ABSTRACT

Landslide risk assessment is the proves of making a decision recommendation on whether existing risks are tolerable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation phases.

The objective of this work is to perform a Quantitative Rockfall Risk Assessment of the Amalfi costal road. The adopted procedure for the analysis of the rockfall risk in the study is articulated in three different steps, each of them with peculiar purposes.

The first step consists on the localization, in the topographical map at 1:5000 scale, of both source and deposition areas of rockfalls occurred in the past, in order to identify the areas historically affected by events of different magnitude. The rockfalls have been localized thanks to the information recoverable in the database.

The second step is devoted to the rockfall frequency analysis by the establishment of the Frequency-Magnitude relationships in the threatened area.

Finally, the third step is aimed to quantitatively assess: i) the impact probability of the vehicle travelling along the Amalfi coastal road by using the Conditional Consequence Model proposed by Roberds (2005); ii) the rockfall risk using the Rockfalls Hazard Rating System Method (Pierson et al., 1990) and the risk to persons travelling on the highway along the Amalfi Coastal road by adopting either the Quantitative Risk Assessment (Fell et al., 2005).

From frequency analysis some conclusion may be obtained. In some years there are no recorded events, because of the lack of data or the loss of the documentary source. The majority of the data come from the last 20 years, because in this period the record of the events is increase thank to the birth of new local authority and to highest attention at the rockfalls. The maximum of the records corresponds to the period of road construction and in summer. This is due to greater records because of the flow of tourists in the area, as the Amalfi Coast an important tourist destination of the Campania Region, while the maximum in November would be actually representative the events that occurred in this period. Stone falls of small size usually do not capture public attention and remain unnoticed. These small events, however, have little impact.

The method of RHRS is applied to nearly 33,91 km of Amalfi road. The total road has been divided in 164 sections each characterized by different values of categories that has been considered in the method. Once identified, all the sections have been rated relative to each other to determine which presented the greatest risk to the public. This method of score consists in a relative risk assessment and the objective is the achievement of a numerical value that indicates the level of risk for each section of the road in order to make their comparison.

From the total rating calculated for each section with the RHRS method it can observe that the most of the sections in which there are events recorded in the database have a high rating that is larger than 360 points, this is due to the frequency that affects greatly the final results.

In the total rating the frequency has a lot of influence in the result which it does make sense. Low rockfall frequency values are associated to low rating of the RHRS in all the studied sections. Besides the frequency, the Percent of Decision Sight Distance, Average Vehicle Risk, Slope Height, and volume of rockfall are most influencing factors.

The method can be applied in mapping the rockfall risk thus allowing the identification of the most dangerous stretches that require protection works. The results provide a rational way to take decisions on where and how to spend construction funds for rock slope projects.

The conditional probability distribution for consequence if a mass of a particular magnitude remains in the roadway has been determined for each roadway section.

The Conditional Consequence (Vulnerability) Model consists of calculating the probability distribution for the number and severity of casualties for each particular hazard, that is represent the volume of rock fall remaining in the road.

With the Quantitative Risk Assessment (QRA) method it estimated the risk to persons travelling on the highway and assessed the tolerability of this risk against the tolerable risk criteria, considering only direct impact falls. The total probability of death for the person most at risk due to direct impact is $2{,}43 \cdot 10^{-5} / annum$. This value is within the tolerable limit.

The two methods, Rockfall Hazard Rating System and the Quantitative Risk Assessment method, can be compared. The values of the risk for each section are consistent with the frequency of the rockfalls and with the visibility of the fallen debris that controls the avoidance of the vehicle collision.

CHAPTER 1

1. Introduction

Landslides are one of the most serious natural hazards in terms of victims and economic impact, besides their interaction with many other natural phenomena. Hence, both the scientific community and the organisms entrusted with the safeguard of the population are strongly committed to reduce their effects.

Landslides, defined as the movement of a mass of rock, debris or earth down a slope (Cruden, 1991), can be triggered by a variety of external stimulus, such as intense rainfall, earthquake shaking, water level change, storm waves or rapid stream erosion that cause a rapid increase in shear stress or decrease in shear strength of slope-forming materials. In addition, as development expands into unstable hillslope areas under the pressures of increasing population and urbanization, human activities such as deforestation or excavation of slopes for road cuts and building sites, etc., have become important triggers for landslide occurrence. Landslides have caused large numbers of casualties and huge economic losses in mountainous areas of the world. The most disastrous landslides have claimed as many as 100,000 lives (Li and Wang, 1992). In the United States, landslides cause an estimated US$1–2 billion in economic losses and about 25–50 deaths annually, thus exceeding the average losses due to earthquakes (Schuster and Fleming, 1986). Li and Wang (1992) conservatively estimated that in China the number of deaths caused by landslides totalled more than 5000 during the 1951–1989 period, resulting in an average of more than 125 deaths annually, and annual economic losses of about US$500 million. Social and economic losses due to landslides can be reduced by means of effective planning and management.

These approaches include: (a) restriction of development in landslide-prone areas, (b) use of excavation, grading, landscaping, and construction codes, (c) use of physical measures (drainage, slope geometry modification, and structures) to prevent or control landslides, and (d) development of warning systems (Slosson and Krohn, 1982; Schuster and Leighton, 1988; Schuster, 1996). Schuster and Leighton (1988) estimated that these methods could reduce landslide losses in California by more than 90%. Slosson and Krohn (1982) stated that enactment of these approaches had already reduced landslide losses in the City of Los Angeles by 92– 97%. However, in spite of improvements in hazard recognition, prediction, mitigation measures, and warning systems, worldwide landslide activity is increasing. This trend is expected to continue in the 21st century for the following reasons (Schuster, 1996):

- increased urbanization and development in landslide-prone areas;
- continued deforestation of landslide-prone areas;
- increased regional precipitation caused by changing climatic patterns.

To address the landslide problem, governmental agencies need to develop a better understanding of landslide hazard and to make rational decisions on allocation of funds for management of landslide risk. However, it is widely accepted that the landslide problem is dominated by uncertainty. This uncertainty arises at all stages in the resolution of the problem, from site characterization to material property evaluation to analysis and design and consequence assessment (Morgenstern, 1997). Recent advances in risk analysis and risk assessment are beginning to provide systematic and rigorous processes to formalize slope engineering practice and enhance slope management (Fell and Hartford, 1997). In recent years, risk analysis and assessment has become an important tool in addressing uncertainty inherent in landslide hazards.

Landslide hazard and *landslide risk* analyses can be carried out, and the results can be expressed, either quantitatively or qualitatively. Quantitative estimates use numerical values or ranges of values, while qualitative estimates use relative terms such as high, moderate and low. Both quantitative and qualitative estimates can be based on either objective (statistical or mathematical) estimates or subjective (professional judgmental or assumptive) estimates, or some combination of both. No standard definitions exist for relative qualitative terms. Therefore, to avoid ambiguity, such terms must be defined with reference to quantitative values or ranges of values.

Quantitative estimates may be no more accurate than qualitative estimates. The accuracy of an estimate does not depend on the use of numbers. Rather, it depends on whether the components of *landslide hazard* and *landslide risk* analyses have been appropriately considered; and on the availability, quality and reliability of required data. The decision whether to carry out and report the results of a *landslide analysis* quantitatively or qualitatively also depends on how the adopted level of landslide safety is expressed and the requirements of the Authority.

Generally, for a large area where the quality and quantity of available data are too meagre for quantitative analysis, a qualitative risk assessment may be more applicable; while for site specific slopes that are amenable to conventional limit equilibrium analysis, a detailed quantitative risk assessment should be carried out.

This study concerns the quantitative risk assessment of rockfall hazard in the territory of Amalfi coast, in particular in the principal communication road of this study area. The quantitative assessment has been chosen for the reasons described above.

CHAPTER 2

2. Methods for landslide risk assessment

The landslide “risk assessment” which is a component of a larger process, generally named “risk management”, aimed at “risk control” (Australian Geomechanics Society 2000).
First of all it must be observed that “risk assessment” is often used by different Authors to mean different things. For example, Fell, Hartford (1997) include both “risk estimation” and “risk evaluation” under this definition (Figure 2.1). The former is essentially based on hazard identification (landslide classification; extent and travel distance of landslide; rate of movement and so on), consequence analysis (elements at risk and their vulnerability estimation) and frequency analysis (qualitative or quantitative analysis based on historical data and triggering factors). Risk estimation is, therefore, obtained by a suggested formula which makes it possible to integrate the hazard identification with the frequency and consequence analyses. Once this process is concluded, risk evaluation calls for policy maker decisions regarding risk acceptability or treatment as well as priorities to be set, according to a complex and, sometimes, iterative procedure which must take into account both technical and socio-economic aspects. At the end of this procedure (risk assessment) and taking into account the selected option (risk acceptance or avoidance, likelihood or consequence reduction) a treatment plan aimed at risk control is set up as the final stage of what the Authors call the “Risk management process”. A similar framework is proposed by Ho et al. (2000), even if some differences arise in comparing their scheme (Figure 2.2) with the one briefly discussed above. Limiting the attention to the topic of interest, it is evident that risk assessment defined in Figure 2.2 is equivalent to “risk analysis” as in Fell, Hartford (1997), including only the questions related to the occurrence of landslides and their consequences.
It must be observed that the scientific literature suggests different methods which, in turn, introduce factors that do not always have the same meaning or the same difficulty in their estimation (Einstein 1997; Dai et al. 2002). So, once again, some considerations are necessary to outline the risk assessment theory and the efforts to be made for its application in common practice.

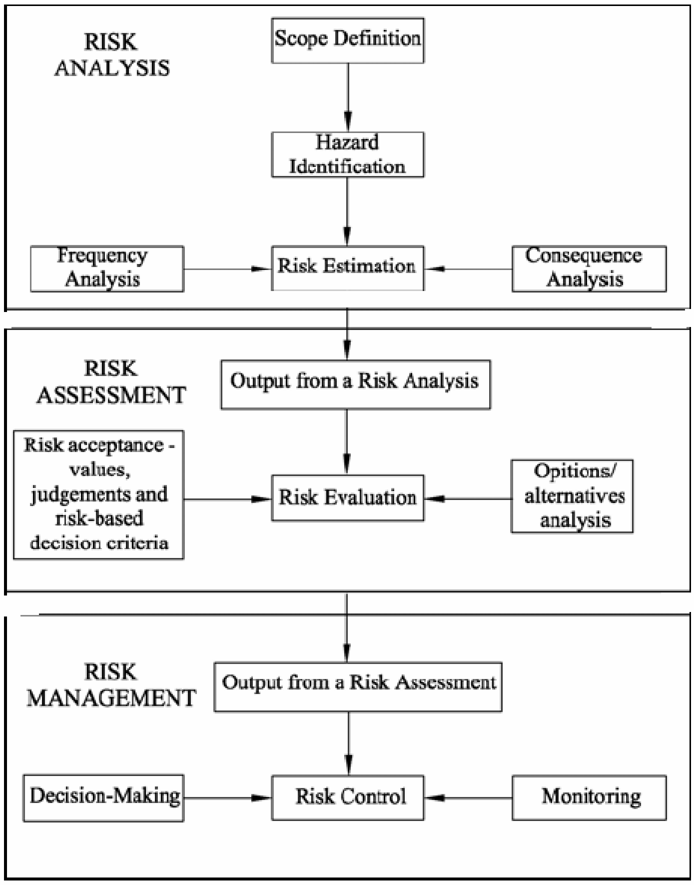


Figure 2.1: Risk management process (after Fell, Hartford 1997)

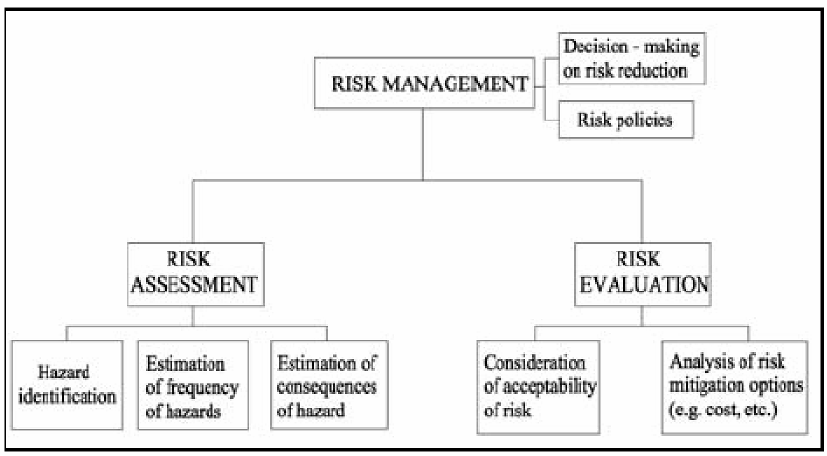


Figure 2.2: Risk management framework (after Ho et al. 2000)

All the proposed methods are based on a formula where occurrence and consequences of landslides are closely combined. The first formula is the one put forward by Varnes (1984) which was adopted by the United Nations during the International decade for natural disasters prevention. According to the Author, risk assessment can be obtained by the equation:

$$R = (H \times V) \times E = R_s \times E$$

where each term is accurately defined in the UNDRO document (1991), which is aimed at providing definitions and meanings easily understood from political, social, technical and economical points of view. Particularly, the document indicates that:
Natural Hazard (H) means the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon.
Elements at risk (E) means the population, properties, economic activities, including public services, etc., at risk in a given area.
Vulnerability (V) means the degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude. It is expressed on a scale from 0 (no damage) to 1 (total loss).
Specific risk (R_S) means the expected degree of loss due to a particular natural phenomenon. It may be expressed by the product of H multiplied by V.
Total risk (R) means the expected number of lives lost, injured persons, damage to property, or disruption of economic activity due to a particular natural phenomenon, and is therefore the product of specific risk (R_S) and elements at risk (E).
After the paper of Varnes, many other methods and developments were proposed; an interesting overview of the subject can be obtained referring to Einstein (1988, 1997), Fell (1994), Fell, Hartford (1997), Leroi (1997). In particular, Einstein (1988) suggests adopting the expression:

$$\text{Risk} = \text{Hazard} \bullet \text{Potential worth of loss}$$

where the hazard represents the probability that a natural phenomenon (danger), geometrically and mechanically characterized, occurs within a given period of time. According to the Author, the danger can be an existing one, such as creeping slope, or it can be a potential one such as rockfall; the characterization of the danger, however, does not include any forecast.
Compared to Varnes, Einstein turns his attention to a better definition of the natural phenomenon generating the risk. An analogous attention is clearly shown by Fell (1994) who furnishes the following expression for risk estimation:

$$R = \sum \left(E \times R_S \right) = \sum \left(E \times P \times V \right)$$

Most of the terms included in this equation are similar to those included in the UNDRO document, even if it must be observed that the hazard is considered as the probability (P) that an instability phenomenon, with a known magnitude (the volume in a broad sense), will occur within a period of time (generally one year). The trend to take the geomechanical aspects of the landslide into account is moreover confirmed by the paper of Fell, Hartford (1997) and by the landslide risk management concepts and guidelines produced by the Australian Geomechanics Society (2000), where detailed indications are furnished even with reference to the estimation of the terms included in formulas more advanced than equation above described.
Finally, with reference to the last Author mentioned above, it must be observed that also Leroi (1997) places his attention on a better definition of landslide characteristics, being the risk expressed

$$R = f\left[P_e, P_t, P_e^{'}\left(MVT, I, X, Y, Z, t, D, V, a, \%, \$\right)\right]$$

where the terms mean:
P_e: Probability in space (source zone);
P_t: Probability in time;
P'_e: Probability in space (propagation area);
MVT: Type of movement;

I=intensity
X, Y, Z: Coordinates of the movement;
t: Date of the movement;
D: Displacement;
V: Velocity;
a: Acceleration;
%: Percentage of damage;
$: Cost of the damage.

This brief summary of the most popular equations points out that the solution of a real problem requires, first of all, the choice of the formula to be adopted. After that, the way of estimating risk factors must be considered according to methods and suggestions analyzed in the paragraphs below.

2.1. Risk factors

Several proposals are available in the scientific literature to estimate risk factors; some considerations are, therefore, necessary in order to avoid misunderstandings or mistakes in risk assessment.
In view of the complexity of the topic under discussion, these considerations will deal with what the Author considers to be the simplest of the previously described formula, i.e. the first equation, which requires answers to apparently simple questions such as:

- *which* potentially damaging phenomenon can occur?
- *where* will the phenomenon take place?
- *when* will the phenomenon occur?
- *what* will the consequences (for population and properties) be?

The several possible answers to these questions are then discussed starting from the intensity (or magnitude) of the phenomenon which strongly affects the natural hazard, the elements at risk and their vulnerability.

2.1.1. Intensity

Estimating the intensity of a natural phenomenon, within a given period of time and area, is one of the most difficult issues to be addressed, as it is strictly related to the history of the landslide or the potentially unstable area.
It is not surprising, therefore, that this factor is defined in different ways by different Authors (Figure 2.3) who associate the intensity to the velocity of the body mass (Cruden, Varnes 1996), to the volume of the instabilized mass (Fell 1994) or consider it as the kinetic energy of the soil mass (Sassa 1988). Other definitions are available in the scientific literature, although each one presents advantages and, at the same time, disadvantages from a theoretical and/or practical point of view (Hungr 1981; DRM 1990).
For instance, the approach proposed by Cruden and Varnes is very useful for distinguishing different typologies of natural phenomena within a large area, especially when the return period to take into account is neglected and the worst expected situation is considered.
On the other hand, the approach of Fell (1994), probably the most valid from a theoretical point of view, requires a thorough knowledge of the landslide history which can be obtained by geological and geotechnical investigations, at small and large scale, to be supported by slope evolution models and in situ monitoring. Moreover, difficulties can arise even if such investigations and studies have been carried out.
Finally, several difficulties can also arise when, according to Sassa (1988), the kinetic energy of the instabilized mass is referred to. Actually, this criterion, easy to be applied in some cases calls for a thorough knowledge of the whole area potentially involved by the instability phenomena, including local factors such as topography and roads which can largely affect the run-out distance of soil masses.

$R = H \cdot E \cdot V$

I

Velocity (Cruden, Varnes 1996)

Class	Description	velocity
7	Extremely rapid	5 m/s
6	Very rapid	3 m/min
5	Rapid	1.8 m/hr
4	Moderate	13 m/mounth
3	Slow	1.6 m/year
2	Very slow	16 mm/year
1	Extremely slow	<16 mm/year

Volume (Fell 1994)

Magnitude	Description	Volume (m^3)
7	Extremely large	$> 5\cdot10^6$
6	Very large	$1\cdot10^6 \div 5\cdot10^6$
5	Medium-large	$2.5\cdot10^5 \div 1\cdot10^6$
4	Medium	$5\cdot10^4 \div 2.5\cdot10^5$
3	Small	$5\cdot10^3 \div 5\cdot10^4$
2.5	Very small	$5\cdot10^2 \div 5\cdot10^3$
2	Extremely small	$< 5\cdot10^2$

Energy (Sassa 1988)

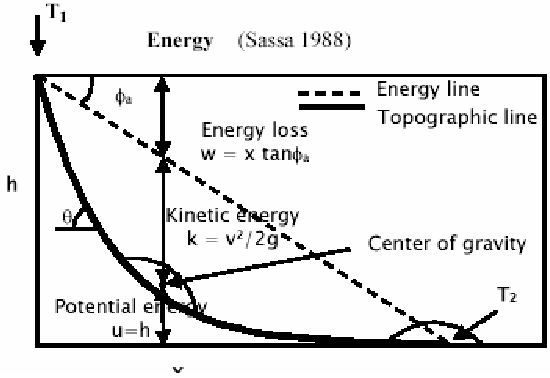


Figure 2.3. Some definitions of landslide intensity

2.1.2. Hazard analysis

According to the framework for landslide risk assessment approached by Fell et al. (2005), the hazard analysis is the process of identification and characterisation of the potential landslides together with evaluation of their corresponding frequency of occurrence.

Landslides (danger) characterisation

Landslide characterisation requires an understanding of the slope processes and the relationship of those processes to geomorphology, geology, hydrogeology, failure and slide mechanics, climate and vegetation. From this understanding it will be possible to:

- classify the types of potential landsliding: the classification system as proposed by Varnes (1984) or modified by Cruden and Varnes (1996) forms suitable systems. A site may be affected by more than one type of landslide hazard: slow rotational earth slides on the site, very rapid rockfall and debris flows from above the site.
- Assess the physical extent of each potential landslide, including the location, areal extent and volume involved.
- Assess the likely initiating event, the physical characteristics of the materials involved, such as shear strength, pore pressure; and the slide mechanics. The latter is critical to understanding the pre and post failure behaviour of the landslide.
- Estimate the resulting anticipated travel distance, travel path, depth and velocity of movement if failure occurs, taking account of the slide mechanics, and estimating the probability that the land slide will effect the area in which the element at risk is located ($P_{T:L}$).
- Identify possible pre-failure warning signs which may be monitored.

A list of possible landslides (dangers) should be developed. Consideration must be given to hazards located off site as well as within the site as it is possible for landslides both upslope and downslope to effect the elements at risk. It is vital that full range of hazards (e.g. from small, high frequency events to large, low frequency events) be properly characterised and considered in the risk analysis. Often the risk is dominated by the smaller, more frequent landslides. The effects of proposed development in an area should also be considered, as these effects may alter the nature and frequency of potential hazards.

Frequency analysis

The frequency of landsliding can be expressed in terms of (IUGS 1997):

- The number of landslides of a certain characteristic that may occur in a study area per years.
- The probability of a particular slope experiencing landsliding in a given period, e.g. a year.
- The driving forces exceeding the resistant forces in probability or reliability terms, with the frequency of occurrence being determined by considering the annual probability of the critical pore water pressures being exceeded in the analysis.
- This should be done for each type of landslide which has been identified and characterised as affecting the analysis.

There are several ways of calculating frequency (IUGS 1997):

(1) Historic data within the area study, or area with similar characteristics, e.g. geology, geomorphology.
(2) Empirical methods based on correlations in accordance with slope instability ranking systems.
(3) Use of geomorphologic evidence coupled with historical data
(4) Relationship to the frequency and intensity of the triggering event, e.g. rainfall or earthquake.
(5) Direct assessment based on expert judgment, which may be undertaken with reference to a conceptual model.
(6) Modelling the primary variable, e.g. piezometric pressures versus the triggering factors, coupled with varying levels of knowledge of geometry and shear strength.
(7) Application of probabilistic methods, taking into account the uncertainty in slope geometry, shear strength, failure mechanism, and piezometric pressures.
(8) Combinations of the above methods.

In practice it may be appropriate and advisable to use more than one method for the analysis. It is important to express the probability of sliding in frequency (per annum) terms, because quantitative risk acceptance criteria for loss of life are usually expressed in annum terms. Financial analysis of damage also usually requires frequency as an input. The authors have a preference for estimating frequencies quantitatively. This given a uniformity of outcomes in quantified terms, allows risk to be compared with quantitative acceptance criteria, and allows comparison with risks from other hazards with which the parties involved may be able to associate.

In the Author’s opinion, the deterministic approach is particularly efficient when it is based on geological and geological-structural maps, cover maps, geomorphological maps and so on. Thanks to these maps it is possible indeed to obtain very accurate landslide inventory maps where the potentially unstable areas, including the zone where the first failure may occur and the zones which may be involved by the instabilized mass, are clearly defined.

Statistical methods, generally developed through G.I.S. database and other processes, essentially perform logistic regression to derive a predictive model for landslide susceptibility.

Statistical methods can also be used for the hazard assessment of fast landslides, as shown by Hungr et al. (1999) who analyze the rock-fall occurrence along the main transportation corridors of South-Western British Columbia (Figure 2.4). Of course, this kind of approach is useful when reliable historical data are available, even if the next instability phenomenon cannot be localized in advance or is difficult to predict. Finally, “Hazard Assessment” can also be defined using the so called “physically based models” which try to analyze the local stability conditions on the basis of topographic, vegetation, hydrological and slope stability models.

Many of these models are available in the literature such as, for example, those proposed by Montgomery, Dietrich (1994), Wu, Sidle (1995), Pack et al. (1998). From a theoretical point of view, these methods are particularly satisfying because they can combine, when used in connection with a GIS database, the spatial and temporal occurrence of the potentially damaging phenomena. However, their use must be carefully evaluated to avoid mistakes due to a variety of reasons, such as the underestimation of the role played by unconsidered local factors as well as the use of simplified models (e.g. the infinite slope stability analysis) which frequently don’t reproduce the real situation.

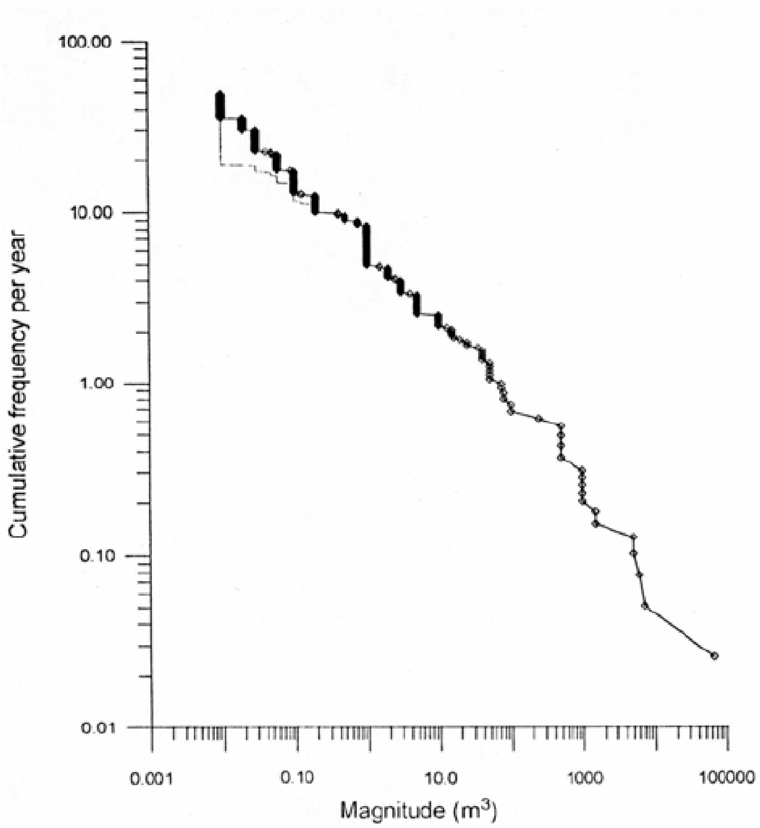


Figure 2.4. Falls along the British Columbia Highway (after Hungr et al. 1999)

2.1.3. Consequence analysis

Consequence analysis involves:

(a) Identifying and quantifying the elements at risk including property and persons.

(b) Assessing temporal spatial probabilities for the elements at risk ($P_{S:T}$).

