POLITECNICO DI TORINO

Department of Structural, Geotechnical and Building Engineering

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The application of the rockfall Susceptibility Index to Failure (SIF) to the case study of Varallo (VC)

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Abstract

This thesis addresses the issue of rockfall instability, focusing on identifying and analyzing areas prone to rockfall events. Specifically, it examines a slope in Varallo (VC, North-West Italy) that has experienced repeated rockfall phenomena over the years, posing risks to the buildings and the adjacent road at its base. Given the need to evaluate large areas, preliminary methods are essential to pinpoint zones requiring detailed analysis. To meet this need, the QPROTO plugin, integrated within QGIS, was used to quantitatively assess time-independent rockfall hazards across three-dimensional terrains using the Cone Method. This approach requires specific input angles, such as the energy angle (φp) and the lateral angle (α), which capture the complex dynamics of rock block movement along slopes. QPROTO generates raster maps that delineate potential invasion zones and quantify rockfall susceptibility. This research introduces a novel method to characterize the source areas, through the definition of the Susceptibility Index to Failure (SIF Index). The proposed framework provides QPROTO users with a systematic approach for estimating input parameters, improving the tool's accuracy and applicability. The effectiveness of this method is demonstrated through a case study in the north-western Italian Alps, showing its potential to enhance rockfall hazard assessments and support informed decision-making in risk management and planning. This study was conducted within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan—NRRP, Mission 4, Component 2, Investment 1.3—DD 1243 2/8/2022, PE0000005).

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1. INTRODUCTION TO ROCKFALL

Rockfalls are a prevalent natural hazard in regions characterized by rugged terrains and steep slopes, often triggered by geological and environmental processes such as earthquakes, rainfall, erosion, and weathering. These events, which involve the detachment and descent of rocks and debris from cliffs or slopes, present significant risks to both the natural environment and human infrastructures. The magnitude and frequency of rockfalls are influenced by various predisposing factors, including geological composition, slope inclination, and climatic conditions. Among the most pressing concerns associated with rockfalls is their potential to disrupt critical transportation networks, such as highways and railroads, which frequently traverse mountainous areas. Such disruptions can have far-reaching consequences, including delays in the transportation of goods, damage to infrastructure, and threats to the safety of travelers.

In addition to transportation networks, settlements and infrastructures located at the base of steep slopes are particularly vulnerable to rockfall hazards. Buildings, bridges, and other structures can be severely damaged or destroyed by falling rocks, posing significant risks to public safety and property. Furthermore, industries such as quarrying, which involve large-scale extraction of rock formations, face heightened risks of rockfalls that can endanger workers and equipment. These challenges underscore the need for comprehensive mitigation strategies to address the multifaceted risks posed by rockfalls.

Effective rockfall mitigation requires a combination of geological assessments, advanced monitoring systems, and technical interventions aimed at stabilizing slopes and protecting vulnerable areas. Structural measures, such as rockfall barriers, rockfall embankments, and catchment systems, play a critical role in diverting or containing falling rocks, thereby reducing the likelihood of damage to infrastructures and injury to individuals. However, the inherently unpredictable nature of rockfalls presents an ongoing challenge for communities and authorities in mountainous regions. Even minor incidents involving small rocks or debris can pose significant risks to road users and pedestrians, highlighting the need for constant vigilance and proactive risk management.

Figure 1.1.1 *Damage due to RockFall*

In summary, rockfalls represent a complex and persistent hazard in mountainous and hilly terrains, with profound implications for both natural ecosystems and human society. Understanding the underlying mechanisms driving rockfalls and implementing effective mitigation strategies are essential steps toward minimizing their impact. This thesis seeks to contribute to this understanding by exploring the factors influencing rockfall dynamics and using QProto plugin to mark out the areas under threat. By doing so, it aims to support the development of strategies that enhance the safety and resilience of communities and infrastructure in rockfall-prone regions.

1.1. RockFall Triggering Factors

The behavior of rockfalls is highly unpredictable, influenced by a variety of factors that can initiate such events along both excavated and natural slopes. These triggering factors can be broadly categorized into two groups: structural and environmental. Structurally, the presence of potentially unstable rock blocks on the slope surface is a primary prerequisite. For individual pebbles or boulders, this instability often results from prior movement, while for larger rock blocks, the presence of sufficient fissures or fractures is necessary to create blocks that are prone to detachment. Additionally, the slope must be steep enough to promote instability and facilitate the continued movement of dislodged rocks or boulders once initiated.

Environmental factors, on the other hand, typically act as triggering mechanisms but can also contribute to structural instability over time. Physical and chemical weathering are the primary agents responsible for rockfalls. Joints or discontinuities formed by planes of weakness or previous deformation provide pathways for water infiltration and vegetation growth. These processes further weaken the rock mass through mechanisms such as frost and root wedging, erosion, and increased pore water pressure, which reduce cohesive strength and frictional resistance. Water pressure within joints can also play a significant role in destabilizing rock masses.

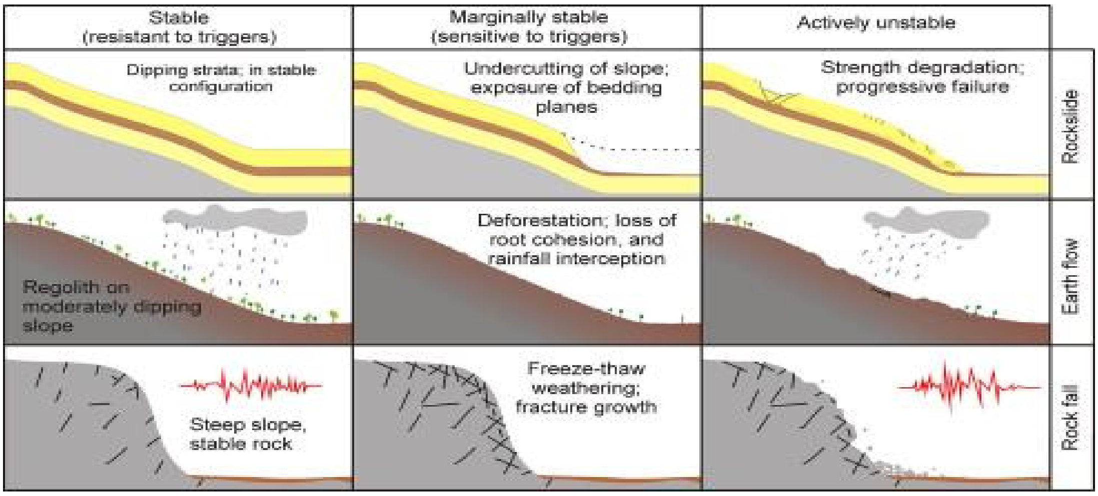

Figure 1.1.2 Demonstration of Triggering Factors
(https://www.sciencedirect.com/science/article/pii/B9780123964526000021)

Heavy rainfall is a common environmental trigger, either through the forceful flow of water or the erosion of stabilizing materials. Differential weathering, where weaker rock layers erode and leave more resistant rock formations unsupported, can create overhanging ledges that are particularly hazardous. Earthquakes are another frequent trigger, though any source of ground vibration—whether natural or manmade—can induce rockfalls. Human activities, such as blasting, construction machinery operation, excavation processes, and even traffic, can generate vibrations capable of triggering rockfalls. Additionally, the movement of people or animals on slopes can also act as a triggering factor.

1.2. Factors Affecting Rockfall

Once rock fall is initiated, its behavior is influenced primarily by geometry and material properties of the slope and rock itself. Slope geometry includes factors such as slope inclination, slope length, surface roughness, and lateral variation. Slope inclination determines zones of acceleration and deceleration, while slope length affects the distance over which a rock can gain or lose momentum. Surface irregularities alter the angle of impact, influencing the bounce characteristics, and lateral variability can channel rocks in specific directions, such as down gullies, potentially affecting their velocity.

The material properties and surface cover of the slope play a significant role in defining the behavior of falling rocks, particularly through the normal and tangential coefficients of restitution.

- The **normal coefficient** of restitution measures the ratio of the relative velocity of the rock after impact to its velocity before impact, perpendicular to the slope surface. It determines the elasticity of the collision, with higher values indicating a more pronounced bounce.
- The **tangential coefficient** of restitution measures the same ratio but parallel to the slope surface, influencing how much of the rock's horizontal velocity is retained after impact.

These coefficients are critical in predicting the trajectory and distance traveled by falling rocks. Rock properties, such as size, shape, mass, and strength, further influence rock fall behavior. Larger and heavier rocks possess greater momentum and are less likely to lodge among surface irregularities, allowing them to travel further. Spherical rocks tend to travel farther than angular ones due to reduced friction, while weaker or weathered rocks may break apart upon impact, altering their trajectory. Human-made alterations to the topography, such as roads or retaining walls, can also create new pathways for rock fall or influence the natural flow of rocks down the slope.

1.3. Rockfall Failure Mechanisms

The likelihood of rock mass failure and the size of the blocks that may be dislodged are fundamentally determined by the characteristics of the rock mass itself. These characteristics govern the size, shape, mass, and strength of the blocks that can be generated during a failure event. In all rock outcrops and cut-slopes observed in the field, discontinuities of some form are invariably present. These discontinuities may have originated either during the formation of the rock material or as a result of subsequent geological processes. Common types of discontinuities include bedding planes, cooling joints, and deformation features such as stress-induced fractures, joints, and faults.

The orientation of these discontinuities, or sets of discontinuities, relative to the slope face plays a critical role in determining the kinematic feasibility and the mode of rock mass failure. When these discontinuities are oriented in specific ways, they can form segments of unstable block masses. This is assessed by analyzing the dip and dip direction of the discontinuity sets in relation to the exposed rock face. Discontinuities that dip out of the slope face have the potential to initiate planar sliding failures, whereas those that dip into the slope face may lead to toppling failures. As the slope angle increases, the likelihood of planar failure also increases. Conversely, if the angle of the joint is less than that of the slope angle, the potential for sliding failure diminishes, and the slope is more likely to remain stable.

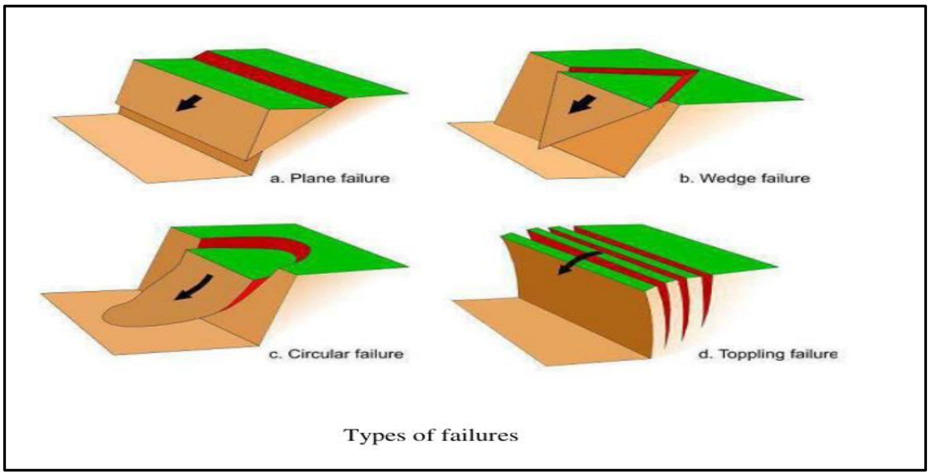

Figure 1.3.1 *Types of RockFall Failures*
Ref. https://slideplayer.com/user/5148433/

The conditions favorable for planar failure can be summarized as follows:

- The dip direction of the planar discontinuity must fall within ±20° of the dip direction of the slope face.
- The dip of the planar discontinuity must be less than the dip of the slope face, ensuring that the discontinuity "daylights" or intersects the slope surface (as illustrated in Figure 1.3.2).
- The dip of the planar discontinuity must exceed the angle of friction of the surface to enable sliding.

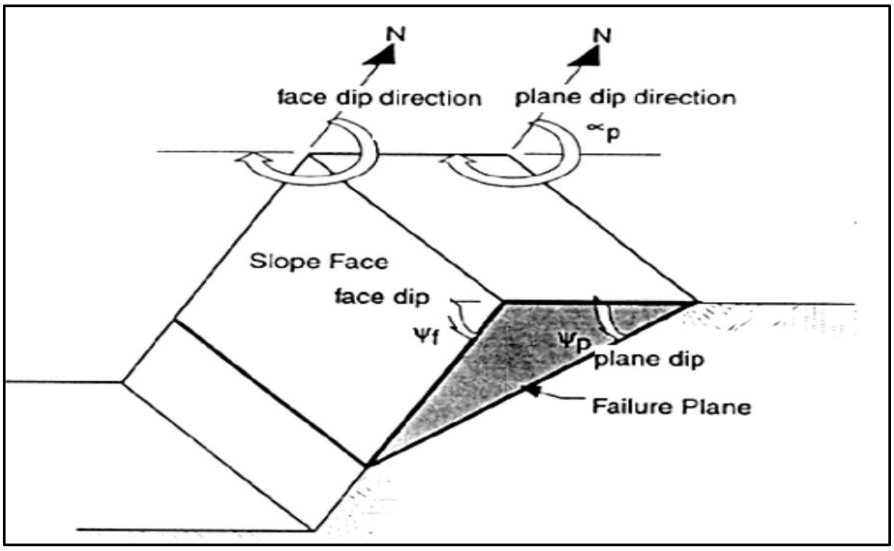

Figure 1.3.2 *Plan Failure with Condition of Failures.*
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The structural conditions for planar failure, as depicted in Figure 1.3.3, are further detailed as follows:

- For wedge failure to occur, the line of intersection between two joint planes must closely align with the dip direction of the slope face. This alignment allows 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 to ensure that the line "daylights," meaning it is exposed on the slope surface, thereby making detachment possible.
- Additionally, the plunge of the line of intersection must exceed the friction angle of the joint surfaces to overcome frictional resistance and allow the wedge to slide.

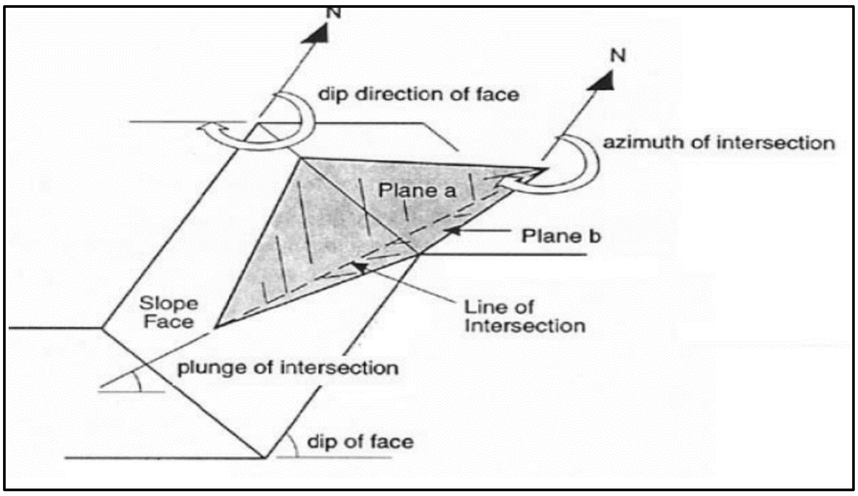

Figure 1.3.3 *Wedge Failure with Condition of Failures.*
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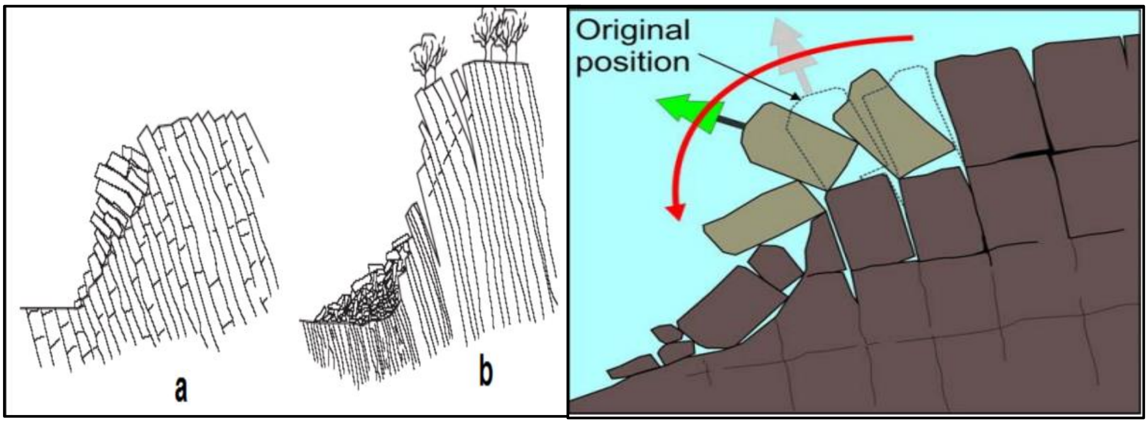


Figure 1.3.4 *Schematic view of Toppling Failure*

Toppling failures, on the other hand, occur when columns or slabs of rock, formed by steeply dipping discontinuities, rotate about a fixed point at or near the base of the slope, followed by slippage between the layers (as shown in Figure 1.3.4). For toppling failure to occur, the center of gravity of the rock column or slab must lie outside the base dimensions of the column. This type of failure is typically associated with jointed rock masses characterized by closely spaced and steeply dipping discontinuity sets that dip away from the slope surface. These conditions are essential prerequisites for toppling failure to take place.

In summary, the stability of a rock mass and the nature of potential failures are intricately linked to the orientation and characteristics of discontinuities within the rock. Understanding these relationships is crucial for assessing slope stability and implementing effective mitigation measures to prevent rockfall hazards.

1.4. Discontinuity Survey of Rock Mass

A discontinuity survey is a critical step in analyzing the structural characteristics of a rock mass, particularly when creating a 2D profile of a rock slope. Such a profile requires specific input parameters that are derived from the detailed assessment of discontinuities within the rock. The survey process begins with the identification of the type of discontinuities present in the rock mass, which may include joints, faults, cleavage, or shear zones. Each type of discontinuity has unique characteristics that influence the stability and behavior of the rock slope.

Once the type of discontinuity is identified, the next step is to measure its key geometric properties. The first of these is the dip, which refers to the angle at which a rock layer or geological structure inclines from the horizontal plane. The dip represents the steepest angle of descent of the rock layer or structure and is a fundamental parameter in slope stability analysis. Alongside the dip, the dip direction must also be measured. The dip direction indicates the compass direction in which the steepest angle of descent occurs, measured clockwise from true north. Together, the dip and dip direction provide essential information about the orientation of the discontinuity relative to the slope face.

Another critical parameter to assess is the persistence of the discontinuity, which refers to the length or extent of the discontinuity along the rock surface. Persistence can vary significantly, and discontinuities may be either open or filled with materials such as clay, debris, or other infill. In cases where discontinuities are open, the aperture—defined as the thickness of the joint opening—must be measured. The aperture provides insight into the potential for water infiltration, weathering, and the overall mechanical behavior of the discontinuity.

In addition to persistence and aperture, the surface roughness of the discontinuity is another important factor to evaluate. Surface roughness describes the texture and irregularities along the discontinuity surface, which influence the frictional resistance and shear strength of the rock mass. Rough surfaces generally provide greater resistance to sliding, while smoother surfaces may facilitate movement. Finally, the distance between fault lines or discontinuities must be measured, as this spacing affects the size and stability of rock blocks within the mass.
After collecting these essential data from the field, the information is used to construct a detailed 2D profile of the rock slope. This profile serves as the foundation for further analyses, including kinematic assessments and stability evaluations. By accurately measuring and documenting the dip, dip direction, persistence, aperture, surface roughness, and spacing of discontinuities, engineers and geologists can better understand

the structural behavior of the rock mass and develop effective strategies to mitigate potential hazards. The survey process, therefore, plays a pivotal role in ensuring the safety and stability of rock slopes in engineering and construction projects.

1.5. Rockfall Hazard Assessment

In the context of rockfall terminology, the concept of rockfall hazard refers to the likelihood or probability of a rockfall event occurring, characterized by a specific magnitude (volume) or intensity (kinetic energy), within a defined area and over a predetermined period of time. This definition encompasses several key elements, including the location (where the rockfall event is likely to occur), the frequency (temporal recurrence of the event), and the magnitude or intensity (the volume of material or energy involved in the event). As a result, the most basic rockfall hazard map should provide a clear representation of the probability of rockfall events of a certain magnitude occurring within a specific area. However, due to the highly dynamic and mobile nature of rockfalls, the propagation (or transit) component must also be incorporated into rockfall hazard assessments. This means that the trajectory, travel distance, and maximum runout of falling rocks must be considered alongside the probability of detachment.

