Chapter 6
Review and Advances in Methodologies for Rockfall Hazard and Risk Assessment

Olga-Christina Mavrouli, Jacoppo Abbruzzese, Jordi Corominas, and Vincent Labiouse

Abstract This section reviews the current methodologies that are used for the assessment of the rockfall susceptibility, hazard and risk. Emphasis is given on quantitative methods although qualitative ones are also discussed. The different methodologies are presented with respect to their application scales (regional, local or site-specific). Highlight is given to recent advances, especially involving the consideration of the magnitude of the events and the intensity of the phenomena at selected locations as well as the incorporation of a quantitative vulnerability into the risk equation.

Abbreviations

RHV	Rockfall Hazard Vector
RHAP	Rockfall Hazard Assessment Procedure
QRA	Quantitative Risk Assessment

O.-C. Mavrouli (✉) • J. Corominas
Department of Geotechnical Engineering and Geosciences, Technical University of Catalonia, BarcelonaTech, Jordi Girona 1-3, SP-08034 Barcelona, Spain
e-mail: olga-christina.mavrouli@upc.edu

J. Abbruzzese • V. Labiouse
Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory for Rock Mechanics (LMR), Station 18, CH-1015 Lausanne, Switzerland

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6.1 Introduction

Risk assessment is increasingly becoming an important tool for the decision-taking in rockfall threatened areas, with regard to the urban or rural zoning and the application of protection measures for the protection of people and infrastructures. For the risk assessment, both hazard and vulnerability components are involved and have to be evaluated. The expression of the hazard and vulnerability of the exposed elements and their superposition in order to yield risk results, as well as the terms in which the risk is expressed define whether the assessment is qualitative or quantitative. Distinct methodologies apply to each case. On one hand, the use of qualitative methods is based on the evaluation of the hazard and vulnerability components using descriptive rankings (for example low, moderate, high), weighted indexes and numerical classification systems leading, accordingly, to descriptive and ordinal risk expressions. On the other hand, quantitative methods use numerical scales or ranges of values that incorporate and express the annual probability of occurrence of a given magnitude rockfall event, or the probability of an expected level of loss, either it refers to economical loss (e.g. risk expressed in €·year^{-1}) or to injury and death of people (expressed in fatalities·year^{-1}).

Qualitative and quantitative methods may be simultaneously or alternatively used, depending on the scale and the objective of the analysis as well as the quality of the input data. Depending on the scale of the analysis more or less sophisticated empirical and analytical models may be used to simulate realistically the rockfall phenomenon during all its stages. These stages mainly include the rockfall detachment from slope face, the possible fragmentation of the detached rock mass upon impact with the ground, the propagation of the rock blocks down the slope and the spatial distribution of their intensity, the potential reach up of the blocks to the exposed elements and impact on them, and, last but not least, the potential loss (property damage or fatality) in case of impact.

To incorporate all the afore-mentioned stages into the risk assessment, the effect of each one of these processes has to be, separately, measured and expressed. To this purpose some key-components of risk, which present a complexity in their measurement and expression have to be investigated. These components mainly are: (i) the rockfall frequency-magnitude (volume) relation that provides results on the number of given rockfall volumes, (ii) the fragmentation effect, which is expressed by the frequency-size distribution of the rockfall mass on its impact with the ground and its separation into blocks that follow independent trajectories, (iii) the spatial distribution of the rockfall intensity, (iv) the vulnerability of the exposed elements and especially of the buildings, considering that it depends on the magnitude (volume) and intensity (velocity) of the rockfalls and incorporating uncertainties relevant to the impact location of the rock on the building, that have a crucial influence on the level of damage.

This section is organized so as to distinguish between hazard and risk assessment methodologies at different scales, respectively. An emphasis is given on the methodologies for the quantitative assessment and the relevant achievements in the framework of the Mountain Risks project are explained.

6.2 Methodologies for Rockfall Hazard Assessment and Zoning

Many different approaches to rock fall hazard assessment and zoning are currently available, and the choice of the most appropriate methodology to be used depends on the purpose (susceptibility, hazard, risk), the scale (regional, local, site specific) and the intended level of detail (preliminary, detailed, advanced) required for the study. In addition, other factors such as time, funds and amount/quality of data may play an important role when deciding which methodology should be applied.

Despite the variety of possible approaches for hazard assessment and zoning, current procedures are not fully satisfying, due to the several uncertainties affecting hazard analyses, particularly for what concerns detailed studies at the local scale. These uncertainties do have an influence on the results, and further work is therefore necessary in order to achieve more objective and reliable hazard zoning.

The following Sections give an overview on both methodologies suitable to regional scale studies and methodologies which can be used at the local scale – the interested reader can find more detailed descriptions of these methodologies in Labiouse and Abbruzzese (2011). Then, uncertainties affecting current procedures are briefly outlined, and finally some new developments towards a more objective and rigorous methodology for rock fall hazard zoning are introduced.

6.2.1 Methods for Rockfall Susceptibility Assessment and Zoning at the Regional Scale

Regional scale zoning is obtained starting from rough input data, and provides a quick yet effective detection of possible conflicts between the rock fall run-out zone and the current or future land use over a given territory, allowing the establishment of which areas must be given priority for detailed zoning at the local scale.

