2.964
3.250

tail index (shape) parameter, ξ	0.5367
scale factor, σ	0.2148
Vs = μ	0.2

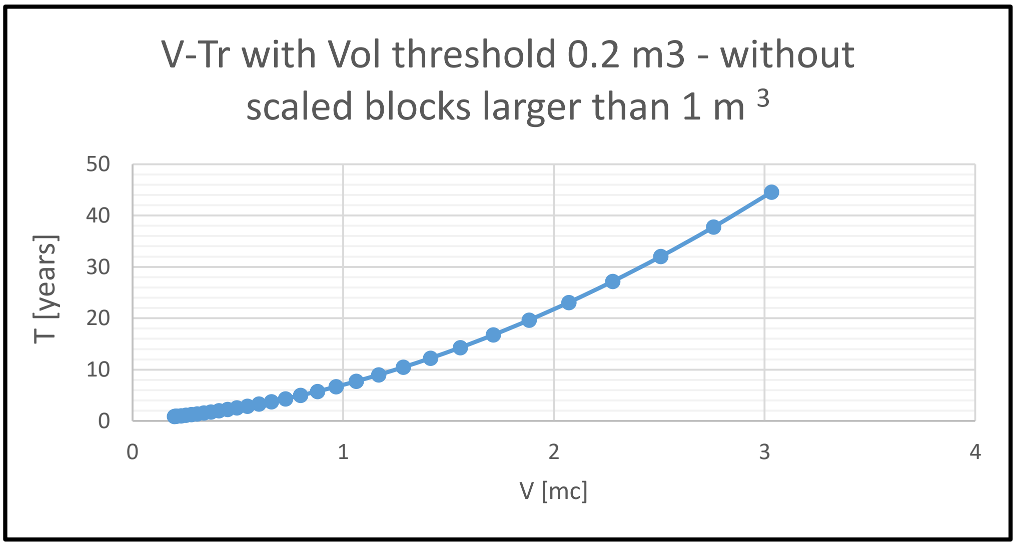
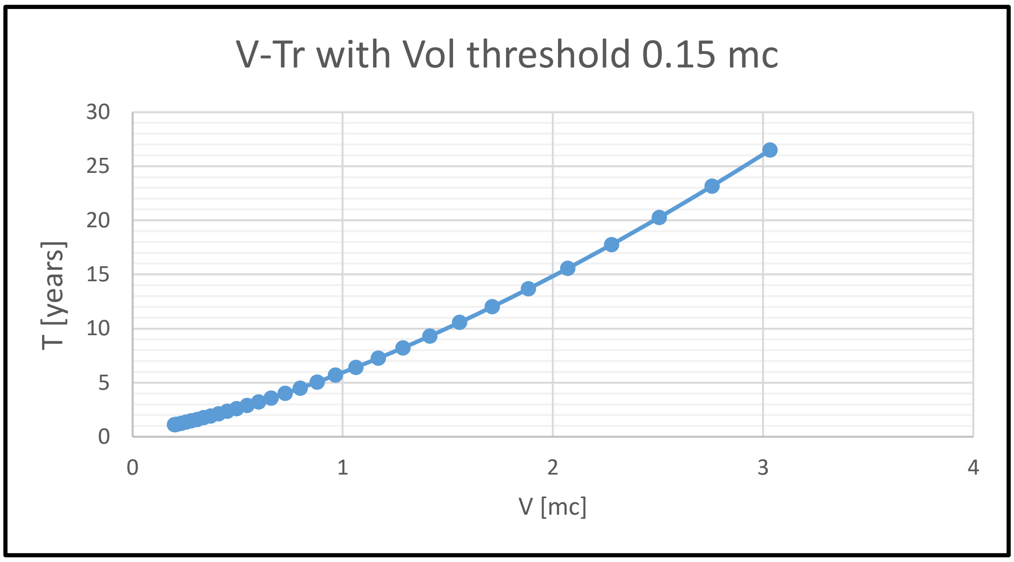


Figure 4.3.3 *NB. For a Tr=25 years approximately the Volume would be approximately 2.1 m ^{3}*

HP 4 – CASE B

Volumes considered: all those ≥ 0.15m ^{3}

tail index (shape) parameter, ξ	0.67
scale factor, σ	0.23
Vs = μ	0.15
λ	1.10



HP 5– CASE B

Volumes considered: all those ≥0.15m ^{3} , excluding the following volumes (from scaling) in m ^{3} :