Rockfall hazards are generally understood to depend on three primary factors:

- Probability of Detachment from the Rock Wall: This refers to the likelihood that a rockfall of a given magnitude (i.e., block size) will originate from a specific source location within a defined timeframe. This parameter is often assessed through a Qualitative Rockfall Hazard Assessment, which evaluates both the spatial probability of occurrence (also known as susceptibility) and the temporal probability (referred to as the probability of failure or frequency). The spatial probability identifies areas where rockfalls are more likely to occur based on geological and geomorphological conditions, while the temporal probability estimates how often such events might happen over time.
- Propagation Down the Slope: This factor focuses on the behavior of falling rocks once they detach from the rock wall. It includes the analysis of the trajectory of the falling blocks, their travel distance, and the maximum runout (the farthest point a rock can reach). Understanding propagation is critical because it

determines the extent of the area that could be affected by a rockfall event. Factors such as slope geometry, surface roughness, and the presence of obstacles or vegetation can significantly influence the propagation of falling rocks.

- Rockfall Intensity (Kinetic Energy): This refers to the energy carried by the falling rocks, which is a function of their mass and velocity. Rockfall intensity is a critical measure of the potential impact of a rockfall event, as it determines the destructive force that the falling blocks can exert on structures, infrastructure, people or the environment. High-intensity rockfalls, characterized by large blocks or high velocities, pose a greater risk to human safety and property.

In summary, rockfall hazard assessments require a comprehensive evaluation of the probability of detachment, the propagation of falling rocks, and the intensity of the event. By integrating these three factors, it becomes possible to develop accurate hazard maps and implement effective mitigation strategies to reduce the risks associated with rockfalls. This holistic approach ensures that both the source and the potential impact areas are considered, providing a more complete understanding of rockfall hazards in mountainous or steep terrain.

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
- 2d and 3d approaches

2. ROCKFALL DYNAMICS, ANALYSIS AND PROTECTION MEASURES

Rockfall-Analysis

Rockfall analysis is a critical process aimed at evaluating the behavior and potential impacts of falling rocks to assess the hazards they may pose. This analysis is essential for identifying vulnerable areas and implementing effective mitigation measures. It primarily consists of two key components: the invasion area and the intensity of the rockfall event.

Each of these components plays a vital role in understanding the full scope of rockfall hazards and their implications.

Invasion-Area

The invasion area refers to the spatial extent where falling rocks eventually come to rest after their descent. This area is determined by analyzing the paths and final positions of the rocks, providing valuable insights into the zones that may be affected by rockfall events.

Components of Invasion Area

1. **Trajectories**: Trajectories represent the specific paths that rocks follow as they move down a slope. By studying these trajectories, researchers can determine the direction, speed, and distance traveled by the rock blocks. This information is crucial for predicting where rocks are likely to land and identifying areas at risk.
2. **Runout**: Runout refers to the maximum distance that rocks travel before they stop. It is a key parameter for defining the extent of the invasion area. A longer runout indicates that rocks can travel farther, potentially affecting a larger area. Understanding runout helps in assessing the reach of rockfall events and planning protective measures accordingly.

Intensity

The intensity of a rockfall event describes its severity, focusing on the physical characteristics of the falling rocks and their potential to cause damage. Intensity is determined by factors such as the velocity of the rocks and the kinetic energy they carry.

Components of Intensity

1. **Velocity**: Velocity measures the speed at which rocks move as they descend. Higher velocities indicate greater momentum, which can lead to more significant impacts and damage upon collision with structures or the ground. Monitoring velocity helps in evaluating the potential danger posed by falling rocks.
2. **Kinetic Energy**: Kinetic energy quantifies the energy possessed by the rocks due to their motion. It is a critical factor in assessing the destructive potential of a rockfall event. Rocks with higher kinetic energy can cause more severe damage upon impact, making this parameter essential for risk assessment and mitigation planning.

Understanding-Rockfalls

To gain a comprehensive understanding of rockfalls, several key questions are explored. These questions help researchers and engineers analyze the behavior of falling rocks and develop strategies to mitigate their impact.

Dynamics of the falling block

This aspect focuses on how rocks move and transform as they fall. Understanding the dynamics of falling blocks is essential for predicting their behavior and assessing the associated hazards. For instance, observing whether rocks tumble, slide, or bounce during their descent provides valuable insights into their trajectory and potential impact. By studying these dynamics, researchers can better anticipate the paths rocks may take and identify areas that are most vulnerable to damage. This knowledge is crucial for designing effective protective measures and ensuring the safety of people and infrastructure in rockfall-prone regions.

In summary, rockfall analysis involves a detailed examination of the invasion area and intensity of rockfall events, supported by an understanding of the dynamics of falling blocks. By analyzing trajectories, runout, velocity, bounce height and kinetic energy, researchers can assess the potential hazards posed by rockfalls and develop strategies to mitigate their impacts. This comprehensive approach ensures that vulnerable areas are identified and protected, ultimately enhancing safety and reducing the risks associated with rockfall events.

2.1. Phases of Motion

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

2.1.1. Detachment

The process of rockfall begins when a block separates or detaches from the source area. The detachment of a block from the source is influenced by two primary factors: the susceptibility of the source material and the triggering mechanism. Susceptibility refers to the likelihood of a block detaching from the rock mass, which is determined by the inherent properties of the rock mass itself. These properties include the type of rock, the roughness of its joints, the orientation and spacing of discontinuities, the aperture size, the presence of filling material, and the degree of weathering within the rock mass discontinuities. All these factors collectively influence the potential size of the detached block and the manner in which it detaches, whether through toppling or sliding.

The dimensions of the blocks that are released from the rock outcrop are primarily governed by the spacing between the discontinuities within the rock mass. In a rock mass that is highly fragmented and characterized by closely spaced discontinuities, smaller blocks are more likely to be released. This is because the closely spaced fractures or joints create numerous small segments or blocks, as each discontinuity acts as a boundary where the rock can easily break apart. When discontinuities are tightly spaced, they intersect more frequently, leading to the formation of smaller, more fragmented blocks. On the other hand, in a rock mass where discontinuities are widely spaced, larger segments of rock are formed. This is due to the fewer fractures or joints present, which results in the rock being divided into larger, more cohesive volumes. Consequently, when failure occurs in such a rock mass, significantly larger chunks of rock are released. Thus, the spacing of discontinuities plays a critical role in determining the size of the blocks that are produced during a rockfall event.

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

A rock may undergo free fall once it detaches from the source and begins its descent. This phenomenon typically occurs when the slope angle exceeds 70°, allowing the rock to fall freely through the air without significant interaction with the slope surface. However, if the slope angle is less than 70°, the block is more likely to follow a trajectory involving a combination of bounces, rolls, and sliding motions as it moves down the slope. These interactions with the slope surface significantly influence the block's movement and eventual stopping point.

In the context of rockfall dynamics, the first point of contact or impact along a block's trajectory plays a crucial role in determining its subsequent behavior. If the block originates from a source located far above the first impact zone, it tends to accumulate substantial kinetic energy as its potential energy is converted during the fall. This increased kinetic energy allows the block to travel a greater distance, potentially running out of the slope entirely. Conversely, if the source of the block is situated relatively close to the first impact area, the block will possess less kinetic energy upon impact. In such cases, the block is more likely to bounce only once or come to a halt immediately after the initial collision. The height of the source relative to the impact zone, therefore, directly influences the block's energy, movement, and final resting position during a rockfall event.

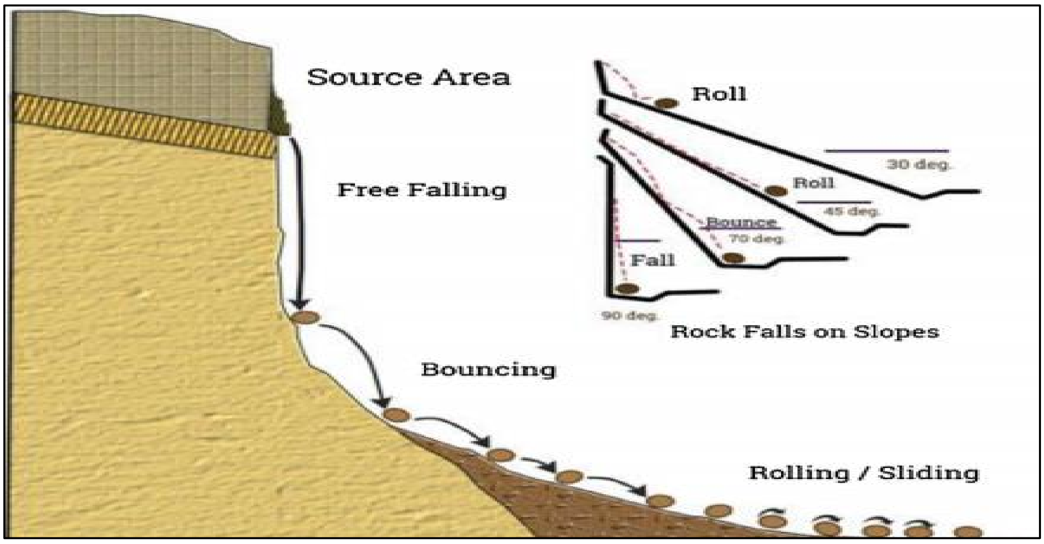


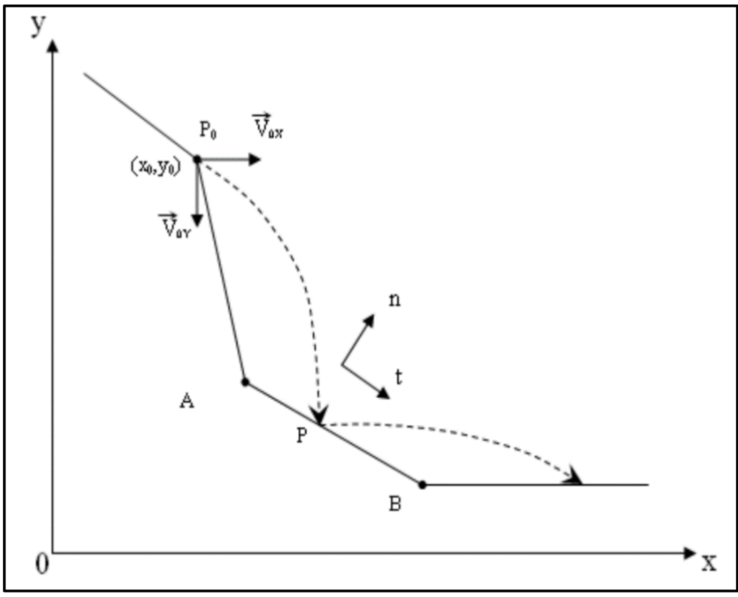
***Figure 2.1.2.1** General modes of motion of rocks*
(Ritchie AM (1963) Evaluation of rockfall and its control. Highw Res Rec 17:13–28)

The overall angular momentum of a block increases significantly after the initial impact and continues to rise until it reaches its maximum rotational velocity. Once this peak velocity is achieved, the block's motion becomes increasingly dependent on subsequent impacts with the slope surface. The ground conditions play a critical role in determining the amount of kinetic energy dissipated during these collisions. Research indicates that a block can lose between **75% and 86%** of its original free-fall energy upon impact with the slope. Hard surfaces, such as rock, allow the block to retain more energy due to their rigidity and minimal deformation. In contrast, softer surfaces like soil or dirt deform under impact, creating scars and absorbing a significant portion of the block's energy. This energy absorption causes the block to decelerate, reducing its runout distance. The combination of kinetic energy from free fall, surface characteristics, and other factors ultimately determines whether the block bounces, rolls, slides, or stops after its initial encounter with the slope.

Another critical aspect of rockfall dynamics is the potential interaction between multiple blocks as they move down the slope. While such interactions are observed in real-world scenarios, their influence on individual block trajectories is not well-documented due to limited data. In typical rockfall events, blocks rarely collide with one another, making block-to-block interactions minimal. However, this dynamic changes in the case of **rock avalanches**, where continuous and frequent block contact leads to more pronounced interactions. Rockfall processes, on the other hand, are characterized by fragmented and sporadic block movement, with only occasional interactions among a small number of blocks. This distinction underscores the differences between rockfall and rock avalanche dynamics, with the latter involving more complex and continuous interactions. Despite the rarity of block collisions in rockfall events, understanding these interactions remains important for accurately predicting trajectories and assessing potential hazards.

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

A block can be launched into a ballistic trajectory after its initial impact with the slope, resulting in a path that resembles a parabolic arc interspersed with bounces. This occurs when the block retains more kinetic energy than is dissipated during the collision. Throughout this phase of the rockfall process, the block maintains a constant horizontal velocity, with aerodynamic drag having a minimal effect. The vertical velocity, however, varies depending on the stage of the block's motion and is primarily influenced by gravity. Air resistance or drag during this phase can be considered negligible, as the block's force and momentum significantly exceed the opposing resistance exerted by the air 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.

Figure 2.1.3.1 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 figure 2.1.3.1 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

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

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

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

2.1.4. Block Slope Interaction

One of the most complex aspects of a rockfall event is the interaction between the falling block and the slope surface. This interaction is not only challenging to analyze but also highly significant, as it directly dictates the block's behavior during the event. The intricacy of this process stems from the dynamics of the block's collision with the ground, which is influenced by a variety of factors. These factors include the block's velocity, impact angle, angular momentum, soil and rock characteristics, slope gradient, block size, block mass, and even weather conditions during impact (for example, wet soils tend to absorb more energy than dry soils). Furthermore, this interaction controls other aspects of the rockfall process, such as the block's launch angle, which is determined by its angular momentum. The angular momentum, in turn, depends on the block's dimensions and how it interacts with the soil properties. The angle at which the block hits the slope surface plays a crucial role in determining whether the boulder gains or loses rotational momentum. This concept is visually represented in the diagram below.

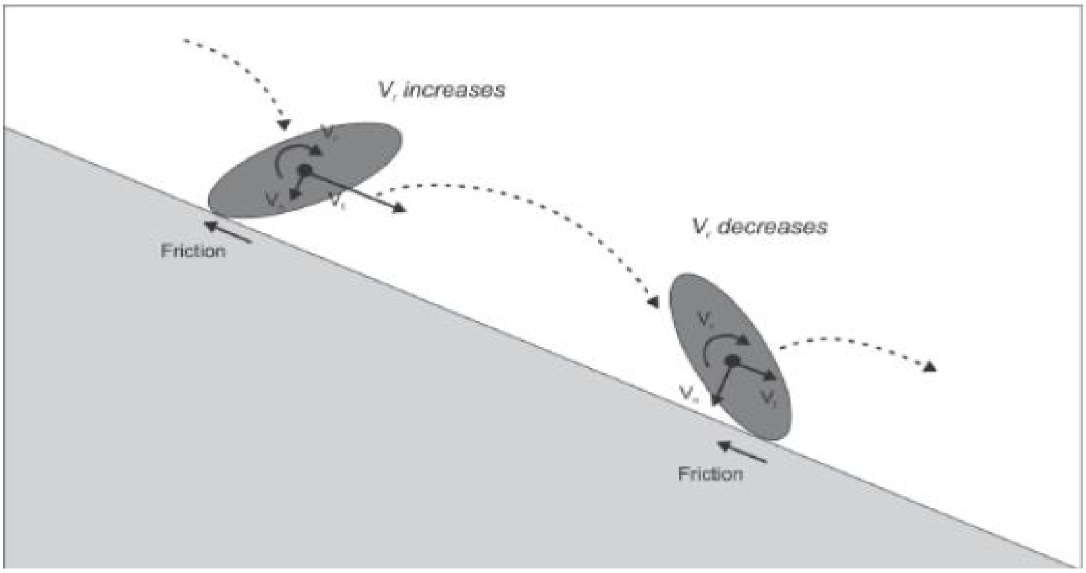


Figure 2.1.4.1 *Block Slope Interaction*
Anthony Botha, *(April 2017) creating an engineering modelling workflow for ramms:: rockfall, using the input parameter sensitivitie.*

2.1.5. Block Motion along the Slope

The trajectory of a falling block during a rockfall can be characterized by counting the number of bounces it undergoes as it moves down the slope. In addition to bouncing, the block may also exhibit rolling and sliding motions, which typically follow a sequence of decreasing energy levels. Rolling occurs when the block rotates around its center of mass while maintaining contact with the slope through at least one point or surface. Sliding, in contrast, happens when the block stops rotating and moves while keeping one of its surfaces in continuous contact with the slope. Transitions between these modes of movement are often driven by changes in the slope's angle. As the slope angle decreases and the potential energy from the fall distance diminishes, the block loses kinetic energy, forcing it to shift to the next phase of motion. Eventually, as the block's kinetic energy and rotational momentum continue to decrease, it may lose the ability to roll entirely, transitioning to sliding. These changes in motion are governed by the interaction between the block's energy, the slope's geometry, and external factors such as surface conditions.

2.1.6. Slope Vegetation

Similar to how the substrate material interacts with falling blocks in the case of grasses and shrubs, vegetation present along the path of a rockfall can significantly influence the movement of the block. This occurs because such vegetation introduces additional drag forces that act upon the block, altering its trajectory and speed. Trees, in particular, play a critical role in this process, as they act as substantial obstacles that a block must either overcome or navigate around. In some cases, trees can effectively slow down or even stop a boulder entirely, depending on their size and strength. Trees with thick, sturdy trunks that are wider than the impacting block have the potential to redirect the block away from its original path. This redirection typically occurs when the block strikes the tree trunk at a point that is offset from its center of mass, causing a change in the block's momentum and direction. The interaction between the block and the tree trunk can lead to a variety of outcomes, including deflection, deceleration, or complete stoppage, depending on the specific conditions of the impact.

Figure 2.1.5.1 *RockFall Protection due to Slope Vegetation*

2.1.7. RockFall Runout

The distance a block travels from its source is influenced by several factors, including its shape, size, and the axis along which it moves. Spherical blocks, for example, tend to move faster and cover greater distances compared to tubular or discoidal ones, even when their mass and composition are similar. This is because spherical shapes generate less friction due to their lack of angular edges and are more efficient at maintaining angular momentum. In contrast, tubular or flat blocks often lose momentum more quickly due to their structural characteristics. However, exceptions exist; for instance, a tubular block moving along its shorter axis can achieve velocities similar to those of a spherical block under specific conditions.

Block size also plays a significant role in determining travel distance. Larger blocks, made of the same material as smaller ones, generally travel farther because their greater mass translates to higher kinetic energy. This energy allows them to overcome obstacles such as talus debris, vegetation, or surface irregularities, which might otherwise slow or stop smaller blocks.

It is important to note that even under consistent release conditions, blocks do not always follow identical trajectories or come to rest in the same location. This variability is due to the influence of slope-related factors such as surface roughness, gradient, and the presence of obstacles. Despite this unpredictability, research has identified certain patterns. For example, larger and more massive blocks typically travel greater distances than smaller ones, and steeper slopes generally enable blocks to move farther from their source. These observations provide valuable insights into the complex dynamics of block movement and the factors that determine their final resting positions.

2.1.8. Conclusion on RockFall Dynamics

The movement of rockfall is inherently unpredictable, leading researchers and geo-practitioners to rely on stochastic methods to account for the randomness involved. Instead of predicting a specific stopping point, they often estimate probabilities, such as a 70% chance that a rock will come to rest within a defined area. To make these predictions, geo-practitioners analyze historical rockfall data, using past events to anticipate future outcomes. Advanced techniques, including computer simulations, are widely used to explore potential trajectories and estimate where rocks might land. These simulations, which can employ both 2D and 3D modeling approaches, provide critical insights into rockfall risks, enabling informed decision-making and the development of effective mitigation strategies.

Rockfall modeling is a complex process that involves numerous factors influencing the outcome. Rockfalls are particularly hazardous due to the high velocities, energy, and erratic motion of falling blocks, which pose significant threats to people, infrastructure, and the environment. While assessing a slope's susceptibility to rockfall is challenging, analyzing events after they occur is relatively simpler, as demonstrated in this thesis. Understanding the characteristics of a boulder's potential trajectory is essential for designing mitigation measures. This thesis aims to identify and define critical parameters, refining models to support better decision-making and risk management in rockfall-prone areas.