The most common approaches usually allow at first for identifying potential unstable areas, according to quick criteria (e.g. slopes defined as unstable if steeper than 45°, as computed from DEMs). Then, the potential run-out of the process can be evaluated using simplified propagation models (Jaboyedoff and Labiouse 2003; Ruff and Rohn 2008), which can be easily implemented in Geographic Information Systems. One of the most common approaches for evaluating rock fall run-out and performing zoning is the 'energy line' method (Heim 1932). According to this method, the maximum predicted run-out distance travelled by a block along a 2D slope profile is given by the intersection of the topography with a line starting either from the location of the rock fall source (Fahrböschung method – Heim 1932), or from the highest point of the talus slope (shadow angle method – Evans and Hungr 1993), and inclined at an angle φ with respect to the horizontal (marked in Fig. 6.1 as φ_F for the former model and φ_S for the latter). The method can also be extended to 3D analyses, e.g. the 'cone method' (Jaboyedoff and Labiouse 2003, 2011). In this

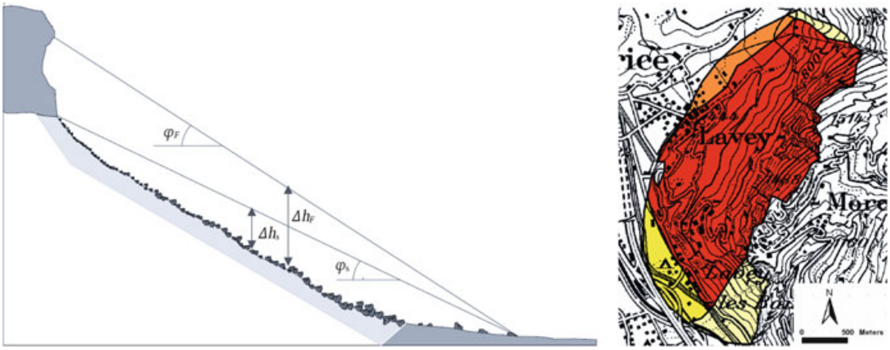

Fig. 6.1 Energy line method. *Left*: 2D definition of the Fahrböschung φ_F and of the shadow angle φ_S (from Abbruzzese 2011). *Right*: example of zoning performed in 3D with the 'cone method' (from Jaboyedoff and Labiouse 2003)

case, the energy line becomes a cone (the location of the cone apex depends on which model is adopted, Fahrböschung or shadow angle) and the areas potentially affected by rock fall trajectories are delineated by the intersection of the cone surface with the 3D topography.

Based on this method, maps representing the degree of run-out susceptibility (rather than hazard, as the failure frequency is not taken into account) can be derived. The obtained maps somewhat differ depending on the variant considered for the run-out model (e.g. Fahrböschung or shadow angle method), and/or because several energy lines may be used, associated to different block volumes (APB 2008) or to different values of probability of reach (Copons 2007). A match between modelled and observed run-out can also be considered, for determining 'proved', 'inferred' and 'potential' run-out zones (Jaboyedoff and Labiouse 2003, 2011).

6.2.2 Methods for Rockfall Hazard Assessment and Zoning at the Local Scale

In those areas where conflicts exist between the potential rockfall run-out and the location of human settlements, as a result of regional scale susceptibility analyses, more detailed hazard analyses are required, for an appropriate land use planning aiming at preserving human lives and properties.

Also at the local scale, a variety of approaches is available for tackling this objective. These approaches can be mostly divided into qualitative and quantitative methods, and some can be used for regulating land use planning for urban development (OFAT/OFEE/OFEFP 1997; MATE/METL 1999; Altimir et al. 2001; Raetzo et al. 2002; Copons 2007), while others are better suited to assessing hazard and/or risk along infrastructures (Pierson and Van Vickle 1993; Hoek 2007; Sasaki et al. 2002).

Qualitative methods mainly rely on expert's advices and/or on semi-quantitative rating-based analyses, while quantitative methods may be based on magnitude-frequency relationships (when more oriented to the characterisation of the hazard at the source area), and/or on trajectory modelling, for describing in detail the potential run-out of the process and its intensity. However, only a few approaches combine frequency and intensity (expressed for rock falls in terms of kinetic energy), as hazard analyses should in fact foresee, according to current definitions of hazard discussed at the international level (IUGS 1997; Fell et al. 2005, 2008; MR 2010). Among all the approaches presented in this Section, therefore, particular attention is paid to quantitative hazard assessment methodologies based on trajectory modelling, that combine rock fall intensity and frequency, and that are used for regulating urban development.

6.2.2.1 Qualitative Approaches

'Expert evaluation approaches' can be divided in two types (Aleotti and Chowdhury 1999): methods based on field geomorphological analyses and methods overlapping several index maps (with or without weighting) in GIS environment.

The LPC method (Interreg IIc 2001; LCPC 2004) provides a purely qualitative, expert's advice-based description of potentially unstable cliffs and associated hazards. At first, potential sources of instabilities are identified according to geological, geometric, geomechanical, topographic and environmental features of the cliff. Based on this information, the hazard is then defined as a function of the volume of the unit block after fragmentation and as a function of the likelihood with which an event producing this block volume occurs within a given reference time. Finally, a qualitative estimate of the run-out determines the likelihood of a given point to be reached by one block.

The Rock Engineering System (RES) method (Mazzoccola and Hudson 1996; Interreg IIc 2001) is based on the General System Theory, which is made for solving numerous high complexity problems in rock mechanics. This approach foresees the definition of the relevant parameters for rock fall hazard assessment and the study of cause-effect relationships between them, as well as of the relative importance of each parameter on hazard.

The R3S2 method (Mölk et al. 2008), proposed in Austria for a preliminary detection of conflicts between rockfall run-out and urban settlements, uses a combination of rating system and empirical run-out model. Once field investigations have been carried out for identifying potential rock fall sources, the shadow angle method is applied in order to delineate the rock fall run-out zone. If run-out zone and areas of urban settlements overlap, a rating system is used for determining the severity of the risk potentially affecting the settlements, based on the scores assigned to factors and parameters influencing rock fall probability of occurrence and potential damages. In particular, on the basis of a 'Frequency/Consequence' diagram, the study area can be characterised by a tolerable risk, or be classified as 'rock fall indication zone' (e.g. a zone requiring more detailed hazard analyses) or be characterised by an unacceptable risk.