(c) Assessing vulnerability of the elements at risk, in terms of property damage ($V_{prop:T}$) and loss of life/injury ($V_{D:T}$) as appropriate.

This has to be done for each of the landslide hazards. Other consequences may include loss of reputation of the owner and geotechnical engineers, consequential costs (e.g. a road is closed for some time affecting businesses along the road), political repercussions and adverse social and environmental affects.

Most of these may not be readily quantifiable, but may need to be systematically considered, in consultation with owners and factored into the decision-making process as appropriate, at least for comprehensive risk analysis studies.

Elements at risk

The elements at risk include the population, building, engineering works, infrastructure, vehicles, environmental features and economic activities which are in the area affected by the hazard. In practical terms, this usually means on the landslide, and/or in the area onto which the landslide may travel if is occurs. It may also include property immediately adjacent to or upslope of the landslide, if the property or its value would be affected by landsliding and infrastructure which may include powerlines, water supply, sewage, drainage, roads and communication facilities. The population at risk includes persons who live, work, or travel through the area affected by the hazard.

It would be usual to categorise vehicles into cars, trucks and buses, because of the different number of persons likely to be in the vehicles.

The elements at risk are likely to be dependent on the nature of the landslide hazard e.g. for a boulder fall, or debris flow at a given site.

Probability of landslide reaching the element at risk ($P_{T:L}$)

The probability of the landslide reaching the element at risk depends on the relative location of the element at risk and the landslide source, together with the path the landslide is likely to travel below the source. It is a conditional probability between 0 and 1.

(a) For buildings which are located on the source landslide $P_{T:L}$ =1.

(b) For buildings or persons located below the source landslide and in the path of the resulting travel of the landslide, $P_{T:L}$ is calculated taking account of the travel distance of the landslide, and the element at risk.

(c) For vehicles or persons in vehicles, or persons walking in the area below the source landslide on the path of the resulting travel of the landslide, $P_{T:L}$ is calculated taking account of the travel distance of the landslide, and the path to be followed by the vehicle or person. Whether the vehicle or person is in the path at the time of the landslide is taken account through the temporal spatial probability ($P_{S:T}$).

Temporal spatial probability ($P_{S:T}$)

The temporal spatial probability is the probability that the element at risk is in the area affected by the hazard at the time of its occurrences. It is a conditional probability, and is between 0 and 1.

(a) For buildings on or in the path of the landslide, the temporal spatial probability is 1.

(b) For a single vehicle which passes below a single landslide, it is the proportion of time in a year when it will be in the path of the landslide.
(c) For all the vehicles which pass below a single landslide, it is the proportion of time in a year when a vehicle will be in the path of the landslide. Where there are a number of potential landslides in any years, e.g. rockfalls, the calculation is more complicate.
(d) For persons in a building, it is the proportion of time in a year which the persons occupy the building (0-1,0). This is likely to be different for each person.

For person in vehicles, the temporal spatial probability will be as for (b) and (c). However it may vary for say one person in a car, and four persons in a car.

For some situations it will be necessary to build into the calculation of temporal spatial probability, whether the persons at risk may have sufficient warning to evacuate from the area affected by the hazard. Persons on a landslide are more likely to observe the initiation of movement and move off the slide than those who are below a slide falling or flowing onto them.

Each case should take into account the nature of the landslide including its volume, and velocity, monitoring results, warning signs, evacuation system, the element at risk, and the mobility of the persons.

Vulnerability ($V_{prop:T}$) and ($V_{D:T}$)

Vulnerability is the degree of loss (or damage) to a given element, or set of elements, within the area affected by the hazard. It is a conditional probability, given the landslide occurs and the element at risk is on or in the path of the landslide. For property, it is expressed on a scale of 0 (no loss or damage) to 1 (total loss or damage) for property.

For person it is usually the probability (between 0 and 1) that given the person is on or in the path of the landslide, the person is killed. It may also include the probability of injury.

Factors that most affect vulnerability of property include:

- the volume of the landslide in relation to element at risk;
- the position of the element at risk;
- the magnitude of landslide displacement and relative displacement within the landslide;
- the velocity of landslide movement.

Landslides which move slowly may cause little damage, other that structures which are on the boundaries of the landslide and hence experience differential displacement.

Factors which most affect the vulnerability of persons include:

- the velocity of landsliding. Person are more likely t be killed by a rapid landslide than slow regardless of the landslide volume;
- landslide volume. Persons are more likely to be buried or crushed by large landslides than small;
- whether the persons are in the open, or in a vehicle or building;
- if they are in a building, whether the building collapses upon impact by the landslide, and the nature of the collapse.

Persons who are buried by a landsliding mass have a high vulnerability.

2.2. Risk estimation

2.2.1. Risk calculation

The risk can be presented in a number of ways:

(a) the annual risk (expected value) in which the probability of occurrence of the danger is multiplied by the consequences summed over all the hazards. This is expressed as damage per annum; or potential loss of lives per annum;
(b) frequency-consequence (f-N) pairs
(c) cumulative frequency-consequence plots.

In the recent years, procedures for Quantitative Risk Assessment (QRA) have been developed and tested. The framework for the use of QRA for landslides and engineered slopes has been recently reviewed by Fell et al. (2005).
Quantitative Risk Assessment (QRA) has become an indispensable tool for management of landslide hazard and for planning risk mitigation measures.

The level of risk can be calculated as a probabilistic equation. The following expression represents the annual risk for property:

$$R_{(prop)} = P_{(L)} \times P_{(T:L)} \times P_{(S:T)} \times V_{(prop:S)} \times E$$

Where:

$R_{(prop)}$ is the annual loss of property value

$P_{(L)}$ is the frequency of the landsliding

$P_{(T:L)}$ is the probability of the landslide reaching the element at risk

$P_{(S:T)}$ is the temporal spatial probability of the landslide reaching the element at risk

$V_{(prop:S)}$ is the vulnerability of the element at risk to the landslide event

E is the element at risk (the value or net present value of the property).

The annual probability that a particular person may lose his/her life $P_{(LOL)}$ can be calculated from:

$$P_{(LOL)} = P_{(L)} \times P_{(T:L)} \times P_{(S:T)} \times V_{(D:T)}$$

Where $V_{(D:T)}$ is the vulnerability of the person to the landslide event, and $P_{(L)}$, $P_{(T:L)}$ and $P_{(S:T)}$ are as defined above.

2.2.2. Qualitative risk assessment

Qualitative risk analysis uses descriptors to describe the frequency of landsliding and the consequences. This may comprise tools such as risk rating systems and risk scoring schemes.
In some cases, the approach may be adopted whereby qualitative risk analysis can facilitate a "first-pass" screening of the more dominant hazards in a given site so that attention can be focused on the more deserving areas or hazards, which can be evaluated in detail using quantitative methods. Qualitative risk assessment may also be used to examine whether a given landslide hazard is posing a significant risk to life and the need for prompt risk reduction measures in order to safeguard public safety, without the need for elaborate quantitative analysis. In general, qualitative risk assessment must be undertaken critically and preferably subject to expert review to avoid spurious outcomes and for it to be value-adding.
The following figure 2.5 gives an example adapted from AGS (2000), where the likelihood incorporates the frequency of landsliding, the probability of the landslide reaching the element at risk and temporal spatial probability. The consequences incorporate the vulnerability and the value of the element at risk.
Combining likelihood with consequence results in a risk matrix divided into 5 classes from very low risk (VL) to very high risk (VH).

Qualitative measures of likelihood of landsliding		
Level	**Descriptor**	**Description**
A	Almost certain	The event is expected to occur
B	Likely	The event will probably occur under adverse conditions
C	Possible	The event could occur under adverse conditions
D	Unlikely	The event could occur under very adverse circumstances
E	Rare	The event is conceivable but only under exceptional circumstances
F	Not credible	The event is inconceivable or fanciful
	Qualitative measures of consequences to the resource	
1	Catastrophic	Resource is completely destroyed or large scale damage occurs requiring major engineering works for stabilization
2	Major	Extensive damage to most of the resource, or extending beyond site boundaries requiring significant stabilization
3	Medium	Moderate damage to some of the resource, or significant part of the site requires large stabilization works
4	Minor	Limited damage to part of the resource, or part of the site requires some reinstatement/stabilization works
5	Insignificant	Little damage

Qualitative risk analysis matrix – classes of risk to resource					
	Consequences to the resource				
Likelihood	Catastrophic	Major	Medium	Minor	Insignificant
Almost certain	VH	VH	H	H	H
Likely	VH	H	H	M	L-M
Possible	H	H	M	L-M	VL-L
Unlikely	M-H	M	L-M	VL-L	VL
Rare	M-L	L-M	VL-L	VL	VL
Not credible	VL	VL	VL	VL	VL

Legend – VH: very high risk; H: high risk; M: moderate risk; L: low risk; VL: very low risk

Figure 2.5: Example of qualitative terminology for use in assessing risk to property – adapted from AGS (2000).

AGS (2000) recommended that those schemes are only applicable to consideration of risks to property. Other schemes may be developed by the geotechnical risk analyst in consultation with the owners or other stakeholders where appropriate, to best suit a given problem.
Qualitative risk assessment is subject to limitations, which include potentially imprecise and subjective description of the likelihood term.

An approach to assess the qualitative risk at small scale was developed by Cascini after the slope movements in 1998, involved the territory of the Campania Region, Southern Italy, causing victims and considerable economic damage (Cascini 2003).
In compliance with Governmental requirements, four risk classes (R) were identified essentially calibrating the expected consequences. In particular the risk level was considered to be:

- Very high (R4), where human life loss and destruction of buildings, infrastructure and environmental as well as interruption of economic activities are expected;
- High (R3), where victims, functional damage to buildings and infrastructure, as well as partial interruption of economic activities are possible;
- Medium (R2), where limited damage to buildings, infrastructure and the environment may occur;
- Low (R1), where social, economic and environmental damage are of marginal relevance.

Not urbanized areas affected by a quiescent, active or potential landslide were also mapped and classified though it was not provided for by the law. According to the risk levels described above, these areas were considered worthy of different attention to be defined following the Cruden and Varnes' classification system (Figure 2.6). Particularly, the attention level was considered to be:

- Very high (A4), if the area was inside the source, transit and invasion zone of extremely rapid, very rapid or rapid landslides;
- High (A3), if it was inside a moderate or slow landslide, both active or quiescent, potentially triggered by an earthquake;
- Medium (A2), if the moderate or slow landslide was inside a not seismic area;
- Low (A1), if the area was involved in a very slow or extremely slow landslide.

Class	Description	Probable Destructive Significance	Typical velocity	Velocity (m/s)
7	Extremely rapid	Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely.	5 m/s	5
6	Very rapid	Some lives lost; velocity too great to permit all persons to escape.	3 m/min	5·10-2
5	Rapid	Escape evacuation possible; structures, possessions, and equipment destroyed.	1.8 m/hr	5·10-4
4	Moderate	Some temporary and insensitive structures can be temporarily maintained.	13 m/mounth	5·10-6
3	Slow	Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase.	1.6 m/year	5·10-8
2	Very slow	Some permanent structures undamaged by movement	16 mm/year	5·10-10
1	Extremely slow	Imperceptible without instruments; construction possible with precautions.	<16 mm/year	<5·10-10

Figure 2.6: Effects caused by landslides (after Cruden, Varnes 1996)

Risk and attention areas, whose meaning can be best clarified by observing the obtained results, were identified all over the territory on a 1:25.000 scale, essentially by producing susceptibility and vulnerability maps which were then overlapped using a simplified procedure.
Before considering the risk assessment procedure, it must be underlined that investigations and studies were mainly aimed at obtaining accurate, territory-wide, geological, geomorphological and inventory maps.
In these maps landslides, their surrounding areas, stage of slope movements and zones potentially affected by fast movements are respectively distinguished on the basis of: Varnes classification; creep evidence; a simplified version of Leroueil et al. (1996) classification and criteria analogous. All the thematic maps were produced essentially by aerial photo interpretation because of the large size of the area and the lack of time.
Starting from the landslides inventory map, the susceptibility map was then obtained on the basis of the Cruden and Varnes criterion (Figure 2.3 par 2.1.1) by identifying the intensity with the maximum expected velocity during a fixed period of time. In particular three different classes of intensity were selected (tab.3), even if no indication was furnished with reference to the return period, mainly because of the lack of knowledge on many geological and triggering factors of the inventoried phenomena.

I ≡ the highest expected velocity	
I	**Landslide types**
High	Flowslides, Rapid earth and debris flows, Rock falls
Medium	Slides and slow earth flows (Occasional reactivation and Active landslides) First failure in brittle materials
Low	Deep-Seated Gravitational (Slope) Deformation, Lateral spreads and Creep zones

Figure 2.7: Intensity classes of the landslides

An example showing the conversion of the landslide inventory maps, which essentially photographs the present situation, into susceptibility maps, indicating the worst expected scenario with reference to the soil mass velocity, is given in Figure 2.9. With reference to the vulnerability maps, all the towns (450) were analyzed, again at 1:25.000 scale, in order to obtain landuse planning maps (Fig. 25) also indicating areas which are not urbanized yet and are considered as expansion areas in the townplanning scheme.

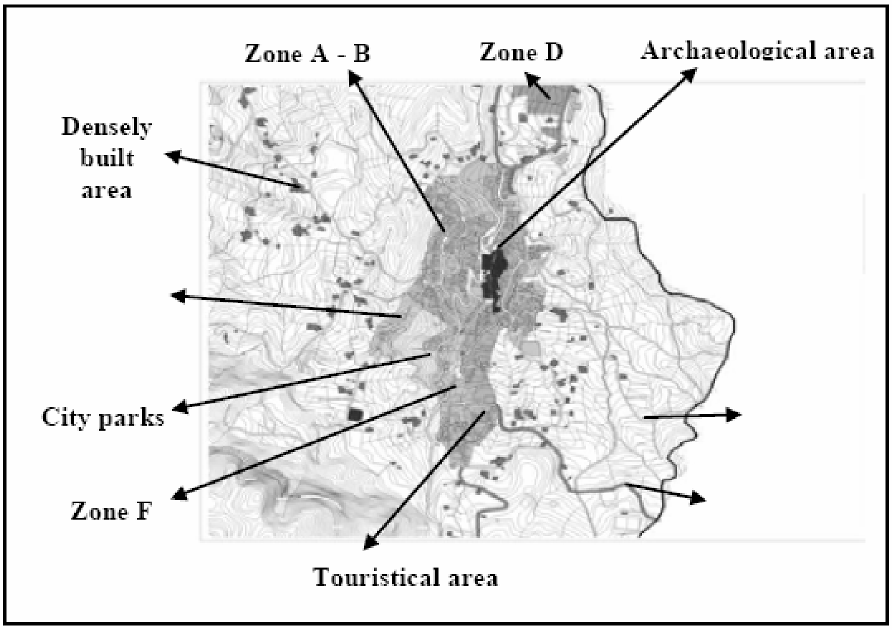


Figure 2.8: Land-use planning map

Moreover, elements at risk such as hospitals, barracks, schools and so on were identified and located. Finally, the buildings inside the landslide area were checked and damage was evaluated according to a simple classification.
Risk levels were defined according to the Varnes formula which calls for the evaluation of hazard, elements at risk and vulnerability. A concise description of the values given to these factors is furnished in Figure 2.7, pointing out that the hazard has been essentially related to the landslide intensity, while the vulnerability has been related to the phenomenon intensity, building typology and whether or not damage is present.
Overlapping the hazard and the vulnerability maps, the risk levels were, therefore, defined using the simple criterion shown in Figure 2.8.
In this way it was possible to classify the risk over the whole territory with the exception of a limited area where further investigations and studies, at a more detailed scale, were considered necessary. An example of risk map is furnished in Figure 2.9, pointing out the predominance of attention areas on risk areas.

$$R = H \cdot E \cdot V$$

I	Buiding tipology	Observed Damages	VULNERABILITY
HIGH	All	Not considered	HIGH
MEDIUM	Strategical building	Not considered	HIGH
	Common building	YES	
	Common building	NOT	MEDIUM
LOW	Strategical building	Not considered	MODERATE
	Common building	YES	
	Common building	NOT	LOW

I	HAZARD	Landslide activity
HIGH	HIGH	active
	MEDIUM	quiescent
MEDIUM	HIGH	active
	MEDIUM	quiescent
LOW	HIGH	active
	MEDIUM	quiescent

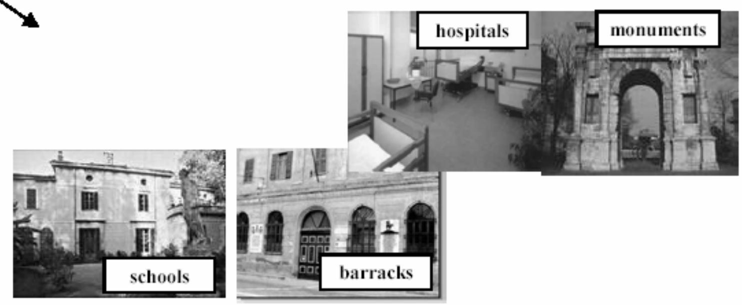


Figure 2.9: Nominal scale for hazard, element at risk and vulnerability (Cascini L.)

	I	HIGH	MEDIUM		LOW	
	HAZARD	**H**	**H**	**M**	**H**	**M**
Vulnerability	high	Hh	Hh	Mh		
	medium		Hm	Mm		
	modest				Hm	Mm
	low				Hl	Ml

R4	
R3	
R2	
R1	

Figure 2.10: Risk level evaluation (Cascini L.)

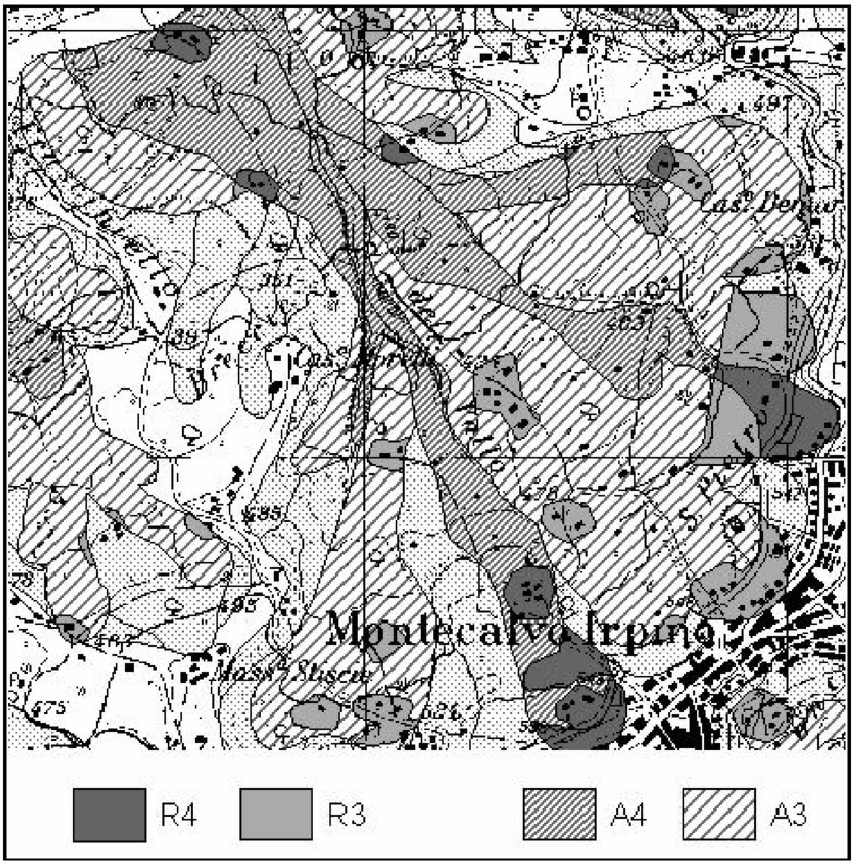


Figure 2.11: Example of risk map, Montecalvo Irpino town. (Cascini L.)

2.3. Risk assessment

2.3.1. Risk assessment process

Risk assessment involves taking the outputs from the risk analysis and comparing them against values, judgements and risk tolerance criteria to determine if the risks are low enough to be tolerable.

The process is one of making judgements, taking account of political, legal, environmental, regulatory and social factors. The decision is usually the responsibility of the owner and regulator, sometimes consulting with the affected public or stakeholders.

Non-technical clients may seek guidance from the risk analyst on whether to accept the risk, but from a legal viewpoint it is important that owner and regulator make the final decision.

Assessment of the risk may involve consideration of values such as:

(a) Property or financial loss: annualised risk cost, financial capability, impact on corporate reputation, for railways and roads, indirect costs (loss of road access) and cost benefit ratio when mitigation measures are being considered,

(b) Loss of life: individual risk to life, social risk (frequency versus number of deaths), annualised potential loss of life and when mitigation measures are being considered cost per statistical life saved.

2.3.2. Risk acceptance criteria

It is important to recognise the difference between acceptable and tolerable risk.

The *acceptable risk* is a risk which everyone impacted is prepared to accept. Action to further reduce such risk is usually not required unless reasonable practicable measures are available at low cost in term of money, time and effort.

The *tolerable risk* is a risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible, and needing to be kept under review and reduced further if possible.

Factors that affect an individual's attitude to acceptable or tolerable risk will include (adapted from AGS 2000):

- Resources available to reduce the risk
- Whether there is a real choice, e.g. can the person afford to vacate a house despite the high risk?
- The individual commitment to the property and its value relative to the individual income.
- Age and character of individual.
- Exposure the individual has experienced in the past, especially with regards to risk associated with landslides.
- Availability of insurance.
- Regulatory or policy requirements.
- Whether the risk analysis is perceived to be reliable.

There are some common general principles that can be applied when considering tolerable risk to loss of life criteria (IUG 1997):

- The incremental risk from a hazard to an individual should not be significant compared to other risks to which a person is exposed in everyday life.
- The incremental risk from a hazard should, wherever reasonably practicable, be reduced.
- If the possible loss of life from a landslide incident is high, the likelihood that the incident might actually occur should be low. This accounts for society's particular intolerance to incidents that cause many simultaneous casualties, and is embodied in societal tolerable risk criteria.
- Persons in society will tolerable higher risks than they regard as acceptable, when they are unable to control or reduce the risk because of financial or other limitations.
- Higher risks are likely to be tolerated for existing slopes than for planned projects, and for workers in industries with hazardous slopes, e.g. mines, than for society as a whole.

These principles are common with other dangers such as Potential Hazardous Industries (PUI) and dams. The IUGS considered that there are other principles that are applicable to risk from slopes and landslides:

- Tolerable risks are higher for landslides on natural hillslides than those from engineered slopes.
- Once a natural slope has been placed under monitoring, or risk mitigation measures have been executed, the tolerable risks approach those of engineered slopes.
- Tolerable risks may vary from country to country, as well as within a country, depending on historic exposure to landslide hazard, and the system of ownership and control of slopes and natural landslides hazards.

There are no universally established individual or societal risk acceptance criteria for loss of life due to landslides. Two important examples are following described:

- *Individual risk*

AGS (2000) suggested that the tolerable risk criteria shown Figure 2.9 might reasonably be concluded to apply to engineering slope. It suggested that acceptable risks are usually considered to be one order of magnitude smaller than these tolerable risks.

Situation	Suggested tolerable risk for loss of life
Existing engineered slopes	10^{-4}/annum person most at risk
	10^{-5}/annum average of persons at risk
New engineered slopes	10^{-5}/annum person most at risk
	10^{-6}/annum average of persons at risk

Figure 2.9: AGS (2000) suggested tolerable risk criteria

- *Societal risk*

The application of social risk to life criteria is to reflect the reality that society is less tolerant of events in which a larger number of lives are lost in a single event, than of the same number of lives are lost in a larger number of separate events.
The use of cumulative *FN* curves to reflect this is not universal. An example which has been trialled on an interim basis to assist landslide risk management of natural hillside hazards is shown in Figure 2.10.

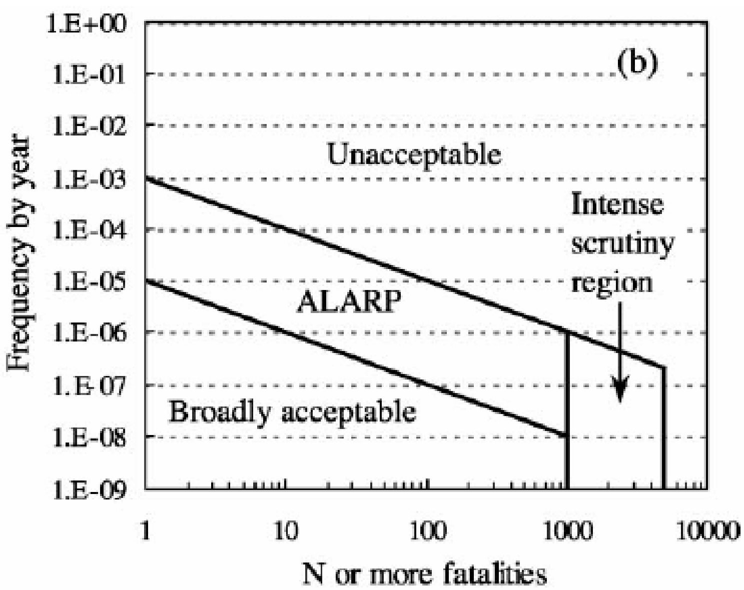


Figure 2.10: Interim societal risk tolerance criteria (Geotechnical Engineering Office 1998)

The *FN* diagram has proven to be useful tools for describing the meaning of probabilities and risks in the context of other risk with which society is familiar. The diagram is a graphical representation of the number of fatalities (N) plotted against the cumulative frequency (F) of N or more fatalities, on a log-log scale. An F-N curve will provide information on the full range of credible fatal scenarios and the corresponding likelihood of occurrence.

Whether such quantitative criteria as the example given are acceptable in principle will depend on the country and legal system in which the landsliding is being considered.
Estimates of risk are inevitably approximate, and should not be considered as absolute values. This is best understood by allowing for the uncertainty in the input parameters, and in reporting the risk analysis outcomes.
Tolerable risk criteria are themselves not absolute boundaries. Society shows a wide range of tolerance to risk, and the risk criteria are only a mathematical expression of the assessment of general societal opinion.
It is often useful to use several measures of tolerable risk criteria, individual and societal risk, and measures such as cost to save a life and maximum justifiable cost if risk mitigation is being considered.
Finally, it must be recognised that QRA is only one input to the decision process. Owner, society and regulators will also consider political, social and legal issues in their assessments and may consult the public affected by the hazard.