1.49
1.68
1.80
2.10
2.96
3.25

tail index (shape) parameter, ξ	0.52
scale factor, σ	0.19
Vs = μ	0.15
λ	1.10

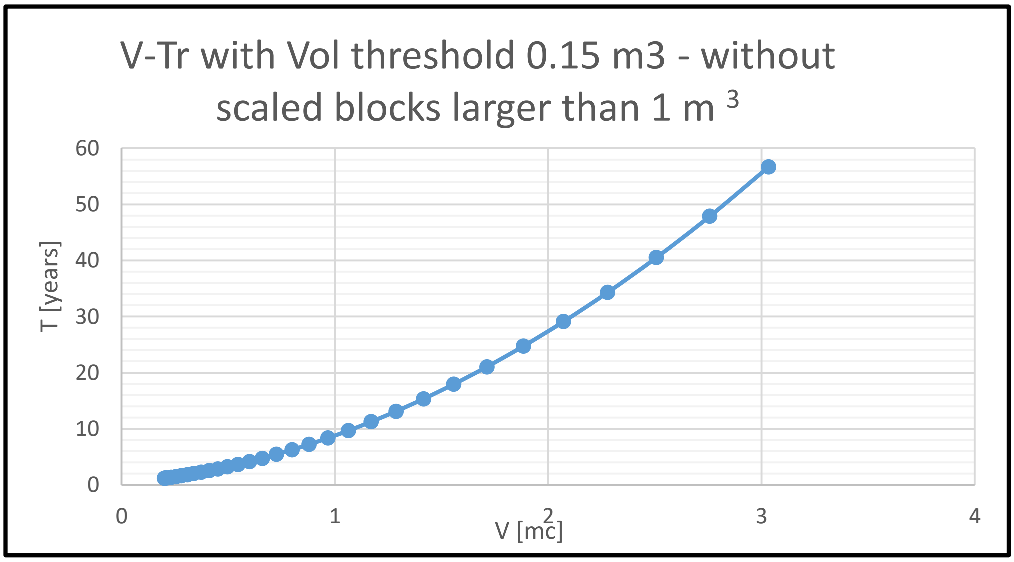


Figure 4.3.5 *NB. For a Tr=25 years approximately the Volume would be approximately 1.9 m* ^{3}

In the calculations and graphs shown above, two design rock block volumes were selected: one at **3.25 m^3**, representing the volume before slope scaling, and another at **2.1 m^3**, representing the volume after slope scaling. These values were used to perform forecasting in Rockfall 2, utilizing the collector feature on the slope.

In the Rockfall 2 Analysis software by Rocscience, the "Collector along Slope" option is used to define specific areas along the slope where to collect data about the rockfall behavior. When this option is enabled, the software will track and record detailed information about the rockfall impacts, such as velocities, bounce heights, and energies, at the specified points or along the designated segments of the slope.