Rockfall propagation is typically modeled using empirical methods, physics-based methods, and probabilistic approaches. Empirical methods rely on historical data and statistical relationships to predict runout distances, while physics-based methods use principles of mechanics to simulate rockfall trajectories, incorporating factors like energy dissipation and bounce height. Probabilistic methods, on the other hand, account for uncertainties in rockfall parameters, using statistical techniques to predict a range of possible outcomes.

In terms of modeling approaches, 2D models are simpler and computationally efficient, focusing on a single cross-section of the slope. They are useful for preliminary assessments but may overlook complex terrain features. 3D models, while more computationally intensive, provide a more comprehensive representation of the slope, capturing lateral variability and complex interactions between the block and the terrain. Both approaches have their strengths and are often used in combination to improve the accuracy of rockfall predictions.

The goal is to develop more accurate models that support effective risk management and mitigation strategies, ultimately reducing the impact of rockfall hazards on communities and infrastructure.

2.2. Rockfall Modelling

In the development of rockfall models, two distinct spatial frameworks are commonly utilized: two-dimensional (2D) and three-dimensional (3D) models. A two-dimensional model simulates the movement of rockfall along a vertical cross-section of a slope, focusing solely on the vertical descent without accounting for any lateral movement within that plane. While this approach simplifies the analysis, it provides a foundational understanding of rockfall dynamics. On the other hand, three-dimensional models are more sophisticated and data-intensive, as they incorporate non-planar lateral movement, offering a more comprehensive representation of how rocks travel down a slope. These 3D models are capable of capturing the complexities of real-world rockfall behavior, including deviations in direction and interactions with terrain features that 2D models cannot address.

2.2.1. 2 Dimensional Models

Two-Dimensional (2D) modeling is a technique used to simulate the trajectory of a rockfall along a slope, focusing primarily on the vertical dimension of movement. This method assumes that the boulder's path is confined to a single plane, allowing for the calculation of travel distance along the slope. However, 2D modeling inherently overlooks lateral movement, which is a critical aspect of real-world rockfall behavior. By restricting the analysis to one plane, the model cannot account for deviations caused by the boulder's shape, terrain irregularities, or interactions with obstacles such as vegetation or uneven surfaces.

The limitations of 2D modeling are particularly pronounced when analyzing non-spherical boulders, as their irregular shapes often cause them to deviate from a straight path. Even spherical boulders, which might appear more predictable, can exhibit unexpected trajectories due to external factors like changes in slope gradient or surface roughness. These complexities, which are not captured in a 2D framework, significantly influence the boulder's actual path and final resting position. Consequently, while 2D modeling offers a simplified approach to understanding rockfall dynamics, its inability to incorporate lateral movement and real-world variables reduces its accuracy and reliability. This underscores the necessity for more comprehensive modeling approaches to better address the multifaceted nature of rockfall events. Although more parameters are needed that are not always available.

2.2.2. 3-Dimensional Modeling

Three-Dimensional (3D) modeling significantly enhances the simulation of rockfall trajectories by incorporating movement in vertical, lateral, and longitudinal dimensions. This approach overcomes the limitations of 2D modeling, which restricts analysis to a single plane, by capturing the full range of boulder behavior, including lateral deviations, rotational dynamics, and interactions with complex terrain features. As a result, 3D modeling provides a more realistic representation of how boulders move and come to rest in real-world environments.

A key advantage of 3D modeling is its ability to account for the influence of boulder shape and orientation on trajectory. For instance, non-spherical boulders, which often exhibit irregular rolling or tumbling motions, can be accurately simulated using methods like the 3D Discrete Element Method (DEM). This technique models the boulder and terrain as a system of discrete elements, enabling detailed analysis of interactions such as bouncing, sliding, and rolling. Additionally, Rigid Body Dynamics can be employed to simulate the boulder as a solid object, solving equations of motion in three dimensions to predict its path, rotation, and final position.

Another strength of 3D modeling lies in its capacity to incorporate real-world terrain complexities, such as uneven surfaces, slope curvature, and obstacles like vegetation or rock outcrops. These factors, which are often overlooked in 2D models, play a critical role in determining the boulder's trajectory and stopping point. By integrating such details, 3D modeling improves the accuracy and reliability of rockfall hazard assessments, making it a valuable tool for risk analysis and mitigation planning.

However, the increased accuracy of 3D modeling comes with higher computational demands and the need for detailed input data, such as high-resolution terrain models and precise boulder characteristics. Despite these challenges, the ability of 3D modeling to capture the multifaceted nature of rockfall behavior makes it indispensable for advanced studies and practical applications in rockfall risk

2.2.3. Rockfall Simulation Approaches

Rockfall simulations are conducted using specialized computer programs designed to model the behavior of falling rocks. These programs aim to analyze and predict various aspects of rockfall dynamics for a specified "design block," including its fall path, maximum runout distance, the envelope of possible trajectories, and the distribution of velocity and energy along those trajectories. By simulating these factors, rockfall models provide valuable insights into the potential risks and impacts of rockfall events, aiding in the development of effective mitigation strategies.

Rockfall modeling programs can be broadly categorized into three main types based on their underlying methodologies:

1. **Lumped Mass Model**: This approach simplifies the rockfall process by treating the falling block as a single point mass. It focuses on calculating the block's trajectory, velocity, and energy while ignoring its rotational motion or shape. While this method is computationally efficient, it may not fully capture the complexities of real-world rockfall behavior, particularly for non-spherical blocks or those interacting with irregular terrain.
2. **Rigid Body Model**: In contrast to the lumped mass approach, the rigid body model considers the block's shape, size, and rotational motion. This method provides a more detailed representation of how the block interacts with the slope, including impacts, rebounds, and rolling motions. While more accurate, this approach requires greater computational resources and detailed input data.
3. **Hybrid Approach**: This method combines elements of both the lumped mass and rigid body models, aiming to balance accuracy and computational efficiency. It may use a simplified point mass representation for certain parts of the trajectory while incorporating rigid body dynamics for critical interactions, such as collisions with obstacles or changes in slope geometry.

Each of these modeling approaches has its strengths and limitations, and the choice of method depends on the specific requirements of the analysis, such as the level of detail needed, the complexity of the terrain, and the available computational resources. By leveraging these tools, scientists and engineers can better understand rockfall behavior, assess risks, and design effective measures to protect people and infrastructure from the hazards posed by falling rocks.

2.2.4. Parameters Required for Rockfall Modeling

Rockfall analysis demands a significant amount of detailed information, as each parameter plays a critical role in accurately assessing and predicting the potential hazards associated with falling rocks. Some of the key parameters required for a comprehensive rockfall analysis include:

2.2.4.1 Choice of Detachment Area

In rockfall analysis, the selection of the initiation area, where a rockfall event begins, is a critical step in determining the trajectory, behavior, and potential impact of falling rocks. This process involves identifying locations on the slope where rocks are most likely to detach and initiate a fall. Several methods are used to pinpoint these areas, including:

1. **Historical Data Analysis**: By examining past rockfall events, areas where rocks have previously detached can be identified. This historical information helps in recognizing patterns and locations that are prone to rockfall, making them likely candidates for future detachment zones.
2. **Physical Slope Inspection**: Conducting a visual assessment of the slope to identify areas where rocks are likely to come loose. Steep slopes, particularly those with a high dip angle, are more susceptible to rockfall. Observing features such as cracks, fractures, or loose material can provide valuable insights into potential detachment areas.
3. **Geological and Geotechnical Assessment**: Evaluating the geological composition and structural integrity of the slope to identify weak zones or unstable sections that may contribute to rockfall initiation.

Once potential detachment areas are identified, two primary methods are used to simulate the initiation of rockfall events in 2d analyses:

- **Line Seeder**: This method involves defining a line along the slope from which rocks are released. It is useful for simulating rockfall scenarios where detachment is likely to occur along a specific section of the slope, such as a cliff face or a fracture line. The line seeder approach allows for a more distributed representation of rockfall initiation.

- **Point Seeder**: In this method, rocks are released from a single point or a small area on the slope. This approach is often used when the detachment zone is localized, such as a specific outcrop or a concentrated area of instability. The point seeder method is simpler but may not capture the variability of detachment locations as effectively as the line seeder.

Both methods play a crucial role in rockfall modeling, as they help define the starting conditions for simulations. The choice between line seeder and point seeder depends on the specific characteristics of the slope and the objectives of the analysis. By accurately identifying detachment areas and using appropriate initiation methods, rockfall models can provide more reliable predictions of rockfall behavior, aiding in hazard assessment and the design of mitigation measures.

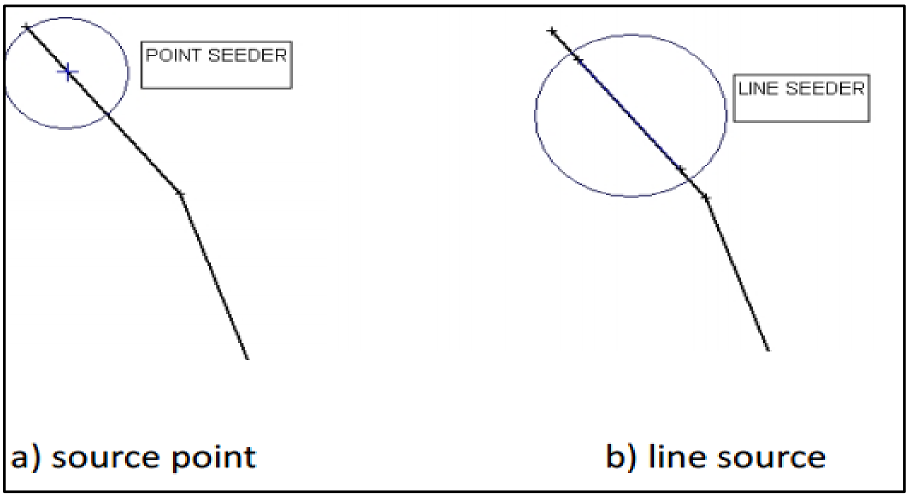


***Figure 2.4.1.1.1** Line seeder and point seeder*

2.2.4.2 Characteristic Design Rock Block Volume

In rockfall analysis, accurately estimating the volume of potentially detachable rock blocks is crucial for assessing the impact and risk of such events. This process involves evaluating historical rockfall data, conducting field measurements, and analyzing the structural discontinuities within the rock mass. These factors help determine the typical size, shape, and mass of rocks that could fall, which are essential for understanding the potential energy and trajectory of rockfalls.

Geo structural surveys play a key role in this process by identifying the degree of fracturing in the rock mass, which directly influences the dimensions of detachable blocks. Field measurements of fallen blocks at the base of a slope provide valuable data on previously collapsed volumes, offering insights into the sizes of blocks likely to detach in the future. To analyze this data, statistical methods are applied, often using software like Dips (from Rocscience), to construct box plots and calculate average block sizes while excluding outliers. This helps estimate representative unstable volumes that can be linked to specific source areas.

The slope geometry and structural characteristics of the rock mass further influence the volume calculations. For instance, steeper slopes or highly fractured rock masses may produce larger or more frequent rockfalls. Additionally, the potential energy of falling rocks, which depends on their mass and the height of the slope, is a critical factor in assessing the impact force and runout distance.

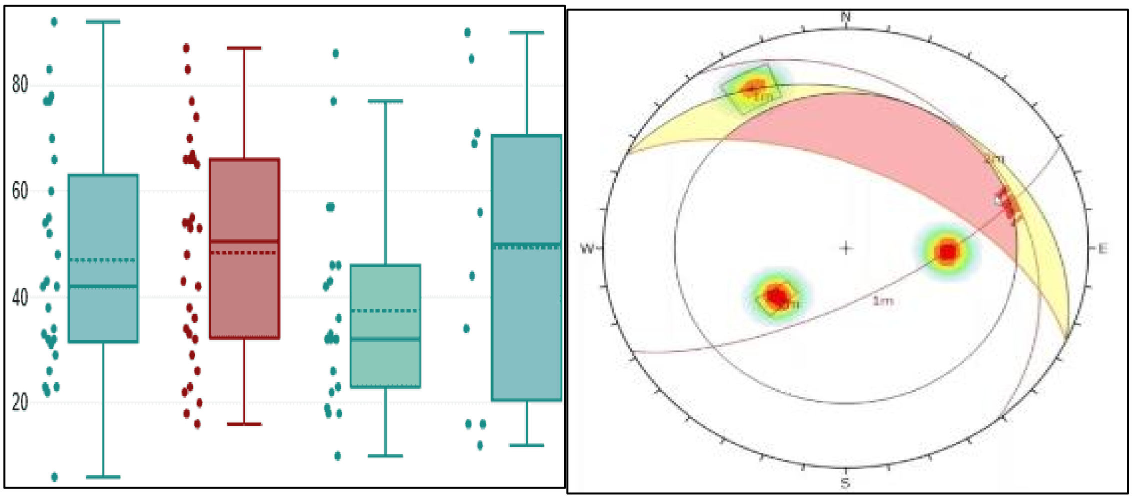


Figure 2.2.4.2.1 Example of Box Plots and geostructural survey using (Rock Science Dips)

2.2.4.3 Initial Velocity of the Blocks

The initial speed at which a rock begins to move when it detaches from a slope is significantly influenced by what we understand and don't understand, a concept known as epistemic uncertainty. This velocity is contingent on the manner in which the rock detaches. If it detaches purely due to gravity, such as a rock becoming loose and starting to fall, the initial velocity is nearly zero as it simply starts to move. However, if the rock is dislodged by an external force, such as water flow (hydraulic pressure) or an earthquake, it might commence its movement with some initial speed, though this speed typically does not exceed 1 meter per second (1 m/s) and may reach up to 1.5 m/s in extreme cases. This initial velocity is adjusted based on historical observations to validate the model through a technique known as back analysis.

When a model incorporates both horizontal and vertical velocity components, it allows for a more detailed representation of the initial motion of falling rocks. These components provide insights into the speed and direction in which the rocks move at the onset of their descent. The direction of the velocity is determined by the relative magnitudes of the horizontal and vertical components. Essentially, the angle or trajectory at which the rock initially moves is dictated by the strengths of these components. For example, if the horizontal velocity component is greater than the vertical component, the rock will predominantly move horizontally. Conversely, if the vertical velocity component is stronger, the rock's motion will be primarily vertical.

In two-dimensional probabilistic methods, the initial velocity can be introduced with statistical variability. Rather than assigning a single, fixed value for the initial velocity, a distribution of velocities is considered. This distribution accounts for the natural variability and uncertainty in the initial motion of falling rocks. By incorporating statistical variability, the model can simulate a range of potential initial velocities, reflecting the natural variation observed in real-world scenarios. This approach enhances the accuracy of hazard assessments and allows for more reliable predictions of potential rockfall trajectories and impacts.

2.2.4.4 Restitution Coefficients

In rockfall analysis, the **coefficient of restitution (COR)** is a critical parameter used to quantify the energy dissipation that occurs during collisions between a falling rock and the slope surface or other obstacles. This coefficient plays a pivotal role in determining how much kinetic energy is retained or lost when two bodies composed of different materials collide and rebound. Specifically, the COR is defined as the ratio of the relative velocity of the rock immediately after impact to its velocity just before impact. By modeling this relationship, analysts can estimate energy loss during collisions and predict the subsequent trajectory, bounce height, and runout distance of falling rocks. The retarding capability of the slope surface—such as its hardness, roughness, or deformability—is a key factor influencing the COR, as these properties dictate how energy is absorbed or transferred during impact.

$$COR = \frac{V_1'}{V_1} \qquad \textbf{Eq (4)}$$

where V1′represents the velocity of the rock after impact and V1 is its velocity before impact. This ratio is typically represented as a decimal value between 0 and 1. A COR of **1** corresponds to a perfectly elastic collision, where no kinetic energy is lost, and the rock rebounds with its full velocity retained. Conversely, a COR of **less than 1** indicates an inelastic collision, where energy is dissipated due to factors like deformation, friction, or fragmentation. A COR of **0** signifies a perfectly plastic collision, where the rock comes to an immediate stop upon impact, with all kinetic energy absorbed by the surface. A statistical variability can also be assumed.

In practical rockfall modeling, the COR is further divided into two distinct components to account for directional energy loss:

1. **Normal Coefficient of Restitution (nCOR)**: This component governs energy loss perpendicular to the slope surface. The nCOR is influenced by the angle of the slope, with studies showing that it tends to increase as the slope angle becomes steeper. This relationship arises because steeper slopes reduce the normal force of impact, allowing the rock to retain more vertical velocity after collision, although in some cases we can assume values varying statistically.
2. **Tangential Coefficient of Restitution (tCOR)**: This component quantifies the reduction in horizontal (tangential) velocity during impact. Unlike the nCOR, the tCOR is primarily affected by surface friction and material properties rather than slope angle. For example, rough or vegetated surfaces significantly diminish tangential velocity due to increased frictional resistance, whereas smooth, hard surfaces may allow greater retention of horizontal motion. Notably, there is no universally defined correlation between slope angle and tCOR, as tangential energy loss depends more on localized terrain characteristics.

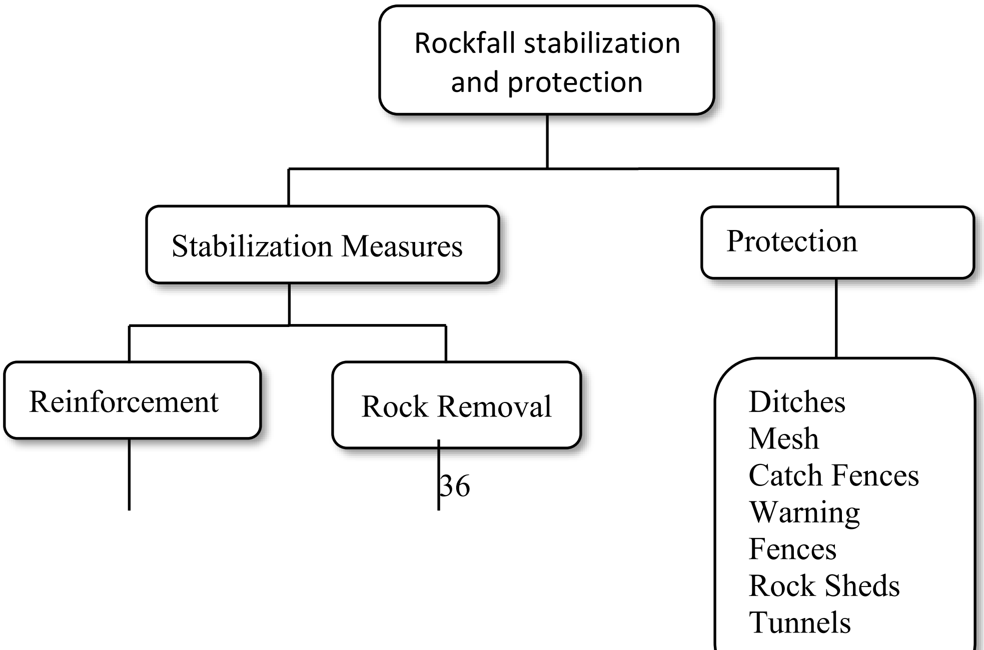
The distinction between nCOR and tCOR is essential for accurately simulating rockfall behavior. For instance, a rocky slope with loose gravel may exhibit a low tCOR due to high friction, causing rocks to decelerate horizontally after impact, while a smooth bedrock surface might permit higher tangential velocity retention. Similarly, a steep cliff face could result in a higher nCOR, enabling rocks to rebound farther vertically. These parameters are often derived through empirical studies, field observations, or laboratory experiments, as they vary widely depending on geological conditions, rock type, and surface composition.

Accurate estimation of the Coefficient of Restitution (COR) is essential for reliable rockfall hazard assessments, as it directly influences predictions of boulder trajectories, impact energies, and runout distances. Overestimating the COR can lead to exaggerated predictions of how far rocks will travel, potentially resulting in unnecessary or over-engineered mitigation measures. Conversely, underestimating the COR may underestimate the hazard, leading to inadequate protective measures and increased risk to infrastructure and human safety.

To address these challenges, advanced rockfall models often incorporate probabilistic ranges for COR values, accounting for natural variability and epistemic uncertainties. This approach ensures that simulations better reflect the complexities of real-world rockfall behavior. Site-specific COR data, derived from field observations and experimental studies, are critical for refining these models and improving their accuracy. Back analysis plays a fundamental role in calibrating COR values. By comparing model predictions with actual rockfall events, engineers can adjust COR values to better match observed behaviors, such as bounce heights, runout distances, and stopping points. This iterative process enhances the reliability of rockfall simulations and supports the design of more effective mitigation strategies, including barriers, catchment areas, and slope stabilization measures. Integrating site-specific data and back analysis ensures that rockfall hazard assessments are both precise and practical, ultimately improving safety and reducing risks.