2.4. Rockfall hazard rating system method

The method of RHRS is a method for the analysis of rockfall risk along roads and motorways and it provides a rational way to make informed decisions on where and how to spend construction funds. It developed by Pierson et al (1990) at the Oregon State Highway Division and modified subsequently by Budetta (2004).
Unlike the other methodology described above for the qualitative risk assessment, this method of score consists in a relative risk assessment, not absolute, and the objective is the achievement of a numerical value that indicates the level of risk. It is considered useful to perform a comparative assessment of risk areas.
Through implementation of the RHRS, management obtains detailed information and a uniform process that can help them make practical decisions on where to allocate money for rock- slope projects.
This method contains some limitations. The rating is partially subjective, in fact some categories require a subjective evaluation, while others can be directly measured and then scored. Although the slope evaluation process is as straightforward as possible, there is still a range of values that a particular slope could receive. This depends to a large degree on the abilities of the raters and how consistently they interpret and apply the rating criteria.

CHAPTER 3

3. Objectives and Methodologies

The objective of this work is to perform a Quantitative Rockfall Risk Assessment of the Amalfi costal road. The adopted procedure for the analysis of the rockfall risk in the study is articulated in three different steps, each of them with peculiar purposes.
The first step consists on the localization, in the topographical map at 1:5000 scale, of both source and deposition areas of rockfalls occurred in the past, in order to identify the areas historically affected by events of different magnitude. The rockfalls have been localized thanks to the information recoverable in the database.
The second step is devoted to the rockfall frequency analysis by the establishment of the Frequency-Magnitude relationships in the threatened area.
Finally, the third step is aimed to quantitatively assess: i) the impact probability of the vehicle travelling along the Amalfi coastal road by using the Conditional Consequence Model proposed by Roberds (2005); ii) the rockfall risk using the Rockfalls Hazard Rating System Method (Pierson et al., 1990) and the risk to persons travelling on the highway along the Amalfi Coastal road by adopting either the Quantitative Risk Assessment (Fell et al., 2005).

3.1. The Conditional Consequence Model

The conditional probability distribution for consequence if a mass of a particular magnitude remains in the roadway will be determining for each roadway section.
As it is note, to assess risks, not just hazards, requires that the "consequences" associated with any particular set of landslide characteristics be assessed, and then be combined with the likelihood of those various sets of landslide characteristics.
Such an assessment of vulnerability can be done in various ways and to various levels of detail and approximation, depending on the particular application. For example, there is no point in assessing vulnerability in great accuracy and detail if the hazards are not assessed in similar accuracy and detail. Conversely, if the hazards are assessed accurately and in detail, then the vulnerability should also be. However, consequences are not often assessed for landslides and well-established methods are not generally available.
The Conditional Consequence (Vulnerability) Model consists of calculating the probability distribution for the number and severity of casualties for each particular hazard, that is represent the volume of rock fall remaining in the road.
Vulnerable elements or elements at risk are those objects that can be affected by landslides, in this study its are the vehicles that move along the SS163 road and its can be categorized as "non- stationary" elements at risk. The elements at risk have particular characteristics as value, dimension, location etc.
The conditional probability distribution for consequence if a mass of a particular magnitude remains in the roadway can be determined for each roadway section as follows:

$$p[C/M_R] = \sum_{alV_i} p[C/V_i, M_R] \times P[V_i/M_R]$$

where:

$p[C/M_R]$ is the conditional probability distribution for consequence C if debris of magnitude M_R remains in the roadway.
$p[C/V_i, M_R]$ is the conditional probability distribution for consequence C if debris of magnitude M_R that remains in the roadway causes event V_i.
$P[V_i/M_R]$ is the conditional probability that debris of magnitude M_R that remains in the roadway will cause event V_i.
V_4 is the event of a vehicle impacting debris remaining in the roadway.
V_5 is the event of a vehicle not impacting debris remaining in the roadway but being in an accident anyway (e.g. due to avoidance or distraction).
V_6 is the event of a follow-on accident due to events V_4 or V_5.
The Figure 3.1 shows the flow diagram of the consequences if debris remains in roadway.

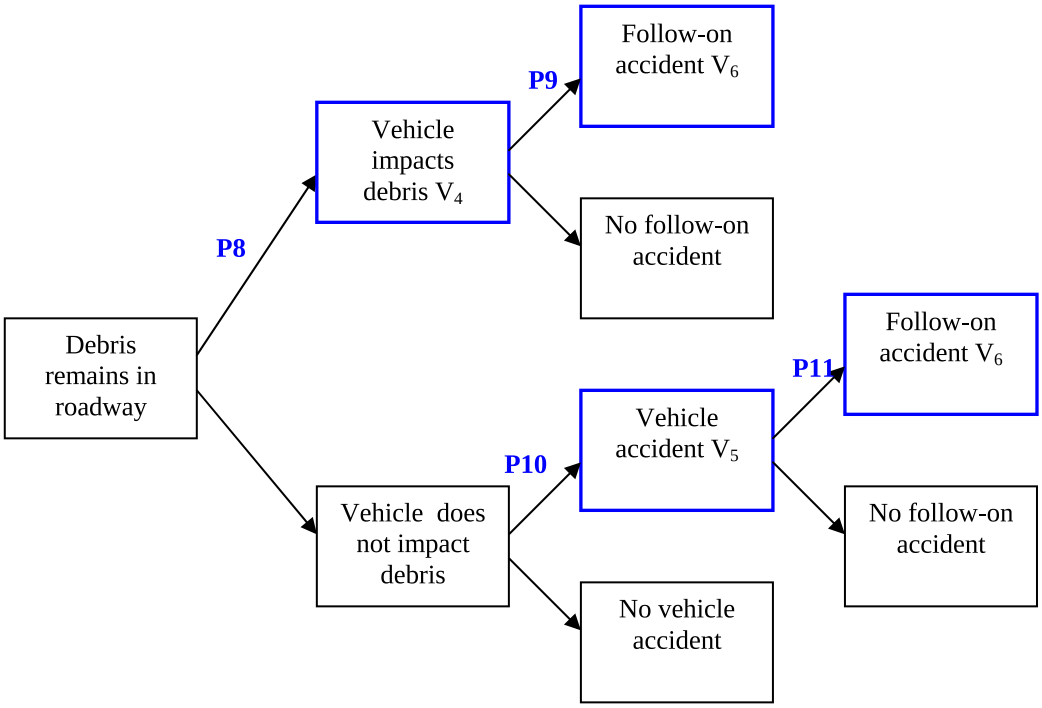


Figure 3.1: The flow diagram of the consequences

3.2 The Quantitative Risk Assessment

With the Quantitative Risk Assessment (QRA) method it will estimating the risk to persons travelling on the highway and assesses the tolerability of this risk against the tolerable risk criteria, considering only direct impact falls.

3.3. The Rockfall Hazard Rating System

3.3.1. The original RHRS method

In order to assess the exposition to the risk associated with rockfalls, and to prioritize budget allocations for maintenance and remediation works, the Oregon Department of Transportation (USA) has developed a classification scheme, designed specifically for motorway cuts, the Rockfall Hazard Rating System (Pierson et al., 1990; National Highway Institute, 1993; Scesi et al., 2001), to identify slopes which are dangerous and require urgent remedial work or further study.
The RHRS provides a rational way for an agency to make informed decisions on where and how to spend construction funds.
The six steps in the process are summarized below (Pierson et al., 1990):

1. Slope Inventory - Creating a geographic database of rockfall locations.
2. Preliminary Rating - Grouping the rockfall sites into three, broad, manageably sized categories as A, B, and C slopes.
3. Detailed Rating - Prioritizing the identified rockfall sites from the least to the most hazardous.
4. Preliminary Design and Cost Estimate – Adding remediation information to the rockfall database.
5. Project Identification and Development – Advancing rockfall correction projects toward construction.
6. Annual Review and Update - Maintaining the rockfall database.

The first step in this process is to make an inventory of the stability conditions of each slope so that they can be ranked according to their rockfall hazard. Then, the rockfall areas identified in the inventory are ranked by scoring the categories.
The RHRS uses two types of slope ratings: the preliminary rating performed during the initial slope inventory, and the detailed rating. The preliminary rating eliminates many slopes from any further consideration. This staged approach is the most efficient and cost effective way to implement the RHRS and is especially useful where agencies have responsibility for many slopes with a broad range of rockfall potential.
The purpose of the detailed rating is to numerically differentiate the risk at the identified sites. Once rated, the sites can be sorted and prioritized on the basis of their scores. These lists are then used to help make decisions on where safety projects should be initiated.
The detailed rating, shown in the Figure 3.1, includes 8 categories by which slopes are evaluated and scored. The category scores are then totalled. Slopes with higher scores present the greater risk. These 8 categories represent the significant elements of a rockfall section that contribute to the overall hazard.
The rating criteria scores increase exponentially from 3 to 81 points so the risk increases from left to right. An exponential scoring system provides a rapid increase in score that distinguishes the more hazardous sites.
This method contains all the elements regarding the rockfall hazard (slope height, geologic character, volume of rockfall/block size, climate and presence of water on slope and rockfall

history) and the vehicle vulnerability (ditch effectiveness, average vehicle risk, percent of decision sight distance, roadway width), so the resulting total score assesses the degree of the exposition to the risk along roads.
In succession, the categories of the RHRS method are described.

<table>
<tr><th colspan="3">Category</th><th>Points 3</th><th>Points 9</th><th>Points 27</th><th>Points 81</th></tr>
<tr><td colspan="3">Slope height</td><td>7,5 m</td><td>15 m</td><td>22,5 m</td><td>> 30 m</td></tr>
<tr><td colspan="3">Ditch effectiveness</td><td>Good catchment</td><td>Moderate catchment</td><td>Limited catchment</td><td>No catchment</td></tr>
<tr><td colspan="3">Average vehicle risk (% of time)</td><td>25%</td><td>50%</td><td>75%</td><td>100%</td></tr>
<tr><td colspan="3">Decision sight distance</td><td>Adequate (100%)</td><td>Moderate (80%)</td><td>Limited (60%)</td><td>Very limited (40%)</td></tr>
<tr><td colspan="3">Roadway width</td><td>13,20 m</td><td>10,80 m</td><td>8,40 m</td><td>6 m</td></tr>
<tr><td rowspan="4">Geologic characteristics</td><td rowspan="2">Case 2</td><td>Structural condition</td><td>Discontinuous joints, favourable orientation</td><td>Discontinuous joints, random orientation</td><td>Discontinuous joints, adverse orientation</td><td>Continuous joints, adverse orientation</td></tr>
<tr><td>Friction</td><td>Rough, irregular</td><td>Undulating</td><td>Planar</td><td>Clay infilling or slickensided</td></tr>
<tr><td rowspan="2">Case 1</td><td>Structural condition</td><td>Few differential erosion features</td><td>Occasional erosion features</td><td>Many erosion features</td><td>Major erosion features</td></tr>
<tr><td>Difference in erosion rates</td><td>Small</td><td>Moderate</td><td>Large</td><td>Extreme</td></tr>
<tr><td colspan="3">Volume of rockfall per event</td><td>2,3 m^3</td><td>4,6 m^3</td><td>6,9 m^3</td><td>9,2 m^3</td></tr>
<tr><td colspan="3">Rockfall History Category</td><td>Few falls</td><td>Occasional falls</td><td>Many falls</td><td>Constant falls</td></tr>
</table>

Figure 3.2: Summery sheet of Rockfall Hazard System (Pierson et al., 1990)

- ✓ **Slope height category.**

This category evaluates the risk associated with the height of a slope. The height measured is the vertical height, not the slope distance. The slope height measurement is to the highest point from which rockfall is expected. If rockfall is generated from the natural slope above the cut slope, the measurement should include both the cut height and the additional vertical height on the natural slope to the rockfall source. This category is directly measured and scored. The higher a rock is located on a slope, the more potential energy it has. The increased energy potential is a greater hazard, and thus a higher rating is given as the slope height increases.

- ✓ **Ditch Effectiveness Category.**

The effectiveness of a ditch is measured by its ability to prevent falling rock from reaching the roadway. Many factors must be considered in evaluating this category. The reliability of the result depends heavily on the rater's experience. Ditch Effectiveness is a subjective category. The risk associated with a particular rock slope section is dependent on how well the ditch is performing in capturing rockfall. When little rock reaches the roadway, no matter how much rockfall is released from the slope, the danger to the public is low and the score assessed is low. Conversely, if rockfall events are rare occurrences but the ditch is nonexistent, the resulting hazard is greater and a higher score is assigned this category.

- ✓ **Average Vehicle Risk (AVR) Category.**

Category 3 represents the spatial probability of occurrence of a vehicle in the rockfall hazard zone. This average vehicle risk (AV R) is obtained by:

$$AVR = \frac{ADT \times SL}{PSP} \times 100\%$$

where *ADT* is the average traffic per day (vehicle/day); *SL* is the hazard zone length (km) and *PSP* is the posted speed limit (km/h).
A rating of 100% means that, on average, one vehicle can be expected to be within the hazard zone 100% of the examined time. A high AV R (>100%) indicates that, at any particular time, more than one vehicle is present within the hazard zone (Pierson et al., 1990).

- ✓ **Percent of decision sight distance**

Category 4 measures the percentage of reduction in the decision sight distance (DSD). DSD represents the length of road (in km) a driver needs in order to make a complex or instantaneous decision. The percent of decision sight distance (PDSD) is obtained by:

$$PDSD = (ASD / DSD) \times 100\%$$

where *ASD* is the actual sight distance (km).
Sight distance is the shortest distance that a six-inch object is continuously visible to a driver along a roadway. Decision sight distance (DSD) is the length of roadway, in feet, required by a driver to perceive a problem and then bring a vehicle to a stop.
The DSD is critical when obstacles on the road are difficult to see, or when unexpected or unusual manoeuvres are required. Throughout a rockfall section the sight distance can change appreciably. Horizontal and vertical highway curves along with obstructions such as rock outcrops and roadside vegetation can severely limit a driver's ability to notice and react to a rock in the road. In addition, poor visibility during stormy weather may cause a reduction in sight distance.

- ✓ **Roadway Width Category**

The available manoeuvring width, along a road to avoid a boulder is measured perpendicular to the motorway centreline from one edge of the pavement to the other and includes the shoulders. If a driver notices rocks in the road, or rocks falling, it is possible for the driver to react and take evasive action to avoid them. The more room there is for this manoeuvre, the greater the likelihood the driver will successfully miss the rock without hitting some other roadside hazard or oncoming vehicle. The measurement represents the available manoeuvring width of the roadway.

- ✓ **Geologic character**

As can be seen from Table ..., the original method shows two cases of conditions that cause rockfalls. Case 1 includes slopes or cuts in which joints, bedding planes, or other discontinuities are the dominant structural features. Rock friction on a discontinuity is governed by the characteristics of the rock material as well as by the surface roughness and properties of any infilling. In Case 2 differential erosion or oversteepened slopes are the dominant conditions that control rockfalls. The different rates of erosion within a slope directly relate to the potential for a future landslide. For these two cases, the scoring criteria are qualitatively fixed and could cause doubts for users on which score to assign.

- ✓ **Volume of Rockfall per Event Category**

In some rockfall events, the failure is comprised of an individual block, ,n others cases, the event may include many blocks of differing sizes.
Larger blocks or volumes of falling rock produce more total kinetic energy and greater impact force than smaller events. In addition, the larger events obstruct more of the roadway reducing the possibility of safely avoiding the rocks. In either case, the larger the blocks or volume the greater the hazard created and thus the higher the assigned score.

- ✓ **Climate and Presence of Water on Slope Category**

The effects of precipitation, freeze/thaw cycles, and water flowing on the slope are evaluated with this category according to the following benchmark criteria.
Water and freeze/thaw cycles both contribute to the weathering and movement of rock materials and a reduction in overall slope stability. This category evaluates the amount of precipitation and duration of freezing periods, because these are measurable quantities that are directly related to features that cause rockfall. In addition, water flowing on a slope promotes erosion and thus is also considered in this category.

- ✓ **Rockfall History Category**

This category rates the historical rockfall activity at a site as an indicator of future rockfall events. Typically, the frequency and magnitude of past events is an excellent indicator of the type of events to expect. The rockfall history directly represents the known rockfall activity at the site. This information is an important check on the potential for future rockfalls.

3.3.2. The modified RHRS method

Several studies in Southern Italy tested the applicability of RHRS and the method showed some critical aspects (Budetta and Panico, 2002). For example, some categories are described qualitatively and may lead to appraisals too much subjective and rough and, therefore, not sensitive enough. This is particularly true for the categories: ditch effectiveness, geologic character, climate and presence of water on slope and rockfall history. In the modified method, developed by Budetta, the ratings for the categories ditch effectiveness, geologic characteristic, volume of rockfall/block size, climate and water circulation and rockfall history have been rendered easier and more objective.
The following Figure 3.2 shows the categories in the modified method.

Category	**Points 3**	**Points 9**	**Points 27**	**Points 81**
Slope height	7,5 m	15 m	22,5 m	> 30 m
Ditch effectiveness	Good catchment: properly designed according to updates of Ritchie's ditch design chart + barriers	Moderate catchment: properly designed according to updates of Ritchie's ditch design chart	Limited catchment: wrongly designed	No catchment
Average vehicle risk (% of time)	25%	50%	75%	100%
Decision sight distance	Adequate (100%)	Moderate (80%)	Limited (60%)	Very limited (40%)
Roadway width	21,5 m	15,50 m	9,50 m	3,50 m
Slope Mass Rating (SMR)	80	40	27	20
Block size	30 cm	60 cm	90 cm	120 cm
Boulder volume	26 dm^3	0,21 m^3	0,73 m^3	1,74 m^3
Volume of rockfall per event	2,3 m^3	4,6 m^3	6,9 m^3	9,2 m^3
Annual rainfall and freezing periods	h=300mm or no freezing periods	h=600mm or short freezing periods	h=900mm or long freezing periods	h=1200mm or long freezing periods
Rockfall frequency	1 per 10 years	3 per years	6 per years	9 per years

Figure 3.3: Summery sheet of modified Rockfall Hazard System (Budetta 2004)

The main modifications regard the introduction of Slope Mass Rating by Romana (1985, 1988, 1991) improving the estimate of the geologic characteristics, of the volume of the potentially unstable blocks and the underground water circulation. Other modifications regard the scoring for the categories "decision sight distance" and "road geometry", while the categories "Average Vehicle Risk" and "Slope height" are the same as the original method.
For these categories, the Italian National Council's standards (Consiglio Nazionale delle Ricerche-CNR) have been used (CNR, 1980). The method must be applied in both the traffic

directions because the percentage of reduction in the decision sight distance greatly affects the results. The modified categories are described in detail below.

- ✓ **Ditch effectiveness**

In estimating the ditch effectiveness, the factors to be considered are: (i) slope height and angle; (ii) ditch width, depth, and shape.
In the original method this ability is estimated qualitatively. As can be seen from Figure 3.3, in the modified method references are to updates of Ritchie's ditch design chart (Ritchie, 1963) proposed by Fookes and Sweeny (1976) and Whiteside (1986). Furthermore, references are made to protection measures (barriers, rock catch fences, wire meshes, etc.) on slopes impending over roads.

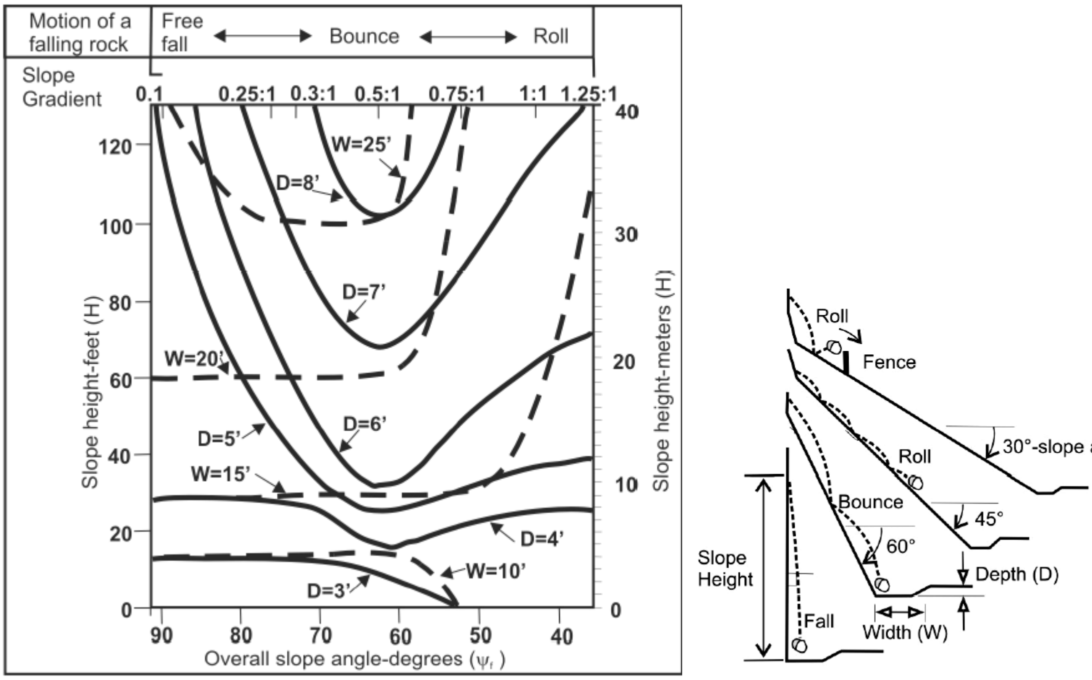


Figure 3.4. Modified Ritchie's design chart to determine required width (W) and depth (D) of rock catch ditches in relation to height (H) and slope angle (Y_f) of hillslope (after Whiteside, 1986)

- ✓ **Percent of decision sight distance (PDSD)**

Because DSD for USA roads is calculated differently as to Italian roads, in the modified method the Italian National Council standards have been used (Ferrari and Giannini, 1975; CNR, 1980). This is best summarized in Figure 3.4.
In the modified method, actual sight distances (ASD) in the two traffic directions should be evaluated because, normally, an object will be most obscured when it is located just beyond the sharpest part of a curve.

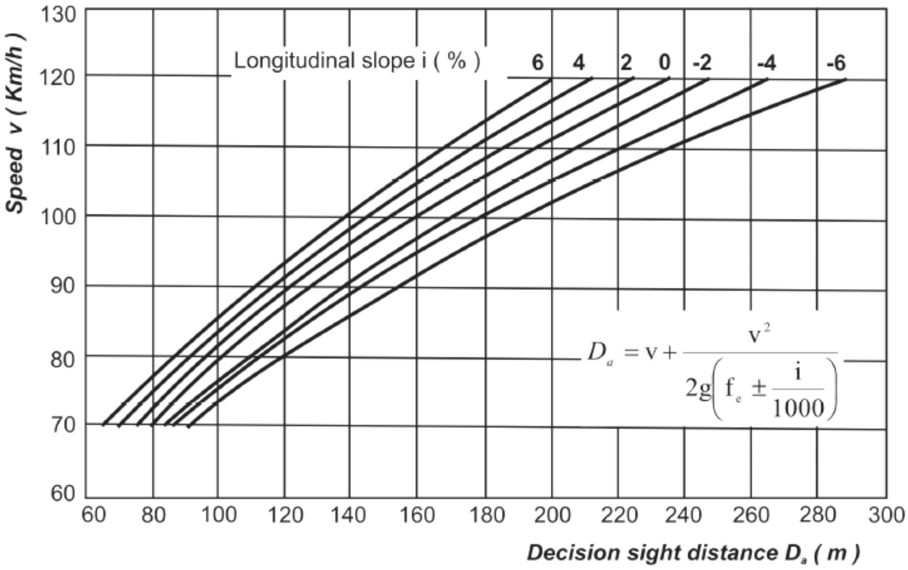


Figure 3.5: Correlations between Decision Sight Distance (D_a) and vehicle velocity (v) for different longitudinal slopes (i) (after CNR, 1980)

✓ **Roadway Width Category**

In the modified method, the Italian National Council standards have been used (road width classes). Therefore the roadway width doesn't include the shoulders that are not practical (CNR, 1980).

✓ **Geologic character**

In the modified method, the Romana's Slope Mass Rating (SMR-Romana, 1985, 1988, 1991) for slope instability hazard evaluation is introduced.

In order to assess the geologic characters that cause rockfalls some parameters are introduced to cover geomechanical features of discontinuities (attitude and shear strength of joints), failure modes (planar, wedge and/or toppling) and cut excavation methods (natural slope, smooth blasting and bulk blasting).

SMR is obtained from RMR (Rock Mass Rating by Bieniawski, 1989) by subtracting a factorial adjustment factor depending on the joint-slope relationship and adding a factor depending on the method of excavation. The basic equation is

$$SMR = RMR - (F_1 \cdot F_2 \cdot F_3) + F_4$$

where F_1 is a factorial depending on parallelism between joints and slope face strikes; F_2 refers to joint dip angle in the planar mode of failure, measuring the probability of joint shear strength; F_3 reflects the relationship between the slope face and joint dip; F_4 is an adjustment factor for the method of excavation.

Because weathering cannot be assessed with SMR, in certain degradable rock masses (like some marls, prevalently calcareous – marly flysch, etc.) the classification must be applied twice: for actual fresh and future weathered conditions (Romana, 1991). Another reason for which Romana's classification has been used in the modified method is to rate the joint spacing and groundwater conditions of rock masses outcropping on slopes. These parameters appear in other categories of RHRS.

- ✓ **Volume of rockfall**

In the original method there is no reference to which volume to employ, the block volume before the rockfall or that coming from the fallen boulder on the road. This specification is very important because the falling rock rarely keeps the original volume without breaking phenomena, after repeated rebounds on the slope. Consequently, in the modified method, the block volume (V_b) before rockfall has been evaluated statistically by means of the main joint sets spacing data (S_1, S_2, . . . , S_n) affecting the rockmass. For rockmass with three joint sets (the most frequent case), V_b is given by

$$V_b = \frac{(S_1 + S_2 + S_3)}{(\sin\alpha \times \sin\beta \times \sin\gamma)}$$

where α, β and γ are the angles between joint sets.

- ✓ **Block size**

This is a new category in the modified method, it is given by

$$D_b = \sqrt[3]{V_b}$$

- ✓ **Climate and presence of water on slope**

In the RHRS method these causes are qualitatively estimated because thresholds of combined triggering parameters are difficult to assign.
In the modified method, the groundwater circulation is already considered in the Romana's Slope Mass Rating (SMR) and the slopes are rated according to mean values of annual rainfalls. Areas receiving less than 600mm per year are moderate-precipitation areas. Areas receiving more than 1200mm per year are considered high-precipitation areas. Finally, for freezing periods the original rating of the RHRS has been applied.

- ✓ **Rockfall history**

In the modified method a careful data base of historical information is necessary for rating. As better rockfalls records are developed, more accurate conclusions for the rockfall potential can be made. The benchmark criteria refer to the frequency or rockfall event in a given period of time.

in this study we are referred to the original method (Rockfall Hazard Rating System, Participants' Manual, Pierson and Van Vickle 1993), even if some modifications about the type of category and the rating have been carried out.