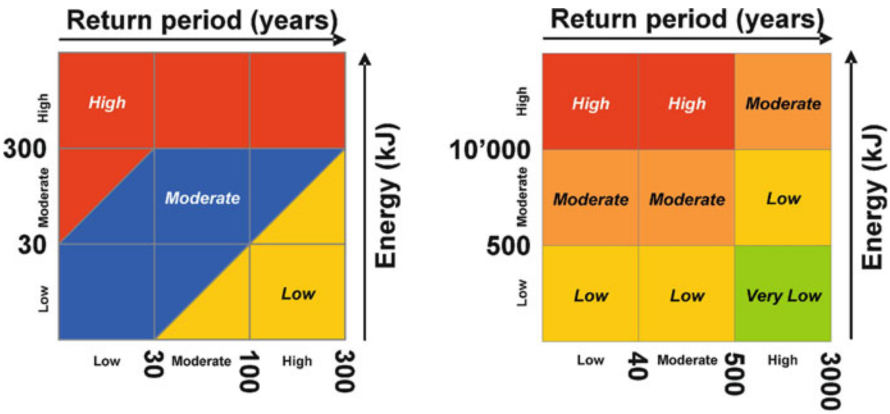

Fig. 6.2 Intensity-frequency diagrams for rock fall hazard zoning. *Left*: Swiss diagram (OFAT/OFEE/OFEFP 1997). *Right*: diagram used in the Principality of Andorra (Copons 2007)

6.2.2.2 Quantitative Approaches

Quantitative approaches are mostly based on rockfall trajectory modelling. Some of them combine intensity and frequency of occurrence according to the definition of hazard (Rouiller et al. 1998; Jaboyedoff et al. 2005; Copons 2007), while others do not really account for one of these parameters (frequency or energy), but may account for others, such as the cliff activity (Mazzoccola and Sciesa 2000) or the height of rebound of the boulders (Crosta and Agliardi 2003; Lan et al. 2007). Examples of procedures combining intensity and frequency are the Matterock and Cadanav methodologies, developed in Switzerland, and a methodology called 'Eurobloc', proposed in the Principality of Andorra.

The Matterock methodology (Rouiller et al. 1998), applied in the Canton of Valais in Switzerland according to the Swiss Codes for hazard zoning (OFAT, OFEE, OFEFP 1997), combines a detailed characterisation of the rockfall departure zone with 2D trajectory simulations. The study of the cliff aims at qualitatively determining a likelihood of mobilisation of the rock mass, depending on factors influencing the stability of the cliff. The propagation is studied on the other hand by means of rockfall trajectory modelling, which allows for determining the probability of reach of the blocks each point of the 2D slope profile, and their kinetic energy. The probability of reach and the likelihood of mobilisation are then combined, in order to obtain a likelihood of occurrence of the event, classified into three categories (low, moderate, high). The rockfall energy is given at each point of the profile by the 90th percentile of the energy distribution values computed at that abscissa with respect to the total number of simulated trajectories. The energy is also classified as low, moderate and high, according to the threshold values reported in the Swiss intensity-frequency diagram (Fig. 6.2). This diagram is finally used for superposing the information on energy and frequency (e.g. inverse of the return period, expressed in this methodology as a likelihood of occurrence) and for determining therefore the corresponding hazard degree, classified as low, moderate or high.

The Eurobloc methodology (Copons 2007), complying with the guidelines proposed in the Principality of Andorra for hazard zoning (Altimir et al. 2001; Copons 2007), combines frequency of the events and energy as follows. The frequency is determined from the analysis of historical data and from field investigations, which allow for estimating return periods associated to specific rockfall volume classes. This frequency, characterising the source area, is classified as low, moderate or high according to threshold values contained in the Andorran intensity-frequency diagram (Fig. 6.2). The class of frequency defined for the source area is then assigned to all the points of the slope located uphill with respect to a 'limit abscissa', which is the point reached by a specific percentage of blocks (with respect to the total number of simulations), whose value is fixed as a function of the volume class. Beyond the limit abscissa, the frequency is considered as low up to the maximum observed run-out, regardless of its classification before this abscissa. The energy at every point of the slope is computed from the envelope of the maximum values obtained from the cumulative energy distribution determined at each abscissa, based on all the computer runs performed. It is classified as low, moderate or high according to the thresholds in the intensity-frequency diagram. The diagram is finally used for obtaining the hazard (classified in four degrees), determined by the combination of frequency and energy.

The Cadanav methodology (Jaboyedoff and Labiouse 2002; Jaboyedoff et al. 2005), developed at the École Polytechnique Fédérale de Lausanne (EPFL) according to the Swiss Guidelines, expresses the hazard in terms of temporal frequency $\lambda(E, x)$ of blocks reaching a given point of the slope x with a given energy E (Eq. 6.1):

$$\lambda(E, x) = \lambda_f x N_{blocks} \times P_r(E, x) \tag{6.1}$$

The rock fall frequency λ_f and the number of released blocks per event N_{blocks} are estimated from field investigations and, particularly concerning the frequency, from available historical data about past events. The probability of reach $P_r(E, x)$ associated to a given energy is obtained defining probability curves for each energy threshold of the Swiss diagram (0, 30 and 300 kJ). These curves represent the percentage of blocks travelling beyond a specific abscissa with an energy equal or higher than the considered threshold. They are built starting from a modification of the energy profiles obtained from the rockfall simulations, e.g. for each trajectory, the raw energy profile is reduced to a step diagram characterised by three energy values only, each corresponding to one of the thresholds in the Swiss diagram. Once the failure frequency and the probability curves yielding the $P_r(E, x)$ values are known, energy and frequency are coupled (Fig. 6.3) according to seven combinations of energy and return period in the Swiss diagram. These combinations are associated to a change in hazard level and, thanks to the $P_r(E, x)$ curves, provide