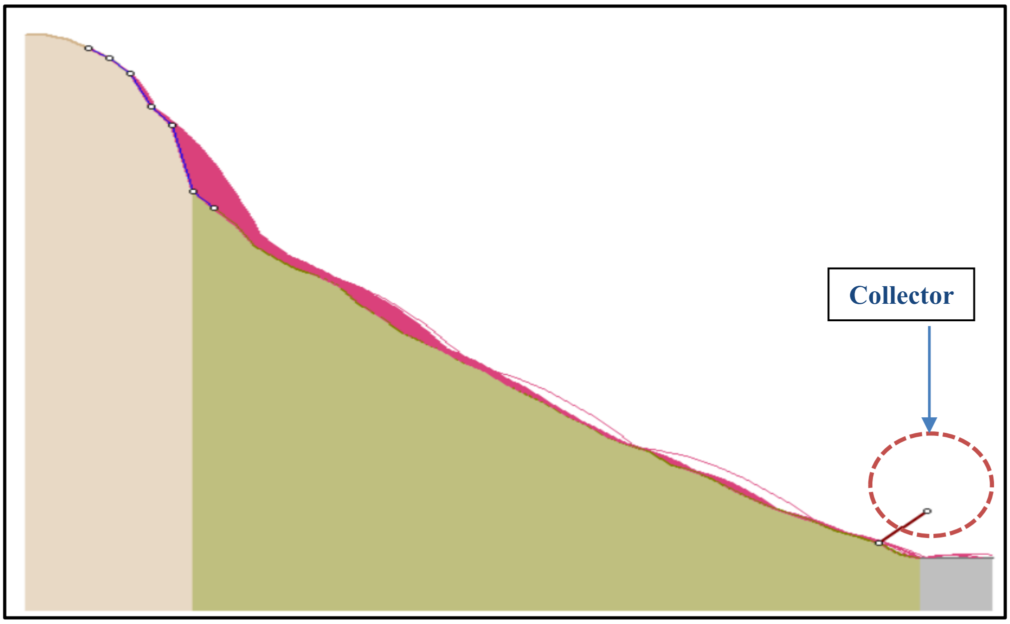


Figure 4.3.6 *Simulated Rockfall Model with Collector along the slope to collect required data*

The analysis has been performed using Rockfall 2 software across all three sections of the slope by using two design block volumes were selected using the **Frequency –Time Return Relation** along with a third value, selected from **box Plot Method** shown in table 4.2-1.

S.No	Methods	Volumes
1	Maximum value of Box Plot	4.20
2	Frequency–Time Return Relation HP2 Case B	3.25
3	Frequency–Time Return Relation HP3 Case B	2.10

Table 4.3.6-1 *Methods used to define three volumes of design rock blocks*

4.4. Comparison Box Plot & Volume – Time return Relation

In this report, the following results are demonstrated for only one of the selected values 3.25 m^3 per section, showing the three corresponding values obtained. The remaining **six values** were also obtained in a similar manner.

The graphs obtained from Rockfall 2 by using three different values at three different sections are shown below,

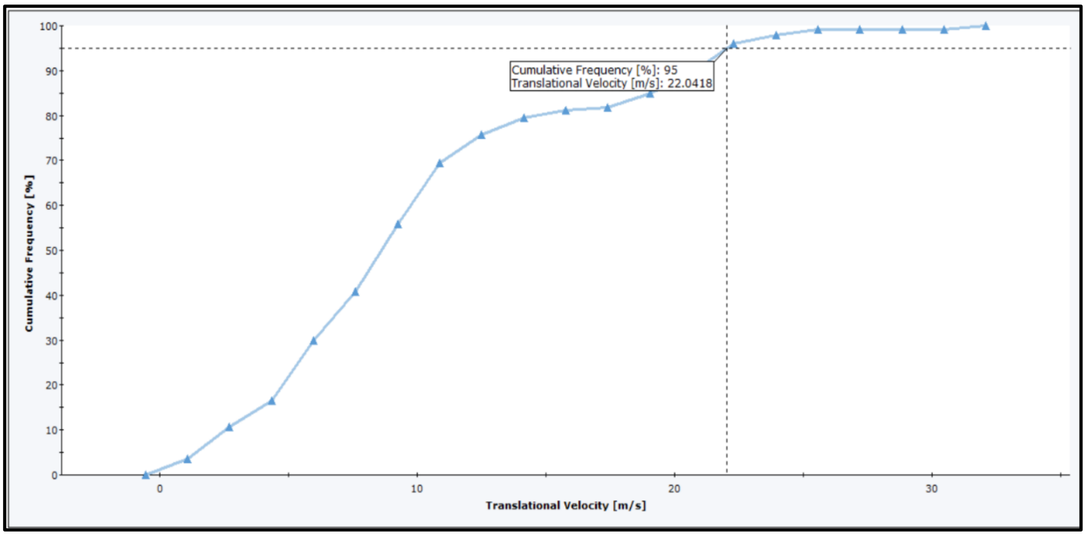


Figure 4.4.1 *95 % percentile Translational velocity of design rock block volume* ***3.250 m^3*** *at section no. 3*