CHAPTER 4

4. The study area

The study area is developed along the northern edge of Gulf of Salerno in Southern Italy. It include 13 Municipalities: Amalfi, Atrani, Cetara, Conca dei Marini, Furore, Maiori, Minori, Positano, Praiano, Ravello, Scala, Tramonti e Vietri sul Male.
It has a total extension of 100 km^2 with a population near 45000 inhabitants.

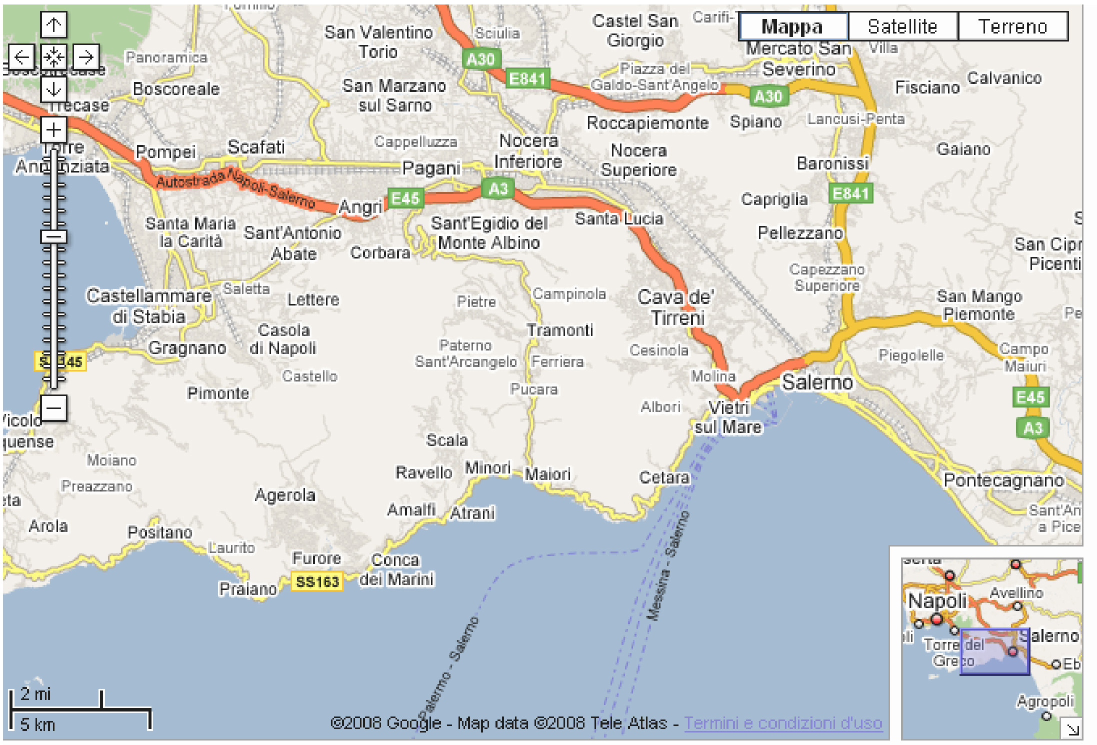


Figure 4.1: Territory of study area

4.1. Geological and geomorphological setting

The landscape is characterized by interrupted sequences of natural rock cliffs alternated by modest shelves spaced along the slope. The foot of the slopes is represented by the coast which is typical of little stretches of beach.
The Amalfi ridge is transversally oriented toward the Apennine mountain range. It's mainly composed by stratified calcareous sequences over 3000 meter composed by dolomite, dolomitic limestone and limestone from the medium Trias to upper Cretaceous age.
On the Mesozoic limestone there are incoherent deposits of vulcanic origin. They mostly consist of piroclastic deposits, which appear all over the region, forming a discontinuous cover. The greatest accumulation is found in the morphologic depressions. At the base of the slopes there is colluvium deposit made of limestone clasts within a silt-sandy matrix of piroclastic origin with uneven degree of cementation.
The geomorphologic structure is recognized by monocline structure with layers oriented toward West-NordWest. It's composed by two principal systems of faults and fractures.

The first one is extended toward NW-SE and NE-SW and it's characterized by horst and graben. The second one is oriented toward N-S and E-W and it's developed along the territory between Tramonti and Nocera Inferiore.
The rockmass is much fractured and there are many fault and joints. The steep and sub vertical cliff faces would create the movements such as rockfalls or rock avalanches, while the covers could create the debris flows

Figura 4.2: Positano-view from the sea

Figure 4.3: Maiori, rocks upcropping on the slope

Figure 4.4: Typical short stretches of beach in Maiori

Figure 4.5: Typical steep cliff faces adjacent to the Amalfi road (SS163)

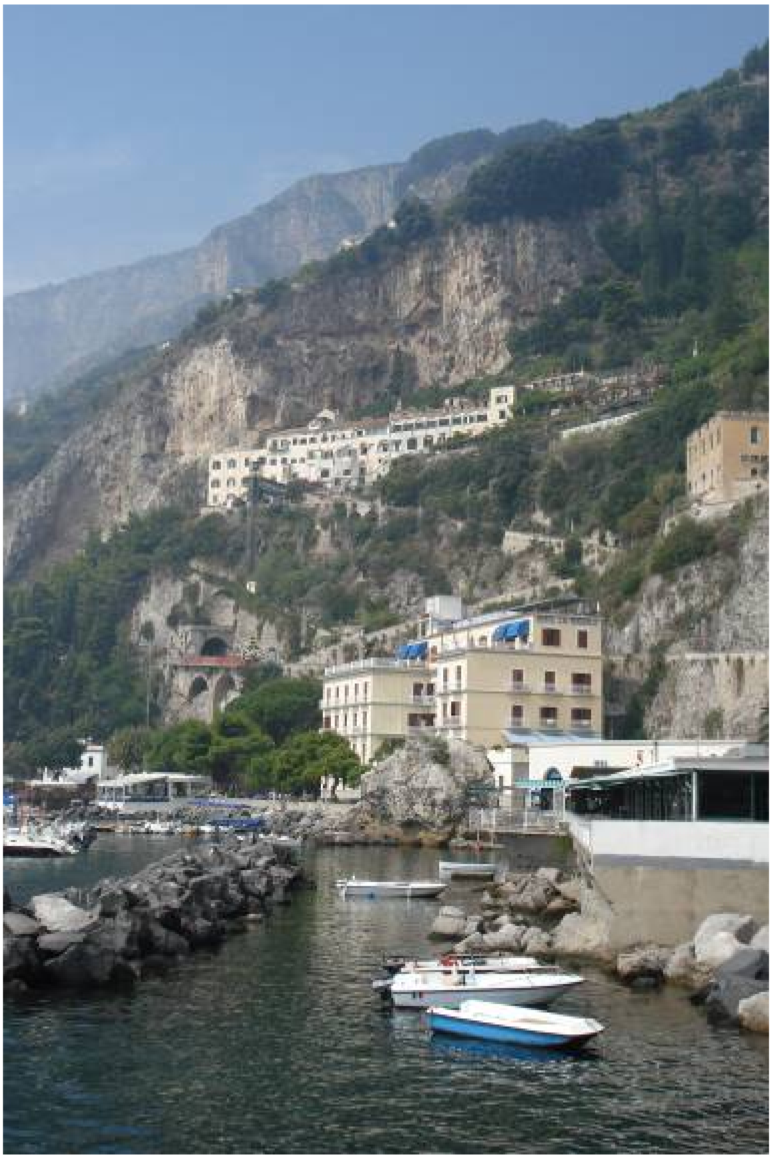


Figure 4.6: Amalfi, in the proximity of the "Hotel dei Cappuccini"

4.2. The rockfall database

In order to assess the quantitative risk assessment, a database provided by Ing. Tagliafierro has been used relating to rockfall incidents occurred in the study area from the beginning of the 19th century until 2001.
The data are available in computer files and he records have been organized in typology of data that concern several information. In succession the type and the quality of the attribute compilated in the database are shown.

- **Data of occurrence:** the period of records is from the beginning of the 19th century until 2001. For some events we have more accurate information about year, month and day of occurrence, for other ones the record haven’t been complete. This is true especially for rockfalls occurred in the 19th century.
- **The municipalities involving rockfall**: they are 13 Municipalities nominated above: Amalfi, Atrani, Cetara, Conca dei Marini, Furore, Maiori, Minori, Positano, Praiano, Ravello, Scala, Tramonti e Vietri sul Male.
- **Triggering factors**: this attribute concerns the factors that could create the rockfalls as rainfall, earthquake and anthropic activities.
- **Injuries and damage**: the consequences of rockfalls have been demolished structures and kill people. Rocks falling on highways have caused strike vehicles, block traffic, cause accidents, and sometimes damage the road.
- **Localization of both the source and the deposit area**: this attribute will be useful to localize the rockfall events on the topographical map at 5:000 scale. In few cases the information are completed and contain detail about the hitted area as the address of damage building or the kilometers of road that the blocks reached after the detachment from the source area. In other cases the information are low and they aren’t used in the location work.
- **The documentary sources**: the database has been constructed by information come from: Librery of “Center of Amalfi History and Culture”, Archive of State of Salerno, Certificates of Genio Civile of Salerno, Technical office of the Mondana Community, Comunal technical offices and Eyewitness.
- **The classifications of rockfalls**: The rockfalls have been aggregated in two classifications. The first classification is based on the likely range of mobilized rock volume. In particular the following three classes have been established:

  - ✓ rockfalls of class A: blocks having a total volume smaller than 1mc;
  - ✓ rockfalls of class B: blocks whose volume is between 1mc and 10mc;
  - ✓ rockfalls of class C: blocks having a total volume larger than 10 mc.

  Note that all volumes are deposit volumes. The study of the documents has identified 315 rockfalls of type A, 104 rockfall of type B and 54 of type C.
  The second classification is base on the type of deposit area:

  - ✓ rockfalls of class U: blocks that hit a urban area
  - ✓ rockfalls of class L: blocks that reached the coast line
  - ✓ rockfalls of class V: blocks interesting principal communication ways.

  You have recorded 140 rockfalls type U, 228 rockfalls type L and 193 rockfalls type V. Only a few of the available records contain details on the mobilized volume of rock during a given event so the volumetric classification, seen above, is the result of

various assumptions made by engineer Tagliafierro in the interpretation of documentary sources.
Usually, the majority of the data come from the last 20 years, because in this period the record of the events is increase thank to the birth of new local authority and to highest attention at the rockfalls.

Year	Month	Day	Locality	Topographical localization	Description of event	Damage	Cause	Origine del documento	Volumetric index	Type of deposit area
1811-1825			Maiori	Grotta dell'Annunziata, exit from Maiori to	rockfall	Deaths in the building site	anthropic activities	"Maiori City" of Filippo Cerasuoli	**C**	**V**
1984	7	12	Praiano	V. com. Fontanella - SS 163.	Collapse of a stretch of road				**C**	**U**
1839	4	4	Maiori	Annunziata Cave	fall of a big block near Annunziata Cave.			Intendenza	**B**	**V**
1846	1	7	Maiori	Locality of "Annunziata Cave"	rockfall along the road			Intendenza	**C**	**V**
1851	10	27	Maiori	Locality of "Annunziata Cave"	blocks falling on the road		rainfall	Intendenza	**B**	**V**
1997	1	10	Positano	Loc. Nocelle.	Landslide				**C**	**U**
1857	9	6	Maiori	Annunziata Cave	fall of a big block near Annunziata Cave.	road damages	rainfall	Intendenza	**B**	**V**
1857	9	26	Maiori	Annunziata Cave	blocks falling on the road			Intendenza	**A**	**V**
1972	7	18	Maiori	SS 163 km 34+600.	blocks falling				**A**	**V**
1829	10	24	Atrani	V. Carmine in proximity of the Church	fall of blocks		rainfall		**A**	**U**
1996	5	20	Conca dei Marini	Cliff on Borgo Marinaro.	Rockfall from cliff in Borgo Marinaro.				**C**	**L**
1983	2	10	Minori	Rock cliff SS 163 km 34.	rockfall danger				**B**	**V**
1997	1	28	Cetara	Port Zone	Detachment of some blocks near the port				**A**	**L**

Figure 4.7: Some information extracted from the database

Figure 4.8 shows the percrnt distribution of rockfall events regarding the deposit area:

- ✓ rockfalls of class U: blocks that hit a urban area
- ✓ rockfalls of class L: blocks that reached the coast line
- ✓ rockfalls of class V: blocks interesting principal communication ways.

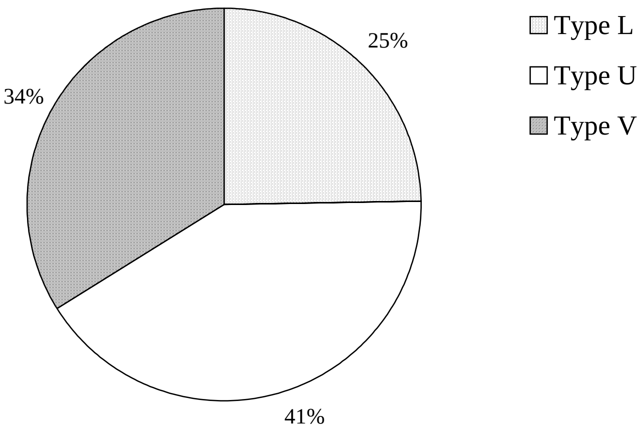
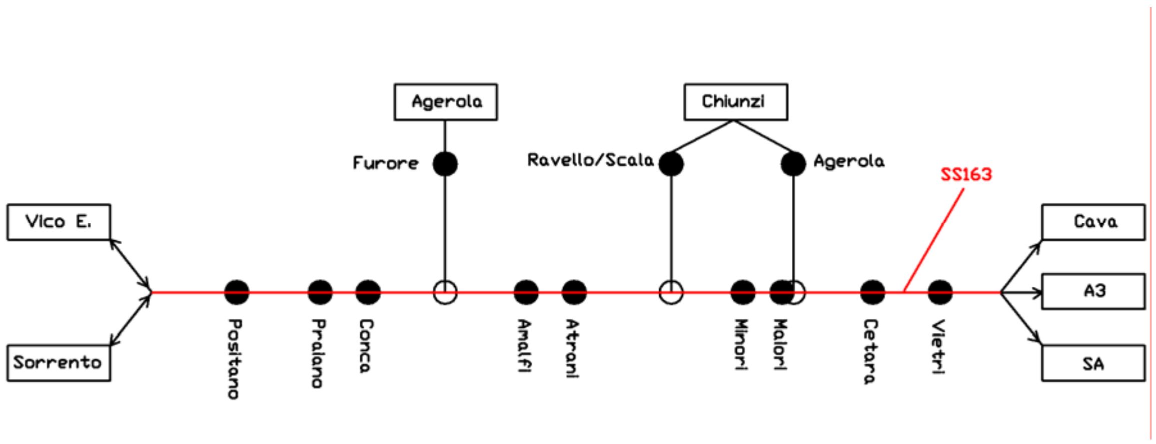


Figure 4.8: Percent distribution of rockfall events regarding the deposit area.

4.3. The SS163 coastal road and the traffic intensity

The Amalfi road (SS163) is the important transportation corridor of this area and support a very high movement as well as tourist traffic. It represents the connection among the inhabited area.
Whereas all the remaining roads, it is clear (appear) that the alternative routes to support the mobility within the Amalfi Coast are limited. This road axis not has functional characteristics consistent with its importance for transport and the flows of question that characterize it.
The whole road follows the contour of the coast and is very tortuous; it is characterized by a variable width that, in some sections, not allows the contemporary passage of a vehicle in each direction.
As regards the remaining part of the road in the area of study, other transportation corridors are constituted by State Roads that from Maiori and from Amalfi move towards l'Agro-Nocerino-Sarnese through the Valico of Chiunzi. These roads, winding and leaning, are very crowded in summer and they are an alternative to S.S.163 to reach some areas of the coast.



A volumetric analysis of the flows of vehicles along the coastal road has been provided by the Professor Carratelli of the University of Salerno. The available data consist in the number of vehicles crossing certain sections on 5 August 2003. The interest sections belong to SS163 and are indicated in Figure 4.9. In the calculations later described only the flow of traffic on the lane closest to the mountain has been considered. This lane is that one in the direction to Positano.

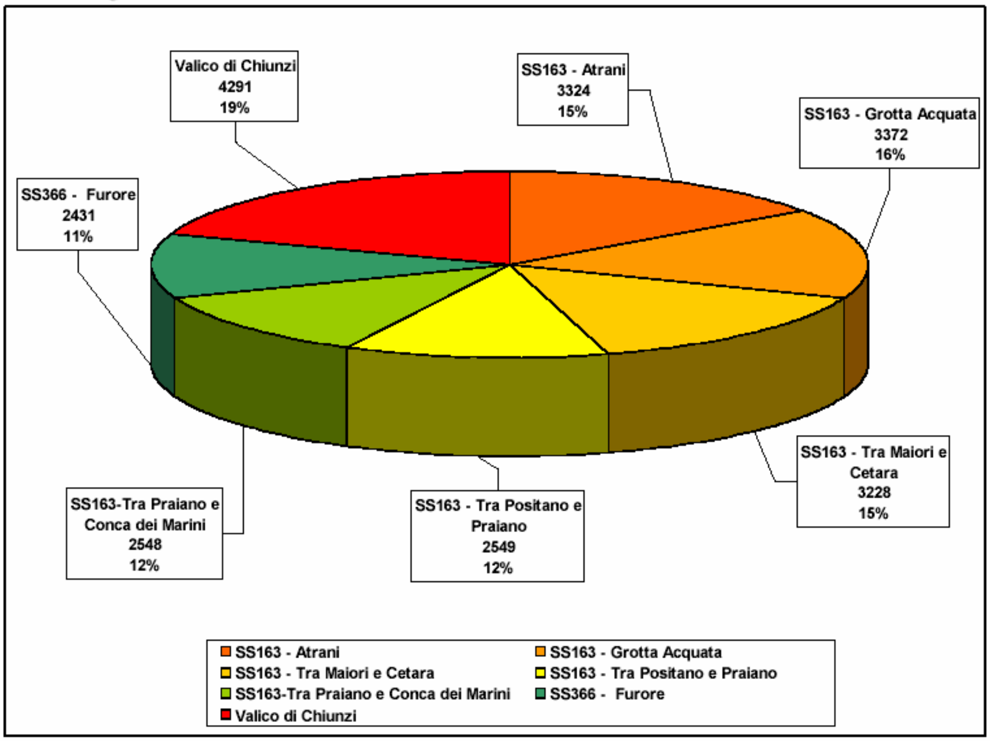


Figure 4.9: Flow of vehicle in both way of driving (5 August 2003)

Sections	directions	
Località Castiglione Panchine "Ravello Città della musica"	Minori	Amalfi
	1657	1667
SS163 - Località Grotta Acquata	Positano	Sorrento
	1705	1667
SS163 - Tra Maiori e Cetara-Piazzola Chiosco c/o Ristorante Capo D'Orso	Cetara	Minori
	1408	1820
Nei pressi della pensione "Il Giardino" Area di sosta "Rent a scooter"	Praiano	Positano
	1200	1349
SS163-Tra Praiano e Conca dei Marini Parcheggio ascensore Grotta Smeraldo	Conca	Praiano
	1250	1298
SS366 - Tra Agerola e l'innesto della SS163 Municipio di Furore	SS163	Agerola
	1134	1297
Valico di Chiunzi - Bivio Maiori Ravello	Costiera	A3
	2155	2136

Figure 4.10: Flow of vehicle in both directions way

A polynomial regression of the third order has been obtained (Figure 4.10). The equation of the curve is $y = -0{,}1517x^3 + 13{,}164x^2 - 334{,}78x + 3876{,}3$ with a coefficient of correlation equal to $R^2 = 0{,}956$, from this equation it obtains for each kilometer of the coastal road the corresponding number of vehicles.

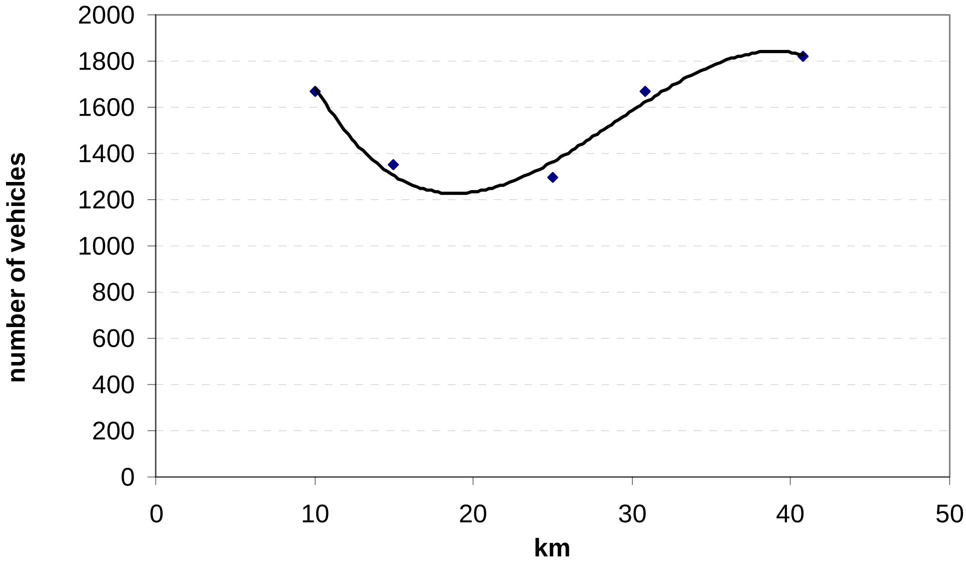


Figure 4.11. Polynomial regression of the third order

CHAPTER 5

5. QRA of the Amalfi Costal Road

5.1. Hazard assessment

5.1.1. Rockfall source and deposit area

The classifications described above have been used to detect, at 1:5000 scale, the areas which historically effected by rockfalls of different magnitude. The rockfalls have been localized thank to the information of the database, so in some cases I localized the rockfalls in the source area and in the other ones in the deposit area.
In the second case, the topographical and morphological maps have been useful to identify the potential block release areas even if this task have been approximate due to the information in the database on area of detachment is not sufficient.

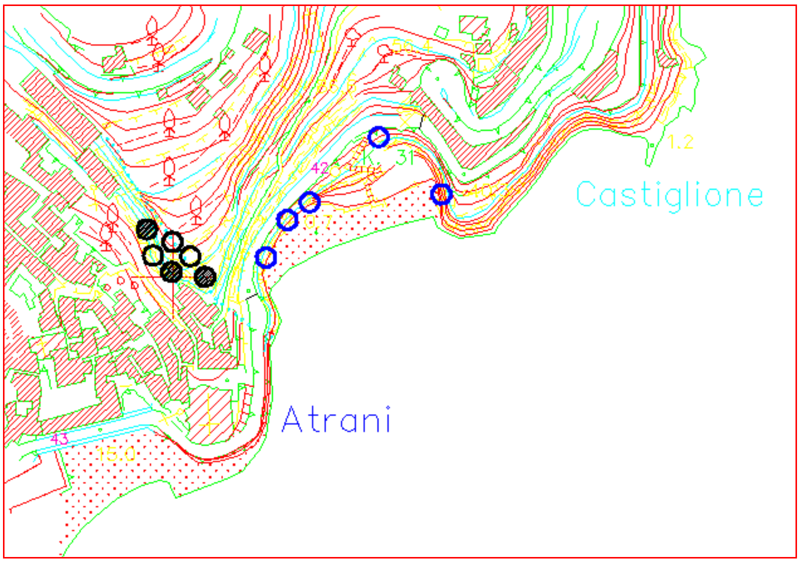


Figure 5.1: Rockfall of type U (A and B) from Monte Aureo and rockfalls of class L-A interesting the beach of Atrani

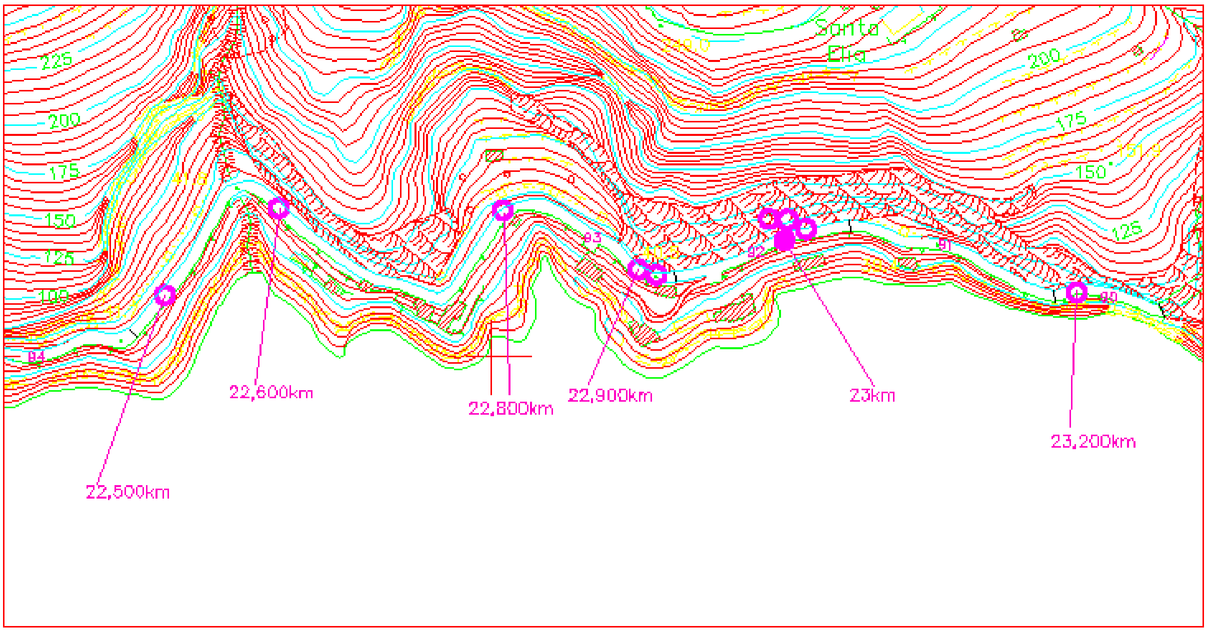
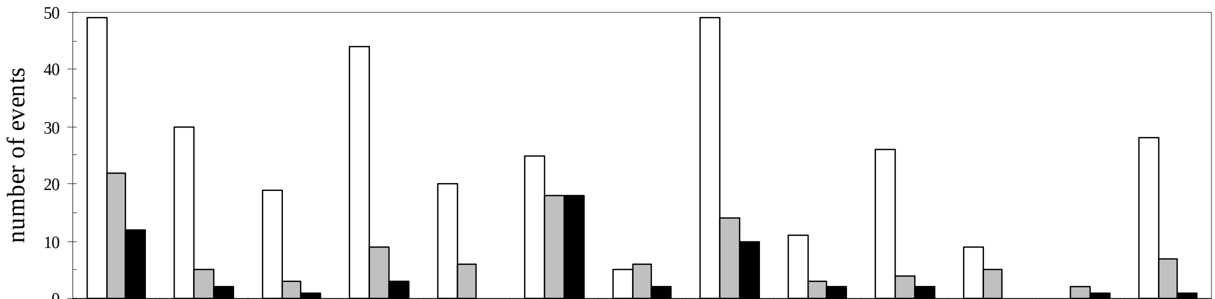


Figure 5.2: A series of rockfall that have involved the costal road

5.1.2. Frequency analysis

As previously mentioned, there is several ways to quantitatively assess the frequency of landslides (Fell et al. 2005): historical data, slope instability ranking systems, geomorphological evidence, relationship with triggering events, expert judgement, modelling primary variable, probabilistic methods or a combination of them.
In the Amalfi Coast the rockfall frequency has been determined from the historical records (Cascini et al. 2002).
The areal distribution of rockfall events, shown in the Figure 5.3, is not homogeneous. It can observe that the municipalities most involved by rockfalls are Amalfi, Conca dei Marini, Maiori and Positano with a predominance of rockfalls that belong to the class A.