2.3. Rockfall Stabilization and Protection Methods

Addressing the issue of rockfall hazards involves two primary strategies: protection and stabilization. Both approaches aim to prevent rocks from causing damage to infrastructure such as roads, railways, buildings, and other critical assets, as well as to protect human lives from the dangers posed by falling rocks. However, the methods employed in each strategy differ significantly in their application and focus. Protective measures are designed to manage rocks that are already in motion, intercepting or redirecting them before they can cause harm. These measures must account for the size and energy of the rocks involved, as larger rocks require more robust and costly solutions. Additionally, the rate at which rocks accumulate in protective systems, such as catchment areas or barriers, must be considered to ensure long-term effectiveness and maintenance feasibility.On the other hand, stabilization techniques focus on preventing rocks from detaching and moving in the first place. This proactive approach involves a variety of methods to enhance slope stability and reduce the likelihood of rockfall. One common technique is scaling, which involves the safe removal of loose or unstable rocks from a slope. Trimming is another method used to eliminate small, irregular sections of rock that could otherwise lead to repeated scaling efforts. During the initial construction of slopes or cuttings, presplit blasting can be employed to create a more stable and controlled slope profile, minimizing the risk of future rockfall. Other stabilization methods include improving drainage systems to reduce water pressure within the slope, which can weaken rock structures over time. The application of shotcrete, a sprayed concrete mixture, can also help prevent weathering and erosion of the slope surface. For individual rocks or larger rock masses, mechanical stabilization techniques such as rock bolts, dowels, anchors, and buttresses are used to secure them in place and prevent movement.These stabilization and protection methods are often illustrated in technical diagrams, such as Figure 2.3.1, which typically showcases ten common stabilization techniques and six protective measures. By combining these approaches engineers can develop comprehensive solutions to mitigate rockfall risks, ensuring the safety of infrastructure and communities in areas prone to such hazards. The choice of methods depends on factors such as the geological characteristics of the slope, the size , the budget of the project and frequency of potential rockfall events, and the specific requirements of the site. Ultimately, a well-designed rockfall mitigation plan integrates both protective and stabilization strategies to address the problem effectively and sustainably.



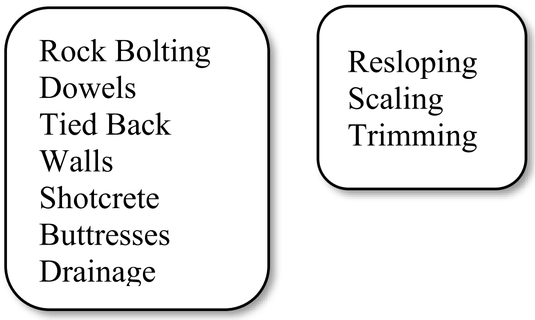


Figure 2.3.1 *Flow Chart for Slope Stabilization and RockFall Protection Measures*
Slope stabilization and protection methods (Wyllie and Nortish, 1996).

2.3.1. 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.

2.3.1.1. Rock Bolts

A rock bolt is a component used in rock stabilization and reinforcement, designed to enhance the stability of rock masses and prevent potential failures. It consists of a high-strength steel rod that is inserted into a pre-drilled hole within the rock mass. The bolt is secured in place using one of two primary methods: grouting, where the hole is filled with a cementitious or resin-based material to bond the bolt to the surrounding rock, or mechanical expansion, where an expansion mechanism, such as a wedge or shell, is used to anchor the bolt firmly within the hole. The exposed end of the rock bolt is fitted with a steel plate, often referred to as a reaction plate or face plate, which serves to distribute the compressive forces generated by the tensioning of the bolt across a wider area of the rock surface.
Rock bolts are strategically installed across potential failure surfaces, such as fractures, joints, or weak zones within the rock mass. The bolts are anchored into stable, sound rock beyond these surfaces to ensure effective reinforcement. When tension is applied to the rock bolt, either during installation or through subsequent loading, it creates a compressive force within the rock mass. This force is transmitted through the reaction plate at the rock surface, effectively altering the stress distribution within the rock. Specifically, the tension in the bolt modifies the normal and shear stresses acting across

the potential failure surface, increasing the resistance to sliding or displacement. By enhancing the overall stability of the rock mass, rock bolts play a vital role in mitigating the risk of potential rock block detachments, slope failure, or other geotechnical hazards. Their application is also widely used in mining, tunneling, and civil engineering projects to ensure the safety and longevity of structures built in or near rock formations.

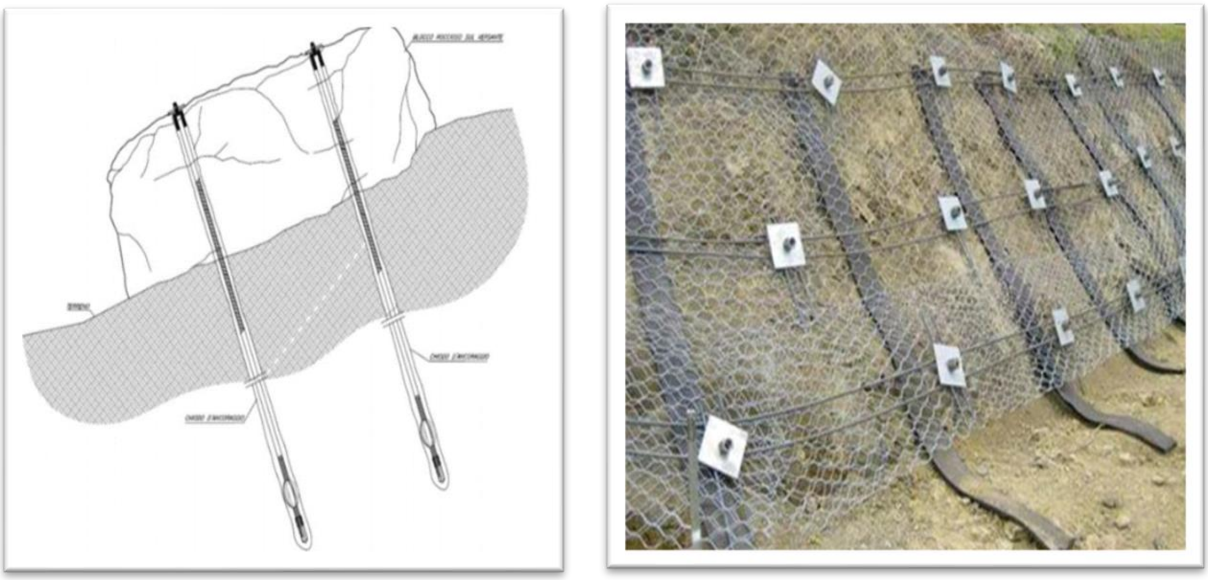


Figure 2.3.1.1.1 Rock Bolt Installation into Slope

2.3.1.2. Dowels

Dowels are essential components in geotechnical and structural engineering, serving as rods or cylindrical elements typically constructed from high-strength reinforcing steel. Their primary function is to provide stability and strength to structures and rock masses, particularly in scenarios where concrete element or rock wedges need to be securely anchored to rock surfaces. These dowels are usually fabricated from carbon steel, a material chosen for its durability and ability to enhance the tensile strength of concrete structures. The installation process involves drilling holes into the rock mass, which are then filled with a specialized mixture known as grout. Grout is a fluid cement-based material that hardens over time, creating a strong bond between the dowel and the surrounding rock substrate. This bonding process ensures that the dowel is firmly anchored, enabling it to effectively transfer loads and stresses between the concrete structure and the rock.

Once the dowel is embedded in the rock, the exposed steel portion is encased in reinforced concrete. This additional layer not only strengthens the connection but also provides protection against environmental factors such as corrosion or weathering. Dowels are typically designed with a diameter of around 25 millimeters and are embedded to a depth of approximately 0.5 meters (or about 1.5 feet) into stable, sound rock. To ensure uniform load distribution and optimal reinforcement, dowels are spaced at regular intervals, usually between 0.5 to 0.8 meters apart. This spacing is carefully calculated based on the specific requirements of the project, including the type of rock, the expected loads, and the structural design.

Dowels play a critical role in stabilizing slopes, securing retaining walls, and reinforcing tunnels or other underground structures. By anchoring concrete to rock, they help prevent movement or failure along potential weak planes or fractures within the rock mass. Their use is particularly important in areas prone to rockfall, landslides, or other geotechnical hazards, where maintaining structural integrity is essential for safety and longevity.

2.3.1.3. Shotcrete

Shotcrete is a highly specialized construction material composed of a fine aggregate mortar that is applied using a pneumatic process, which involves spraying it onto surfaces under high pressure. This method of application allows for precise and efficient coverage, making shotcrete an ideal solution for reinforcing and protecting areas with closely fractured or degradable rock faces. Typically, shotcrete is applied in layers ranging from 75 to 100 millimeters in thickness, creating a durable and resilient barrier. When applied to rock surfaces, shotcrete serves as a protective shield, effectively preventing the detachment and fall of smaller rock fragments while also helping to control the gradual movement of larger rock sections that could otherwise develop into unstable overhangs or ledges.

Shotcrete is widely used in a variety of engineering and construction applications, particularly in areas prone to rockfall, slope instability, or weathering. Its versatility and ease of application make it a valuable tool for stabilizing rock faces in tunnels, mining operations, highway cuts, and other geotechnical projects. By providing immediate surface protection and reducing the risk of rock detachment, shotcrete enhances safety and prolongs the lifespan of structures built in challenging geological conditions. Additionally, its ability to conform to irregular surfaces and its rapid curing time further contribute to its effectiveness as a stabilization solution. Overall, shotcrete represents a practical and reliable method for addressing rockfall hazards and improving the stability of vulnerable rock surfaces.

2.3.1.4. Re-sloping

In scenarios where loose or weathered material, known as overburden, is present in the upper sections of a slope or excavation, implementing targeted strategies to address instability and reduce rockfall hazards becomes essential. A widely adopted method involves designing the slope geometry to account for the differing strength characteristics between the upper weathered layers and the underlying stable bedrock. Specifically, the overburden or weakened rock is excavated at a gentler angle compared to the steeper inclines used for the more solid, unweathered rock beneath. This intentional flattening of the slope angle serves to counteract the inherent instability of weathered materials, which are more susceptible to erosion, gravitational forces, and loss of cohesion over time. By creating a shallower gradient, the shear stress acting on the slope is reduced, thereby lowering the risk of detachment and collapse of rock masses or debris.

Steeper slopes in such areas are particularly hazardous, as they amplify the effects of gravity and accelerate weathering processes, leading to frequent rockfall incidents. In contrast, a flatter slope design enhances stability by distributing the weight of the overburden more evenly and minimizing the likelihood of abrupt failures. However, the effectiveness of this approach depends heavily on understanding the site-specific conditions, as overburden layers can exhibit significant variability in thickness, composition, and mechanical properties even within short distances. For instance, pockets of highly fractured rock or zones saturated with water may require additional stabilization measures beyond slope angle adjustments.

To ensure the success of this strategy, comprehensive site investigations are imperative. These investigations typically include geological surveys, geotechnical testing, and slope stability analyses to map the extent and characteristics of the overburden. Techniques such as core drilling, soil sampling, and ground-penetrating radar may be employed to assess subsurface conditions. Furthermore, engineers must consider external factors like precipitation patterns, freeze-thaw cycles, and seismic activity, which can exacerbate weathering and compromise slope integrity over time. By integrating these insights, the slope design can be tailored to balance safety, cost, and environmental impact. This proactive approach not only mitigates immediate rockfall risks but also enhances the long-term durability of the slope, reducing maintenance needs and safeguarding adjacent infrastructure and ecosystems.

2.3.1.5. Trimming

A commonly utilized method to reduce this risk is trimming, which consists of several steps designed to safely remove hazardous overhanging blocks. Before initiating any trimming activities, a comprehensive assessment of the rock slope is performed to identify unstable areas and potential overhangs. The trimming process generally starts with drilling holes into the overhanging rock mass. These holes are strategically placed to weaken the rock structure and enable controlled removal. Once the holes are drilled, controlled blasting techniques may be used 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.

2.3.1.6. Scaling

Scaling refers to the process of removing loose rock, soil, and vegetation from the face of a slope using various hand tools. These tools include scaling bars, shovels, and circular saws, among others. The primary objective of scaling is to enhance the stability and safety of the slope by eliminating any potentially hazardous materials that could fall or slide down.

On steep slopes, scaling activities require additional safety measures to protect workers. Typically, workers are supported by ropes that are securely anchored at the crest of the slope. These ropes are tied to climbing harnesses worn by the workers, providing them with the necessary support and stability while they carry out the scaling operations. The use of ropes and climbing harnesses ensures that workers can safely navigate the steep terrain and perform their tasks without the risk of falling.

The scaling process is a critical component of slope maintenance and stabilization efforts. By removing loose materials, workers can prevent rockfalls and landslides, which could pose significant risks to infrastructure and human safety. Scaling is often performed in conjunction with other slope stabilization techniques, such as trimming and controlled blasting, to achieve comprehensive and effective results. Through careful planning and execution, scaling helps to mitigate the dangers associated with unstable slopes and contributes to the overall safety and stability of the environment.

2.3.1.7. Rockfall Protection Measures

An effective method of mitigating the hazard posed by rock falls is to allow the rock falls to occur while controlling their distance and direction of travel. It outlines several rock fall control and protection methods, including catchment ditches, barriers, wire mesh fences, mesh hung on the face of the slope, and rock sheds. The common feature of these protective structures is their energy-absorbing capabilities, which either stop the rock fall over a certain distance or deflect it away from the area being protected.

These systems can control rocks with diameters as large as 2 to 3 meters, falling from heights of several hundred meters, and impacting with significant energy. Rigid structures, such as reinforced concrete walls or fences with stiff attachments to fixed supports, are generally unsuitable for stopping a falling rock due to their lack of energy-absorbing properties. Instead, more flexible and absorbent methods are preferred to effectively manage and mitigate the hazards associated with rock falls.

2.3.1.8. Ditches

Catch ditches are designed to intercept and capture rocks that dislodge from higher elevations, thereby preventing them from reaching vulnerable areas below. The primary principle behind catch ditches is to provide a barrier that redirects the trajectory of falling rocks, consequently 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, such as its height and width, are critical 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, thus minimizing the potential for damage and injury. Moreover, catch ditches can also serve to channel debris away from infrastructure or property, further enhancing their protective function. These ditches are an essential component of rockfall protection systems, ensuring that falling rocks do not pose a threat to nearby structures or human safety. Through careful planning and implementation, catch ditches can significantly reduce the risks associated with rockfalls and contribute to the overall safety of the area.

2.3.1.8. Meshes

This approach entails installing a wire mesh directly onto the surface of a rock slope, forming a barrier that helps contain falling rocks and prevents them from bouncing onto roads or other vulnerable areas below. One major advantage of using draped mesh is that it reduces the required dimensions of any catch ditch at the toe of the slope. Since the mesh 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 challenging terrain make traditional ditch construction difficult or impractical.
Different types of mesh materials may be used depending on the specific requirements of the site. For instance, chain link mesh is suitable for controlling smaller rock falls with dimensions less than about 0.6 meters on steep faces. Woven wire rope mesh can 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. This versatility ensures that the appropriate type of mesh is used to meet the unique needs of the site, enhancing overall safety and effectiveness in mitigating rock fall hazards.

2.3.1.9. Nets and Fences

Nets and fences play a crucial role in rockfall protection systems, aiming to mitigate the impact of falling rocks on steep rock faces, ditches, and talus run-out zones. When a rock strikes a net or fence, the mesh or barrier deforms, activating energy-absorbing components over a prolonged collision time. This gradual energy dissipation significantly enhances the structures' ability to stop rolling rocks, enabling 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, thereby minimizing potential damage.

Figure 2.3.1.9.1 *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 municipality 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 3.1.1), while in the lower part 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

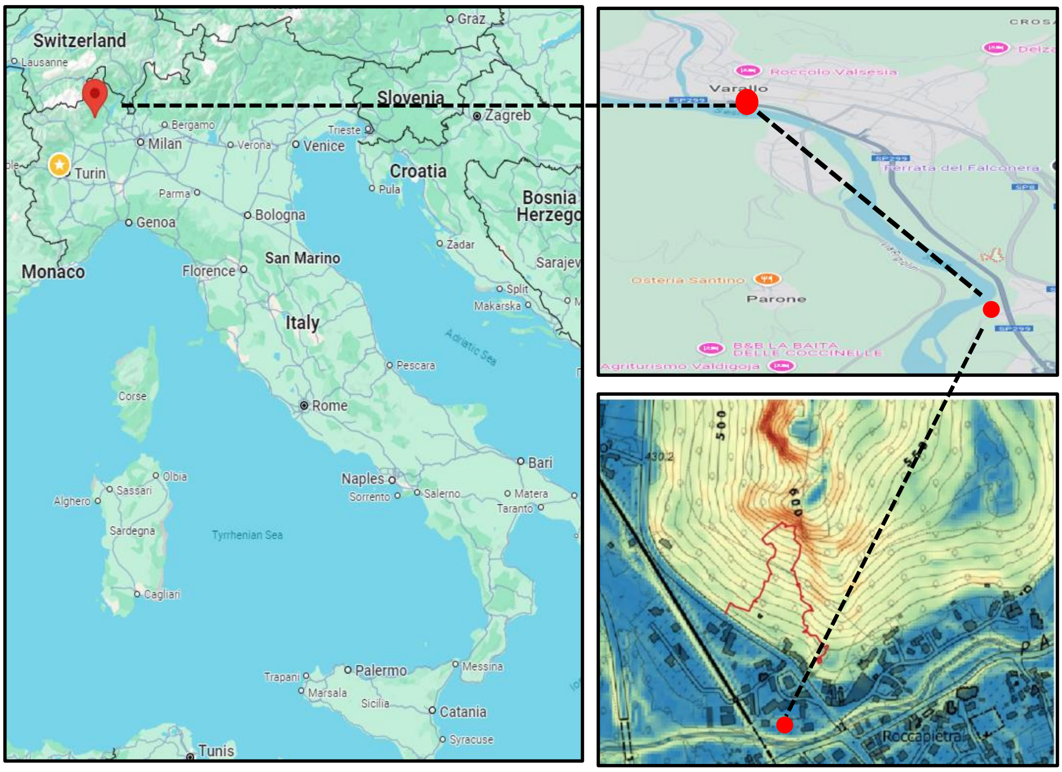


Figure 3.1.1 *Route Map of Case Study Location near Varallo province Vercelli (VC)*

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 poses 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 3.1.3.1 , 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 3.1.3.1 3 *m^3 Block stopped on the municipal road Via Fratelli Varalli.*

Figure 3.1.3.2 *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 3.1.3.3** rocky spur is located in the vicinity of a historic residence situated below **Via F.lli Varalli

As shown in Figure 3.1.3.3 an entire rocky spur is located within 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 3.1.1.1 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.

4. A New Methodology to Assess the Release Influence of Rockfall Source Areas

4.1 Rockfall Susceptibility Index to Failure

To evaluate the susceptibility to failure of potentially unstable rock blocks, the key factors responsible for their detachment—classified as preparatory, pre-disposing, and triggering factors—were identified. These factors were selected through an extensive review of existing literature [ANDRIANI and PELLEGRINI, 2014; ARPA PIEMONTE et al., 2013; BIENIAWSKI, 1989; CANUTI and CASAGLI, 1994; CASTEDO et al., 2017; COROMINAS et al., 2014; CROSTA et al., 2006; DEL RÍO and GRACIA, 2009; GERIVANI et al., 2020; HANTZ et al., 2021; MARQUES, 2018; MATTM-REGIONI, 2018; ROMANA, 1993; VV.AA., 2001, 2008], building upon and updating the framework proposed by NAPOLI et al. [2023]. These factors are systematically organized in Table 4.1 , which is divided into two main sections: factors relevant to any geographical context and factors specific to coastal and marine environments. Each factor (denoted as f pedex) is categorized into distinct classes, with a numerical score (P) assigned based on the level of susceptibility to failure, ranging from 0 (lowest susceptibility) to 3 (highest susceptibility). An exception to this scoring system is made for stabilization measures, such as bolts and anchorages. If these measures are deemed sufficiently effective, they can be assigned a negative score (up to -1) because they reduce the likelihood of rock block detachment.