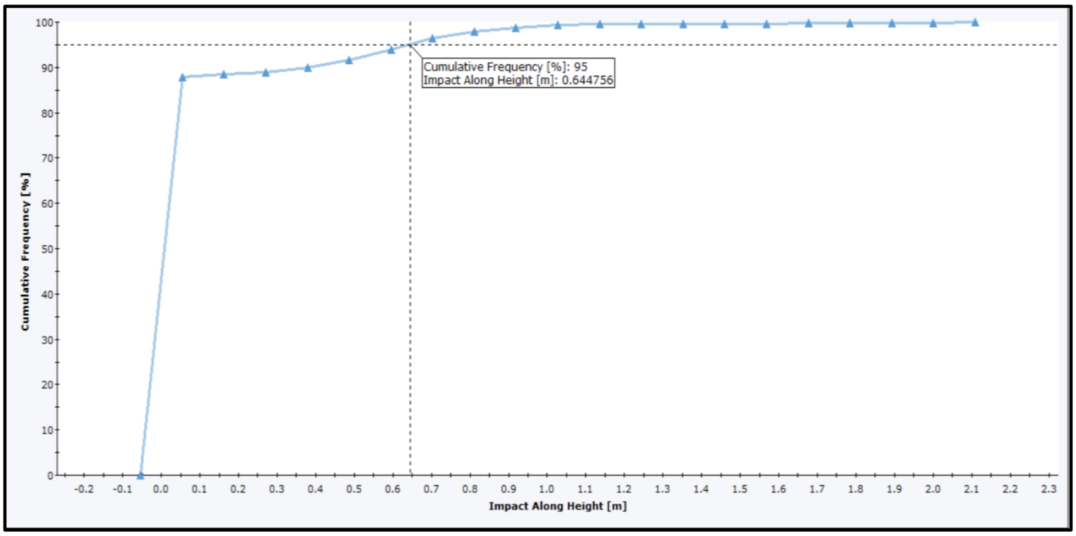


Figure 4.4.2 *Impact height along the slope for barrier height design of rock volume* ***3.250 m^3*** *used in section 3*

The results seen from Fig 4.2.2.1 and Fig4.2.2.2 indicated a clear benefit from the slope scaling process. The larger rocks were effectively removed during the scaling, leaving behind only smaller rocks. Due to their reduced size, these smaller rocks have lower kinetic energy, which, in turn, reduces the cost of designing barriers. This is because lower energy levels in falling blocks require less resistant (kinetic energy-absorbing) materials for effective barrier construction. Therefore, the overall cost of protective measures decreases as a result of slope scaling, which mitigates the impact energy of falling rocks.

Sections	Volume (m^3)	Velocity (m/s)	Bounce Height (m)
Sections 1	4.2	19.97	1.81
	3.25	19.97	1.81
	2.1	19.97	1.81
Sections 2	4.2	2.85	1.04
	3.25	2.85	1.04
	2.1	2.85	1.04
Sections 3	4.2	22.04	0.644
	3.25	22.04	0.644
	2.1	22.04	0.644
Section 4	4.2	25.37	3.14
	3.25	25.37	3.14
	2.1	25.37	3.14
Section 5	4.2	22.68	0.728
	3.25	22.68	0.728
	2.1	22.68	0.728

Table 4.3.6-1 *Velocity and Bounce height along 5 different sections using 3 different design rock block volumes*

It can be clearly observed from the table that the velocity of the each and every profile doesn't change with respect to its different design rock block volume therefore we have selected 5 single maximum values of both translational velocity and block height from all the five sections, using design block volume of 3.250 m^3 because of being more realistic, for further designing the barrier based on its kinetic energy, design bounce height and elongation

5. Rockfall Barrier Design

Rockfall barriers are designed to mitigate the impact of falling rocks by absorbing their energy and preventing them from reaching vulnerable areas. The design of these barriers involves several critical parameters, as indicated in the provided slides.

First, the energy absorption capacity of the barrier and its behavior during impact are crucial factors. The barrier must be capable of withstanding the kinetic energy generated by the falling rocks without failing. Additionally, the maximum downslope displacement or elongation of the wire mesh during impact is another key consideration, ensuring that the barrier stretches within acceptable limits without allowing the rocks to breach it. The acting loads on the foundation and other structural components during impact must also be carefully evaluated to ensure overall system stability.

Manufacturers are responsible for providing information on these parameters and must ensure that their products comply with the performance assessment standards outlined in the EAD 340059-00-0106. The standard define two energy levels:

1. **The Maximum Energy Level (MEL)**
2. **Service Energy Level (SEL)**

In simpler terms, **SEL** is the amount of kinetic energy from falling rocks that the barrier is designed to absorb and manage under typical scenarios, without sustaining damage that would require repair or compromise its effectiveness. The SEL is a critical value used to ensure that the barrier can perform reliably under everyday conditions, as opposed to extreme events. In contrast, the Maximum Energy Level **(MEL)** represents a more extreme condition, where the barrier must withstand higher energy impacts that are less frequent but still possible. For a barrier to be effective, it should be designed so that the MEL is greater than or equal to three times the SEL, indicating a robust safety margin for handling more severe rockfall events.