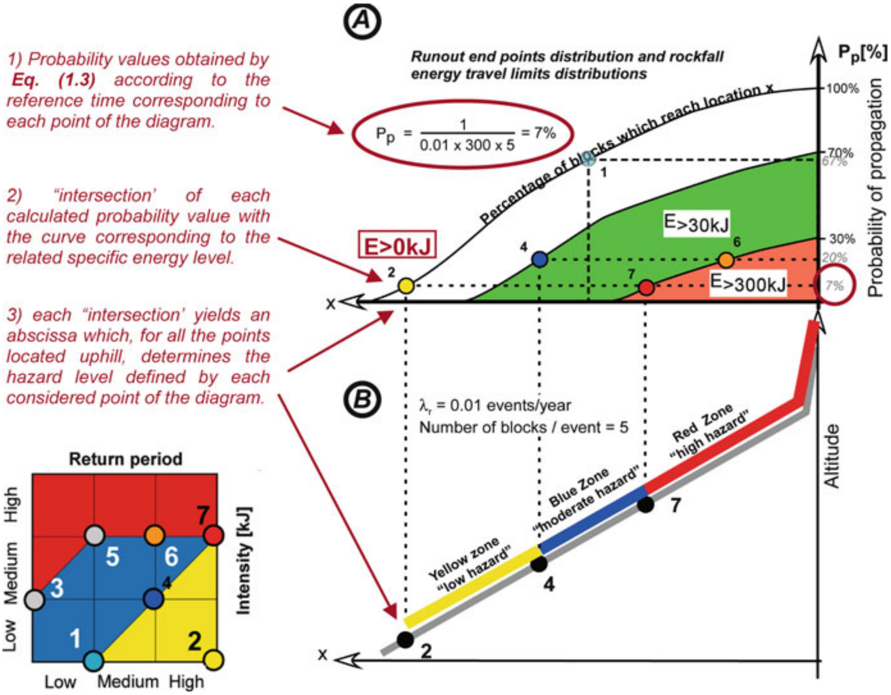

Fig. 6.3 Cadanav methodology, determination of the hazard zone limits (Jaboyedoff et al. 2005). In the example, events releasing five blocks with a failure frequency of one event over 100 years are considered

the extent of the respective hazard zones: low, moderate, high. In particular, when several points may provide the extent of the same hazard zone, the one giving the most downhill limit is considered.

Other examples of methodologies using trajectory modelling, but not coupling intensity and frequency, are the A.D.R.G.T. method (Desvarreux 2002, 2007), developed in the Rhone-Alpes Region in France, the R.H.A.P. (Mazzoccola and Sciesa 2000) and the RHV (Crosta and Agliardi 2003) methodologies, developed in the Lombardia Region in Italy, and the procedure based on the Rockfall Analyst code (Lan et al. 2007), developed in Canada.

The A.D.R.G.T. method only provides a zoning of probabilities of reach, classified as low, moderate or high based on specific probability threshold values. The hazard is classified accordingly, as low, moderate and high, without accounting for energy and frequency of the rockfall events.

The Rockfall Hazard Assessment Procedure (R.H.A.P) accounts for probability of reach and rockfall activity (which gives a qualitative information on the failure likelihood), but not for energy. Based on the combination of these two parameters, it yields zoning maps constituted by five degrees of hazard.

The Rockfall Hazard Vector (RHV) methodology is based on 3D rockfall simulations and provides maps featuring 3 levels of hazard, obtained by combining the frequency of reach, the maximum energy and the maximum height of rebound at each cell of a DEM by means of a three-dimensional matrix diagram.

The Rockfall Analyst code, developed as a GIS extension, allows the performance of 3D rockfall simulations, by means of which rockfall frequency of reach, maximum energies and heights of rebound are determined at each DEM cell. The raw results provided by the computations are then processed using various interpolation techniques (e.g. Kriging), and finally combined at every cell of the topographic model (given by a DEM) by means of a weighted sum yielding the hazard, which can be classified into a given number of degrees (e.g. five).

6.2.3 Quantitative Approaches for Hazard Assessment: Uncertainties and Challenges

Quantitative approaches for hazard assessment should in principle provide a more rigorous and reliable hazard zoning compared to qualitative methods, as they are less dependent on subjective procedures and expert's advice. However, as mentioned in the introduction, several uncertainties characterise as well these techniques, in relation to the assumptions behind each methodology. Consequently, the variety of possible approaches proposed so far yield zoning results which vary a lot, according to the used methodology, as well as to the national guidelines based on which these procedures were developed (Abbruzzese and Labiouse 2010a, b). Differences in hazard zoning related to assessment techniques may constitute a questionable result, since the obtained maps are meant to be basic documents for land use planning (Labiouse and Abbruzzese 2011; Abbruzzese 2011). More precisely, uncertainties affect at first the estimation of the failure frequency (Corominas and Moya 2008). Methods for estimating the temporal frequency of failure are usually based on magnitude-frequency relationships, but most of the times the main problem of these procedures is the lack of historical data used for calibrating the chosen mathematical model (e.g. power law) at a given site. Consequently, it is common in the current practice to estimate rock fall likelihood of failure using qualitative methods (as in the Matterock methodology), even though such types of approaches involve a lot of subjectivity and experts' judgement with respect to quantitative methods.