The rockfall Susceptibility Index to Failure (SIF), which ranges from 0 to 1, is calculated for each rockfall source point using the following formula:

$$\mathbf{SIF = (\Sigma Pfi - \Sigma min(Pfi)) / (\Sigma max(Pfi) - \Sigma min(Pfi))} \qquad \mathbf{Eq\ (5)}$$

where:

- F pedex : Represents the pedex factor listed in Table 4.1.
- Pf pedex : Denotes the weight assigned to the pedex factor in Table 4.1.
- Σmin(Pf pedex): Is the sum of the minimum weights that can be assigned to all factors in Table 4.1.
- Σmax(Pf pedex): Is the sum of the maximum weights that can be assigned to all factors in Table 4.1.

TABLE A - General							
PARAMETER / WEIGHT, P	-1	-0.5	0	0.5	1	2	3
Slope angle			<15°	15°-30°	30°-45°	45°-70°	>70°
Rock mass structural conditions*			Massive rock with no or a few discontinuities (Jn=0.5÷1)	One set of discontinuities (Jn =2÷3)	Two sets of discontinuities (Jn =4÷6)	Three sets of discontinuities, rock mass subdivided into small cubes (Jn =9÷12)	More than three sets of discontinuities, highly fractured rock mass (Jn =15÷20)
Conditions of discontinuities *			Very rough surfaces; not continuous; no separation; unweathered wall rock	Slightly rough surfaces; separation <1 mm; slightly weathered walls	Slightly rough surfaces; separation <1mm; highly weathered walls	Slickensided surfaces or gouge <5 mm thick or separation 1-5 mm; continuous	Soft gouge >5 mm thick or separation >5 mm; continuous
Stability conditions *			Stable		Partially stable	Unstable	
Fracturing degree of the rock mass **			Low		Medium	High	Very high
Expected rockfall events			Few events (1/10 years) - no rockfall scars		Occasional events (3/year)	Many events-visible rockfall scars (6/year)	Numerous and frequent events (9/year)
Precipitation			Low		Moderate	Intense	
Aggravating conditions							
Unstable blocks and/or overhanging sectors			None			Present	
Geological singularities (presence of faults, low resistance interlayers, heterogeneity, etc.)			None		Present		
Seepage/water			No/a few water seeps on slope		Numerous water seeps on slope		
Lateral or foot torrential erosion			None		Present		
Seismicity			Low		Moderate	High	
Stabilization works	Fully efficient/ effective	Partially efficient/ effective	None				

Figure 4.1.1 *Susceptibility Index to Failure (SIF) table*

In cases where certain factors cannot be evaluated—for example, due to limited visibility of the slope or lack of available data—their contribution is excluded from the summations Σmin(Pf pedex) and Σmax(Pf pedex). This exclusion ensures that the SIF index is not influenced by assumptions about factors that cannot be accurately assessed. On the other hand, if a factor is entirely absent in the study area (e.g., freeze-thaw cycles or wave energy), its weight is set to 0, but it is still included in the summations to maintain consistency in comparative analyses. This approach is particularly important when comparing different sites (e.g., Site A and Site B) to guide decision-making processes, such as identifying areas that require further investigation or the implementation of mitigation measures. For example, if freeze-thaw cycles are absent in Site A but present in Site B, the SIF index for Site B will be higher, reflecting its greater susceptibility to failure and influencing the outcomes of hazard analyses.

This methodology provides a comprehensive and scalable framework for assessing rockfall susceptibility across various environments and scales. By systematically evaluating causative factors and calculating the SIF index, this approach ensures reliable and practical results that can support informed decision-making in hazard analysis and mitigation planning.

4.2 An Overview of Runout Susceptibility Analysis with QPROTO

The assessment of susceptibility and hazard remains one of the most challenging aspects in the field of rockfall risk estimation. Specifically, evaluating the hazard level involves three critical steps:

- **Spatial Identification of Involved Areas**: This step focuses on determining the geographical zones that could be affected by rockfall events.
- **Computation of Rockfall Intensity**: This involves calculating the kinetic energy of falling blocks, which serves as a measurable indicator of the event's intensity.
- **Definition of Temporal Occurrence**: This step addresses the frequency or likelihood of rockfall events occurring over time.

Regarding the first two steps, various methodologies are available to analyze the spatial progression of rockfall phenomena. Advanced 3D analytical models, for example, incorporate the inertia of rock blocks, providing a detailed understanding of the energy involved. Simplified models, however, reduce the rock block to a dimensionless point within a 2D or 3D framework, ignoring the effects of block shape and size. These simplified approaches are often applied at both large (site-specific) and local scales, following recommendations by Corominas et al. (2014) for detailed risk analyses or the design of protective measures. For smaller-scale applications, such as territorial planning or preliminary studies, even more simplified models can be used. In such cases, the runout model must be both simple and reliable to address the limited availability of data and associated uncertainties.

Among the various methodologies, the **Energy Angle Method (EAM)** is one of the most widely used. Developed by Onofri and Candian (1979) and based on the earlier **Fahrböschung** concept by Heim (1932) (describes the angle between the horizontal and the line connecting the highest point of a rockfall or landslide's detachment zone to the farthest point of deposit. This "apparent friction angle" reflects the mobility of the falling material: steeper angles indicate shorter runout distances, while shallower angles suggest greater mobility and longer travel. Although simplistic, it provides a quick estimate of hazard extent based on slope geometry and is widely used in preliminary rockfall and landslide assessments), the EAM simplifies the rockfall process into an equivalent sliding motion of a rigid block along a straight line, known as the **energy line**, connecting the rockfall source to the farthest point of deposition at the slope's base. The slope of this energy line is defined by the **energy angle**, referred to as the **shadow angle** when the source point is located at the apex of a talus slope. Beyond rockfall, this model is also applied to other slope instability phenomena, such as snow avalanches and shallow landslides the representation in given in figure 4.2/

In recent decades, the EAM has been integrated into various computational tools, including those within Geographic Information System (GIS) environments. One notable example is the **CONEFALL** tool, developed by Jaboyedoff and Labiouse (2011), which estimates potential rockfall areas using only a Digital Terrain Model (DTM) and a grid file of rockfall sources. CONEFALL employs a series of cones with apexes at the rockfall source points to determine whether a DTM cell lies below the energy line, thereby identifying the propagation area. The intersection of these cones with the slope surface delineates the affected zone, and a basic energy balance calculation provides the kinetic energy within this area. This 3D adaptation of the EAM is commonly referred to as the **Cone Method (CM)**.

The CM has been further refined in **QPROTO**, an open-source, cross-platform plugin designed for the QGIS 3 environment. QPROTO conducts a viewshed analysis using the GRASS GIS function **r.viewshed**, constrained by a visibility cone defined by three angles:

- **Dip Direction θ**: Orients the cone relative to north.
- **Energy Angle ϕp**: Shapes the cone in the vertical plane.
- **Lateral Spreading Angle α**: Confines the cone in the horizontal plane.

This approach enables the identification of propagation zones and supports preliminary susceptibility assessments in rockfall-prone areas.

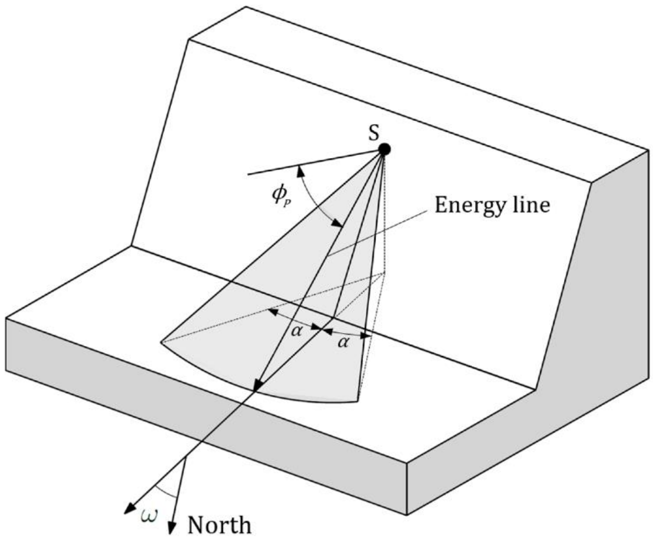


Figure 4.2.1 *3D Spatial definition of the visible cone within the QPROTO Plugin*

At this stage, a pertinent question arises regarding the appropriate values to assign to these angles (referred to as "cone angles") in preliminary hazard analyses. Numerous researchers have proposed statistical approaches to estimate ϕp based on the percentage of stopping points. For example, Onofri and Candian (1979), through field observations, noted that 100% of observed blocks stopped when ϕp exceeded 28.5°, while 50% stopped when ϕp exceeded 32°. In contrast, a statistical analysis of the Principality of Andorra case study yielded values of 41.3°, 39.5°, and 36.9° for the 90th, 99th, and 99.9th percentiles, respectively. Lied (1977) observed that all blocks came to rest within an angle range of 28° to 30°. Other researchers have proposed maximum values for these angles based on various case studies. For instance, Evans and Hungr (1993) suggested a maximum shadow angle of 27.5° and a ϕp of 24°, while Wieczorek et al. (1998) recommended a lower ϕp value of 22°. The significant variability and site-specific nature of these studies highlight the need for a reliable representation of rockfall phenomena through the energy line, taking into account factors such as block characteristics (e.g., shape, volume, resistance) and slope conditions (e.g., inclination, length, roughness, vegetation). Recent studies have sought to clarify the influence of these factors on the energy line. For example, Rickli et al. (1994) classified angles based on block resistance and size, referencing German mountain cases: (i) ϕp = 33° for small rocks with low resistance and smooth surfaces or larger blocks with high resistance and rough slopes; (ii) ϕp = 35° for medium-sized blocks; and (iii) ϕp = 37° for small blocks with high resistance and very rough slopes. More recently, Volkwein et al. (2018) presented findings from extensive in situ rockfall testing, providing detailed insights into block trajectories on grass slopes, which are valuable for calibrating both numerical trajectory simulations and simplified energy line-based analyses. These examples underscore the importance of analyzing the dependence of the energy line on all factors influencing rockfall trajectories for the effective application of the Cone Method.

Regarding the lateral angle α, limited guidance is available in the literature. Generally, the lateral dispersion of rockfall phenomena depends on three factors: macro-topographic (slope morphology, steepness, presence of channels, ridges, etc.), micro-topographic (slope surface roughness), and dynamic (interactions between the block and slope, vegetation, protective structures, etc.). Based on numerical models, Azzoni et al. (1995) suggested that lateral dispersion typically amounts to 20% of the slope length, decreasing for short and steep slopes but increasing for irregular or channeled slopes. Agliardi and Crosta (2003) found a higher value of 34% of slope length. Using a 3D rockfall simulation program, Crosta and Agliardi (2004) analyzed simulated slopes with varying steepness, roughness, and pixel sizes, concluding that lateral dispersion varied little with slope steepness, with maximum values generally below 10%. However, they observed that greater slope roughness led to increased lateral dispersion.

4.3 The QPROTO Plugin

The **QPROTO plugin** (QGIS Predictive ROckfall TOol) was developed to implement the **Cone Method** within the **QGIS environment**, a user-friendly, open-source geographic information system supported by the **Open Source Geospatial Foundation (OSGeo)**. The plugin utilizes the **GRASS GIS 7 module r.viewshed**, which evaluates the visibility of surrounding areas from a set of predefined viewpoints. Each viewpoint acts as the apex of a **visibility cone**, covering a specific portion of the slope. As outlined in Figure 4.3, the geometry of the cone is defined by three key angles: the **dip direction θ**, the **energy angle** $\boldsymbol{\phi p}$, and the **lateral angle** $\boldsymbol{\alpha}$. Additionally, a **visibility distance** parameter sets the maximum extent of the analysis. The fundamental assumption is that each viewpoint corresponds to a potential rockfall source, meaning the entire visible area of the slope could be reached by falling boulders originating from that source.

When multiple source points are considered, the plugin identifies rockfall-prone zones by analyzing the overlap of visibility cones. This process generates a **frequency map**, where areas with higher frequencies indicate greater visibility from multiple sources. These zones are interpreted as being more susceptible to rockfall events, as they are more likely to be reached by falling blocks from various origins.

Using the **Cone Method** , it is also possible to calculate the **velocity v(x,y)** of a falling block at any point **P(x,y)** on the topographic surface. This is achieved through the following equation :

$$v(x,y) = \sqrt{2g\left[H(x_0, y_0) - h_p(x,y) - tan\phi_p \cdot \sqrt{(x-x_0)^2 - (y-y_0)^2}\right]}, \quad \textbf{Eq (6)}$$

where:

- **g** is the acceleration due to gravity,
- **(x_0, y_0)** are the coordinates of the source point **S**,
- **$H(x_0, y_0)$** is the elevation of the source point,
- **$h_p(x,y)$** is the elevation of the topographic surface at point **P(x,y)**,
- **ϕ_p** is the energy angle.

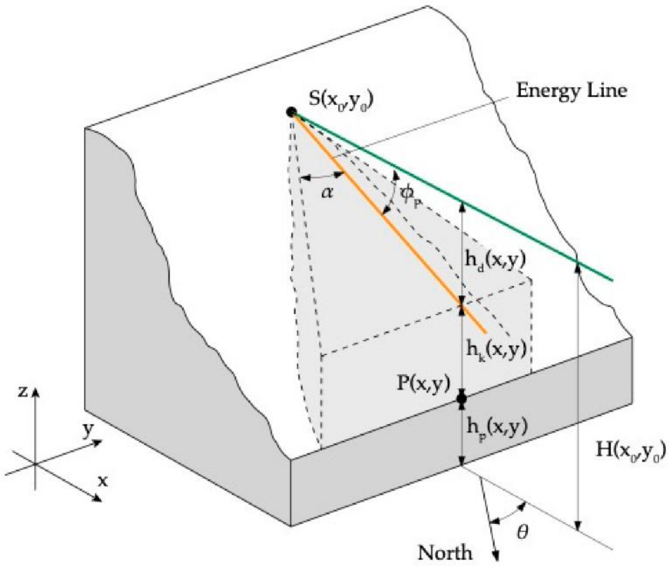


Figure 4.3.1 *3D Sketch of cone within the QPROTO Plugin*

In Figure 4.3, the heights associated with point **P(x,y)** are linked to the **energy balance** of the falling block. **$H(x_0, y_0)$** represents the total energy content of the block, defined by the principle of energy conservation as the sum of:

- **Potential energy ($h_p(x,y)$)**,
- **Kinetic energy ($h_k(x,y)$)**,
- **Frictional or dissipative energy ($h_d(x,y) = PS \cdot \tan \phi_p$)**.

Thus, the **kinetic energy Ek(x,y)** at any point within the cone can be calculated using the following relationship :

$$E_k(x,y) = \frac{1}{2} m [v(x,y)]^2 \qquad \textbf{Eq (7)}$$

where:

- **m** is the mass of the block,
- **v(x,y)** is the velocity of the block at point **P(x,y)**.

It is important to note that the calculated energy does not account for the complex combination of phenomena such as free flight, bouncing, rolling, and sliding, which typically occur during the propagation phase. Instead, these phenomena are simulated through an equivalent sliding motion along a plane with an inclination equal to ϕp. As a result, the velocity and energy values obtained through this method should be interpreted with caution, particularly when compared to the results of more detailed and accurate propagation analyses. Nevertheless, the energy estimation provided by the Cone Method offers a preliminary assessment of hazard, which can be useful for identifying the most critical zones within a large area in terms of both process intensity and susceptibility.
To incorporate the characteristics of rockfall sources into the hazard estimation, the QPROTO plugin allows users to assign a detachment propensity index (DI) to each source point. The DI serves as a weighting factor, highlighting the source zones that are most likely to trigger rockfall events. This index can be defined based on available information about the study area, such as historical data, fracture density maps, and the inclination of the slope in the source zones, combined with the results of rapid on-site

surveys. The DI enables the calculation of a weighted frequency map (i.e., a susceptibility map) and time-independent hazard maps (spatial hazard maps).

- The **susceptibility map** is a raster file that illustrates the distribution of rockfall phenomena across the invasion area, highlighting the zones most likely to be affected. This map provides a simplified, non-temporal probability of rockfall occurrence.
- The **time-independent hazard maps** combine the detachment propensity of each source point with the estimated kinetic energy in a given cell of the invasion zone. Each cell in these maps corresponds to weighted energy values, providing a more nuanced understanding of hazard distribution.

It is worth noting that the term "time-independent" is used because defining the DI typically does not involve temporal data, especially at small and medium scales where information about rockfall occurrence frequency is often limited. However, if temporal data (e.g., an estimated return period) is available, the QPROTO plugin can incorporate this information to generate time-based hazard maps, either by substituting or complementing the detachment propensity index. While these aspects of hazard analysis are not the focus of this study, further details on hazard calculation methodologies can be explored in the relevant literature.

For the proper execution of QPROTO, in addition to the core QGIS algorithms, the plugin requires GRASS 7 and SAGA GIS open-source modules to create and manage vector and raster files, as well as to perform the viewshed analysis. Users must define a set of source points, each representing a potential rockfall block, within specified source areas. Each source point must be associated with a set of attributes, as listed in Table 4.2. Some of these attributes, such as point elevation and aspect, can be directly inferred from the Digital Terrain Model (DTM). Others, such as the energy angle ϕp, the lateral angle α, and the detachment propensity index (DI), must be estimated based on available information about the slope geometry and conditions. Additionally, the boulder mass can be defined in relation to a specific scenario, characterized by a reference block volume.

No.	Attribute	Description
0	ID	Identification number of the source point
1	Elevation	Height of the source point a.s.l. (m)
2	Aspect	Dip direction ω of the slope in the source point (°)
3	Energy angle	Energy line angle ϕp of the cone with apex in the source point (°)
4	Lateral angle	Lateral angle α of the cone with apex in the source point (°)
5	Visibility distance	Distance to which the analysis can be extended, i.e., the maximum runout distance assumed for rockfalls originating from the source cells (m)
6	Detachment propensity	Propensity of each source point to generate rockfalls (it can be, for example, the SIF) (-)
7	Boulder mass	Mass of the block (kg), utilized for the computation of the kinetic energy of masses at various points on the slope—a method not employed in this study

Table 4.1 *List of contents for Qproto Analysis*

The QPROTO analysis produces 10 raster files, summarized in table 4.2. The first raster, labeled "count," represents the unweighted passage frequency for each cell in the runout area, indicating the number of source points that view the cell. The second raster, "susceptibility," displays the weighted passage frequency, calculated as the sum of the detachment index (DI) values from the source points that view each cell. The next three rasters (v_min, v_mean, and v_max) represent the minimum, mean, and maximum velocity, respectively, computed for each cell. Based on these velocity rasters, the corresponding energy rasters (e_min, e_mean, and e_max) are derived using Equation (3). Additionally, two time-independent hazard maps (w_en and w_tot_en) are generated by multiplying the detachment index (DI) with the kinetic energy for each cell in the runout area. Along with these raster outputs, the analysis also produces the Finalpoints vector shapefile and the _log.txt logfile, which contains a detailed report of the analysis. After the computation, the outputs are automatically loaded into the QGIS environment.

Type	Description
count	Raster map: Number of source points that can view each cell
susceptibility	Raster map: Weighted view frequency
v_min	Raster map: Minimum computed block velocity
v_mean	Raster map: Mean computed block velocity
v_max	Raster map: Maximum computed block velocity
e_min	Raster map: Minimum computed kinetic energy
e_mean	Raster map: Mean computed kinetic energy
e_max	Raster map: Maximum computed kinetic energy
w_en	Raster map: Maximum weighted kinetic energy
w_tot_en	Raster map: Total weighted kinetic energy
Finalpoints	Shape file: Details on points located in the runout zone
_Log.txt	Log file: Report of the computed analysis

Table 4.2 *List of QPROTO output files*

The velocity and energy rasters are measured in meters per second (m/s) and joules (J), respectively. While the susceptibility and hazard files are also expressed in joules (J), they are classified on a five-level scale: very low, low, medium, high, and very high.

4.4 Analytical Steps and Results Using QPROTO

4.4.1 Formation of Attributes Table

The table 4.1 presented outlines a comprehensive set of parameters used to evaluate the probability of rock block detachment and classify the relative stability of rock slopes. These parameters are essential for assessing rockfall hazards and can be effectively utilized in QGIS software with the Qproto plugin for spatial analysis and hazard mapping. Below is a detailed description of the table and its components, which will be incorporated into this thesis. In the case study the parameters are ranging between values 0 to 3.