SEL refers to the kinetic energy of a rock block impacting the barrier, where the barrier must meet specific performance criteria. These criteria include:

1. **Multiple Impact Resilience**: The barrier must be able to stop the block after two impacts at the same energy level without failure.
2. **Structural Integrity**: After the first impact, the barrier must remain intact with no ruptures in its components. Additionally, the mesh openings should not exceed twice their original size.
3. **Residual Height**: Post-impact, the barrier's height (measured between the lower and upper parts of the mesh) must be at least 70% of its original height, ensuring that it still provides effective protection.
4. **Second Impact Stoppage**: The barrier must also be able to stop the block after the second impact, confirming its ability to endure repeated stresses.

Maximum Energy Level (MEL) of a rockfall protection kit is defined as the kinetic energy of a standard block impacting the net fence. For the barrier to be considered effective, it must meet specific criteria: the MEL must be at least three times greater than the Service Energy Level (SEL), the barrier must successfully stop the block, and the block should not touch the ground during the impact until the barrier has reached its maximum elongation. During MEL testing, both the maximum displacement of the barrier and the forces exerted on the foundations are measured to assess the system's performance.

5.1. Methodology of Rockfall Barrier Design:

Using the trajectory analysis, we have design a new barrier based on the following calculations

- EBTE $\gamma E \geq E_{design}$
- $hi \geq h_{design}$
- $d_{design} \geq d_A$

Where;
EBTE γE is the energy certificated by the producer divided by the factor of safety equal to 1.2 or 1 if the verification is done on the basis of the MEL or SEL value of kinetic energy, respectively.

h_i is the barrier height declared by the manufacturer.

- $\mathbf{d_A}$ is the elongation of the wire mesh declared by the manufacturer.
- $\mathbf{E_{design}}$, hdesign are the required kinetic energy and height obtained on the basis of propagation analysis.
- $\mathbf{d_{design}}$ is the distance between the location of the barrier and the element at risk.

Moreover, the number of barriers required to cover the area at risk is defined in accordance with the post spacing of the rockfall barrier.

After the runout analysis done with Rockfall, we perform the design of the rockfall barrier in accordance with the Guidelines for rockfall barrier.

The calculation of the total kinetic energy ($\mathbf{E_{design}}$), bounce height ($\mathbf{h_{design}}$) is performed to verify that the selected barrier chosen from a catalogue respects the conditions:
The $\mathbf{E_{design}}$ is calculated as:,

$$E_{design} = \frac{1}{2}\ m_{design}\ V^2_{design}$$

$\mathbf{m_{design}}$ is calculated as:

$$\mathbf{m_{design}} = (Vol_b\ \gamma_{rock})\ r_m = (Vol_b\ \gamma_{rock})\ \gamma_g \cdot \gamma_{vol}$$

Where;

Vol_b is the rock block volume

$\boldsymbol{\gamma_g}$ is the Factor of safety = 1.

$\boldsymbol{\gamma_{vol}}$ is the factor of safety used based on the method used to choose the characteristic volume.

$\boldsymbol{\gamma_{rock}}$ is the intact rock unit volume & $\mathbf{V_{design}}$ is calculated as:

$$V_{design} = V_t\, \gamma_F = V_t \cdot \gamma_{Tr} \cdot \gamma_{Dp}$$

Where:

V_t is the 95% of the block velocity values obtained from the analysis.

γ_{Tr} is equal to 1.02 for propagation models calibrated by means of a back analysis.

γ_{Dp} is equal to 1.02 for a topography with a good detail and precision.

For the Calculation of h_{design}:

$$h_{design} = h_t \gamma_F$$

Where:

h_t is the 95% bounce height obtained from the analysis.