	Amalfi	Atrani	Cetara	Conca dei Marini	Furore	Maiori	Minori	Positano	Praiano	Ravello	Scala	Tramonti	Vietri sul Mare
□ A	49	30	19	44	20	25	5	49	11	26	9	0	28
▨ B	22	5	3	9	6	18	6	14	3	4	5	2	7
■ C	12	2	1	3	0	18	2	10	2	2	0	1	1

Figure 5.3. Areal distribution of rockfall events (Cascini et al. 2002)

Differences in regard to the typology of the hit area may be attributable to the morphology (Figure 5.4). Cetara, for example, has 61% of rockfalls of type L, in confirmation that there is a concentration of events in proximity of the coastal line; Atrani has a prevalence of phenomena at the area urbanized (rockfalls of type U) while Conca dei Marini and Furore have a higher localization of the events along the road infrastructures (rockfalls of type L).

It is noted, finally, that most of events of greater intensity (type C) is mainly in the urbanized (61% of the acquired data).

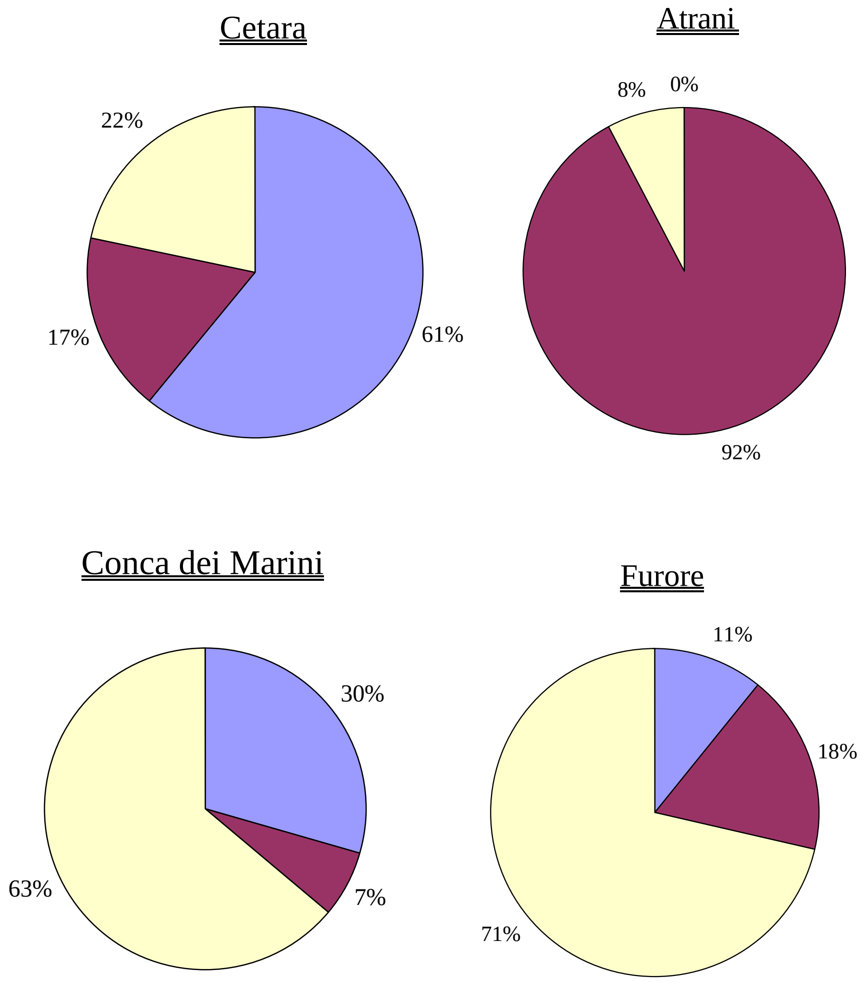


Figure 5.4: The percentage distribution of rockfalls in regard to the typology of the hit area

In the monthly distribution of rockfall events (Figure 5.5) you can seen that the rockfalls of the class A occurred mainly in November, with lower frequency in January and August.
The maximum in summer is due to greater records because of the flow of tourists in the area, as the Amalfi Coast an important tourist destination of the Campania Region, while the maximum in November would be actually representative the events that occurred in this period.
The rockfalls of class B concentrate in the month of October, January and May with two minimum in April and August and the rockfalls of class C occurrence in the winter period (December-January) and in the beginning of the spring (March-April).

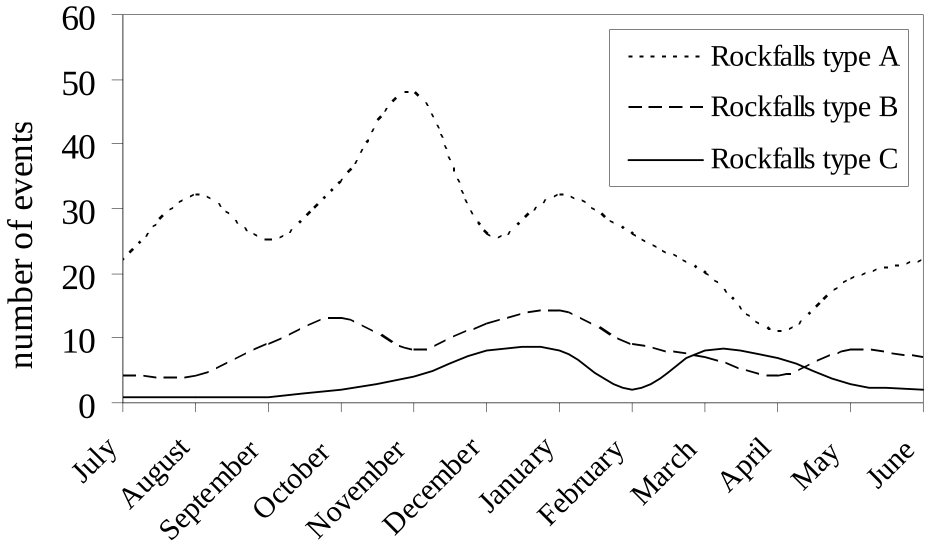


Figure 5.5: The monthly distribution of rockfall events (Cascini et al. 2002)

Temporal distribution of rockfall events (Figure 5.6) for each class of mobilized volume has been constructed.
Stone falls of small size usually do not capture public attention and remain unnoticed. These small events, however, have little impact (Corominas et al. 2005).
The historical record includes the vast majority of rockfall events of class A that reached the urban area, the beach and the road during the 20 years from 1980 until 2000.
The curve of the rockfall events of the class B increase corresponding to the period of road construction and they have an exponential development from 1960, when the records are increase thank to the birth of new local authority. The horizontal trend of the curves is due to the lack of data or the loss of the documentary source.
The cumulative historical series related to rockfalls of the class C, instead, is the good quality also for the past century especially when there are information corresponding to lose of life or destruction of religious buildings.
Therefore, the magnitude-frequency curves obtained using these results, provide only a minimum estimation of the actual rockfall activity at the release area. However, we should keep in mind that the frequency we must consider is that of the events able to reach the area where the exposed elements are located. To this purpose, these records are considered suitable for carrying out the risk analysis.
On the other hand, the historical records aren’t fully complete and consequently the results must be interpreted with care (Corominas et al.2005).

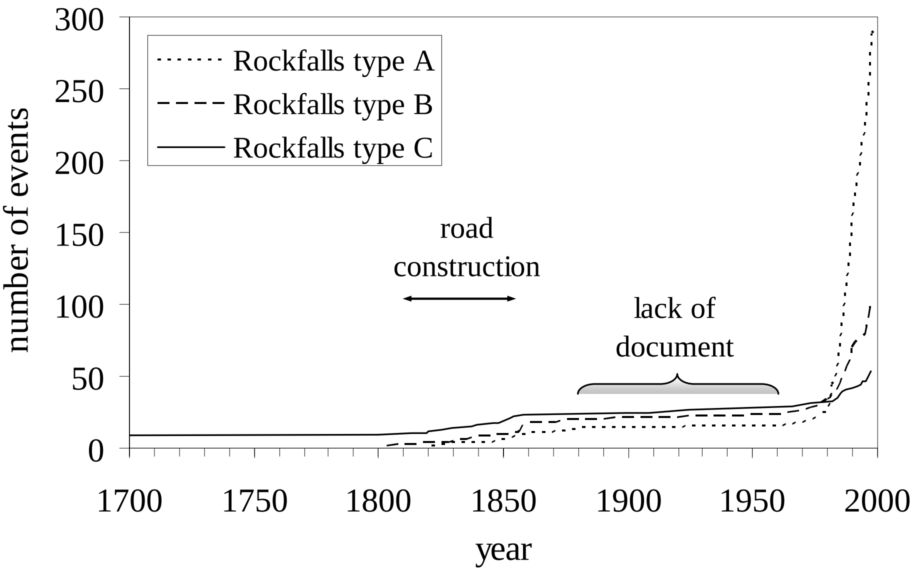


Figure 5.6: Absolute cumulative frequency of rockfall events (Cascini et al. 2002)

5.1.3. Magnitude- frequency curves

Frequency-magnitude analyses are common approaches to characterize the occurrence of natural hazard phenomena such as earthquakes, floods and snow avalanches (Corominas et al. 2005).

In the last years, several distribution laws for frequency-magnitude of rockfalls have been proposed based on the statistical analysis of series of past events (Hungr et al. 1999).

The magnitude of rockfalls is usually expressed by the volume of the detached mass. The maximum movement velocity and the kinetic energy are most important intensity attributes (Hungr et al. 1999).

In order to construct the magnitude-frequency curves, the volume of the deposited rock masses from available record has been used. The size of block reaching the slope foot is usually much smaller than that of the detached rock mass at the cliff face. This is because the impacts on the ground make the falling rock mass disintegrate into smaller pieces, often bounded by discontinuities. As the rockfall propagates downhill the movement consists of the displacement of the individual block with divergent trajectories. Only a small percentage of the block are able to reach the lower part of the talus slope.

In this case, using the volume of the mass at the deposited area to carry out the risk analysis would give realistic results, because the magnitude it must consider is that of the events able to reach the area where the exposed elements are located.

Magnitude- frequency curves have been constructed. On the horizontal axis (in logarithmic scale) there is the mobilized volume in cubic meters and the average frequency on the vertical one.

Due to lack of details on the mobilized volume of rock, the curves has been obtained taking into account the three classes of mobilized volume (class A, B and C) and the frequency has been calculated considering the volumetric range. In particular F is the value of frequency of rockfalls that mobilize a volume equal to the lower extreme of the range, while $\bar{F}$ corresponds to the higher extreme of the range.

	Volumetric range	
	Lower value	Higher value
Rockfalls of class A	0,01	1
Rockfalls of class B	1	10
Rockfalls of class C	10	1000

I have defined the domain, between a lower line and an upper one, in which the real M-F curve might be (Figure 5.7). The two curves have been obtained by plotting the point that correspond to the extreme values of the volumetric classification. The points have been determined by using the following expressions:

$$F_1 = \frac{n_A + n_B + n_C}{\Delta t} = \overline{F}_1 \quad ; \qquad F_2 = \frac{n_B + n_C}{\Delta t} = \overline{F}_2 \quad ; \quad F_3 = \frac{n_c}{\Delta t}; \overline{F}_3 = \frac{1}{\Delta t}$$

The value of frequency of points 1 and $\overline{1}$ is calculated in the same way and it's the ratio between the total number of rockfalls that have a volume greater than 0,1m^3 (rockfalls belong to class A, B and C) and Δt, that represents the length in years of the rockfall records (200 years). The point 1, that belongs to lower line, correspond to 0,01 m^3, while the point $\overline{1}$ of the upper line correspond to 1m^3. Those points are the extreme values of the range of rockfall volumes of the class A. The same procedure has been followed to calculate the average frequency of the points 2 and 3

The average frequency of the point 2 and $\overline{2}$ is the ratio between the number of rockfalls that have a volume greatest 1m^3 (events of class B and C) and Δt. The point 2 corresponds to 1 m^3, while the point $\overline{2}$ corresponds to 10m^3; this value of magnitude is the boundary value of the volumetric range of the class B. The points number 3 and $\overline{3}$ represent the last points of the curves and they have been obtained assuming that the maximum volume of detached blocks belongs to a range between 10 and 1000. F_3 is calculated as the ratio between the numbers of rockfalls that belongs to class C and the period of records, while $\overline{F}_3$ is the ratio between 1 and Δt, where 1 represent the unique rockfall event of 1000 m^3.

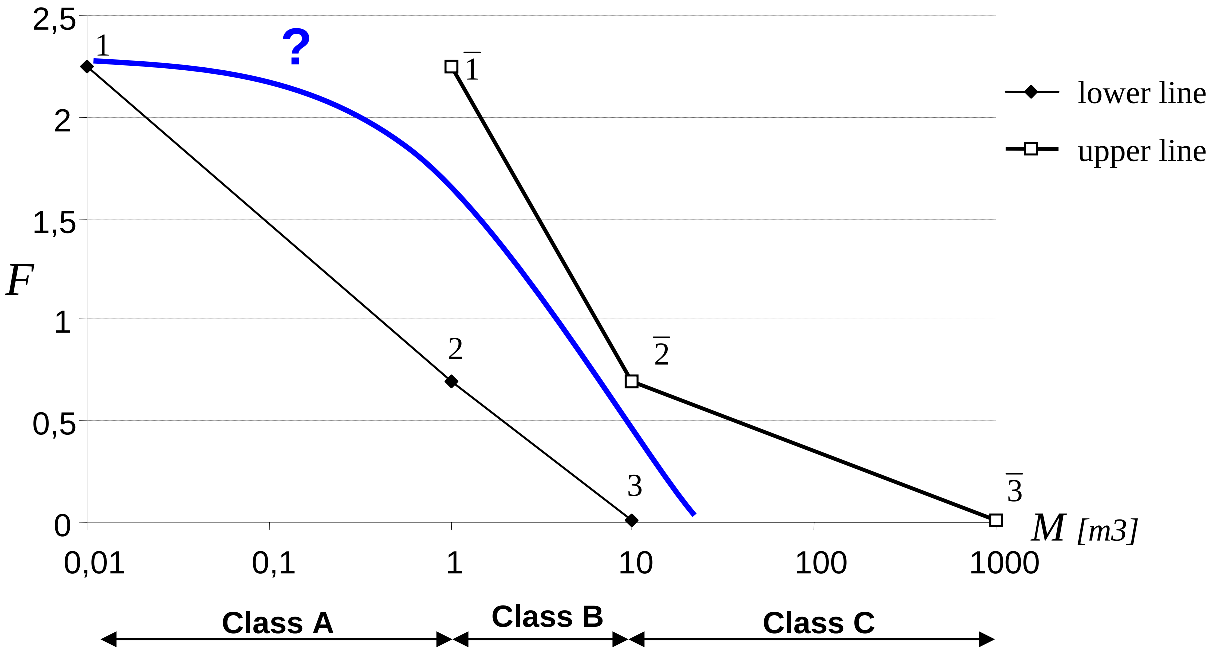


Figure 5.7: Magnitude-frequency curve for whole Amalfi Coast , in blue is indicate the hypothetical real f-M curve

The magnitude- frequency curves for each Municipality have been constructed (Figure 5.8). For some Municipalities as Vietri sul Mare and Positano, the curves are incomplete; in fact, there aren't the points three because of the lack in the database of the rockfalls belonging to class C.

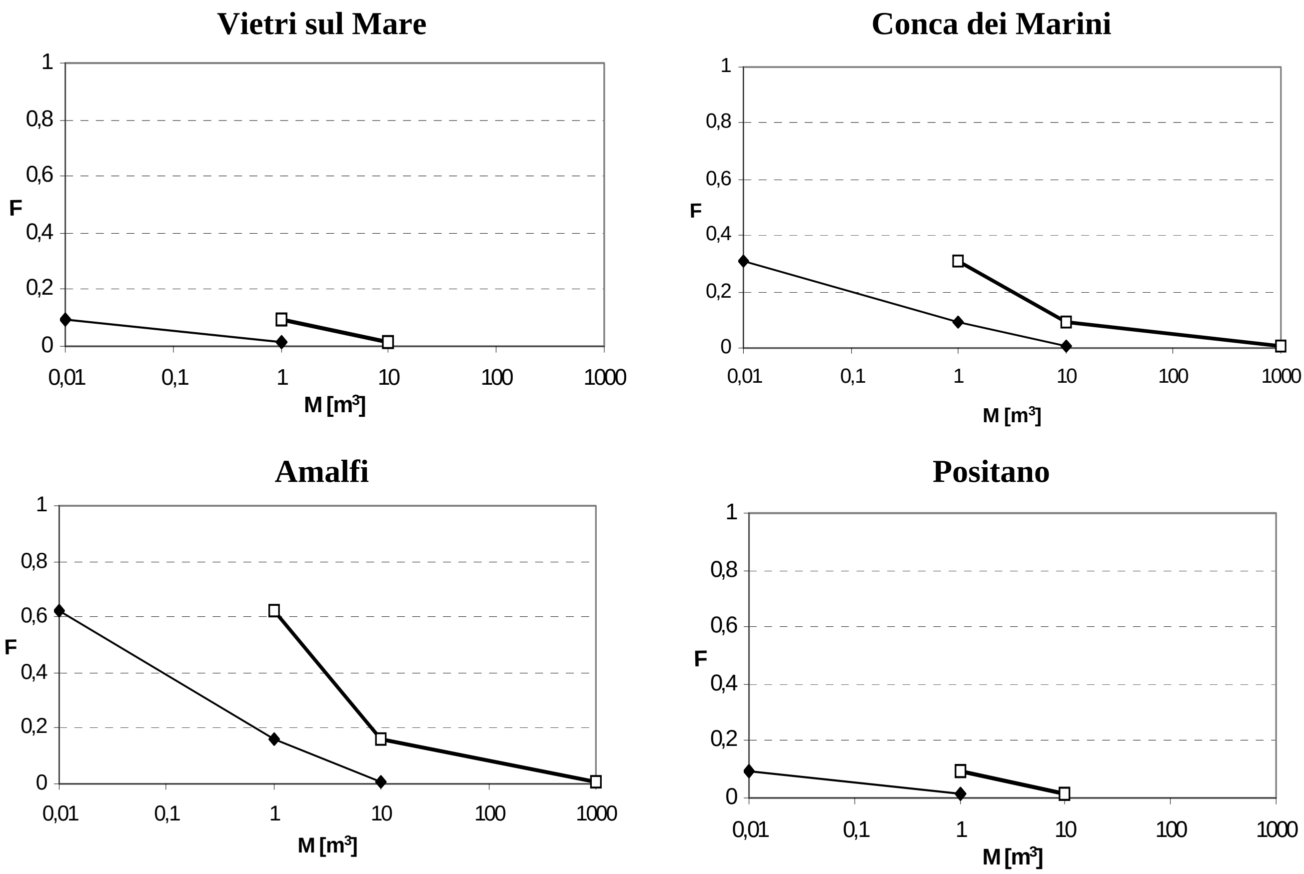


Figure 5.8: Magnitude-frequency curve for each Municipalities of Amalfi Coast

Massive rockfalls, involving a volume lager than 10 m^3, seem to be rare. Only one event has been observed during the recorded span of time, with a volume of about 1000 m^3.
Rockfall frequency may change through time and it depends on the length of the observation period. With reference to the frequency assessment, an in depth analysis of the issues related to the frequency-magnitude curves have been developed.
Several periods of time smaller than 200 years have been considered. According to that described in the previous paragraph, the annual average frequency increase in the 20th century especially in the period between 1980 and 2000 (Figure 5.9). This is true because in this period the database is more accurate.
For this reason in order to assess the quantitative risk it will be considering this period of time for rockfalls of class A and B, while for rockfalls of class C all the database will be using.

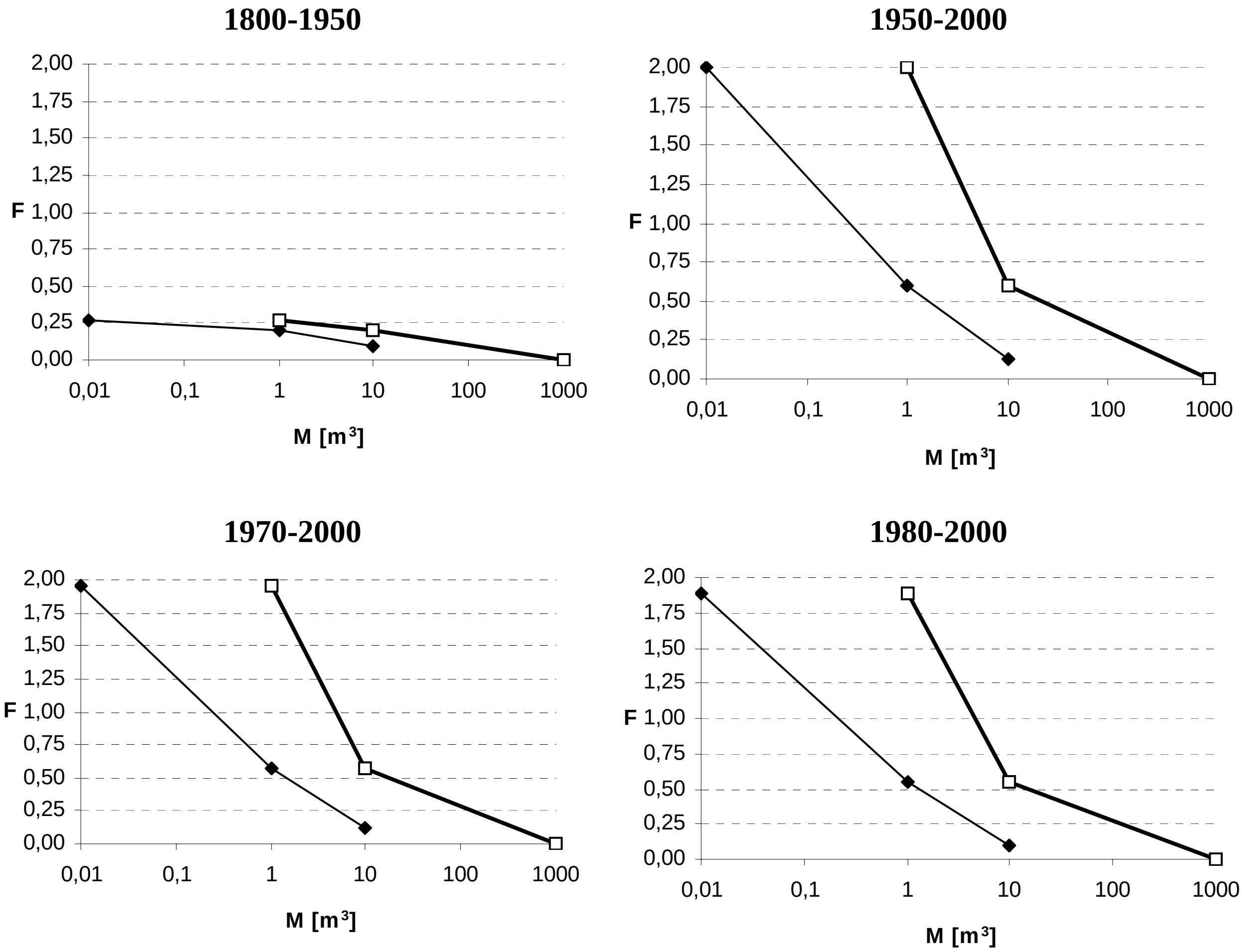


Figure 5.9: Magnitude-frequency curve for the period between 1980 and 2000

5.2. Conditional consequence model: debris remaining in the roadway

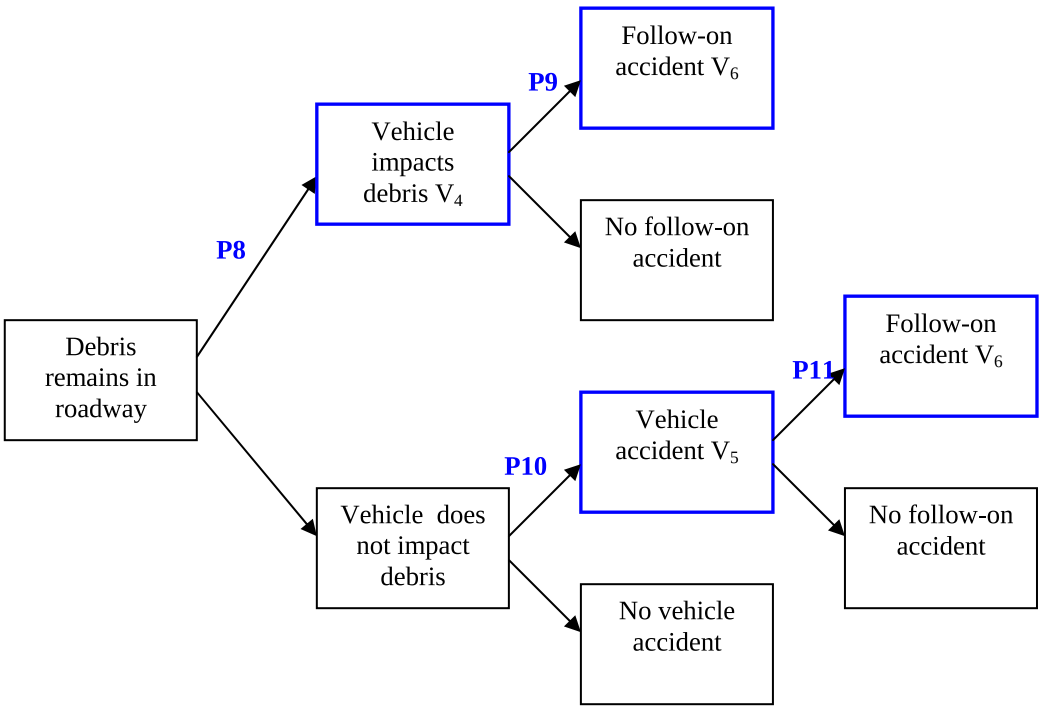
5.2.1. Calculation of $P[V_i/M_R]$

The conditional probabilities that debris of magnitude M_R that remains in the roadway will cause event V_i are obtain as described above:

$$P[V_4/M_R] = P8$$
$$P[V_5/M_R] = (1-P8)*P10$$
$$P[V_6/M_R] = P8*P9+(1-P8)*P10*P11$$

where:

$p[C/M_R]$ is the conditional probability distribution
for consequence C if debris of magnitude M_R remains in the roadway.
$p[C/V_i, M_R]$ is the conditional probability distribution for consequence C if debris of magnitude M_R that remains in the roadway causes event V_i .
$P[V_i/M_R]$ is the conditional probability that debris of magnitude M_R that remains in the roadway will cause event V_i .
V_4 is the event of a vehicle impacting debris remaining in the roadway.
V_5 is the event of a vehicle not impacting debris remaining in the roadway but being in an accident anyway (e.g. due to avoidance or distraction).
V_6 is the event of a follow-on accident due to events V_4 or V_5.