Another source of uncertainties is linked to the calibration of trajectory simulation codes and to the post-processing of their results. On one hand, attention should be paid to the calibration of the codes, which should be carefully done based on field data, in order for the trajectory results (and then zoning maps) to be reasonably representative of the situation observed on site. On the other hand, also the processing of the raw trajectory results does have an influence on zoning, as the values obtained for energy and probability of reach depend on the adopted processing method. In addition, the number of runs computed in a simulation and the presence of possible outliers in the modelling results may also condition zoning (Abbruzzese et al. 2009).

Finally, the techniques for combining energy and frequency may differ substantially and be more or less rigorous from one approach to the other, e.g. some procedures are semi-quantitative, and account only qualitatively for the failure frequency, or some others combine intensity and frequency by simply superposing this information instead of fully coupling the two parameters (Abbruzzese et al. 2009). Further work is therefore undoubtedly necessary for improving rigour and reliability of hazard assessment and zoning practices.

6.2.4 New Cadanav Methodology for Rockfall Hazard Zoning at the Local Scale

Among the presented procedures based on trajectory modelling, the Cadanav methodology proposes a more objective, reproducible and fully quantitative technique for assessing rockfall hazards with respect to the others, and it really allows for combining failure frequency, propagation of the process and intensity.

Despite these advantages, some points certainly need to be further improved for this methodology, with particular regards to the consequences on zoning of the energy profiles modification and of the limited number of energy-return period couples considered for hazard assessment (seven couples only). For this purpose, a new version of Cadanav was developed (Abbruzzese 2011; Abbruzzese and Labiouse 2013), which allows to remove these simplifications and extend the applicability of the previous version, by improving the way trajectory modelling results are used for hazard zoning and by proposing a new method for coupling rockfall energy and frequency.

The new Cadanav methodology evaluates the hazard degree by means of 'hazard curves'. They are built starting from the cumulative distribution of the energy values at each point of the slope, as obtained from the rock fall simulation results, and by combining these cumulative probabilities with the failure frequency at the source area, in order to obtain the frequency of occurrence of an event of a given intensity at a given point of the slope.

The hazard curves are described at each slope unit by energy-return period couples, to be superimpose to an intensity frequency diagram in order to determine which hazardous condition prevails at that point of the slope. In particular, when a hazard curve is superimposed to an intensity-frequency diagram:

– if the curve is entirely located inside one single domain of the diagram, corresponding to a given hazard level, the considered point of the slope is assigned that hazard level;
– if the curve crosses more than one hazard domain, the hazard degree is established based on the most unfavourable condition (e.g. higher hazard degree).

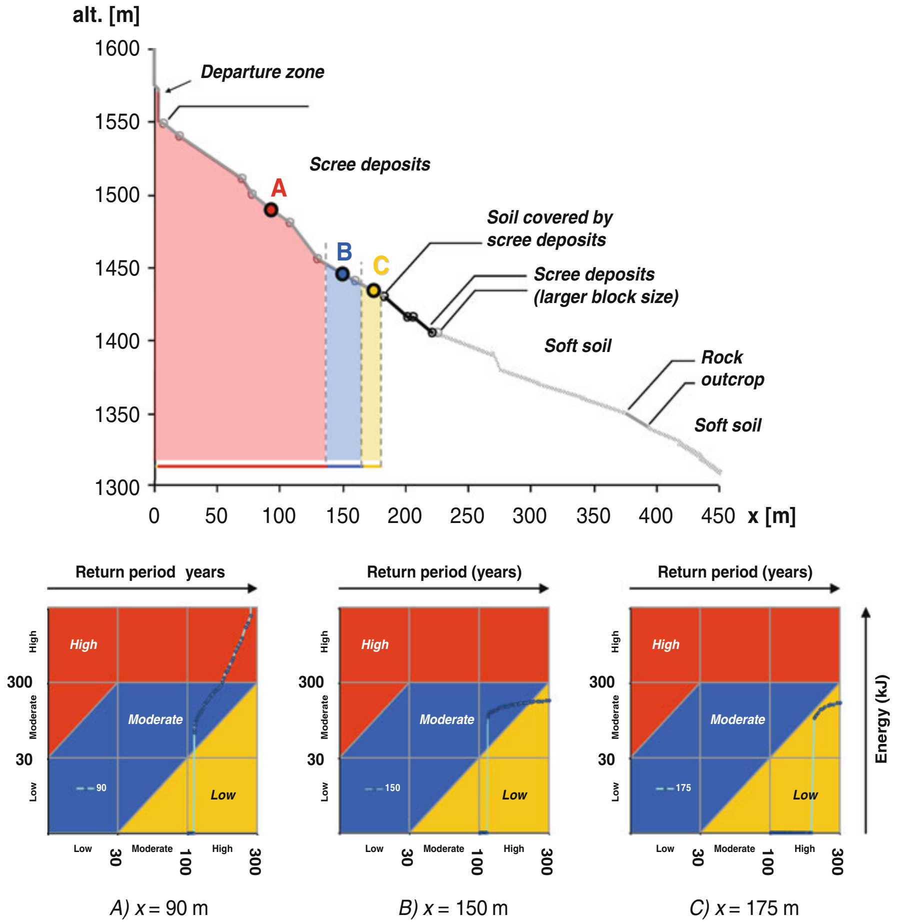

Fig. 6.4 New Cadanav methodology: hazard zoning along a 2D slope profile, performed according to the Swiss guidelines. The hazard curves reported for points A, B and C show the application of the criterion for assigning the degree of hazard at a given abscissa, and how the hazard evolves down-slope

Figure 6.4 illustrates an example of hazard zoning performed along a 2D slope profile characterising a Swiss site. The zoning was obtained from a 2D simulation run for a 10 m^3 block volume, assuming a failure frequency of 1 block failing on average every 200 years per unit length of cliff, and a block size of 2 m. Together with the extent of the hazard zones along the profile, hazard curves are reported for 3 abscissas (Points A, B and C), in order to show the way the hazard degree is determined, based on the superposition of the curve with the Swiss intensity-frequency diagram. The curves also allow the quick visualisation of the hazardous conditions potentially affecting each location of the study site.