The d_{design} is the distance between the barrier and the element at risk with the hypothesis that the element at risk is located at the end of the slope (x = 0, y = 0) and the barrier is located where the collector was placed

The analysis on Rockfall was conducted using design block volumes across three different sections. A block volume of 3.250 m^3 was selected for all three sections because the resulting values for V_t and h_t were identical across these sections,

Sections	Volume (m3)	Velocity (m/s)	Bounce Height (m)
Sections 1	4.2	19.97	1.81
	3.25	19.97	1.81
	2.1	19.97	1.81
Sections 2	4.2	2.85	1.04
	3.25	2.85	1.04
	2.1	2.85	1.04
Sections 3	4.2	22.04	0.644
	3.25	22.04	0.644
	2.1	22.04	0.644
Section 4	4.2	25.37	3.14
	3.250	25.37	3.14
	2.100	25.37	3.14
Section 5	4.2	22.68	0.728
	3.25	22.68	0.728
	2.1	22.68	0.728

5.1.1. E_{design} and H_{design} Calculation for Section 1:

Parameter	Values	Units
Vol_b =	3.25	m^3
r_{rock} =	2358	Kg /m3
r_g =	1	
r_{vol} =	1.02	
m_{design} =	**7817**	**Kg**
r_{Tr} =	1.02	
r_{Dp} =	1.02	
V_t =	19.97	m/s
V_{design} =	20.78	m/s
E_{design} =	**1687**	**KJ**
h_t =	0.72	m
r_F =	1.04	
h_{design} =	**0.75**	**m**
d_{design}	**31.20**	**m**

Table 5.1.1-1 Design parameters for barrier design of Section 1

Now we select a rock fall barrier that suits our E_{design}, h_{design} and d_{design}. The barrier selected is from GeoBrugg Technical data sheet – RXE 3000 . It has the following characteristics:

E_{BTE} = 3019 kJ
h_i =   = 3.53 m
Category A of ETAG 027 So, verifying the values:

$$\frac{E_{BTE}}{\gamma_E} \geq E_{design}$$

$$= \frac{3019}{1.2} = \mathbf{2512} \geq \mathbf{1687\ kJ}$$

$$h_i \geq h_{design}$$

$$= 3.53 > \mathbf{0.75}$$

$$d_{design} \geq d_A$$

Where,

$$d_A = d_{producer} \cdot \gamma_{Dp}$$

γ_{Dp} is the factor of safety equal to 1.3

= 31.20 > (6.97) (1.3) = **9.01 m**

5.1.2. E_{design} and H_{design} Calculation for Section 2:

Parameter	**Values**	**Units**
Vol_b =	3.25	m^3
r_{rock} =	2358	Kg /m3
r_g =	1	
r_{vol} =	1.02	
m_{design} =	**7816**	**Kg**
r_{Tr} =	1.02	
r_{Dp} =	1.02	
V_t =	2.85	m/s
V_{design} =	2.96	m/s
E_{design} =	**34.36**	**KJ**
h_t =	0.00072	m
r_F =	1.04	
h_{design} =	**0.00074909**	**m**
d_{design}	**27.13**	**m**

Table 5.1.2-1 Design parameters for barrier design of Section 2

Now we select a rock fall barrier that suits our E_{design}, h_{design} and d_{design}. The barrier selected is from GeoBrugg Technical data sheet – 500 . It has the following characteristics:

E_{BTE} = 500 kJ

h_i =   = 1.71 m

Category A of ETAG 027 So, verifying the values:

$$\frac{E_{BTE}}{\gamma_E} \geq E_{design}$$

$$= \frac{500}{1.2} = 416 \geq \mathbf{34\ kJ}$$

$$h_i \geq h_{design}$$

$$= 1.71 > 0.00074$$

$$d_{design} \geq d_A$$

Where,

$$d_A = d_{producer} \cdot \gamma_{Dp}$$

γ_{Dp} is the factor of safety equal to 1.3

= 27.13 > (3.6) (1.3) = **4.6**

5.1.3. E_{design} and H_{design} Calculation for Section 3:

Parameter	Values	Units
Vol_b =	3.25	m^3
r_{rock} =	2358	Kg /m3
r_g =	1	
r_{vol} =	1.02	
m_{design} =	**7816.77**	**Kg**
r_{Tr} =	1.02	
r_{Dp} =	1.02	
V_t =	22.04	m/s
V_{design} =	22.930416	m/s
E_{design} =	**2055.04**	**KJ**
h_t =	0.64	m
r_F =	1.04	
h_{design} =	**0.67**	**m**
d_{design}	**30.19**	**m**