General Parameters

1. Slope Angle:

The slope angle is categorized into different ranges, from less than 15° to more than 70°. Steeper slopes generally exhibit a higher probability of rock detachment due to increased gravitational forces acting on the rock mass. Value ranging between 0 to 0.5 for slope angles less than 30 and from 1 to 30 for values ranging between 30 and 70.

2. Rock Mass Structural Conditions:

This parameter evaluates the number and nature of discontinuities in the rock mass, quantified by the Joint Number (Jn). The conditions range from massive rock with no or few discontinuities (Jn=0.5-1) to highly fractured rock masses with more than three sets of discontinuities (Jn=15-20). The structural conditions significantly influence the stability of the rock mass. Values ranging between 0 to 0.5 if joint number less than 3 and from 1 to 3 for joint number greater than 3.

3. Conditions of Discontinuities:

The characteristics of discontinuities, such as surface roughness, separation, and weathering, are assessed. These range from very rough, unweathered surfaces to soft gouge-filled or highly separated and continuous discontinuities. The condition of discontinuities plays a critical role in determining the likelihood of rock block detachment. Value ranging between 0 to 0.5 if discontinuity is less than 1 mm and from 1 to 3 for discontinuity greater than 1mm.

4. Stability Conditions:

The overall stability of the rock mass is classified as stable, partially stable, or unstable based on the aforementioned parameters. This classification helps in understanding the potential for rockfall events. Values ranging from 0 for stable and 1 to 2 for partially stable and unstable rock mass respectively.

5. **Fracturing Degree of the Rock Mass:**

The degree of fracturing is categorized from low to very high, indicating the intensity of rock mass fragmentation. Higher fracturing degrees generally correlate with increased instability. Values ranging from 0 to 3.

6. **Expected Rockfall Events:**

This parameter estimates the frequency of rockfall events, ranging from few events (1/10 years) to numerous and frequent events (9/year). The frequency of events provides insight into the historical and potential future activity of rockfalls in the area. Values ranging from 0 in case of few and from 1 to 3 for occasional and numerous events.

7. **Precipitation:**

The intensity of precipitation is classified as low, moderate, or intense. Precipitation can influence the stability of rock slopes by affecting water seepage and erosion, thereby increasing the risk of rockfall. Values ranging from 0 for low and from 1 to 2 for moderate and intense rainfall.

Aggravating Conditions

- **Unstable Blocks and/or Overhanging Sectors:**

The presence of unstable blocks or overhanging sectors can significantly increase the risk of rockfall. These features are critical in assessing the immediate hazard potential. Value ranging from 0 for none and 2 if present.

- **Geological Singularities:**

Features such as faults, low resistance interlayers, and heterogeneity are considered. Their presence can exacerbate instability and contribute to the likelihood of rockfall events. Value being 0 if none and 1 if present.

- **Seepage/Water:**

The extent of water seepage on the slope is noted, ranging from no or few seeps to numerous seeps. Water seepage can weaken the rock mass and reduce its stability. Value being 0 if none or few seeps and being 1 in case of numerous.

- **Lateral or Foot Torrential Erosion:**

The presence of erosion at the slope's base or sides can undermine stability. Erosion removes supporting material, increasing the risk of slope failure. Value being 0 if none and 1 if present.

- **Seismicity:**

The level of seismic activity is categorized as low, moderate, or high. Higher seismicity increases the likelihood of rockfall due to ground shaking and resultant destabilization. Value being 0 if its low and 1 to 2 if moderate or high respectively.

- **Stabilization Works:**

The effectiveness of any stabilization measures is assessed, ranging from fully effective to none. The presence and efficiency of stabilization works directly impact the overall stability of the slope. Values range from -1 to 0.5 for fully and partially effective respectively, and 0 in case of nonexistence.

fid	Pendenza	DTMAspectMe	DetachmPro	Mass	Elevation	En.L.An	Slope Ang	Slope A.F	R.M.S.C	Cond.o.Dis
618	27.327470779	146.94287284	0	5302	498	27	27	0.5	2	2
566	26.504325867	202.48785182	0	5302	534	38	26	0.5	2	2
403	42.134117126	306.46390431	1	5302	618	36	42	1	3	2
404	39.291496277	259.24165215	1	5302	492	36	39	1	3	2
405	38.699501038	258.78192895	1	5302	500	36	39	1	3	2
406	38.238502502	260.81047539	1	5302	507	36	38	1	3	2
407	42.349960327	269.88735582	1	5302	516	36	42	1	3	2

F.D.O.R.M	Lithology	Exp.R.E	Water	U.B or O.S	Aggr Cond	Lat erosio	Thaw cycle	deatch cof
1	0	0.5	2	2	1	0	0	0.44
1	0	0.5	2	2	1	0	0	0.44
2	1	0.5	2	2	1	0	1	0.62
2	1	0.5	2	2	1	0	1	0.62
2	1	0.5	2	2	1	0	1	0.62
2	1	0.5	2	2	1	0	1	0.62
2	1	0.5	2	2	1	0	1	0.62

Figure 4.4.1.1 *QGIS table filled with attributes*

After the filling of attributes, the next step is to calculate the Detachment Proficiency using equation 1. This equation can be set up in QGis using the icons marked in Figure 4.4.1.2 which leads to the opening of Expression dialog

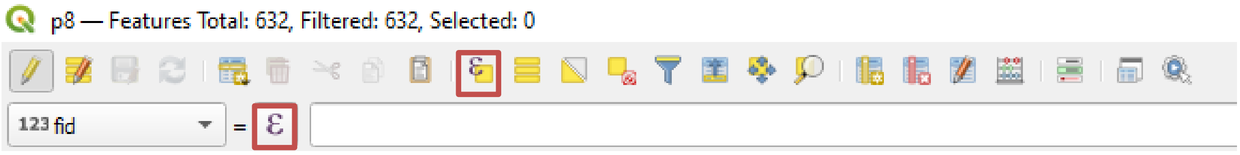


Figure 4.4.1.2 QGIS equation toolbox

In this you can create the equation as desire as it is presented in the figure under using the equation 1 in figure 4.4.1.3

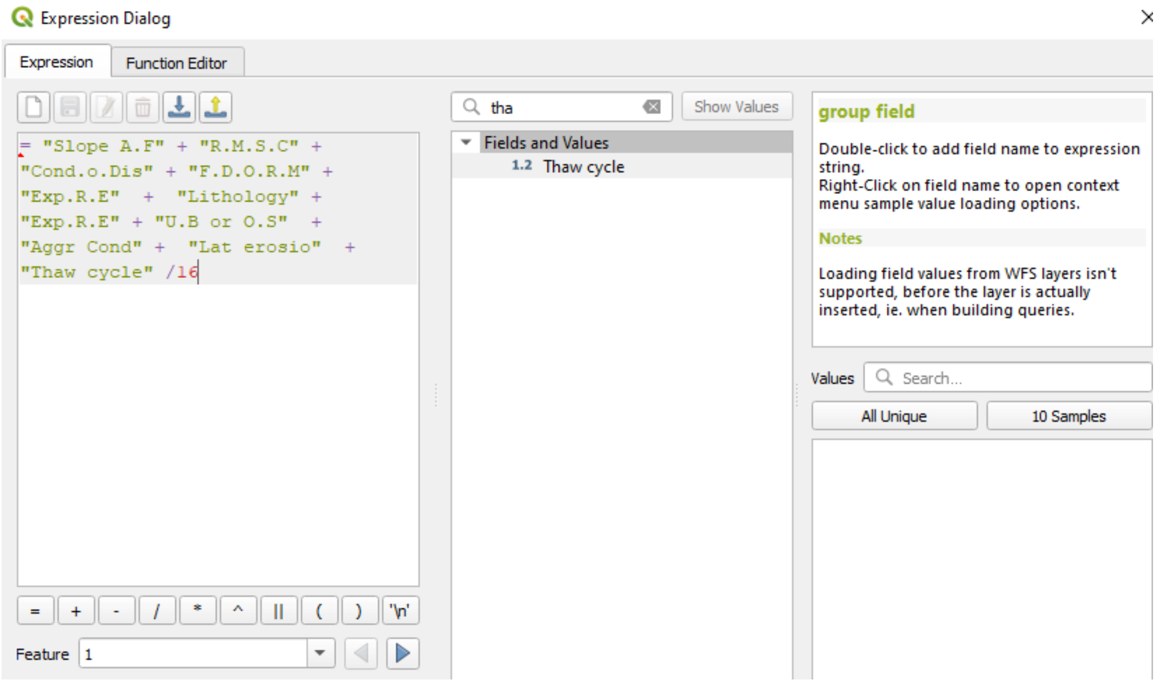


Figure 4.4.1.3 QGIS Expression dialog

4.4.2 Calculation of Energy Line Angle:

To determine the energy line angle, the graphs presented in Figure 4.4.2.1 were utilized, where graph (a) illustrates the energy line angles for non-forested areas, while graph (b) depicts the energy line angles for forested areas. In our specific case, since the slope under consideration is forested, graph (b) was used to gain a more accurate and relevant understanding of the analysis being conducted by the QPROTO plugin. The energy line angle is a critical parameter in rockfall analysis, as it helps define the trajectory and energy dissipation of falling blocks, which are influenced by factors such as slope steepness, surface roughness, and the presence of vegetation. By focusing on the forested scenario, we ensure that the analysis aligns with the actual conditions of the study area, thereby improving the reliability of the results.

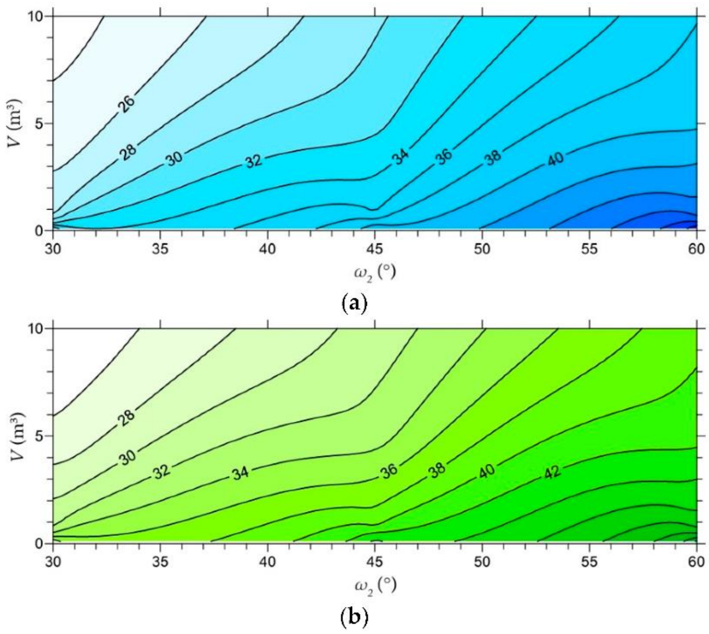


***Figure 4.4.2.1** Graph a (deforested) and Graph b (Forested) values for ELA*

Based on the proposed methodology, several key factors, including slope inclination, forest coverage, and block volume. These factors play a significant role in determining the behavior of rockfalls, as they influence the energy dissipation and runout distances of falling blocks. The derived values are considered conservative because they correspond to the second percentile of the cumulative distribution function (CDF). This statistical approach ensures that the estimates represent a lower-bound scenario, meaning that in 98% of cases, the actual energy angles are likely to exceed these values. Consequently, this implies that the blocks may travel shorter distances along the slope in most real-world situations, as the conservative estimates account for the most extreme or worst-case scenarios.

The use of the second percentile as a reference point ensures that the analysis remains cautious and accounts for variability and uncertainty in the input parameters. By treating these values as a lower-bound reference, we adopt a risk-averse approach, which is particularly important in the context of hazard assessment and mitigation planning. This conservative interpretation helps to ensure that the potential impacts of rockfall events are not underestimated, thereby providing a safer and more reliable basis for decision-making. Furthermore, this approach allows for the development of robust mitigation strategies that can effectively address even the most severe rockfall scenarios, thereby enhancing the resilience of the affected areas.

In summary, the energy line angle was derived using the forested scenario graph from Figure 4.5, as it closely matches the conditions of the study area. The conservative estimates for the energy angle were calculated by considering slope inclination, forest coverage, and block volume, with the values corresponding to the second percentile of the CDF. This ensures that the analysis accounts for the majority of potential scenarios, with the actual energy angles likely exceeding the estimates in 98% of cases. By adopting this conservative approach, the analysis provides a reliable lower-bound reference, which is essential for accurate risk assessment and the development of effective mitigation measures. This methodology not only enhances the credibility of the results but also ensures that the potential impacts of rockfall events are adequately addressed, thereby safeguarding lives, infrastructure, and the environment.

4.4.3 Interface of Qproto Plugin :

In figure 4.4.3.1 the interface of Qproto plugin is displayed which focuses on what information is necessary for the input in plugin to derive results regarding the respective case study

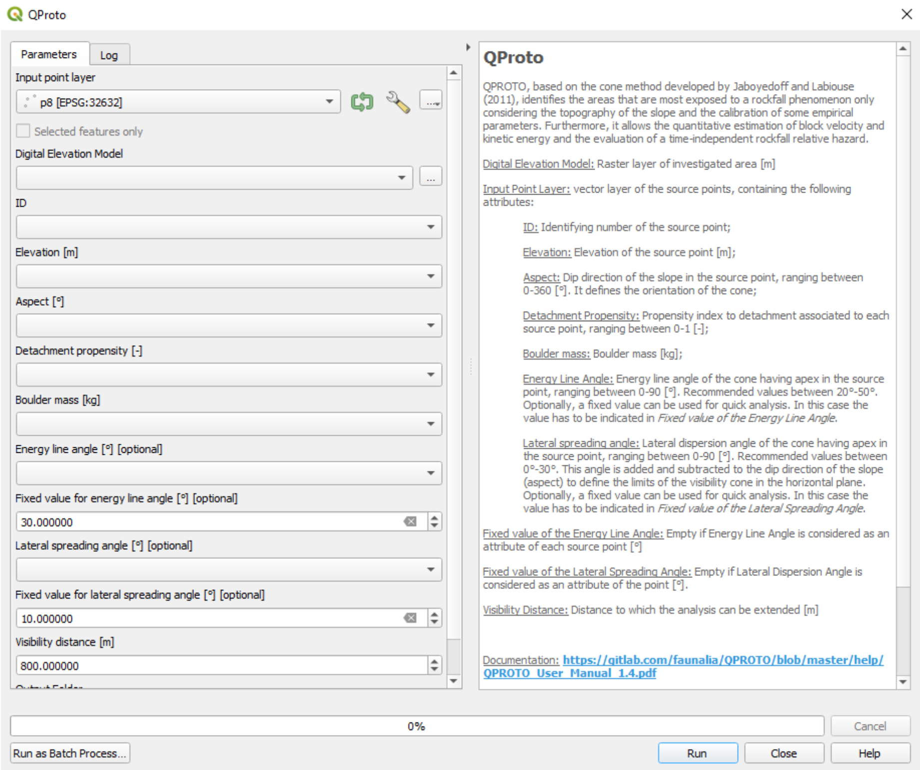


Figure 4.4.3.1 *Interface of Qproto in QGIS*

In order to carry out the analysis the points are selected using the selection tool which gives us the freedom to do analysis on certain or all points at the same time. The selection of points is shown in figure 4.4.3.2

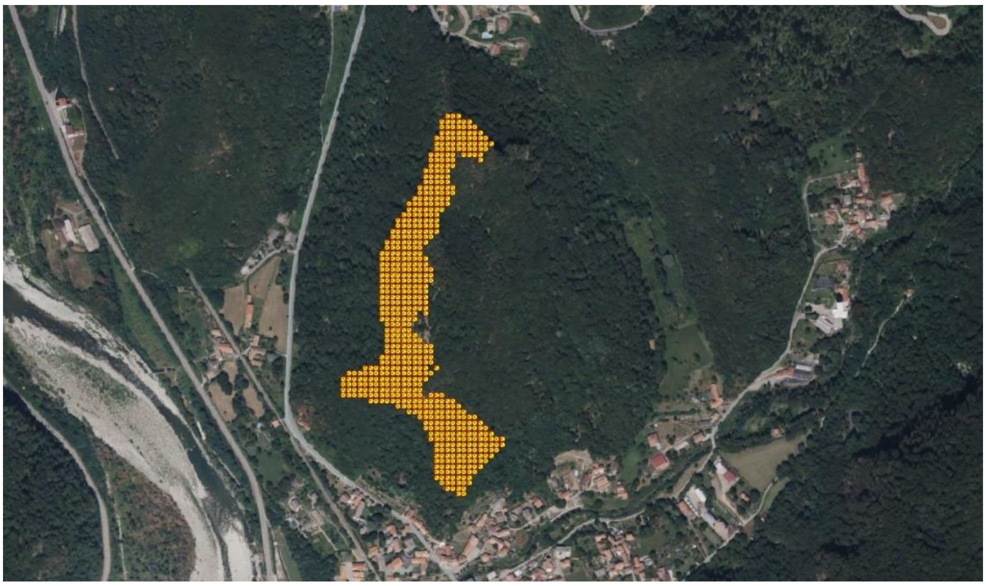


Figure 4.4.3.2 *Selection of points in QGis*

4.4.4 Discussion on Results of QPROTO:

The results obtained from QPROTO offer a detailed and multifaceted analysis of rockfall dynamics, encompassing critical parameters such as susceptibility, maximum and minimum velocities, maximum and minimum energy values, and the probable final points of rockfall trajectories. Each of these parameters plays a vital role in understanding the behavior and potential impact of rockfall events. Susceptibility, for instance, quantifies the likelihood of rockfall occurrence in specific areas based on factors such as slope geometry, material properties, and environmental conditions. This metric is essential for identifying zones that are inherently more prone to instability and rockfall activity.

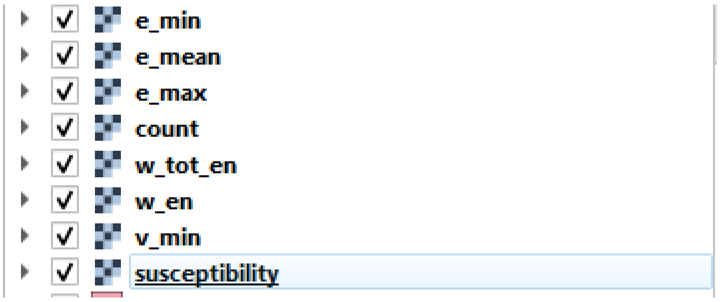


Figure 4.4.4.1 Final files of analysis by Qproto

In addition to susceptibility, the maximum and minimum velocities calculated by QPROTO provide insights into the speed at which falling rocks may travel, which is crucial for assessing the kinetic energy they carry and the potential damage they can cause upon impact. Similarly, the maximum and minimum energy values help quantify the destructive potential of rockfalls, allowing us to evaluate the severity of potential impacts on structures, ecosystems, and human populations.

However, among these parameters, our analysis will primarily focus on susceptibility and the final points of rockfall trajectories. These two aspects are particularly significant for risk assessment and mitigation planning. Susceptibility enable us to prioritize areas that require immediate attention, as they indicate regions with a higher probability of rockfall occurrence. Meanwhile, the final points of rockfall trajectories provide critical information about where the rocks are likely to come to rest after their descent. This is especially important for identifying the areas that may be directly affected by falling rocks, such as roads, buildings, or other infrastructure located at the base of slopes.

By concentrating on susceptibility in figure 4.4.4.2 and final points in figure 4.4.4.3, we can develop a clearer and more comprehensive picture of the areas that are most vulnerable to rockfall hazards. This approach not only helps in identifying the zones at risk but also aids in understanding the spatial distribution of potential impacts. For instance, areas with high susceptibility and a high concentration of final points are likely to experience more frequent and severe rockfall events, necessitating urgent mitigation measures. On the other hand, regions with lower susceptibility and fewer final points may require less intensive interventions.