Compared to the original Cadanav, the new methodology provides a sounder and more rigorous zoning, and, even though it was here applied based on rockfall simulations on a 2D slope profile, it can be easily used as well for hazard zoning starting from trajectory modelling on a 3D topography. In addition, as the construction of the hazard curves does not depend on the diagram they are then superimposed to, the new Cadanav methodology can be easily applied with any intensity-frequency matrix.

6.3 Approaches for Rockfall Risk Assessment

6.3.1 Methods for Rockfall Risk Assessment and Mapping at the Regional Scale

At regional scale, both qualitative and quantitative risk analyses can be performed (Remondo et al. 2005) but usually, for regional scale analyses the quality and quantity of available data are poorer and of lower precision and accuracy in comparison with those that can be collected for site-specific and local analysis. Thus in order to avoid inconsistencies, qualitative analysis is usually preferable and empirical models are most often implemented (Corominas and Mavrouli 2011a).

Qualitative risk analysis is simpler and quicker to perform than quantitative. It requires knowledge of the hazards, the elements at risk and their vulnerabilities, expressed in qualitative (or semi-quantitative) terms, typically as ranked attributes (IUGS Working Group on Landslides, Committee on Risk Assessment 1997) e.g. risk rating systems, risk scoring schemes and risk ranking matrices. The qualitative expression of risk serves in providing a relative comparison of risks for different sites and in facilitating prioritization of follow-up actions, at regional scale. Official qualitative landslide risk assessment systems exist in USA, Canada, China, Italy and Spain. A review of them is presented by Pantelidis (2011), amongst which is the Rockfall Hazard Rating System (Pierson et al. 1993). Most of these systems use the concept of detailed rating to numerically differentiate the risks at the identified sites. The detailed rating includes a number of factors on which basis slopes are evaluated and assigned a score referring to both hazard and consequences.

In many cases, geographical information systems can also be used for the elaboration and the superposition of factors that are involved in risk evaluation (van Westen 2010). The procedure concerns the organization of information for every component of the hazard, exposure and vulnerability into different levels and the models used are in most cases deterministic.

For regional analysis, the exposure and vulnerability of the elements at risk are often considered as a single term. This means that buildings inside the zones of possible rockfall reach have a deterministic vulnerability value depending on their typology and no consideration is made on the potential location of the rockfall impact on the building, which is crucial for the resulting damage.

6.3.2 Methods for Rockfall Risk Assessment and Mapping at the Local/Site Specific Scale

In comparison with regional scale, for local and site-specific scales the acquisition of more precise and accurate data is feasible, thus permitting the use of more precise and sophisticated empirical and analytical models.

For local and site-specific scales, risk assessment can be as well both qualitative and quantitative. Risk in that case can be calculated as the product of the probability of the rockfall occurrence, the probability of encounter with the exposed elements and their vulnerability. The output is the probability of loss (e.g. annual), and is expressed by Eq. 6.2:

$$R = H \times E \times V \quad (6.2)$$

where, H is the probability of the occurrence of a rockfall of a given magnitude, E is the probability of the encounter with the element or set of elements at risk (property, persons), and V is the vulnerability of the exposed element(s).

The risk calculation takes place by assessing each of these components and combining them. For site-specific and local scales, the hazard may include information on the exact location of the rockfall source and the rockfall run-out by propagation analysis, taking into consideration the local topographical characteristics. The reach distance of the rockfall is calculated probabilistically rather than deterministically.

The vulnerability of the exposed buildings may be calculated probabilistically as well, considering the uncertainty of the impact location, on which their final damage level depends (see Sect. 6.3.3.2).

6.3.3 Quantitative Risk Assessment (QRA)

The QRA practices for landslides, including rockfalls, that are applied all over the world present a large variability, which in turn results from the variety of procedures applied for the determination of each parameter involved in the risk assessment. Besides the rich investigation in this scientific field, which is accompanied by numerous reports and published articles, in the last decades an effort has been done for the establishment of official guidelines or even practices, to be applied by national or local authorities and practitioners, for the quantification of the risk related to landslides, including rockfalls. Such examples are the Hong-Kong guidelines (ERM 1998), and the Australian Guidelines for the landslide management (AGS 2007). Other important contributions are those by Hungr (1997) and Fell et al. (2005), among others.

The general framework for rockfall quantitative risk analysis is multidisciplinary, and consists of the following activities:

- Hazard analysis, including the assessment of the size, probability, velocity and reach of the potential rockfall.

- Identification of the number and characteristics of the elements at risk and their spatio-temporal probability.
- Vulnerability analysis of the elements at risk.
- Calculation of the risk from the hazard analysis, elements at risk and the vulnerability.

The hazard level is usually associated with the probability of having a rockfall magnitude (volume) and/or intensity (velocity) as discussed in Sect. 6.2. The investigation of the elements at risk involves their identification (e.g. persons, buildings, vehicles, infrastructures, other types of property . . .), the temporal-spatial probability of them being affected by a rockfall event, and their vulnerability, which refers to the potential of loss in case that they are hit by a rockfall of a certain magnitude and intensity. The value of the exposed elements might be expressed in absolute terms (e.g. euros) or in relative (e.g. ratio of repair cost to the value of the building).

The rockfall phenomenon is characterized by a lot of uncertainties, which should be incorporated at all the aforementioned stages depending on the scale and the desired level of detail. Thus the risk evaluation requires the use of probabilistic approaches.