Table 5.1.3-1 *Design parameters for barrier design of Section 3*

Now we select a rock fall barrier that suits our E_{design}, h_{design} and d_{design}. The barrier selected is from GeoBrugg Technical data sheet – RXE 3000 . It has the following characteristics:

E_{BTE} = 3019 kJ
h_i = = 3.53 m
Category A of ETAG 027 So, verifying the values:

$$\frac{E_{BTE}}{\gamma_E} \geq E_{design}$$

$$= \frac{3019}{1.2} = \mathbf{2512} \geq \mathbf{2055\ kJ}$$

$h_i \geq h_{design}$

$= 3.53 > \mathbf{0.67}$

$d_{design} \geq d_A$

Where,

$d_A = d_{producer} \cdot \gamma_{Dp}$

γ_{Dp} is the factor of safety equal to 1.3

$= 30.19 > (6.97)\,(1.3) = \mathbf{9.01\ m}$

5.1.4. E_{design} and H_{design} Calculation for Section 4:

Parameter	Values	Units
Vol_b =	3.25	m^3
r_{rock} =	2358	Kg /m3
r_g =	1	
r_{vol} =	1.02	
m_{design} =	**7816.77**	**Kg**
r_{Tr} =	1.02	
r_{Dp} =	1.02	
V_t =	22.69	m/s
V_{design} =	23.61	m/s
E_{design} =	**2178.05**	**KJ**
h_t =	3.14	m
r_F =	1.04	
h_{design} =	**3.25**	**m**
d_{design}	**32.86**	**m**

Table 5.1.4-1 Design parameters for barrier design of Section 4

Now we select a rock fall barrier that suits our E_{design}, h_{design} and d_{design}. The barrier selected is from GeoBrugg Technical data sheet – RXE 3000 . It has the following characteristics:

E_{BTE} = 3019 kJ

h_i = = 3.53 m

Category A of ETAG 027 So, verifying the values:

$$\frac{E_{BTE}}{\gamma_E} \geq E_{design}$$

$$= \frac{3019}{1.2} = \mathbf{2515} \geq \mathbf{2178\ kJ}$$

$h_i \geq h_{design}$

= 3.53 > **3.25 m**

$d_{design} \geq d_A$

Where,

$d_A = d_{producer} \cdot \gamma_{Dp}$

γ_{Dp} is the factor of safety equal to 1.3

= 32.86 > (6.97) (1.3) = **9.01 m**

5.1.5. E_{design} and H_{design} Calculation for Section 5:

Parameter	Values	Units
Vol_b =	3.25	m^3
r_{rock} =	2358	Kg /m3
r_g =	1	
r_{vol} =	1.02	
m_{design} =	**7816.77**	**Kg**
r_{Tr} =	1.02	
r_{Dp} =	1.02	
V_t =	22.68	m/s
V_{design} =	23.59	m/s
E_{design} =	**2176.13**	**KJ**
h_t =	0.7	m
r_F =	1.04	
h_{design} =	**0.73**	**m**
d_{design}	**27.83**	**m**

Table 5.1.5-1 Design parameters for barrier design of Section 5

Now we select a rock fall barrier that suits our E_{design}, h_{design} and d_{design}. The barrier selected is from GeoBrugg Technical data sheet – RXE 3000 . It has the following characteristics:

E_{BTE} = 3019 kJ

h_i = = 3.53 m

Category A of ETAG 027 So, verifying the values:

$$\frac{E_{BTE}}{\gamma_E} \geq E_{design}$$

$$= \frac{3019}{1.2} = \mathbf{2515} \geq \mathbf{2176\ kJ}$$

$$h_i \geq h_{design}$$

= 3.53 > **0.73 m**

$$d_{design} \geq d_A$$

Where,

$$d_A = d_{producer} \cdot \gamma_{Dp}$$

γ_{Dp} is the factor of safety equal to 1.3

= 27.83 > (6.97) (1.3) = **9.01 m**

5.1.6. Final Results of Design and Manufacturers declared parameters

The following Table 5.1.6-1 and Table 5.1.6-2 below shows the final results of design parameters calculated and the capacity parameters of wire mesh declared by manufacturer GeoBrugg