- <u>The probability that a vehicle will impact debris of amount M_R remaining in the roadway (P8).</u>

This probability is a function of traffic characteristics and of M_R. It is assumed that the driver in a vehicle either sees the debris in his lane immediately (if the distance to the debris, which on average is half the vehicle spacing, is less than the "maximum sight distance") or not until he comes within sight distance (if the distance to the debris is more than the "maximum sight distance"). Once the driver sees the debris in his lane, it is assumed that he tries to stop and that he will hit the debris (event V_4) if his vehicle's "stopping distance" is greater than the available distance, which is the smaller of half the vehicle spading and the maximum sight distance. Hence, the probability is calculated as:

$$P8 = P[lane1] \times \left(1 - \phi\left\{\frac{\ln(d_x) - \ln(m[d_d])}{\ln(COV(d_d) \times m[d_d])}\right\}\right)$$

where:

- ✓ *P[lane1]* is the probability that debris in the road will be in the driver's lane, assumed to equal 50% if M_R<10m^3 and 100% if $M_R \geq 10$m^3
- ✓ d_x is the available stopping distance, which is the minimum of half the vehicle spacing (on average) and the maximum sight distance, which in turn is a function of the size of the object, illumination and road curvature.
- ✓ $m[d_d]$ is the nominal stopping distance, which is a function of vehicle velocity
- ✓ $COV[d_d]$ is the coefficient of variation of the stopping distance
- ✓ $\phi\{\ \}$ is the standard normal cumulative distribution

The probability only for one traffic direction has been calculated, in particular for the right way because it is more nearly to the hazard zone where there is the cliff face.
The vehicle's nominal stopping distance is the distance from the moment in which the driver sees the debris on the road until when the car stops completely.
It is given by the sum of reaction distance and braking distance.

$$d_d = d_r + d_b$$

- d_r is the distance driving in the reaction time (Δt_r), between when he sees the object and when he starts braking, which is a function primarily of driver awareness, it has been fixed like to 1 second. Whereas the car moves in uniform rectilinear mote the reaction distance results:

  $$d_r = V_v \cdot \Delta t_r$$

  where:
  V_v is the vehicle velocity. It is variable in each section because it depends on the trend of road. In the sections in which there is a curve or an inflection or stretch rectilinear the velocity is respectively 30km/h, 40km/h and 50km/h.
  The values of d_r for different velocity are:

V_v	d_r
30 km/h	8,33 m
40 km/h	11,11 m
50 km/h	13,89 m

- d_b is the distance covered from the moment in which the vehicle begins to brake to the moment in which is completely stop:

$$d_b = \frac{1}{2} A \cdot \Delta t_b^{\ 2} \ (1)$$

Δt_b is the braking time calculated as the ratio between the vehicle velocity and the deceleration equal to 5 m/s^2:

$$\Delta t_b = \frac{V_v}{A}$$

The values of Δt_b for different velocity are:

V_v	Dt_b
30 km/h	1,67 s
40 km/h	2,22 s
50 km/h	2,78 s

Speigare le 3 velocità che sn, come già fatto

Consequentially the values of braking distance calculated for three velocities are:

V_v	d_b
30 km/h	6,94 m
40 km/h	12,34 m
50 km/h	19,29 m

The sum of two distance provides the vehicle's nominal stopping distance that results

V_v	d_d
30 km/h	**15,28 m**
40 km/h	**23,46 m**
50 km/h	**33,18 m**

Inserting the $\Delta t_b = \frac{V_v}{A}$ in the expression (1) it obtain:

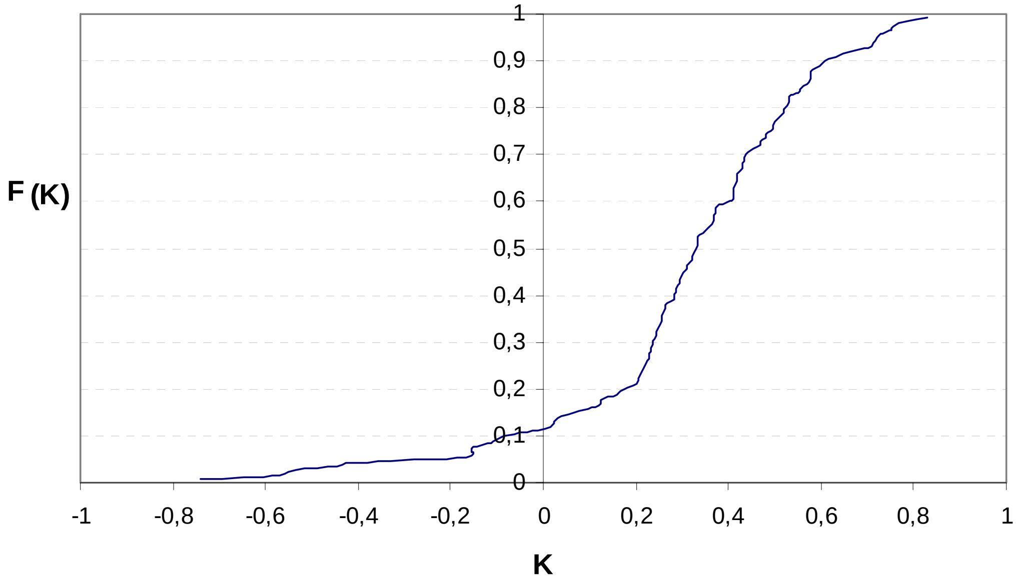
$$d_b = \frac{1}{2A} \cdot V_v^{\ 2}$$

in which the term $C_{b=} \frac{1}{2A}$ is the vehicle's breaking coefficient, which is a function primarily of the type and condition of tires and road surface.

The nominal stopping distance (*m[d_d])* is the mean of the three values of d_d and *COV[d_d]* is the coefficient of variation of the stopping distance which equals the standard deviation by the mean.

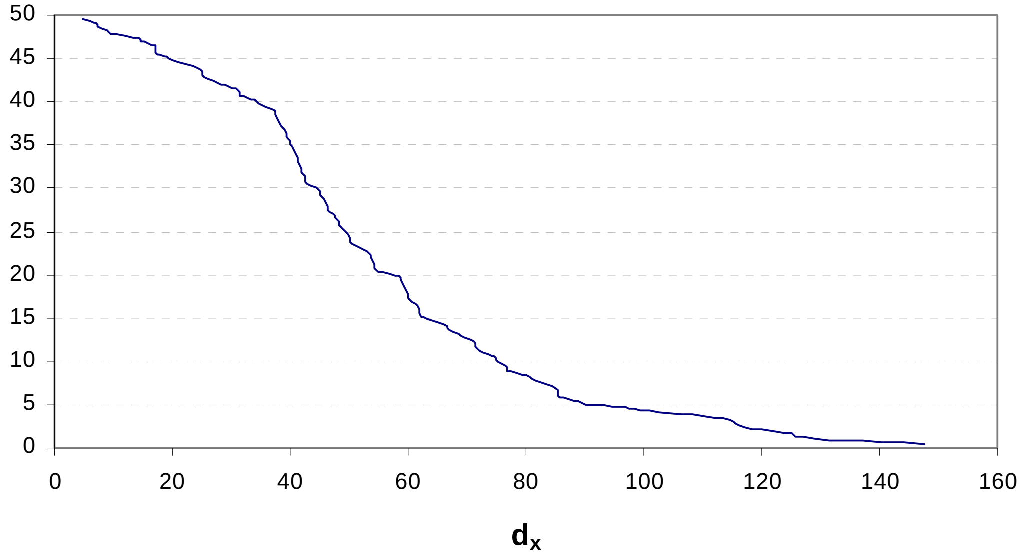
m[d_d]= 23,97 m
COV[d_d]=0,37

The standard normal cumulative distributions $\phi\left\{\frac{\ln(d_x)-\ln(m[d_d])}{\ln(COV(d_d)\times m[d_d])}\right\}$ is shown below in which $K=\frac{\ln(d_x)-\ln(m[d_d])}{\ln(COV(d_d)\times m[d_d])}$ represent the probabilistic variable.

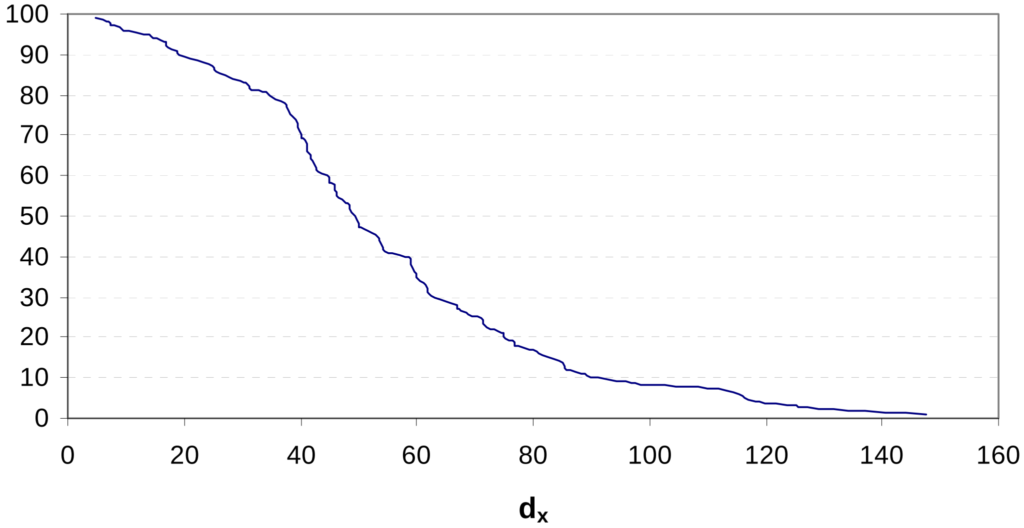


Subsequently the probability P8 for debris of amount M_R=1m^3 (rockfalls of class A and B) and debris of amount M_R=10m^3 (rockfalls of class C) are represented.

Probabilty P8 (rockfalls A and B)



Probability P8 (rockfalls C)



- The probability that a follow-on accident will occur after a vehicle has impacted debris of amount M_R remaining in the roadway (P9).

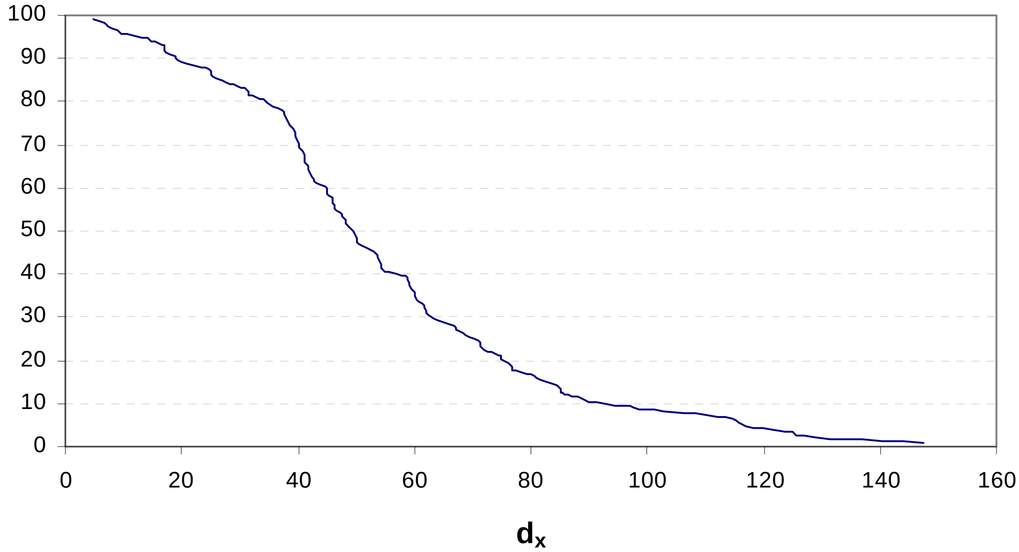
This probability is a function primary of traffic characteristics and it is calculated by:

$$P9 = 1 - \phi\left\{\frac{\ln(d_x) - \ln(m[V_d])}{\ln(COV(V_d) \times m[V_d])}\right\}$$

where:

- ✓ d_x is the available stopping distance
- ✓ $m[d_d]$ is the nominal stopping distance
- ✓ $COV[d_d]$ is the coefficient of variation of the stopping distance
- ✓ $\phi\{\ \}$ is the standard normal cumulative distribution, that it's the same of the probability P8.

Probabilty P9



- The probability that a vehicle will have a accident due to debris of amount M_R remaining in the roadway, but not due to direct impact (P10).

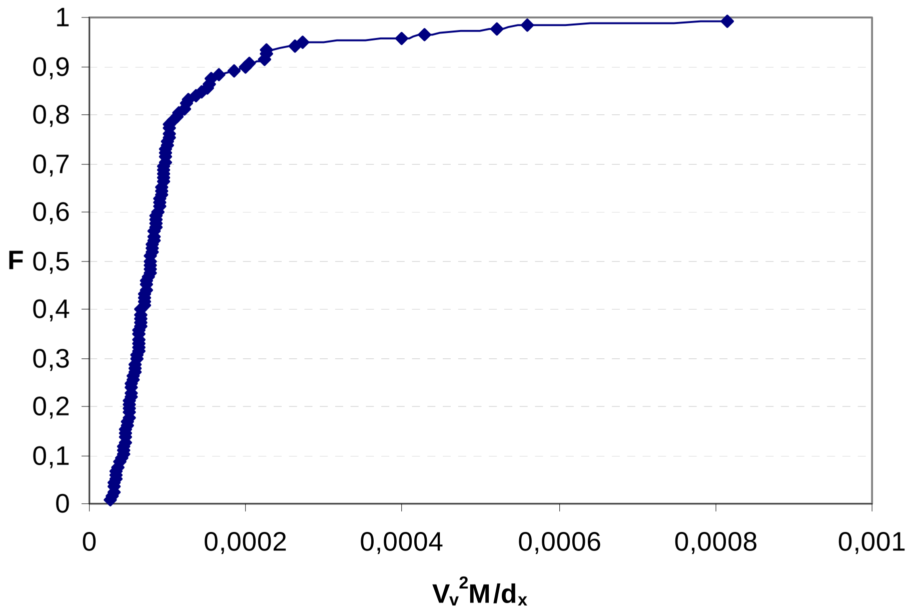
This probability is a function of traffic characteristics and of M_R. it increases with: increasing vehicle velocity V_v^2; decreasing distance to the debris d (minimum of debris sight distance and half vehicle spacing) and increasing debris size in the roadway $M_R^{1/3}$. it has been assumed that P10 can be expressed as a function of $\{V_v^2 \times M_R^{1/3}/d\}$.

$$P10 = P[lane1] \times \phi\left\{\frac{\ln\{V_v^2 \times M_R^{1/3}/d\} - \ln\{[V_v^2 \times M_R^{1/3}/d]_{50}\}}{\ln\{[V_v^2 \times M_R^{1/3}/d]_{84}\} - \ln\{[V_v^2 \times M_R^{1/3}/d]_{50}\}}\right\}$$

where:

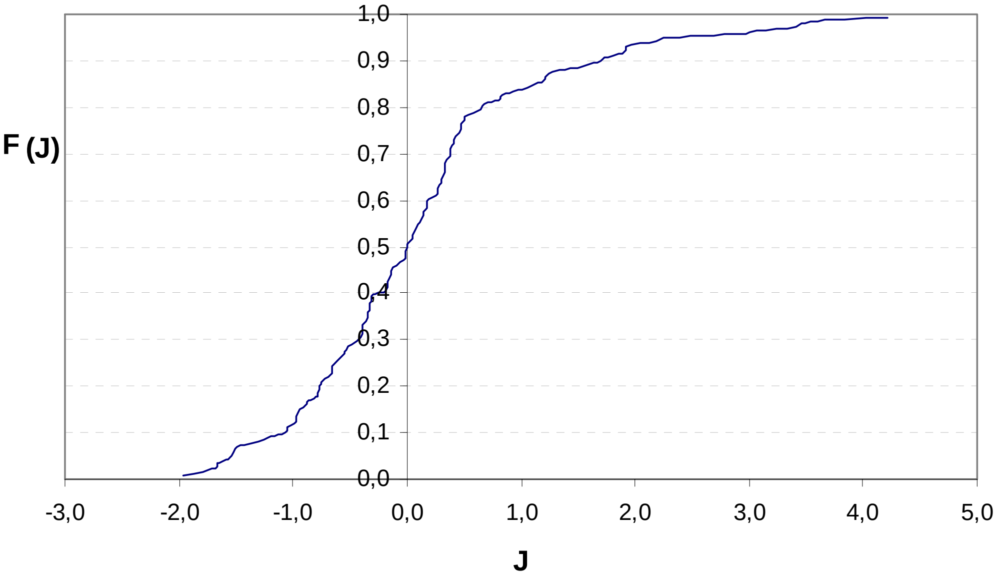
- ✓ *P[lane1]* is the probability that debris in the road will be in the driver's lane, assumed to equal 50% if M_R<10m^3 and 100% if $M_R \geq$ 10m^3
- ✓ *d* is the distance to debris in the road when the driver becomes aware of it
- ✓ $[V_v^2 \times M_R^{1/3}/d]_{50}$ is the value of $[V_v^2 \times M_R^{1/3}/d]$ for which P10 equals 50%
- ✓ $[V_v^2 \times M_R^{1/3}/d]_{84}$ is the value of $[V_v^2 \times M_R^{1/3}/d]$ for which P10 equals 84%

this is the normal distribution of $[V_v^2 \times M_R^{1/3}/d]$ where V_v is fixed and equal to 50 km/h and M_R is the volume of debris (1m^3).

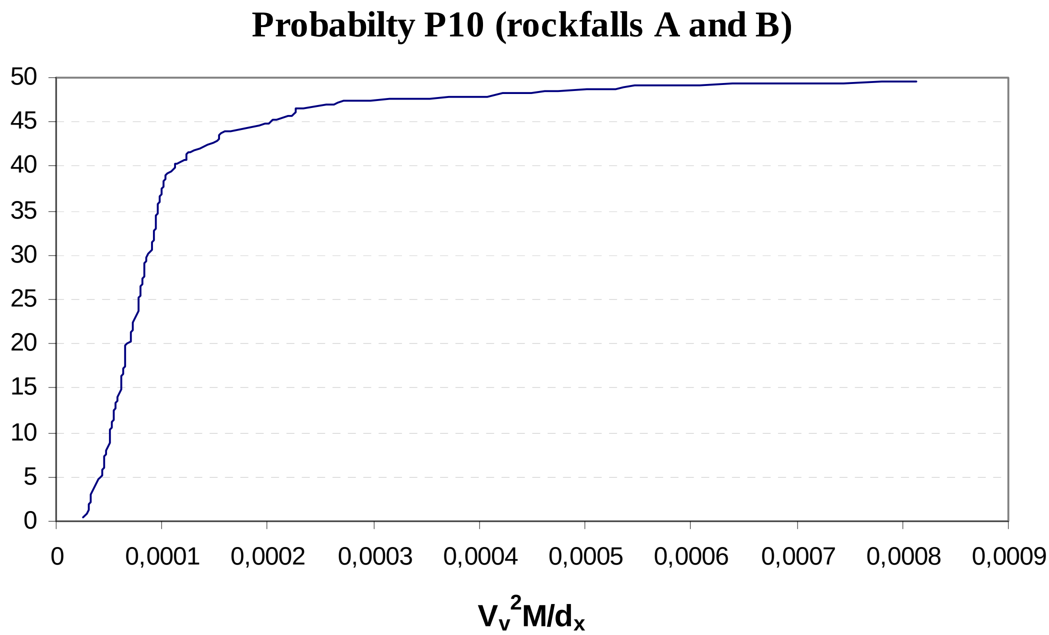


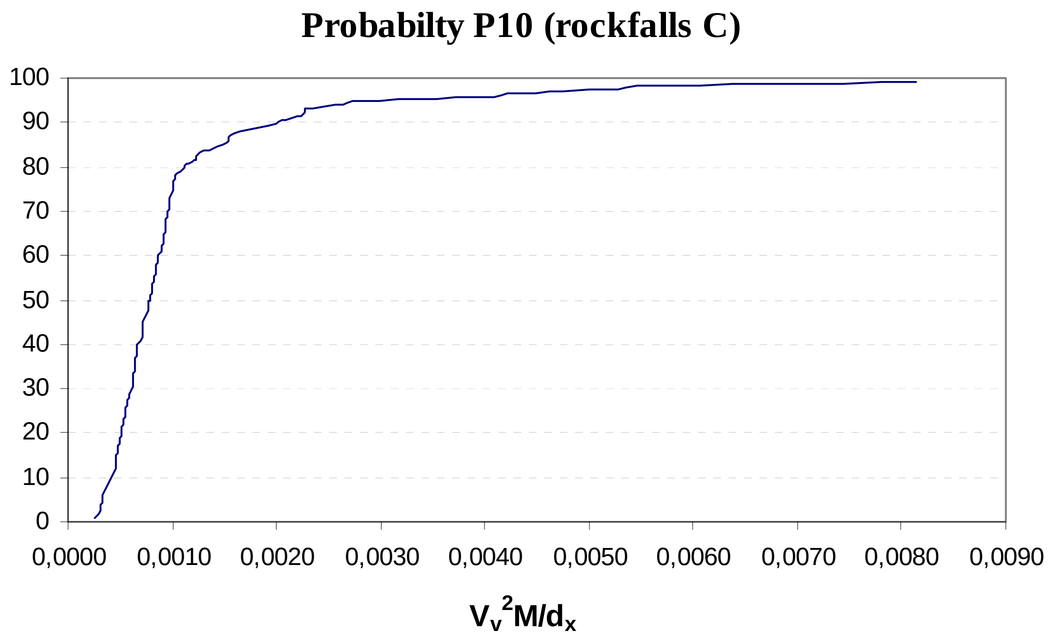
from this distribution it's possible obtained the values of $[V_v^2 \times M_R^{1/3}/d]_{50}$ and $[V_v^2 \times M_R^{1/3}/d]_{84}$ respectively for F= 50% and F= 84%.

The standard normal cumulative distributions $\phi\left\{\dfrac{\ln\{V_v^2\times M_R^{1/3}/d\}-\ln\{[V_v^2\times M_R^{1/3}/d]_{50}\}}{\ln\{[V_v^2\times M_R^{1/3}/d]_{84}\}-\ln\{[V_v^2\times M_R^{1/3}/d]_{50}\}}\right\}$ is shown below in which $\dfrac{\ln\{V_v^2\times M_R^{1/3}/d\}-\ln\{[V_v^2\times M_R^{1/3}/d]_{50}\}}{\ln\{[V_v^2\times M_R^{1/3}/d]_{84}\}-\ln\{[V_v^2\times M_R^{1/3}/d]_{50}\}}$ is the probabilistic variable.



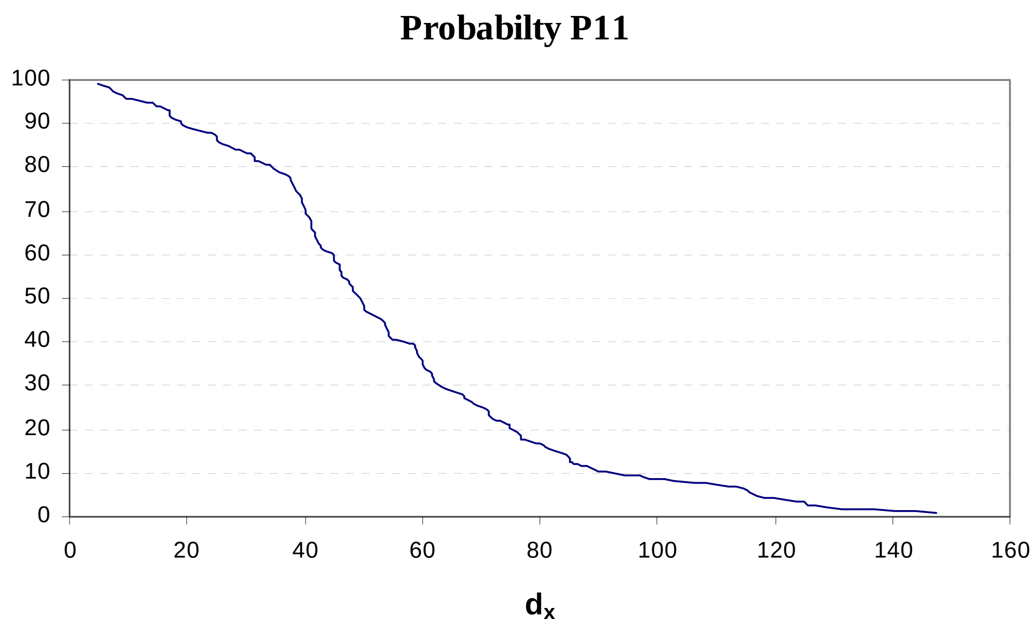
The probability that a vehicle will have an accident due to debris of amount M_R (1m^3 for events of class A and B and 10m^3 for class C) remaining in the roadway, but not due to direct impact is shown following.





- The probability that a follow-on accident will occur after a vehicle has had an accident due to debris of amount M_R remaining in the roadway, but not due to direct impact (P11).

This probability is a function of traffic characteristics in the similar way as for P9. It has been assumed that P11=P9.



The conditional probability distribution $p[C/V_i, M_R]$ for consequence C has not been calculated for lack of data concerning the values of vehicle velocity recorded along the road.

5.3. Application of RHRS method in the Amalfi Coastal Road

In Amalfi Coast many kilometre of roadway pass through steep terrain where rock slope adjacent to the highway are common. The rockfalls occurred in this area are partially the result of how the highway system has evolved.