Methodologies used worldwide for QRA due to landslides vary according to the type of mechanism, the applied scale, and the available input data. For what concerns rockfall risk, several important contributions to the field of QRA were made by Hungr et al. (1999), Bell and Glade (2004), Roberds (2005), Corominas et al. (2005), Agliardi et al. (2009), Li et al. (2009).

Corominas and Mavrouli (2011a) give details for the expressions that are used to quantify the risk for elements located on a slope potentially affected by rockfall trajectories. The expression formatted in Eq. 6.3 can be used:

$$\mathrm{R = P(R_i)xP(D : R_i)xP(S : T)xVxC} \tag{6.3}$$

where R is the expected loss due to rockfall $\mathrm{R_i}$, $P(R_i)$ is the probability of a rockfall of magnitude i, $P(D{:}R_i)$ is the probability of a rockfall reaching a location at a distance D from the source, $P(S{:}T)$ is the spatio (S) and temporal (T) probability of the element at risk (probability of encounter with the rockfall), V is the vulnerability of the exposed element impact of a rockfall and C is the value of the element at risk.

The component $P(R_i)$ refers to either the temporal probability or the frequency, depending on the expected outcome from the risk equation. For example, if the objective is the calculation of the probability over a given time span of either the partial or total loss for an exposed element due to a potential rock impact then the temporal probability is used. If the objective is to estimate the cumulative damage (e.g. in euros) due to all potential rock impacts over a given period of time, then frequency may be used instead (Hungr et al. 2005; Agliardi et al. 2009). The parameters $P(R_i)$ and $P(D{:}R_i)$ refer to the hazard, P(S:T) to the exposure and V to the vulnerability.

For a detailed analysis, $P(D{:}R_i)$ may be substituted by the probability of a rockfall reaching a location with a given kinetic energy, $P(E_j{:}R_i)$. On the other hand, for the same rockfall magnitude (i) and intensity (j), depending on the type of the element at risk, the vulnerability $V(R_{ij})$ is different; so to calculate the risk, for every type of element the risk has to be calculated separately and summed-up. To obtain the risk for each exposed element, Eq. 6.3 becomes:

$$R(P) = \sum_{i=1}^{i} \sum_{j=1}^{j} \left[P(R_i)xP(E_j : R_i)xP(S : T)xV(R_{ij}) \right] xC \tag{6.4}$$

where, $R(P)$ is the expected loss to the property due to rockfall, $P(R_i)$ is the probability of a rockfall with a magnitude i, $P(E_j{:}R_i)$ is the probability of the rockfall reaching the exposed element(s) with a certain kinetic energy Ej, given that a rockfall has occurred, $P(S{:}T)$ is the temporal-spatial probability of the element at risk, $V(R_{ij})$ is the vulnerability of the exposed element for a rockfall of magnitude i and kinetic energy E_j and C is the value of the exposed element.

Small size and mid-size rockfalls usually begin by the detachment of a more or less coherent rock mass that after the first impact with the slope face splits into several pieces. The latter is the case of a fragmental rockfall which is characterized by the independent movement of individual rock fragments after detachment from a rock face (Evans and Hungr 1993).

For taking fragmentation into account, $P(R_i)$ can be substituted by $\lambda(R_s)$, which is the frequency of rockfalls of a defined block size ‘s’, and it is given by the Eq. 6.5 (Corominas and Mavrouli 2011b):

$$\lambda(R_s) = \sum_{i=1}^{i} [\lambda(R_i) \cdot \times \cdot N_s(R_i)] \tag{6.5}$$

where $\lambda(R_s)$ is the frequency of blocks of ‘s’ volume, $\lambda(R_i)$ is the frequency of rockfalls of ‘i’ volume and $N_s(R_i)$ is the number of blocks of ‘s’ volume due to rockfall of ‘i’ volume.

6.3.3.1 Exposure and Vulnerability

The exposure of an element to rockfalls is expressed by the inherent temporal-spatial impact probability of it being affected during or after an event. Rockfalls present the peculiarity of the punctual effect of their impact on specific exposed elements and key-locations on them, instead of the areal distribution of landslides, rock slides and rock avalanches. For fragmental rockfalls usually only buildings at the first row next to a slope and people inside, are affected. Analytical expressions for the calculation of exposure of buildings, vehicles and people, can be found in Corominas and Mavrouli (2011a). For small scales, considering of the impact probability on specific exposed elements is not permitted by the resolution of the analysis. Conversely, for local and site-specific scales the impact probability is a basic component of the consequences analysis that could be incorporated into the vulnerability assessment. Impact probability may be calculated for structures (spatial), vehicles (spatial and temporal) and people (spatial and temporal).

6.3.3.2 Risk to Buildings – Infrastructures

To assess the performance of a structure struck by a rockfall, both the intensity and impact location must be considered (Mavrouli and Corominas 2010a). These two parameters determine whether there will be initial damage to load-bearing structural elements (e.g. columns) and whether this will affect the overall structural stability. With reference to the impact location, there are, in general, three possibilities: (1) a free-fall rock dropping on the roof, (2) a rock moving along a trajectory path and hitting the exposed façade, and (3) a rock passing through the façade and perforating a floor slab on a downward movement. In terms of impact effects, damage can be categorized into the following groups: primary structural damage (of primary structural elements such as columns, beams, etc.) that determines the overall stability of the building; secondary structural damage (of secondary load-bearing elements such as slabs, etc.); primary nonstructural damage that may cause injuries (e.g., infill walls,ceilings, etc.); secondary nonstructural damage (e.g., furniture, fixtures, etc.); and damage to services (electrical and mechanical equipment, etc.).

For reinforced concrete structures, the location of the impact on the exposed façade is fundamental (Fig. 6.5). Damage to a nonstructural element (e.g., an infill wall) is not critical to building stability, but collapse of a structural element, such as a column or a beam, may initiate progressive collapse. So, in a nonstructural impact, the damage is restricted to the nonstructural element itself, but in a structural impact, the final damage may vary from slight to total.