Sections	Volume (m3)	E_{design} (kJ)	h_{design} (m)	d_{design} (m)
Section 1	3.25	1687.15	0.75	31.20
Section 2	3.25	34.36	0.00	27.13
Section 3	3.25	2055.04	0.67	30.19
Section 4	3.25	2178.05	3.94	32.86
Section 5	3.25	2176.13	0.73	27.83

Table 5.1.6-3 Results of design parameters using block volume 3.25 m^3

Sections	Volume (m3)	EBTE (kJ)	h_i (m)	d_A (m)
Section 1	3.25	2515	3.53	9.01
Section 2	3.25	416	1.71	4.7
Section 3	3.25	2515	3.53	9.01
Section 4	3.25	2515	3.53	9.01
Section 5	3.25	2515	3.53	9.01

Table 5.1.6-4 parameters declared by manufacturer GeoBrugg for verification with design parameters

From the results of both the design and manufacturer-declared parameters, Sections 4 and 5 are identified as critical for rockfall safety due to the higher energy requirements and barrier height. Section 4 stands out, as both the design energy and manufacturer-specified energy absorption values are high (2457 kJ and 2515 kJ, respectively), indicating a significant rockfall hazard. However, the barrier heights and arrest distances provided by the manufacturer appear to align well with the design needs, ensuring sufficient protection for the critical sections. It has been found from the results of simulation and barrier design calculation that, the region between sections 3 – 4 is critical in terms of rockfall

6. Conclusion

This thesis has addressed the critical issue of rockfall instability and its mitigation, focusing on the specific case of a slope in Varallo (VC), North-West Italy. Through 2D stochastic analyses using the Rock Science simulation tool, we have assessed the rockfall hazards and proposed effective mitigation strategies to protect the road located at the base of the slope. The study began by estimating the volume of the rock blocks, using a range of methodologies from simple observational approaches to more sophisticated statistical analyses. By conducting back analyses of the November 2023 rockfall event, we defined the key parameters for simulating rockfall trajectories. Once the key parameters are identified with back analysis, three different design block volumes have been estimated using two different methods, Simplest Box Plot (based on blocks already fallen at the base of the slope) to a more complex Statistical Analysis method (Volume – Return time Relation)described in this thesis. The volumes obtained from these methods are then used in Rockfall 2 simulation to estimate its translational velocity and impact height. The safety barriers have been designed on the basis of simulated results in Rockfall 2. These simulations, applied across various scenarios with different block volumes, allowed for a comprehensive understanding of the rockfall dynamics in the area.

The research culminated in the design of two targeted intervention strategies aimed at reducing the rockfall risk based on the outcomes of the trajectory analyses. These proposed measures not only enhance the safety of the infrastructure but also offer valuable insights into the broader field of rockfall hazard mitigation. The methodologies and approaches outlined in this thesis can serve as a foundation for future studies and practical applications in similar geological contexts, contributing to more robust and informed solutions for mitigating rockfall risks.

References

[1] *A. B. U. O. Canterbury, "Creating An Engineering Modelling Workflow For Ramms::Rockfall, Using The," P. 88, 2017.*

[2] *The computer simulation and prediction of rock fall, Durham theses, Durham, 2001, p. 268.*

[3] *B. Peng, Rockfall Trajectory Analysis - Parameter Determination and Application, Centurbury, 2000.*

[4] *A. M. Fanos, Rockfall Hazard Assessment Based On Airborne Laser Scanning And Gis In Tropical Region, Malaysia, 2016.*

[5] *M. L. N. M. B. D. P. Valerio De Biagi, "Estimation of the return period of rockfall blocks according to their size," Nat. Hazards Earth Syst . Sci., p. 11, 2017.*

[6] *M. B. F. C. M. C. V. L. Maria Lia Napoli, "The Susceptibility Index to Failure (SIF) and the Source Affecting Index to characterize rockfall release areas," p. 8, April 2024.*

[7] *M. L. N. M. B. a. D. P. Valerio De Biagi, "Estimation of the return period of rockfall blocks according to their size," Natural Hazards and Earth System. Sciences., p. 11, 2017.*

[8] *A. Mariella Illeditsch, "Determination of meaningful block sizes for rockfall Modeling," Natural Hazards, p. 27, 2024.*

[9] *V. D. B. D. P. Maddalena Marchelli, "Reliability-based design of rockfall passive systems height," Rock Mechanics and Mining Sciences , p. 9, 2024.*