The method has been applied to the coastal road (SS163) along nearly 33,91 km from Vietri sul Mare (km 44,91) to Positano (km 11). The total road has been divided in 164 sections each characterized by different values of categories that has been considered in the method.

Among the 164 risk section it include also those in which the rockfall events have been recorded in the database and for which we have more information thank to the availability of database.

The topographical and morphological maps have been useful to identify the sections in which there aren't the rocks outcropping on the slope. These sections don't have a potential block release areas and so it haven't considered in the implementation of the method.

The study begins with the localization of rockfalls along the Amalfi Road (SS163) to identify areas where those are occurred and that would most likely affect the roadway. The 38 sections identified in the database are shown in Figure 5.12, that takes into account the kilometers in which the rock is hit and the type of rockfall that is occurred (rockfall of class A, B and C). For rockfalls belong to A and B classes, the events occurred during the 20 years from 1980 until 2000 have been considered, because as we can see from the temporal distribution of events (Figure 5.6) the database is more complete, while for the rockfalls C all the events in the database have been take into account. Once identified, all the sections have been rated relative to each other to determine which presented the greatest risk to the public. To accomplish this goal, a rating system was needed.

We are referred to the original method (Rockfall Hazard Rating System, Participants' Manual, Pierson and Van Vickle 1993), even if some modifications about the type of category and the rating have been carried out. The block size category hasn't estimated for lake of data. The climate and presence of water on slope is a redundant category, because it represents a triggering factor related with the rockfall frequency that represents the last category of method. For this reason this category has not been taken account.

Kilometres	**Number of rockfall events**		
	Class A	**Class B**	**Class C**
44,700	1	1	
41,600			1
39,250	1		
34,606			1
34,580			2
34,000	2	1	
29,650	1		
29,400	5	1	
29,300	1		
29,000	1		
28,100	1		
26,700	6	1	
26,420	2		
26,400	3	1	
26,350	1		
26,300	1		
25,500	2	1	
25,400	4		
25,300	7	2	
25,100	1		
24,200	1		
23,700	1		
23,200	1		
23,000	3	1	
22,900	2		
22,800	1		
22,600	1		
22,500	1		
22,200	1		
22,000	1		
21,050	1		
20,740	1		
19,150	1		
16,400	1		
14,850	1		
13,600	4		
12,200	4		
11,650	1		

Figure 5.12: Kilometres in which the rockfall events are occurred

The eight category and the modifications brought to each one of them are sequentially shown.

Slope height category

The slope height has been obtained considering the contour lines in the topographical map at 1:5000 scale. The representative rating is the same as the original method.

Category	Points 3	Points 9	Points 27	Points 81
Slope height	7,5 m	15 m	22,5 m	> 30 m

To estimate the detailed rating of the category score, the exponential function $y = e^{0,1465x}$ has been found by the values in benchmark criteria. The horizontal line indicates that for height larger than 30m the rating is constant and equal to 81 points.

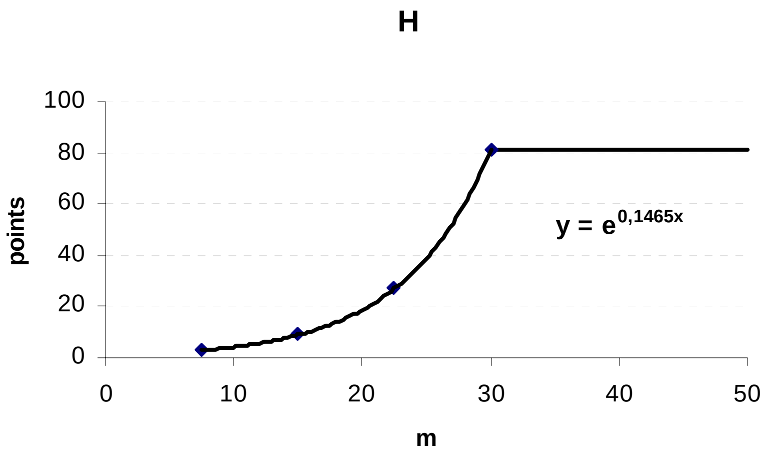


Figure 5.13: Exponential function for the score computations of slope height category in the RHRS method

Ditch Effectiveness Category

The studied sections of the road are without a ditch because there is a very little available space along the crossed fault scarp, so the rating of this category for each section is 81.

Category	Points 3	Points 9	Points 27	Points 81
Ditch effectiveness	Good catchment	Moderate catchment	Limited catchment	No catchment

Average Vehicle Risk (AVR) Category

With the AVR category, the risk associated with the percentage of time a vehicle is present in the rockfall section has been evaluated. The percentage is obtained by using the shown formula based on slope length, average daily traffic (ADT), and the posted speed limit at the site.

$$AVR = \frac{ADT \times SL}{PSP} \times 100\%$$

where ADT is the average traffic per day (vehicle/day); SL represents the hazard zone length in kilometres and it has been obtained with the help of the topographical and morphological maps and PSP is the posted speed limit (km/h). The results are based on the established benchmark criteria of the original method.

Category	Points 3	Points 9	Points 27	Points 81
Average vehicle risk (% of time)	25%	50%	75%	100%

The exponential function of the AVR category is $y = e^{0,0439x}$.

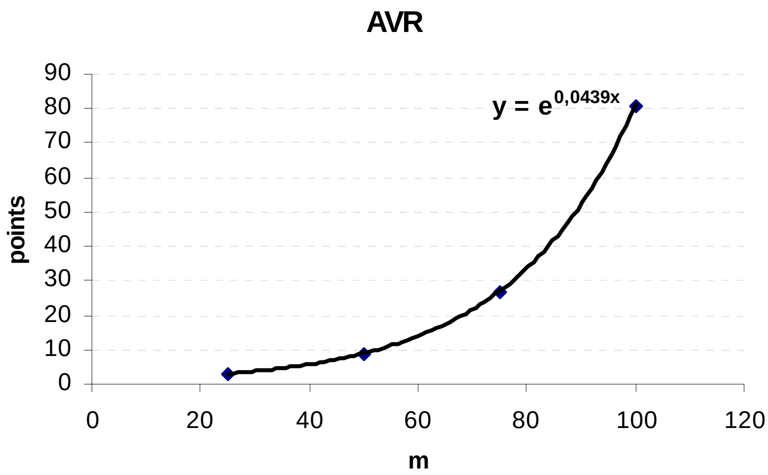


Figure 5.14: Exponential function for the score computations of the AVR category in the RHRS method

The value of AVR is different for each section because SL, PSP and ADT change. In particular, SL in many cases coincides with the length of the section, ADT is calculated from the equation previously described $y = -0{,}1517x^3 + 13{,}164x^2 - 334{,}78x + 3876{,}3$ entering in x the mean kilometre corresponding to the section.
PSP is variable in each section because it depends on the trend of road. In the sections in which there is a curve or an inflection or stretch rectilinear the velocity is respectively 30km/h, 40km/h and 50km/h.

Percent of decision sight distance

As mentioned above, the percent of decision sight distance (PDSD) is obtained by:

$$PDSD = (ASD / DSD) \times 100\%$$

The DSD represents the length of road a driver needs in order to make a complex or instantaneous decision; it depends on the speed and the urban, suburban, or rural environment. The Figure 5.15 shows the values for decision sight distance for several speed and avoidance maneuver (A: Stop on rural road, B: Stop on urban road, C: Speed/path/direction change on rural road, D: Speed/path/direction change on suburban road, E: Speed/path/direction change on urban road).

Metric (m)					
Speed (km/h)	**A**	**B**	**C**	**D**	**E**
50	70	155	145	170	195
60	95	195	170	205	235
70	115	235	200	235	275
80	140	280	230	270	315
90	170	325	270	315	360
100	200	370	315	355	400
110	235	420	330	380	430
120	265	470	360	415	470

Figure 5.15: Low design values for decision sight distance for selected avoidance manoeuvre

In this study the most recurrent cases are the last two one: E when the road pass thought the inhabited centre and D in the case in which the road doesn't in the inhabited centre. As velocity it is considered 30km/h or 40km/h or 50 km/h.
The benchmark criteria of the original method are the following:

Category	Points 3	Points 9	Points 27	Points 81
Decision sight distance	Adequate (100%)	Moderate (80%)	Limited (60%)	Very limited (40%)

If the PDSD is smaller than 40%, the correspondent score is 81.
The exponential function of the PDSD category is $y = 729e^{-0,0549x}$.

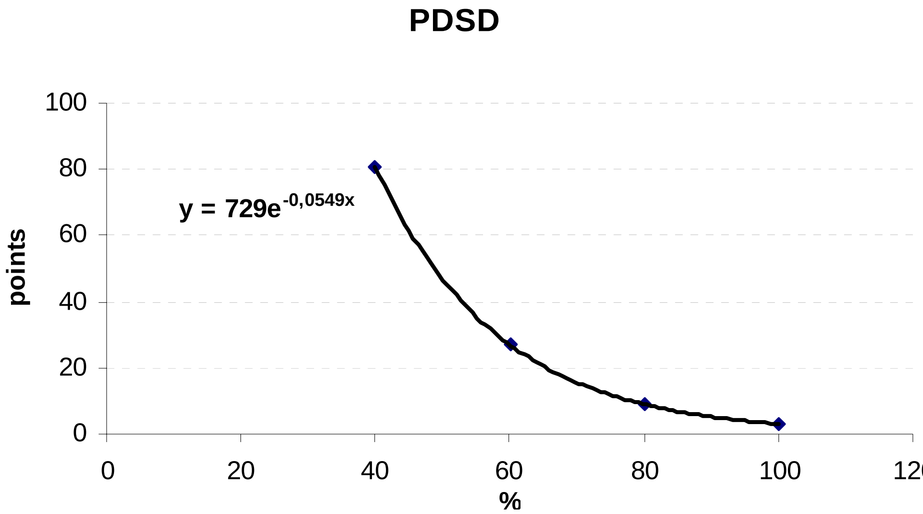


Figure 5.16: Exponential function for the score computations of the PDSD category in the RHRS method

Roadway Width Category

The roadway width is measured perpendicular to the highway centreline on the topographical map. It's variable for each section. The benchmark criteria are:

Category	Points 3	Points 9	Points 27	Points 81
Roadway width	13,20 m	10,80 m	8,40 m	6 m

The exponential function of this category is $y = 1262e^{-0,4678x}$.

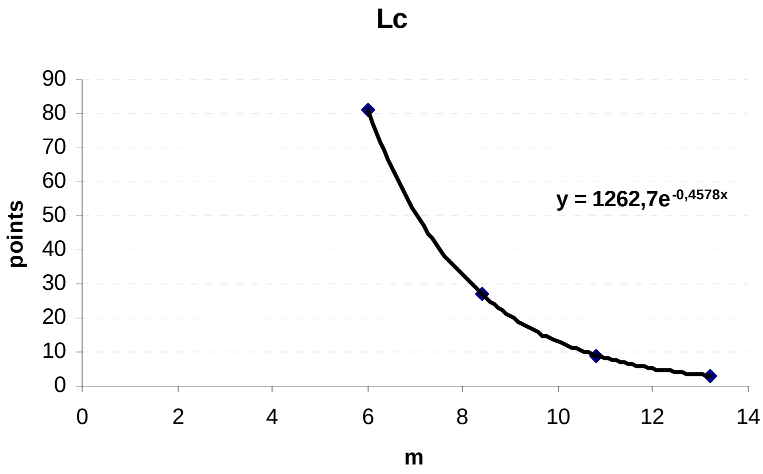


Figure 5.17: Exponential function for the score computations of the L_c category in the RHRS method

Geologic character

In the slopes of the study area differential erosion or oversteepening is the dominant condition that controls rockfall, so the second case has been considered. In particular the sum of 3 points and 9 points is assigned to this category.

Category			Points 3	Points 9	Points 27	Points 81
Geologic characteristics	Case 2	**Structural condition**	Discontinuous joints, favourable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
		Friction	Rough, irregular	Undulating	Planar	Clay infilling or slickenside
	Case 1	**Structural condition**	Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion features
		Difference in erosion rates	Small	Moderate	Large	Extreme

Volume of Rockfall per Event Category

This information is available only for the 38 section in which the rockfall events are occurred, so the volumetric classification from the database has been considered. In particular for rockfalls of class A which the representative volume is smaller than $1m^3$ the correspondent

rating is 9, for rockfalls of class B, between $1m^3$ and $10m^3$, the score is 27, finally for the events of class C, with volume bigger than $10m^3$ have been considered 81 points.
About the other section, it is hypothesized the occurrence at least of a rockfall A therefore the correspondent score results 9.

Category	**Points 3**	**Points 9**	**Points 27**	**Points 81**
Volume of rockfall events	-	Class A $<1m^3$	Class B $1m^3$-$10m^3$	Class C $>10m^3$

Rockfall frequency

The frequency is normalized describing in terms of the number of slides per length of source area / annum. The criteria used for assigned the score are the following:

Rockfall frequency	**value**	**points**
very high	>0,1	81
high	0,1-0,05	27
moderate	0,05-0,01	9
low	0,01-0,005	3
very low	<0,005	0

In the sections for which we haven’t rockfall events recorded in the database the frequency is very low.

Results of the RHRS Method

The total rating calculated for each section with the RHRS method is represented in Figure 6.1. It can observe that the most of the sections in which there are events recorded in the database have a high rating that is larger than 360 points, this is due to the frequency that affects greatly the final results.

The section with lower rating (196,26) is the number 15 (Figure 6.2) that it is located close to the urban centre of Erchie (from the 41,53 km to 41,73 km).

The section 78 is the most exposed to the risk with a score of 481, it is an elbow road characterized by the slope height of 75m. In this section three rockfall of class A and one of class B have been recorded in the database.

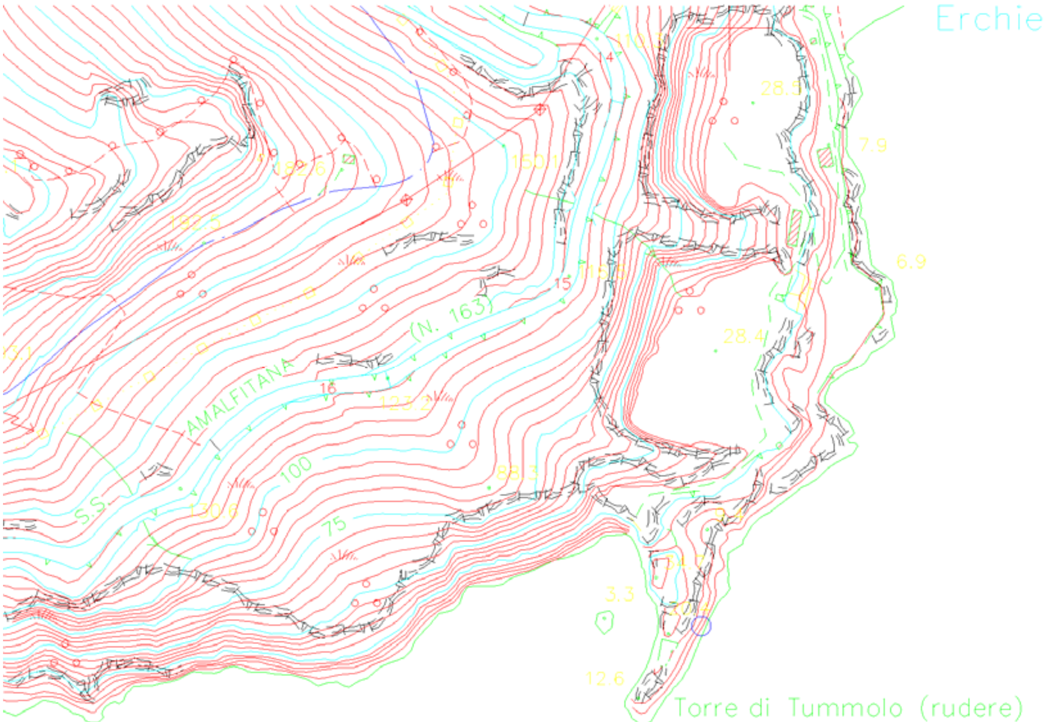


Figure 5.19: The section 15 with the lower rating in the RHRS method

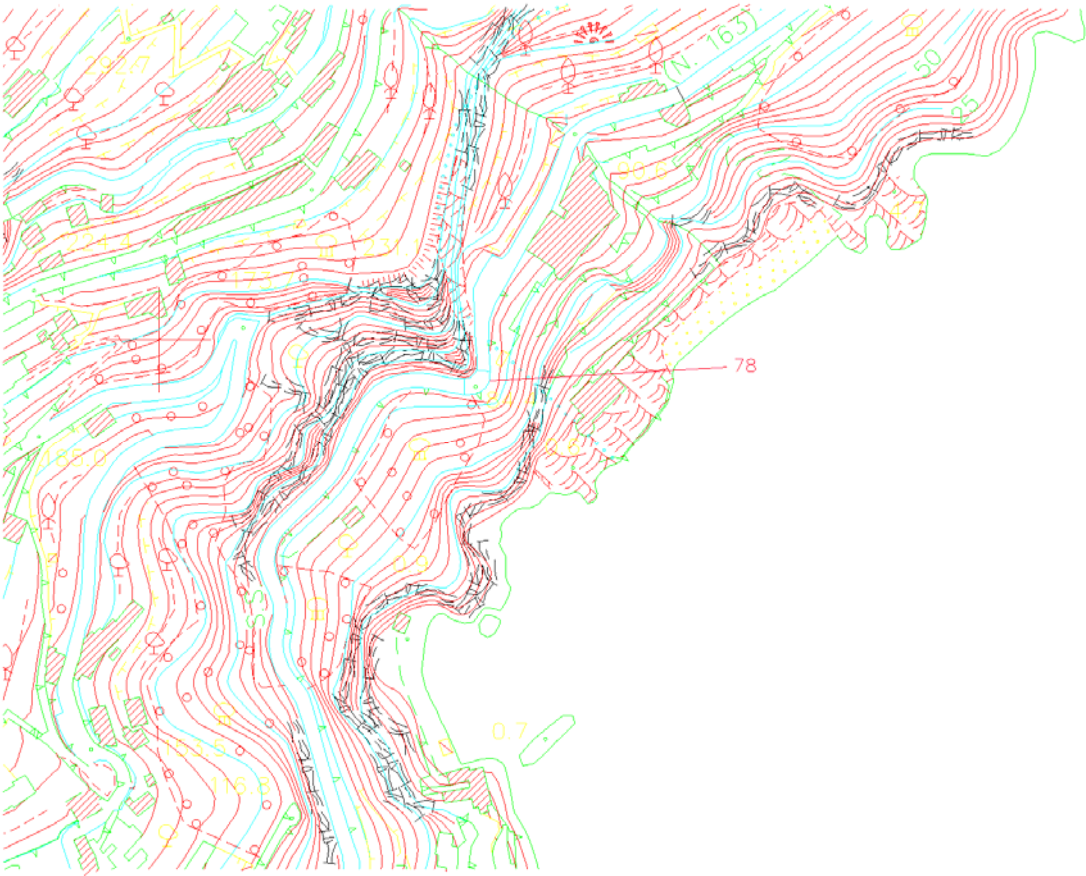


Fig. 5.20: Section 78, the most exposed to the rockfall risk (481 scores).

The tables below show the values of the categories that more affect the final rating and the respective scores for the section 15 and 78.

section	H	H score	AVR	AVR score	PDSD	PDSD score	frequency	frequ score	total rating
	m		%		%				
15	10	4,33	18,836	2,286	85,515	6,67	very low	0	**196,26**

section	H	H score	AVR	AVR score	PDSD	PDSD score	frequency	frequ score	total rating
	m		%		%				
78	75	81,000	5,568	1,277	36,191	81,00	very high	81	**481,28**

The difference in the total final score between all sections is manly due to frequency of rockfalls events. In fact, as described in the Figure…., the considerable reduction in the value of the frequency greatly affects the total rating of the sections. Also the category Percent of Decision Sight Distance, Average Vehicle Risk, Slope Height, volume of rockfall are more sensitive with respect to remaining categories.

In the RHRS's original method the slopes with scores lower than 300 are classified for remedial works with low urgency, whereas those higher than 500 need immediate stabilization measures. It would be better not to assign preestablished values, but in homogeneous areas for geological characteristics and traffic conditions to employ different remedial works whenever the relative scores have been assigned. Using a continuum of points allows flexibility in evaluating the relative impact of conditions that are variable by nature.

It is to be remembered that this method is a preliminary tool for mapping the road risk assessment and then to allow more detailed investigations with geotechnical and geomechanical stability analysis in dangerous areas. Further applications in other geological environments are needed to better check its suitability for rockfall risk assessment.

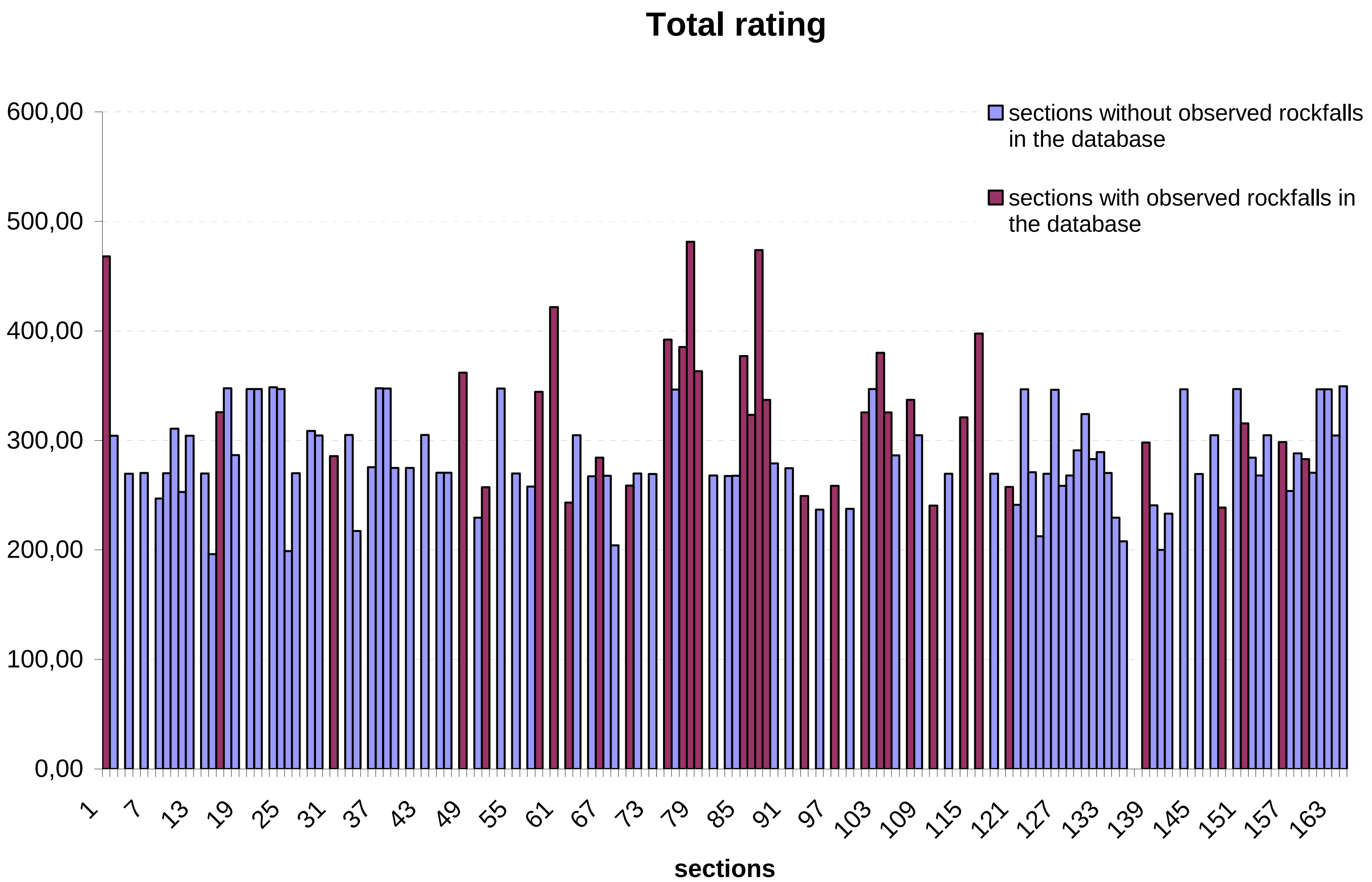


Figure 5.18: Total rating in the RHRS method

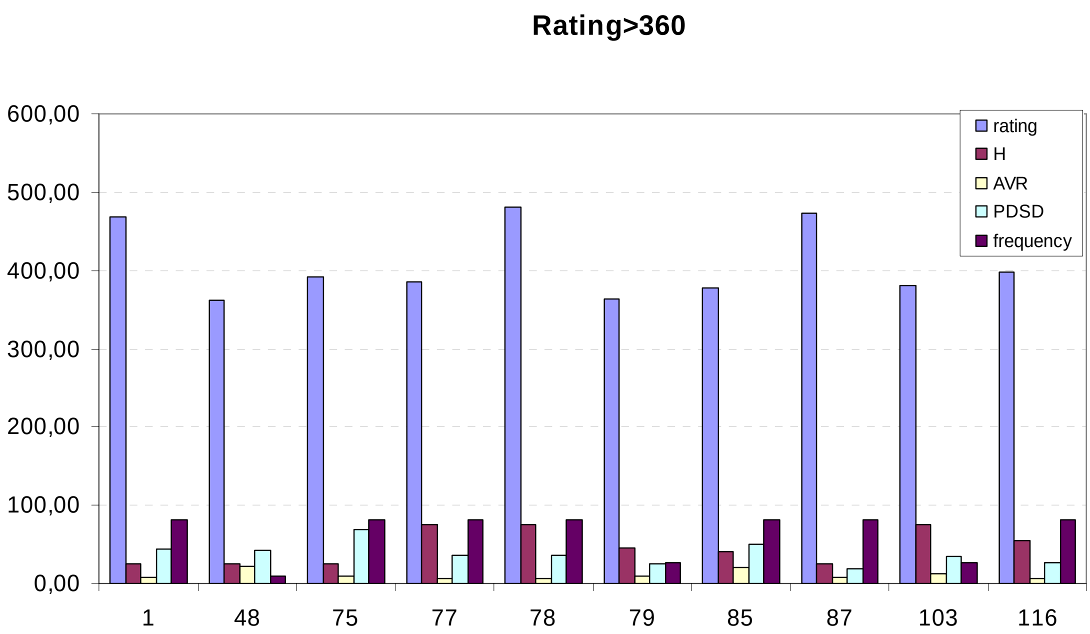
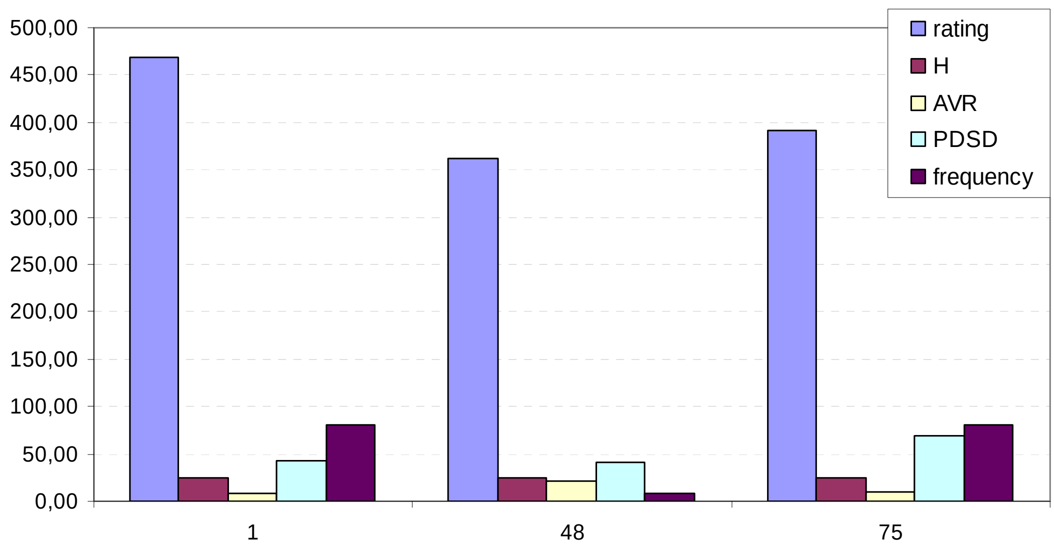


Figure 5.21: Section with rating larger than 360

In the following diagram it can see that the greater rating is that correspondent to the section number 1, for which the frequency score is 81. The rating is also affected by Average Vehicle at Risk (AVR), in fact if the slope height is constant in all three sections, where the AVR is relatively low the section gains high points, this is the case of section 1 that have the AVR of nearly 8%. In the section 75 instead the low percentage of (9,5 %) is set off against the value of Percentage Decision Sight Distance (PDSD). The section 48 has a rating lower than the other two sections because the AVR and PDSD have a medium value.