Details on the quantitative evaluation of the vulnerability of buildings for incorporating this aspect into the risk equation are given in Chap. 8 of this book. A vulnerability index to be used directly for the risk quantification is given by Mavrouli and Corominas (2010b). It considers the variation of the damage according to the impact location of rockfalls, and is calculated as a function of the rockfall magnitude and velocity:

$$\mathrm{V(R_{ij})} = \sum_{K=1}^{k} (P_{ek} X\ RRC_k) \leq 1 \tag{6.6}$$

where $V(R_{ij})$ is the vulnerability for a rock block with a magnitude 'i' and intensity (velocity) 'j', $P_{e,k}$: is the encountered probability of a rock with a possible structural and nonstructural element of the building 'k' that may be struck by a rock block of magnitude 'i' and RRC_k is the relative recovery cost that corresponds to the strike of a possible structural and nonstructural element of the building 'k' by a rock block of magnitude 'i' and velocity 'j'.

Fig. 6.5 Nonstructural damage at a workshop in Santa Coloma (Principality of Andorra) due to rockfall in April, 2008. No further damage was produced because none of the columns were impacted and broken by the block

6.3.3.3 Risk to Persons

People are vulnerable to rockfalls depending on their location with respect to the rockfall path. In many cases different vulnerabilities have been considered for people of different ages and particular conditions (for example people in hospitals). Conservatively, it can be considered that when a person is hit by a rock block, he/she will die, but in many real events, slight injuries instead of fatalities have been observed. Thus the vulnerability of persons due to rockfalls should consider the magnitude of the event as well (Bunce et al. 1997).

The risk to persons can be expressed either for an individual or for a group of people (societal). In the latter case the societal risk is expressed through a F-N (frequency-mortality) chart. For the F-N chart, the annual probabilities of 1, 2, ... and up to n persons being injured or killed due to rockfalls in a given region are calculated and then summed up. For this, the density of the population in a building is considered, depending on its use (e.g. school, workshop, residential).

6.3.4 Forthcoming Improvements in Risk Assessment: Integrating Vulnerability in the Risk Equation

Within the Mountain Risks project the main improvement achieved for the quantitative risk assessment is the incorporation of the vulnerability into the risk equation, particularly with regard to fragmental rockfalls. To this end, an analytical approach was followed. The advantages of such approach are the objectivity and the incorporation of the uncertainty of the impact location on key structural elements, as well as the response of the whole structural system. This provides a realistic evaluation of the response of the buildings. This procedure requires the analysis of a representative set of cases and different building typologies.

6.4 Conclusion

The methodologies for the QRA vary significantly depending on the landslide type, the scale of the analysis, the considered exposed elements and the techniques used for collecting input data. Quantitative estimates provide more objective and comparable hazard and risk results than the qualitative ones.

The cases presented in this chapter summarise the progress experienced in rockfall hazard and risk assessment during the last few years. The advance has been evident in the consideration of the magnitude of the events, the intensity of the phenomena at selected locations and in the vulnerability assessment. One of the main challenges in quantitative rockfall hazard zoning at both local and regional scales is the spatial distribution of the hazard levels which are better described by the kinetic energy rather than by the magnitude (size) of the event. To this end, rockfall hazard curves have become extremely helpful. They are built based on the cumulative distribution of the energy values at each point of the slope obtained by trajectographic analyses and combining them with the failure frequency at the source area. This yields the frequency of occurrence of an event of a given intensity at a given point of the slope.

The risk analysis has benefited from the progress produced in the evaluation of the vulnerability of the exposed elements. The analytical approaches are more objective and incorporate the uncertainty of the impact location on key structural elements and the response of the whole structural system. The vulnerability obtained can be directly integrated in the risk equation. However, these approaches require the consideration of a large variety of structural typologies and arrays which analyses are not yet available.

Despite this progress, further research is still required before QRA could become a routine. Determining the size of the potential rockfalls is still a challenge. Magnitude-frequency relations are fundamental input data for quantitative hazard and risk analysis, however the scarcity of good quality geological and historical data in many regions restricts its construction. On the other hand, magnitude-frequency analyses assume the existence of steady conditions for both triggers and slopes. This assumption is, however, arguable in some geological contexts, particularly in alpine mountainous regions which were glaciated during Pleistocene times. The conditions responsible for the rockfall frequency after the glacial retreat, which is often the observed frequency, might no longer exist (Wieczorek and Jager 1996).

An additional difficulty is the fact that small size and mid-size rockfalls usually begin by the detachment of a more or less coherent rock mass that after the first impact produces fragmental rockfalls. The fragmentation mechanism is not currently included in trajectographic models and may strongly affect the reliability and validity of the results. The detachment of such type of rockfalls without considering their fragmentation will give unrealistic travel distances and impact energies in excess of what should be expected.

Segregating the risk equation has highlighted the role of the exposure of the elements at risk (spatio-temporal probability of the elements at risk) which has received little attention so far. Traditional approaches used in risk analysis tend to simplify risk in two main components: hazard and vulnerability. Nevertheless, practical application of QRA has shown that exposure, particularly for mobile elements at risk (cars, trains, persons) has a strong influence in risk results and on the probability of loss of life. The consideration of exposure within vulnerability is not an appropriate way to address this issue because vulnerability is an intrinsic property of the element at risk while exposure may be a transient attribute even for buildings which exposure to landslide hazards is conditioned by the presence of other (future) buildings within the landslide track. Simplified approaches are often required for evaluating the exposure, such as for instance, assuming the same exposure for all buildings in a neighbourhood. This type of approaches may be acceptable for small scale analyses but must be refined when working at either local or site specific scale.

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