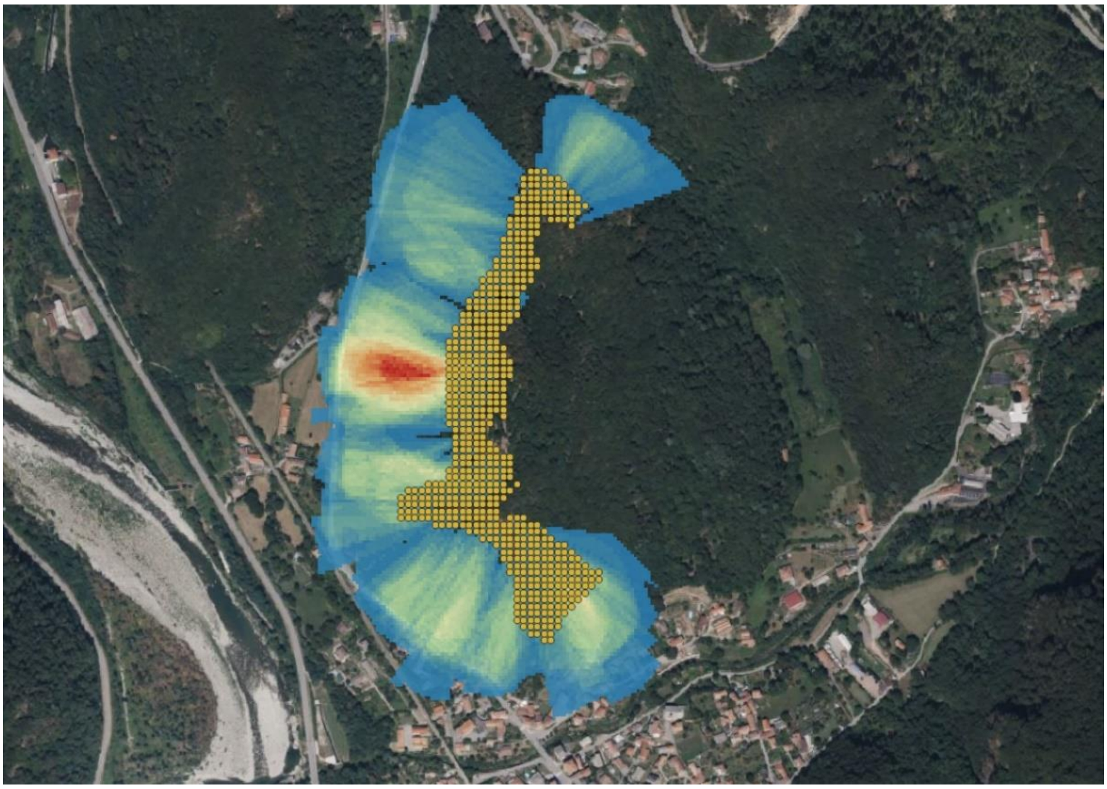


Figure 4.4.4.2 *Results of susceptibility by Qproto*

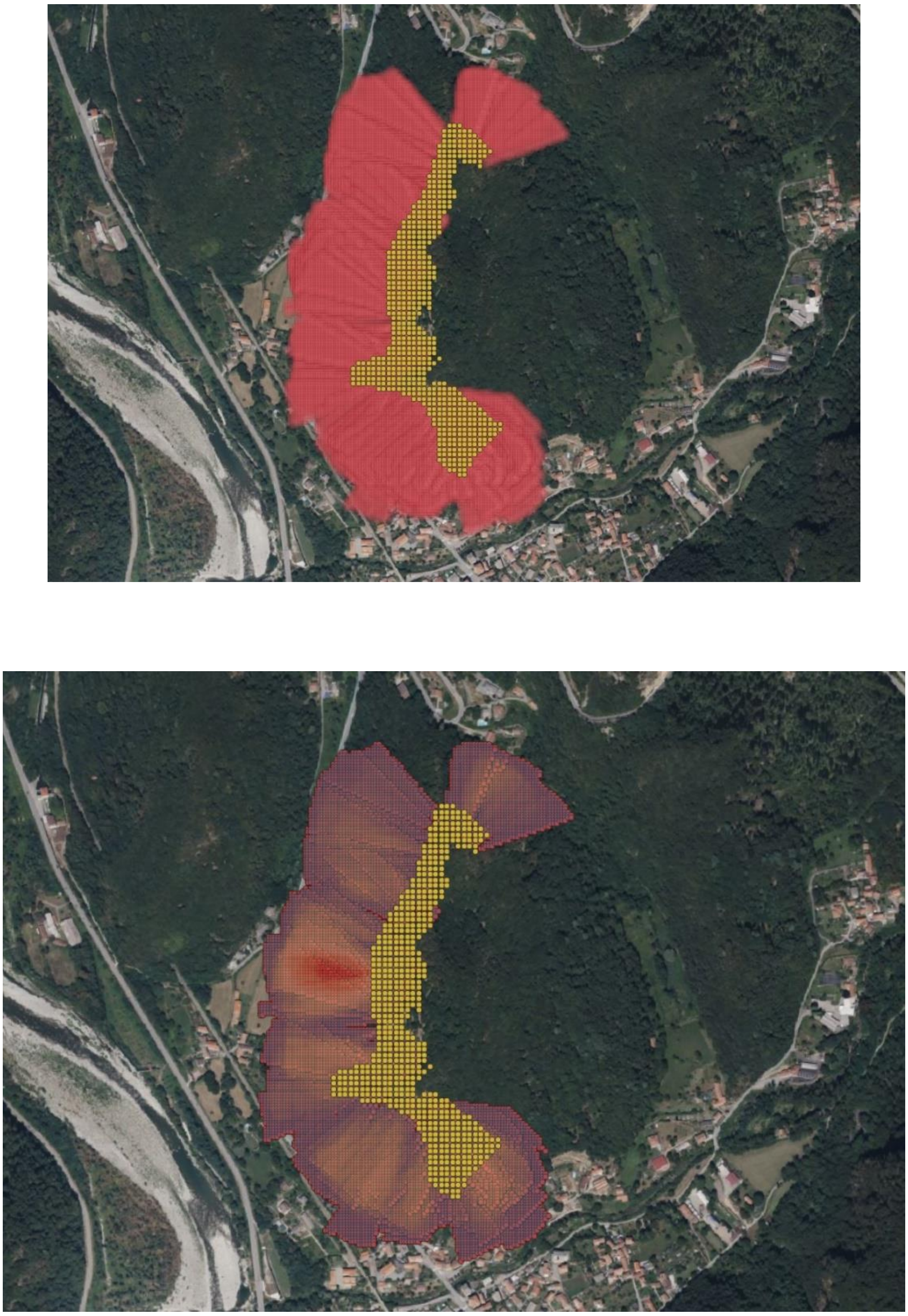


Figure 4.4.4.3 Results of final points by Qproto

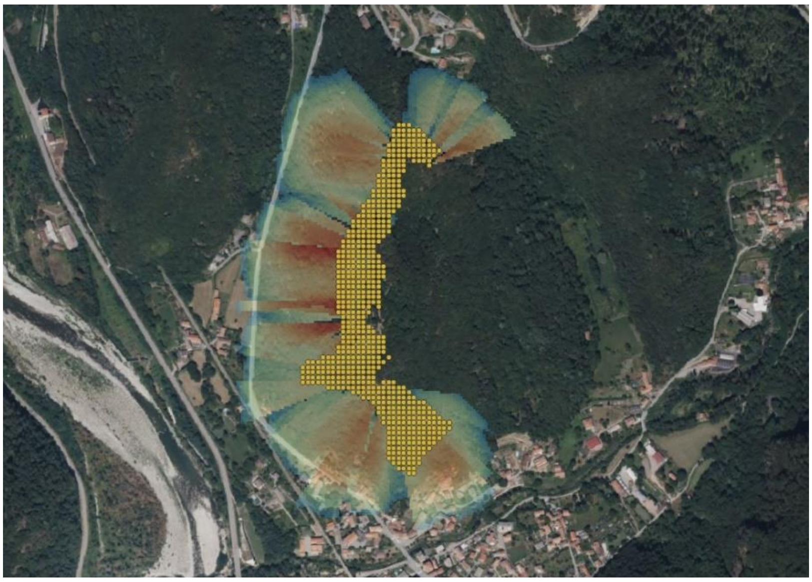


Figure 4.4.4.4 Results of Maximum energy by Qproto

Figure 4.4.4.5 Results of Minimum energy by Qproto

In addition, the results from QPROTO, related to maximum energy in figure 4.4.4.4 and minimum energy in figure 4.4.4.5 can also be derived, particularly those related to susceptibility and final points of rockfall trajectories, provide a robust foundation for assessing rockfall hazards and developing targeted mitigation strategies. By focusing on these key parameters, we can better understand the areas most likely to be affected by instability and take proactive steps to minimize risks, thereby safeguarding lives, property, and the environment. This comprehensive approach ensures that mitigation efforts are both efficient and effective, ultimately contributing to the resilience and safety of communities in rockfall-prone regions.

The areas that are critical to our case are the houses and road infrastructure. The areas that are in the red region are the ones where susceptibility is high, but those regions are mainly away from the critical infrastructure although the blue region in our case study also gives a perspective that some regions can be still affected due to rock fall. The final points that can be seen in figure 4.4.4.3 give a hypothetical idea that where the rocks can travel to. The regions where the level curves are near to each other have a higher tendency of rockfall and also road infrastructure can be damaged in those cases. Polygons are created in the software to highlight the area that can be affected and are discussed further.

4.5 *Highlighting the areas at risk of impact from the Results:*

Building on the analysis of susceptibility and rockfall trajectory endpoints derived from QPROTO, the next step involves spatially delineating areas at risk of rockfall using QGIS software. The QPROTO outputs, including susceptibility values and coordinates of rockfall endpoints, are imported into QGIS as georeferenced data layers.

Once the data is imported, the rockfall endpoints are analyzed to identify clusters or concentrations of points, as these areas represent zones where falling rocks are most likely to accumulate. Areas with both high susceptibility and a high density of endpoints are flagged as high-risk zones, while regions with lower susceptibility and fewer endpoints are classified as lower risk.

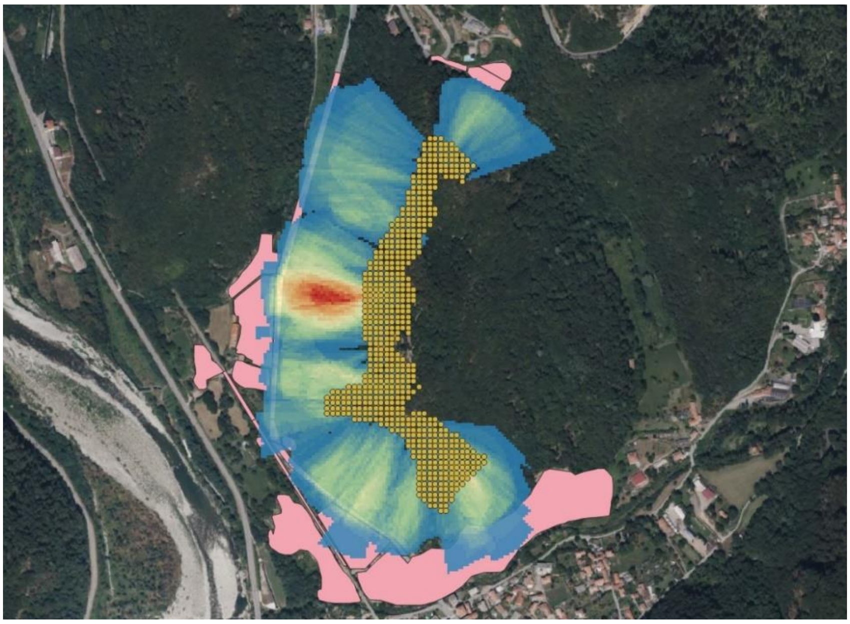


Figure 4.5.1*Polygons highlighting the area under influence*

The resulting risk maps provide a clear and intuitive visualization of the areas that are marked with pink polygons as seen in figure 4.5.1 which include houses and road infrastructure vulnerable to the impact

The final step involves validating the polygons using field data or historical rockfall records to ensure their accuracy and reliability. Once validated, these polygons serve as a critical tool for decision-making, guiding the implementation of mitigation strategies such as protective barriers, slope stabilization, or land-use planning. By clearly delineating risk zones, the polygons enable stakeholders to prioritize resources and efforts effectively, ensuring that the most vulnerable areas receive the necessary attention. This approach not only enhances the safety of communities and infrastructure but also contributes to the sustainable development of rock-fall prone regions.

5. Rockfall Back Analysis for Model Validation

Back analysis is a critical technique used to calibrate and validate rockfall simulations. It relies on data from historical rockfall events to fine-tune simulation parameters, ensuring the model accurately reflects real-world outcomes. This process not only validates the model's reliability but also helps identify and address any inconsistencies. Proper validation is crucial for dependable risk assessment and the development of effective mitigation strategies.

Beyond simply replicating past events, back analysis provides an opportunity to learn from discrepancies between observed and simulated results. These differences often reveal limitations in current models or gaps in data. By systematically analyzing these variations, researchers can enhance their models, improving their ability to predict future rockfall events with greater precision.

Before analyzing recent events, it is essential to accurately determine critical parameters such as friction angle, initial rock volume, starting position of the rock, and material properties. These factors are often challenging to assess but are vital for reliable simulations.

Data from previous rockfall events is collected to conduct a thorough back analysis. This involves gathering detailed information about past incidents to guide the calibration of the simulation model. The historical data serves as a benchmark to evaluate the accuracy of the model's predictions. Key aspects of this data collection process include:

- **Block Volume:** The volume of the rock from past events is used as a reference.

- **Simulation Calibration:** Computer simulations are performed using a trial-and-error approach. Parameters are adjusted iteratively until the simulation results align with the observed outcomes, such as the final resting position of the rock on the road.

Once the simulated results match the real-world data, the selected parameters are deemed suitable for rockfall analysis. This validated model can then be used to calculate critical information, such as the kinetic energy of recent rockfall events, runout distances, and other valuable insights for risk assessment and mitigation planning.

5.1 Model Setup

To perform a 2D back analysis of rockfall, the initial and essential step involves extracting the coordinates of the slope to create a 2D profile using the RocScience software "Rocfall 2." This process starts with QGIS, a robust open-source Geographic Information System (GIS). Within QGIS, a contour map derived from the Digital Terrain Model (DTM) of the specific site—in this instance, Varallo (VC)—is utilized to delineate sections that represent the slope. These sections are then used to generate the 2D profile required for the analysis in Rocfall 2. This step ensures that the slope geometry is accurately captured, providing a reliable foundation for subsequent rockfall simulations.

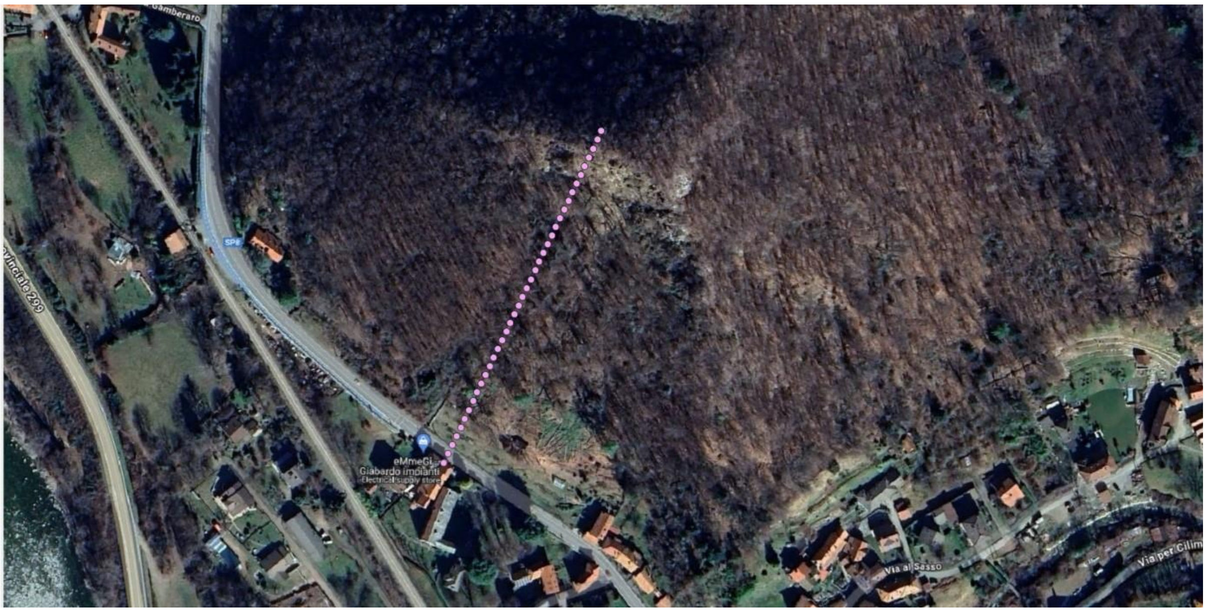


Figure 0.1 *Section drawn from DTM of Varallo (VC) Site of Rockfall occurred in November 2023*

A Digital Terrain Model (DTM) is a digital representation of the Earth's surface, excluding features such as vegetation and structures, focusing solely on the bare ground. It plays a vital role in numerous geospatial applications, including hydrological modeling, slope stability assessments, and, particularly, rockfall analysis.

To proceed with the analysis, the coordinates along the selected slope sections are carefully extracted. These coordinates are critical for creating an accurate representation of the terrain in simulation software. After drawing the sections on the contour map, the next step involves exporting the coordinates into a structured format. This is accomplished by saving the coordinates as a CSV file using Excel. The CSV file organizes the data into two columns: one for the x-coordinates (representing the horizontal distance along the slope) and one for the z-coordinates (representing the elevation). This formatted data is then ready for use in the simulation software, ensuring precise terrain modeling for the rockfall analysis.

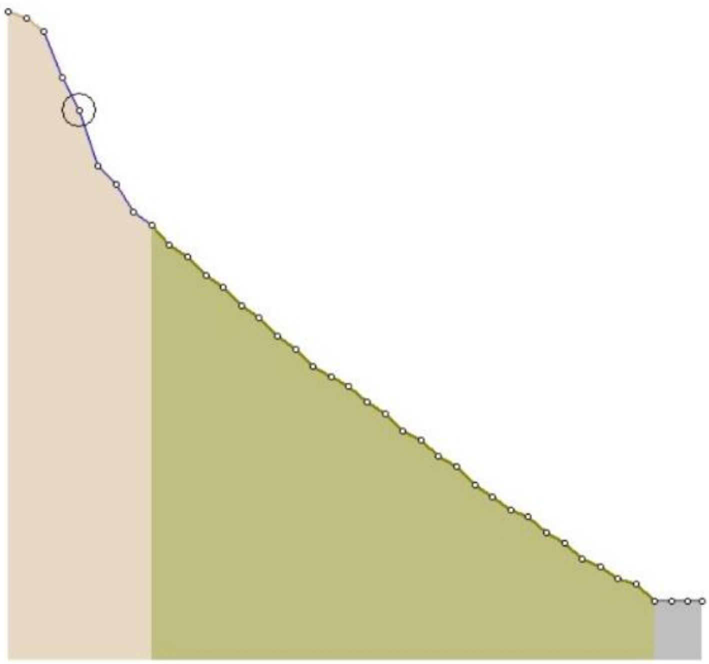


Figure 5.1.2 *Profile of slope drawn in Rockfall 2 by extracting co-ordinates from QGIS DTM Model*

The extracted coordinates are subsequently imported into Rocfall 2. Within the software, the 2D profile of the slope is generated using these imported coordinates, which precisely represent the terrain based on the DTM data obtained from QGIS. The simulation process is initiated by inputting these coordinates into Rocfall 2 and conducting simulations with various parameters, such as initial velocity, restitution coefficient, and friction angle. These parameters are further elaborated in the following section. This step ensures that the slope geometry is accurately modeled, enabling reliable rockfall simulations for analysis and validation.

5.2 Initial Parameter Selection

The initial parameters play a significant role in determining the outcomes of rockfall analysis and the accuracy of the predictions generated by simulation models. Among these parameters, the only fixed value used as a reference is the block size, which is set at 3 cubic meters. This value is based on the rockfall event that occurred in 2023 in the area of interest, where a block of this size detached from the hillside and eventually came to rest on the asphalt road. The selection of other parameters is typically informed by a combination of literature review, empirical data, and site-specific conditions. Below, we discuss the key parameters commonly considered and the reasoning behind their initial selection.