The piece of Amalfi road represented in the Figure 5.22 is the most hazardous; this is manly due to the trend of road.

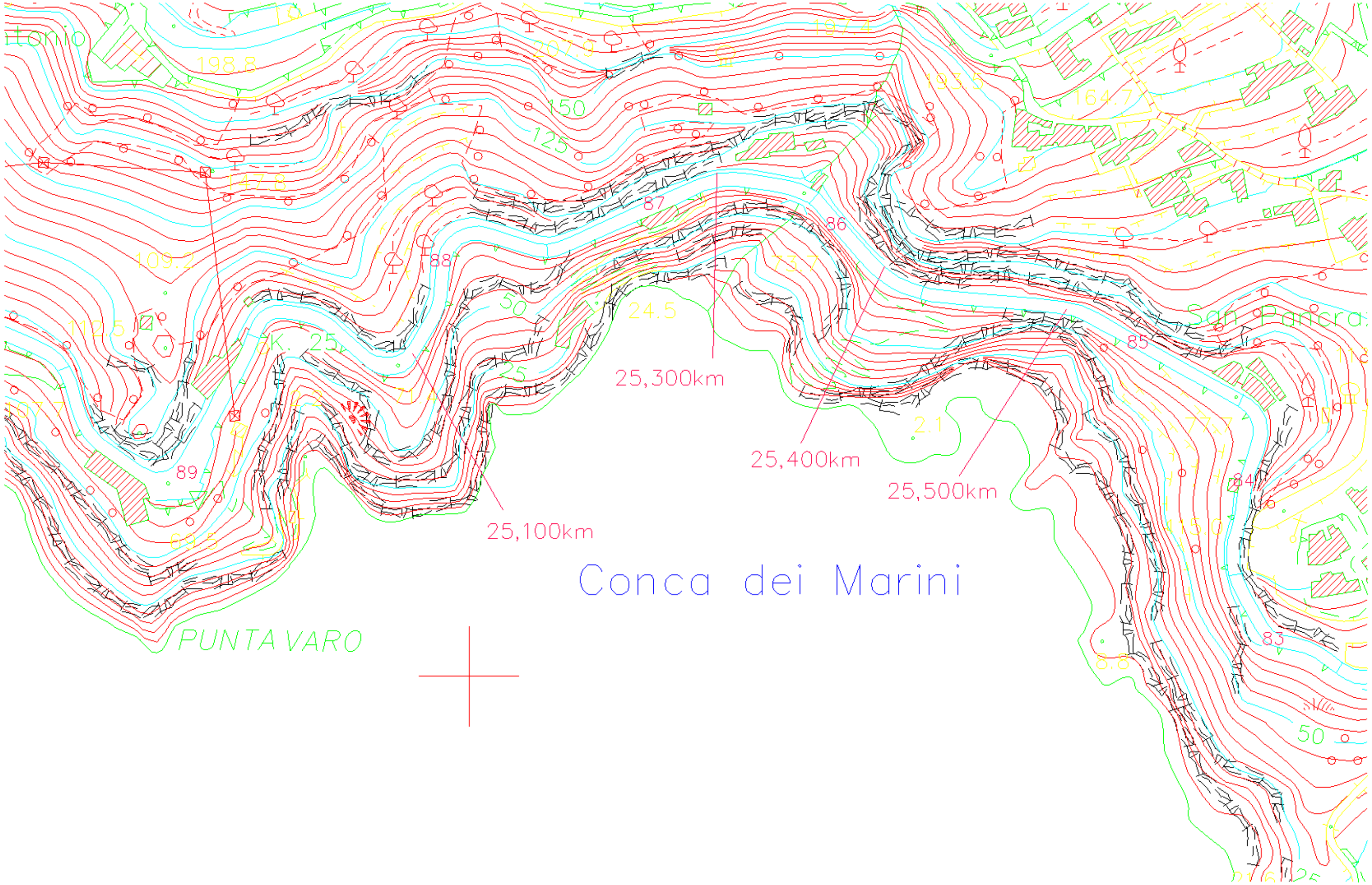


Figure 5.22: Section from 83 to 89 in Conca dei Marini

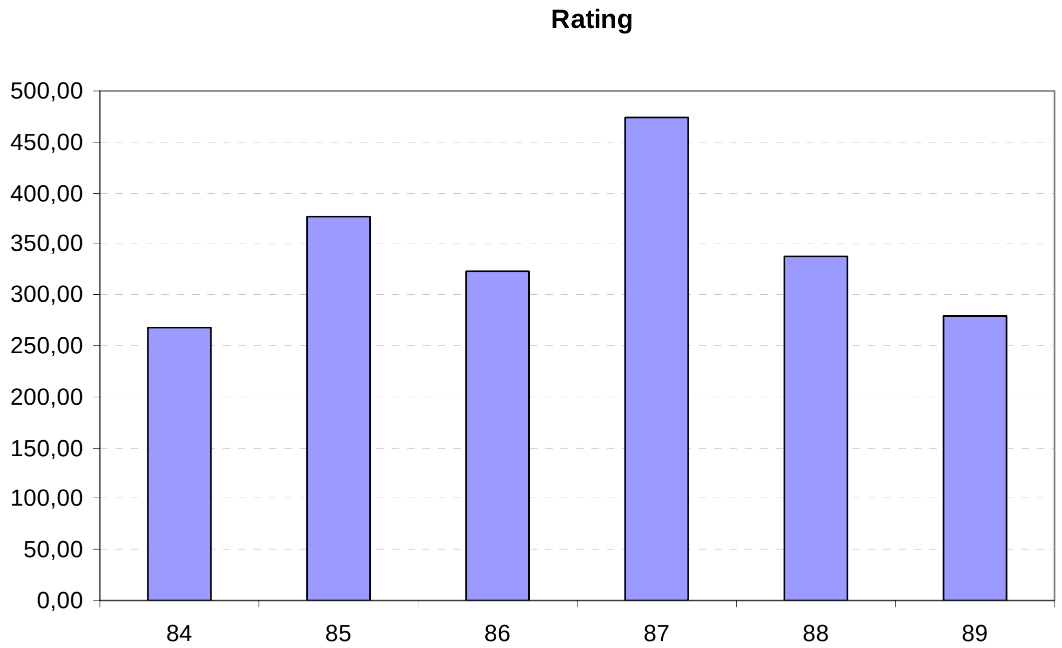


Figure 5.23: Total rating of section from 84 to 89 in Conca dei Marini

5.4. Quantitative Risk Assessment (QRA)

In this paragraph it will be calculating the risk to persons travelling on the highway along the Amalfi Coastal road by adopting the Quantitative Risk Assessment (Fell et al., 2005) and it will be assessing the tolerability of this risk against the tolerable risk criteria. It only considers direct impact falls. It will consider as way of running the most close to the slope.
First of all, it will be calculating the total risk along all the Amalfi coastal road, that it extent for 33,05 km, than this frequency will be normalizing and dividing by the kilometre of road in order to obtained the average risk; finally it will be calculating the risk along several section of the road that are differently exposed to the risk according to the results of the RHRS method. The latter step is important to compare both RHRS method and the QRA results.

5.4.1. Total risk assessment

- Frequency analysis

The total rockfall events along the Amalfi coastal road that are recorded in the database are 80 including 66 of class A, 10 of class B and 4 of class C. The frequency of rockfalls for each class results:

$$F_A = \frac{n_A}{\Delta t} \longrightarrow F_A = \frac{66}{20} = 3{,}30 / annum$$

$$F_B = \frac{n_B}{\Delta t} \longrightarrow F_A = \frac{10}{20} = 0{,}50 / annum$$

$$F_C = \frac{n_C}{\Delta t} \longrightarrow F_A = \frac{4}{200} = 0{,}02 / annum$$

where for the rockfalls of type A and B the period of records (Dt) is 20 years and for the events of class C is 200 years. The frequency in day results:

$$F_A = 0{,}00904 / day$$
$$F_B = 0{,}00137 / day$$
$$F_C = 0{,}00005 / day$$

- Consequence analysis

Once evaluated the frequency, it calculate for each rockfall class the temporal spatial probability $P_{(S:T)}$ of vehicles and the vulnerability of the persons in the vehicles $V_{(D:T)}$ in order to estimate the risk.
The probability of a vehicle occupying the length of road onto which the rock falls is given by:

$$P_{(S:T)} = \frac{N_V}{24} \times \frac{L}{1000} \times \frac{1}{V_V}$$

where:
N_V is the average number of vehicles/day
L is the average length of vehicle (metres)
V_V is the velocity of vehicle (km/hour)

From the available data on traffic intensity described in the paragraph 4.3, the average number of vehicles travelling in the Amalfi coastal road is 1560. The average length of the vehicles is 6 metres, and its velocity is 50 km/h, ignoring the width of the boulder.

$$P_{(S:T)} = \frac{1560 vehicles}{24h} \times \frac{6m}{1000} \times \frac{1}{50 km/h} = 0{,}0078$$

The vulnerability of the persons in the vehicles is based on published information and judgement, it is estimated that is 0,3.

The annual probability of the person most at risk losing his/her life by driving along the road is:

$$P_{(LOL)} = \left(1 - \left(1 - P_{(S:T)}\right)^{N_R}\right) \times V_{(D:T)}$$

and it is estimated for each rockfall class:

$$\begin{cases} P^A_{(LOL)} = \left(1 - (1 - 0{,}0078)^{0{,}00904}\right) \times 0{,}3 = 2{,}12 \cdot 10^{-5} \,/\, annum \\ P^B_{(LOL)} = \left(1 - (1 - 0{,}0078)^{0{,}00137}\right) \times 0{,}3 = 3{,}22 \cdot 10^{-6} \,/\, annum \\ P^C_{(LOL)} = \left(1 - (1 - 0{,}0078)^{0{,}00005}\right) \times 0{,}3 = 1{,}29 \cdot 10^{-7} \,/\, annum \end{cases}$$

The total probability of death for the person most at risk is the sum of the three probabilities above:

$$P_{(LOL)} = P^A_{(LOL)} + P^B_{(LOL)} + P^C_{(LOL)} = 2{,}46 \cdot 10^{-5} \,/\, annum$$

From Figure 5.11 shows the tolerable individual risk for existing slopes is $1 \cdot 10^{-4} \,/\, annum$, so the risk is within the tolerable limit.

Situation	Suggested tolerable risk for loss of life
Existing engineered slopes	10^{-4}/annum person most at risk
	10^{-5}/annum average of persons at risk
New engineered slopes	10^{-5}/annum person most at risk
	10^{-6}/annum average of persons at risk

Figure 5.11: AGS (2000) suggested tolerable risk criteria

5.4.2. Average risk assessment

It proceeds to assess the average risk considering the normalized frequency. The frequency is described in terms of the number of slides per length of the Amafi coastal road ($L_r = 33{,}05 km$).

$$F_A = \frac{n_A}{\Delta t \cdot L_r} \longrightarrow F_A = \frac{66}{20 \cdot 33{,}05} = 0{,}10 / annum$$

$$F_B = \frac{n_B}{\Delta t \cdot L_r} \longrightarrow F_A = \frac{10}{20 \cdot 33{,}05} = 0{,}02 / annum$$

$$F_C = \frac{n_C}{\Delta t \cdot L_r} \longrightarrow F_A = \frac{4}{200 \cdot 33{,}05} = 0{,}001 / annum$$

The frequency in day results:

$$F_A = 2{,}74 \cdot 10^{-4} / day$$
$$F_B = 4{,}14 \cdot 10^{-5} / day$$
$$F_C = 1{,}66 \cdot 10^{-6} / day$$

The probability of a vehicle occupying the length of road onto which the rock falls and the vulnerability of the persons in the vehicles have the same value of the precedent analysis and are $P_{(S:T)} = 0{,}0078$ and $V_{(D:T)} = 0{,}3$.

The annual probability of the person most at risk losing his/her life by driving along the road is for each rockfall class is:

$$P_{(LOL)} = \left(1 - \left(1 - P_{(S:T)}\right)^{N_R}\right) \times V_{(D:T)}$$

$$\begin{cases} P^A_{(LOL)} = \left(1 - (1 - 0{,}0078)^{2{,}74 \cdot 10^{-4}}\right) \times 0{,}3 = 6{,}43 \cdot 10^{-7} / annum \\ P^B_{(LOL)} = \left(1 - (1 - 0{,}0078)^{4{,}14 \cdot 10^{-5}}\right) \times 0{,}3 = 9{,}74 \cdot 10^{-8} / annum \\ P^C_{(LOL)} = \left(1 - (1 - 0{,}0078)^{1{,}66 \cdot 10^{-6}}\right) \times 0{,}3 = 3{,}90 \cdot 10^{-9} / annum \end{cases}$$

The probability of death for the person most at risk is:

$$P_{(LOL)} = P^A_{(LOL)} + P^B_{(LOL)} + P^C_{(LOL)} = 7{,}4 \cdot 10^{-7} / annum$$

It can observe that this probability is lower than that total, because in this case the normalized frequency is lower than the total frequency.

5.3.3. Risk assessment for sections

According to the results of the Rockfall Hazard Rating System method three pieces of road have been considered. They include three sections of the RHRS method and are:

- the section in which the rating is major (section *a*)
- the section with average rating (section *b*)
- and the section with a lower rating (section *c*)

❖ Section *a*:

The section most exposed to the risk in the Rockfall Hazard Rating System is the 78. The section *a* go from 26,1 km to 26,8 km and represents a part of the road between the section 75 and 81 in the RHRS method. It have a length of $L_r = 0{,}70km$ and there aren't recorded rockfall events belong to class C.
The normalized frequency is:

$$F_A = \frac{n_A}{\Delta t \cdot L_r} \longrightarrow F_A = \frac{12}{20 \cdot 0{,}70} = 0{,}86 / annum$$

$$F_B = \frac{n_B}{\Delta t \cdot L_r} \longrightarrow F_B = \frac{3}{20 \cdot 0{,}70} = 0{,}21 / annum$$

and the frequency in day results:

$$F_A = 2.35 \cdot 10^{-3} / day$$
$$F_B = 5{,}84 \cdot 10^{-4} / day$$

From the available data on traffic intensity described in the paragraph 4.3, the average number of vehicles travelling in this section is 1423, so the probability of a vehicle occupying the length of road onto which the rock falls is:

$$P_{(S:T)} = \frac{1423 vehicles}{24h} \times \frac{6m}{1000} \times \frac{1}{50km/h} = 0{,}0071$$

The vulnerability of the persons in the vehicles is based on published information and judgement, it is estimated that is 0,3. The annual probability of the person most at risk losing his/her life by driving along the road is for each rockfall class is:

$$P_{(LOL)} = \left(1 - \left(1 - P_{(S:T)}\right)^{N_R}\right) \times V_{(D:T)}$$

$$\begin{cases} P^A_{(LOL)} = \left(1 - \left(1 - 0{,}0071\right)^{2{,}35 \cdot 10^{-3}}\right) \times 0{,}3 = 5{,}03 \cdot 10^{-6} / annum \\ P^B_{(LOL)} = \left(1 - \left(1 - 0{,}0071\right)^{5{,}84 \cdot 10^{-4}}\right) \times 0{,}3 = 1{,}26 \cdot 10^{-\text{¡}6} / annum \end{cases}$$

The total probability of death for the person most at risk is:

$$\boxed{P_{(LOL)} = P_{(LOL)}^{A} + P_{(LOL)}^{B} = 6{,}3 \cdot 10^{-6} / annum}$$

- Section *b*:

The section *b* go from 31 km to 29,3 km and represents a part of the road between the section 53 and 58 in the RHRS method, where the section with a average rating is the number 53. It have a length of $L_r = 0{,}70 km$ in which there are recorded only a rockfall events of class A. The normalized frequency is:

$$F_A = \frac{n_A}{\Delta t \cdot L_r} \longrightarrow F_A = \frac{1}{20 \cdot 0{,}70} = 0{,}0071 / annum$$

The frequency in day results:

$$F_A = 1{,}95 \cdot 10^{-5} / day$$

the average number of vehicles travelling in this section is 1568, the vulnerability of the persons in the vehicles is 0,3 and the probability of a vehicle occupying the length of road onto which the rock falls is:

$$P_{(S:T)} = \frac{1568 vehicles}{24h} \times \frac{6m}{1000} \times \frac{1}{50 km/h} = 0{,}008$$

The annual probability of the person most at risk losing his/her life by driving along the road is for each rockfall class is:

$$P_{(LOL)} = \left(1 - \left(1 - P_{(S:T)}\right)^{N_R}\right) \times V_{(D:T)}$$

$$\boxed{P_{(LOL)} = \left(1 - (1 - 0{,}008)^{1{,}95 \cdot 10^{-5}}\right) \times 0{,}3 = 4{,}62 \cdot 10^{-7} / annum}$$

- Section *c*:

The section with a lower rating in the Rockfall Hazard Rating System is number 15. The section *b*, that go from 40,89 km to 41,82 km, represents a part of the road between the section 14 and 18 in the RHRS method. It has a length of $L_r = 0{,}97 km$ and only a rockfall of class C is recorded in the database.

The normalized frequency is:

$$F_C = \frac{n_C}{\Delta t \cdot L_r} \longrightarrow F_A = \frac{1}{200 \cdot 0{,}70} = 0{,}007 / annum$$

The frequency in day results:

$$F_C = 1{,}96 \cdot 10^{-5} / day$$

The average number of vehicles travelling in this section is 1809 and The probability of a vehicle occupying the length of road onto which the rock falls is:

$$P_{(S:T)} = \frac{1809 vehicles}{24h} \times \frac{6m}{1000} \times \frac{1}{50km/h} = 0{,}0090$$

The vulnerability of the persons in the vehicles is always based on published information and judgement, it is estimated that is 0,3.

The total probability of death for the person most at risk is:

$$P_{(LOL)} = \left(1 - \left(1 - P_{(S:T)}\right)^{N_R}\right) \times V_{(D:T)}$$

$$\boxed{P_{(LOL)} = \left(1 - \left(1 - 0{,}009\right)^{1{,}41 \cdot 10^5}\right) \times 0{,}3 = 5{,}3 \cdot 10^{-8} / annum}$$

Summing up the result is:

RHRS method		QRA	
section	rating	section	risk
78	481,28	*a*	$6{,}3*10^{-6}$
53	347,45	*b*	$4{,}62*10^{-7}$
15	196,26	*c*	$5{,}3*10^{-8}$

From the table above the two methods, Rockfall Hazard Rating System and the Quantitative Risk Assessment method can be compared. The values of the risk for each section are congruent with the respective rating.

The observed risk with the RHRS method changes in a range between 481,28 and 196,26 scores. The risk for the section is nearly to the average risk considering the normalized frequency ($7{,}4 \cdot 10^{-7} / annum$), but there are same sections in which the risk is an order of size major, for those sections it is possible to implement mitigation measures like the construction of protection fences.

6. Conclusion

The work described has provided a procedure to calculate the risk of rockfall activity in the Amalfi Coast, in particular along the provincial Amalfi road (SS163) that is the important transportation corridor of this area and support a very high movement as well as tourist traffic. The whole road go through a landscape characterized by interrupted sequences of natural rock cliffs and it follows the planoaltimetric development of the coast therefore it's very tortuous.
A database of rockfall incidents occurred in the study area from the beginning of the 19th century until 2001 have been available. The documentary sources contain information about data of occurrence, triggering factors, injuries and damage, localization of both the source and the deposit area.
Thanks to the information of the database it was possible localize of rockfall events in the topographical map at 1:5000 scale in order to identify the areas which historically effected by rockfalls of different magnitude. Subsequently the analysis of the rockfall hazard will be implementing with the establishment of a rockfall Frequency-Magnitude relationship in the threatened area.
In some years there are no recorded events, because of the lack of data or the loss of the documentary source. The majority of the data come from the last 20 years, because in this period the record of the events is increase thank to the birth of new local authority and to highest attention at the rockfalls.
Several rockfall events increase corresponding to the period of road construction and in summer. This is probably due to greater flow of tourists in the area, as the Amalfi Coast an important tourist destination of the Campania Region. Stone falls of small size usually do not capture public attention and remain unnoticed. These small events, however, have little impact.
The method of RHRS has been applied to nearly 33,91 km of Amalfi road. The total road has been divided in 164 sections each characterized by different values of categories that has been considered in the method. Once identified, all the sections have been rated relative to each other to determine which presented the greatest risk to the public. This method of score consists in a relative risk assessment and the objective is the achievement of a numerical value that indicates the level of risk for each section of the road in order to make their comparison.
From the total rating calculated for each section with the RHRS method it can observe that the most of the sections in which there are events recorded in the database have a high rating that is larger than 360 points, this is due to the frequency that affects greatly the final results.
The section 78 is the most exposed to the risk with 481 scores, it is an elbow road characterized by the slope height of 75m. In this section three rockfall of class A and one of class B have been recorded in the database.
is larger than 360 points, this is due to the frequency that affects greatly the final results.
In the total rating the frequency has a lot of influence in the result which it does make sense. Low rockfall frequency values are associated to low rating of the RHRS in all the studied sections. Besides the frequency, the Percent of Decision Sight Distance, Average Vehicle Risk, Slope Height, and volume of rockfall are most influencing factors.
The method can be applied in mapping the rockfall risk thus allowing the identification of the most dangerous stretches that require protection works.
The results provide a rational way to take decisions on where and how to spend construction funds for rock slope projects.

The conditional probability distribution for consequence if a mass of a particular magnitude remains in the roadway has been determined for each roadway section.

The Conditional Consequence (Vulnerability) Model consists of calculating the probability distribution for the number and severity of casualties for each particular hazard, that is represent the volume of rock fall remaining in the road.
Risk can be reduced by reducing the vulnerability. The vulnerability is a function of: a) the number of vulnerable elements potentially affected by a particular landslide; b) the probability that they will intersect the landslide ground movement, both spatially and temporally; and c) their damage functions with respect to ground movement. Hence, vulnerability can be reduced in the following ways:

- decrease the probability that vulnerable elements will both spatially and temporally intersect ground movement, by:
  - moving non-stationary vulnerable elements to less hazardous locations
  - increasing awareness, detection, and warning of hazards (either detected movement or trigger conditions), and subsequent avoidance (evacuation or temporary exclusion, followed by inspection before resuming normal use)

- decrease damage functions for vulnerable elements with respect to ground movement, by:
  - strengthening or increasing resistance to ground movement
  - emergency plan for once initial (direct) damage has occurred to prevent follow-on consequences
  - insurance

The optimal vulnerability reduction program depends on the application, and is a function of the cost (including financial and socioeconomic) and effectiveness of implementing the various possible approaches. Such costs can typically be reasonable estimates directly, whereas the effectiveness (or benefit) typically must be evaluated in terms of subjectively assessed specific changes in particular vulnerability factors and then an analysis of how those changes reduce risks (e.g. using the same risk model).

With the Quantitative Risk Assessment (QRA) method it estimated the risk to persons travelling on the highway and assessed the tolerability of this risk against the tolerable risk criteria, considering only direct impact falls.
The total probability of death for the person most at risk due to direct impact is $2{,}43 \cdot 10^{-5}\,/\,annum$. This value is within the tolerable limit.
The two methods, Rockfall Hazard Rating System and the Quantitative Risk Assessment method, can be compared. The values of the risk for each section are consistent with the frequency of the rockfalls and with the visibility of the fallen debris that controls the avoidance of the vehicle collision.

The two methods, Rockfall Hazard Rating System and the Quantitative Risk Assessment method, can be compared. The values of the risk for each section are congruent with the respective rating. The results show that the greater risk is related to the section presenting higher rating; the smaller risk corresponds to the section with a lower rating; finally the sections with the rating values between 481,28 (greater rating) and 196,26 (smaller rating) present the risk ranging from to $6{,}3 \cdot 10^{-6}$ (higher risk) to $5{,}3 \cdot 10^{-8}$ (lower risk).

QRA requires further improvements because the exiting database has some uncertainties and it’s no complete. It can implement some preventive measures like the periodic reconnaissance of the whole cliff area. Helicopter flights are programmed on annual basis with the purpose of detecting precursory signs of instability of any large rock mass that could facilitate the adoption of preventive and evacuation measures ahead of time.

In order to reduce risk along the Amalfi coastal road, it is possible implement mitigation measures like the construction of protection fences. The protective structures should be the woven wire-rope nets or rockfall fences. The method of selecting the appropriate fence should be base on the results of the simulated energies and rebound heights with the Eurobloc code (Lopez et al. 1997; Copons et al. 2001). Rockfall fences cannot provide absolute protection to the element at risk. Therefore it is necessary to evaluate the efficiency of the rockfall barriers and the residual risk.

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Index of the figures

Index