5.3 Initial Velocity

Determining the initial velocity of a rockfall is often complicated due to epistemic uncertainty, which stems from incomplete knowledge about the conditions that trigger the event. The initial velocity can vary widely depending on the detachment mechanism and the physical characteristics of the site. When a rock block detaches solely due to gravity, the initial velocity is typically near zero, as there is no additional force driving its movement at the start. However, if external forces, such as seismic activity or erosion, contribute to the detachment, the initial velocity may be greater than zero. In this case study, it is assumed that the rock detaches and moves purely under the influence of gravity. The Rocfall 2 software allows users to specify both horizontal and vertical velocities for the block. For this analysis, an initial velocity of 0.1 m/s was used as a starting point, followed by a trial-and-error approach to refine the value until the desired results were achieved. In more advanced analyses, particularly those using 2D probabilistic methods, the initial velocity is often treated as a variable parameter with statistical variability. However, in this case study, no standard deviation was assumed, and the values for the coordinates were kept at zero.

The X-coordinates in Figure 5.3.1 represent the horizontal distance along the slope, while the Y-coordinates represent the elevation of the terrain model. This approach ensures that the slope geometry is accurately represented, providing a reliable basis for the rockfall simulations.

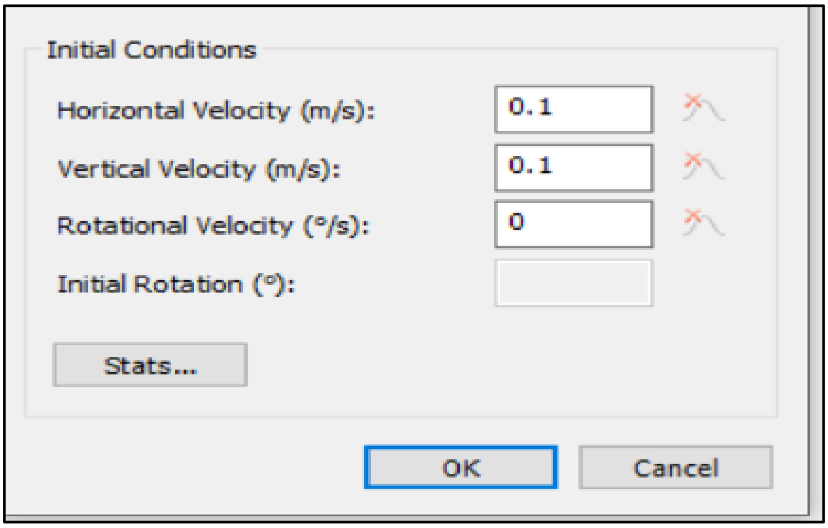


Figure 5.3.1 *Demonstration of Adding initial velocity values in Rockfall 2 for developing 2D Profile of Slope*

5.4 Slope Material Library

The materials composing a slope can vary significantly from the crest to the toe, as well as across different cross-sections. Even in cases where the material appears homogeneous, key parameters essential for rockfall analysis, such as the coefficients of restitution, may remain uncertain. In Rocfall 2, the Slope Material Library feature enables users to either create custom materials or select predefined ones from the library. The most critical parameters to define for slope materials are the friction angle and the coefficients of restitution.

In rockfall simulations, the normal restitution coefficient (RN) typically ranges between 0.3 and 0.5, while the tangential restitution coefficient (RT) usually falls between 0.8 and 0.95. The lower sections of the slope are often covered with vegetation and soft soils, whereas the upper sections consist of bedrock and asphalt. However, even minor adjustments to the restitution coefficients can lead to significant variations in simulation outcomes. For example, a slope segment with an RN of 0.4 will behave quite differently from the same segment with an RN of 0.5. Engineers are generally more familiar with the concept of the friction angle, which can be specified for each slope segment with reasonable confidence.

Figure 5.4.1 demonstrates how four distinct materials have been assigned to the slope, reflecting real-world conditions similar to the study site. The asphalt material is readily available in the software's material library, while the properties of the other three materials—Bowen & Bewel, Pitea & Clayton, and Clean Hard Bedrock (Hock)—are derived from established tables that best match the site's actual conditions. These values were initially used in the analysis but were later refined through back analysis of a previous rockfall event. The back analysis is considered satisfactory when the simulation results align with approximately 80% of the observed event in terms of trajectories, runout, bounce height, and total kinetic energy. This calibration process ensures the model's reliability for future predictions.

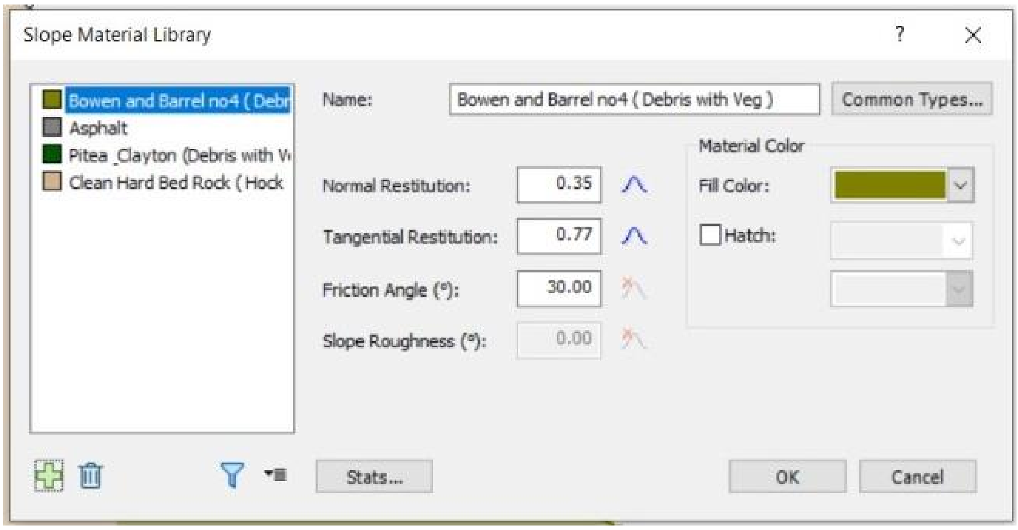


Figure 5.4.1 Demonstration of Adding slope material values in Rockfall 2 for developing 2D Profile of Slope

5.5 Starting Location of Rockfall

The starting point for rockfall simulations can be defined anywhere on or above the slope surface. Rocfall 2 offers advanced functionality, allowing users to specify the initial position using either a single point (referred to as a "point seeder") or a polyline (referred to as a "line seeder"). When using the line seeder, the software randomly selects starting positions along the defined polyline for each rock. This approach is particularly useful when the exact origin of the rockfall is uncertain, but a plausible range of starting points can be identified, such as along the upper sections of the slope.

In this case study, the line seeder method was employed because the precise location of the initial rockfall detachment is unknown, though it is likely situated in the upper region of the hill where the rock mass is fractured. The line seeder feature also allows users to specify the number of rocks to be simulated. For this analysis, 10,000 rock blocks were selected to ensure statistical validity, meaning that increasing the number of simulations beyond this point would not significantly alter the results. The line seeder can be manually defined on the slope or by inputting coordinate values. Typically, the upper sections of the hill are chosen as starting points, as rocks in these areas possess the highest potential energy and are most susceptible to detachment. This approach ensures a realistic and comprehensive simulation of rockfall behavior.

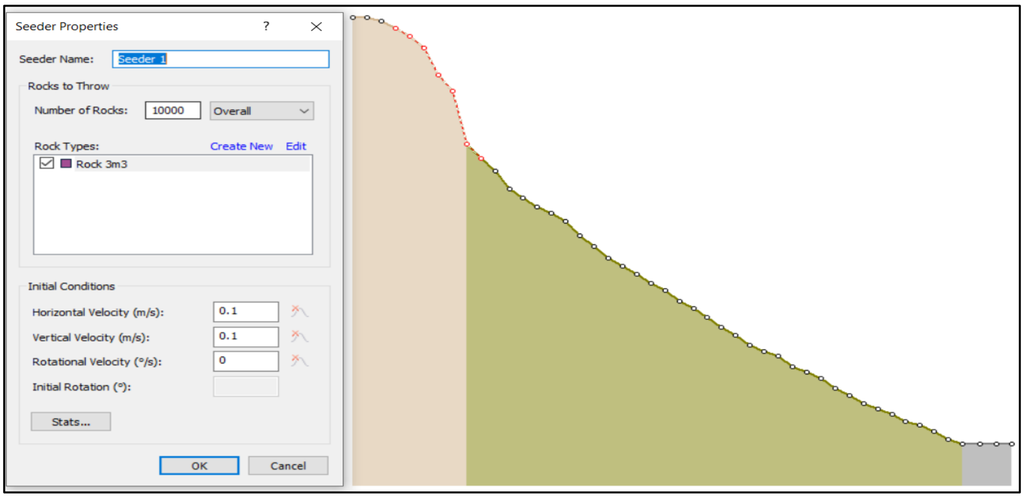


***Figure 5.5.1** Location of Line seeder in the slope profile made in Rockfall 2*

5.6 Graph Barrier and collectors

In Rocfall 2D, **Graph Barriers** and **Collectors** are essential tools for analyzing and interpreting rockfall simulation results.

Graph Barriers are virtual boundaries placed along the slope to track and record the kinetic energy, velocity, and bounce height of rocks as they pass through specific points. These barriers help engineers assess the impact energy and behavior of falling rocks at critical locations, such as near infrastructure or protective measures. By analyzing data from graph barriers, users can evaluate the effectiveness of mitigation strategies and identify high-risk zones.

Collectors, on the other hand, are horizontal or inclined surfaces defined at the base of the slope or other strategic locations to capture and count the number of rocks that reach specific areas. They provide valuable information about the runout distance, distribution, and frequency of rockfall events. Collectors are particularly useful for designing protective structures, such as barriers or catchment areas, and for assessing the potential hazard to downstream assets.

Together, graph barriers and collectors enhance the accuracy and practicality of rockfall simulations, enabling engineers to make informed decisions for risk assessment and mitigation planning.

From this tool we will be mainly focusing on the impact along height and translational kinetic energy as this help us in trial and error method for calculating values for the barrier design

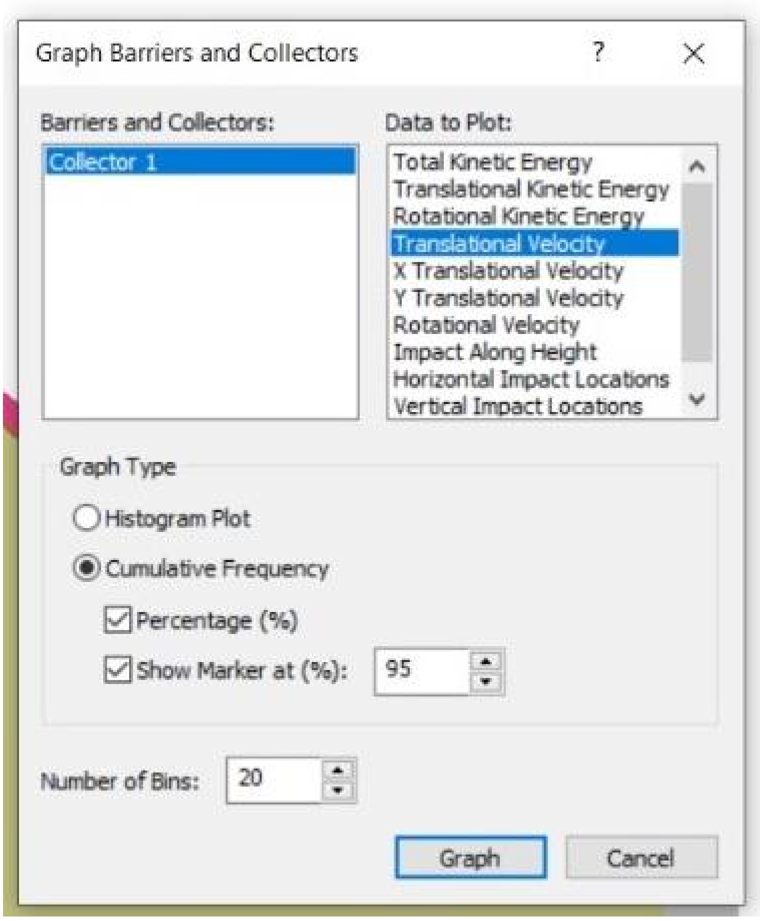


Figure 5.6.1 *Demonstration of plotting data for collector in Rockfall 2 for developing 2D Profile of Slope*

5.7 Results and Discussions

Rocfall 2 provides a range of outputs to support statistical analysis and the development of mitigation strategies. Among these outputs, the software generates plots that display key parameters such as the **maximum velocity**, **kinetic energy**, and **bounce height** of rocks across the entire slope profile. These plots, referred to as "envelopes" in the software, are crucial for identifying high-risk areas where protective measures may be needed. Additionally, Rocfall 2 produces histograms that illustrate the distribution of velocity, kinetic energy, and bounce height at various points along the slope. These outputs help engineers analyze rockfall behavior in detail and design effective corrective actions to reduce risks.

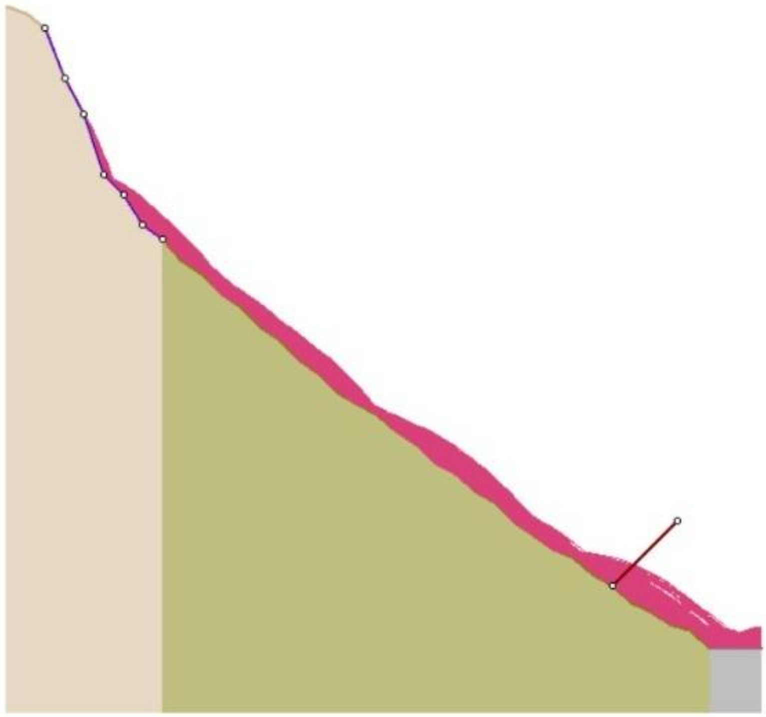


Figure 0.1 *Simulated Model IN Rockfall 2*

One of the most critical outputs for validating a back-analysis model in rockfall simulations is the **rock endpoints graph**. This graph is arguably the most significant single piece of data generated by the software, as it reveals the final resting positions of the rocks. These endpoints are crucial for determining whether the parameters used in the simulation accurately replicate past rockfall events. The distribution of rock endpoints is displayed graphically within the program, providing a clear visual representation of where the rocks come to rest.

In this case study, a past rockfall event from November 2023 was used as a reference for back analysis. During this event, a 3 m^3 rock detached from the hillside and stopped on the asphalt road. To validate the back-analysis model, it was essential that at least some of the 10,000 simulated rock blocks reached the asphalt road, mirroring the real-world outcome. The results showed that the selected parameters for the model exhibited a reasonable degree of similarity to the historical event, as illustrated in figure 5.7.2 . This alignment between the simulated and observed endpoints confirms the model's accuracy and reliability for future predictions.

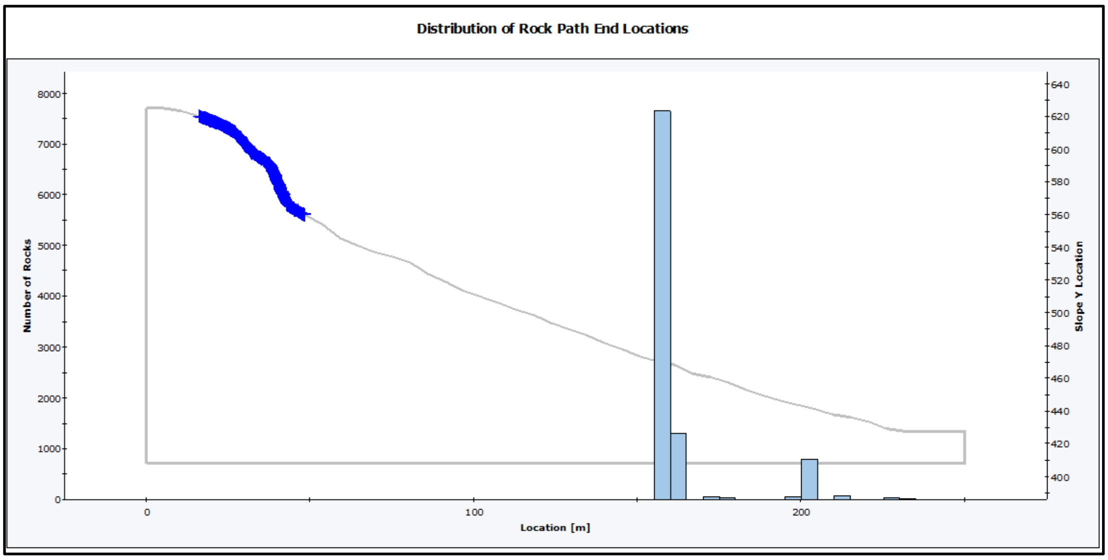


Figure 5.7.2 *Statistical distribution of the end points along the slope in Rockfall 2*

The graph generated using the Rocfall 2 software illustrates the statistical distribution of rockfall endpoints along the slope. The X-axis represents the horizontal distance in meters, while the left Y-axis indicates the percentage of rocks that come to rest at each coordinate. The tallest bar and the steepest initial drop in the cumulative curve highlight a critical zone around 100 meters from the detachment point, suggesting a key area for potential mitigation measures. Additionally, approximately 18 to 22 blocks are captured within the asphalt road zone. This outcome confirms that the data is sufficient to refine the parameters outlined in **Table 5.7.1**, enabling accurate rockfall forecasting for recent events.

Using these values we will continue to design our barrier in which we will focus on the parameters mentioned above . We are going to use trial and error method to find the values that are near to the likely scenario in that are focusing primarily on translational velocity , impact height and total kinetic Energy.

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** 5.7.1 Final parameters determined through Back Analysis used for forecasting rockfall.*

6. Conclusion:

In conclusion, the comprehensive analysis conducted using the QPROTO plugin, combined with the integration of spatial data in QGIS, provides a robust framework for assessing rockfall hazards and delineating risk zones in forested slopes. By deriving the energy line angle from the forested scenario graph in Figure 8, we ensured that the analysis accurately reflects the conditions of the study area, thereby enhancing the reliability of the results. The calculations based on slope inclination, forest coverage, and block volume, were derived using the second percentile of the cumulative distribution function (CDF).

This approach ensures that the values represent a lower-bound reference, accounting for the majority of potential scenarios, as the actual energy angles are likely to exceed these estimates in 98% of cases. This conservative methodology is critical for risk assessment, as it provides a cautious and reliable basis for understanding the behavior of rockfalls, including their trajectories, energy dissipation, and runout distances.

The creation of polygons in QGIS to represent risk zones further refines the analysis by translating quantitative data into actionable spatial information. By analyzing rockfall endpoint clusters and overlaying susceptibility values, we were able to identify high-risk areas where mitigation efforts are most urgently needed. The use of tools such as kernel density estimation, buffer analysis, and convex hulls allowed for the precise delineation of these zones, ensuring that the resulting risk maps are both accurate and intuitive. These maps serve as a vital tool for decision-makers, enabling them to prioritize resources and implement targeted mitigation strategies, such as protective barriers, slope stabilization, or land-use planning, in the most vulnerable areas.

Overall, this integrated approach—combining QPROTO's quantitative analysis with QGIS's spatial capabilities—provides a comprehensive understanding of rockfall hazards in forested slopes. By adopting a conservative methodology and focusing on key parameters such as energy line angles, susceptibility, and endpoint distributions, the analysis ensures that potential risks are not underestimated. This, in turn, supports the development of effective and sustainable mitigation strategies, ultimately enhancing the safety and resilience of communities, infrastructure, and ecosystems in rockfall-prone regions. The insights gained from this study not only contribute to the field of rockfall hazard assessment but also highlight the importance of leveraging advanced tools and methodologies to address complex geotechnical challenges in a proactive and informed manner.

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