Grant Agreement No.: 226479

SafeLand

Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies

7th Framework Programme
Cooperation Theme 6 Environment (including climate change)
Sub-Activity 6.1.3 Natural Hazards

Deliverable 2.9

Toolbox for landslide quantitative risks assessment

Work Package 2.3 - Development of procedures for QRA at regional scale and European scale

Deliverable/Work Package Leader: UPC   Revision: [3] –**Final**

January, 2012

Rev.	Deliverable Responsible	Controlled by	Date
3	UPC	AMRA	

SUMMARY

The objective of this deliverable is to improve or develop toolboxes (a set of precompiled computer routines) that can be used by stakeholders, practitioners and other interested parties for the quantitative evaluation of the key components that are involved into the landslide zoning and risk calculation (hazard, vulnerability of the exposed elements...). This contribution aims to facilitate the consistent use of information gathered through different means of observations and information, as a first step towards the development of automatic procedures for the quantification of risk in landslide exposed areas.

Note about contributors

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CONTENTS

1 INTRODUCTION

The methodologies and procedures that are used for landslide zoning, hazard assessment and vulnerability evaluation relevant to the landslide risk, include many sub-procedures for the quantification of the key components.

The guidelines that were proposed in D2.4 for the landslide susceptibility, hazard and risk assessment, zoning and mapping and the methodologies that were described for the physical vulnerability of elements at risk to landslides included in D2.5 and for the evaluation of the socio-economic impact of landslides (societal vulnerability) in D2.6, can constitute a base for the development of toolboxes that can be used by stakeholders, practitioners and other interested parties for the quantitative evaluation of the key components that are involved into the landslide zoning and risk calculation (hazard, vulnerability of the exposed elements...). The toolboxes that are included in this deliverable comprise a set of precompiled computer routines that facilitate the calculation of landslide hazard, vulnerability and risk parameters. They can be used for the quantification of the risk and of the vulnerability, for landslides and rockfalls. In comparison with the quantification of hazard these topics have a poorer background and attention has being increasingly drawing to them during the last decades.

Deterministic and probabilistic approaches for the quantification of the parameters can/have be used. The tools that are included in this deliverable serve for:

- Rockfall quantitative vulnerability of buildings (UPC)
- Rockfall quantitative risk assessment for protection galleries (ETHZ)
- Rockfall quantitative risk assessment (UNIMIB)

The deliverable D2.9 includes the present manuscript and the toolboxes (computer applications). This manuscript is addressed to the end-users and it includes the description of each toolbox, the prerequisite inputs and the obtained outputs and the followed methodology and possible limitations for its use.

2 QUANTITATIVE VULNERABILITY OF BUILDINGS FOR ROCKFALLS

(UPC)

2.1 DESCRIPTION AND OBJECTIVE OF THE UTILITY

The developed toolbox can be used for the calculation of the vulnerability of a reinforced concrete frame buildings to rockfalls and the calculation for fragility curves, both in function of the velocity and the size (diameter) of the rock blocks. The toolbox is an application of the methodology that was developed by Mavrouli and Corominas (2010a, 2010b).

The vulnerability that is calculated using this toolbox can be included in the risk equation by incorporating the uncertainty of the impact location of the rock block and the subsequent damage level. The output is a weighted vulnerability that ranges from 0 to 1 and expresses the potential damage that a rock block causes to a building in function of its velocity and size. The vulnerability is calculated by the sum of the products of the probability of block impact on each element of the building and its associated damage state, the latter expressed in relative recovery cost terms. The probability of exceeding a specific damage state such as non-structural, local, partial, extensive or total collapse corresponding to low, moderate, high and very high damage, respectively, is also important for the quantification of risk. To this purpose the developed toolbox included the calculation of the fragility curves for a given building and rock velocity.

The toolbox is developed using the software Excel by Microsoft (version Microsoft Office 2007). The input and output information is organized in Excel sheets and the user is required to provide the necessary information for the calculations, by filling-up the required cells (marked in white with black border).

2.2 INPUTS

The input information that is required for the calculation of the vulnerability and of the fragility curves diagram mainly consists in data concerning on one hand the properties of the building, and on the other, the rock motion characteristics.

The required data and their symbols are summarized in the following tables.

Table 2.1 Input data

Rock motion data			
Description	Symbol	Units	Observations
Rock Diameter	d	m	a range of rock diameters is required
Rock velocity	v	m/s	a range of rock velocities is required
Building geometry data related to the exposed facade			
Average width of walls	lw	m	

Average width of columns	lc	m	
Number of columns on the façade	n	m	
Column capacity data			
Average axial load	P	MN	
RC compressive strength	fck	Mpa	
Section width	b	m	
Section length	d	m	
0.5 x Average column height	L	m	
constant k	k		1 for displ. ductility <2, 0,7 for ductility >7 linear interpolation for inbetween values
Diameter of shear reinforcement	φ	m	
Number of shear bars /section	n		
Distance of shear reinforcement	s	m	
Shear span	a	m	
Transverse tensile yield strength	fyv	Mpa	
Longitudinal steel yield resistance	fyl	Mpa	
Long. steel reinforcement area %	ρl	no units	
Transv. steel reinforcement area %	ρv	no units	
Dynamic Increase Factor in order to consider the high strain rate:	DIF	no units	see CEB 1990
Damage data			
RRC=repair cost/value of the building			Values specified judgmentally or analytically according and to Mavrouli and Corominas (2010a)
RRC for damage of the walls:		no units	Considered for destruction of an infill wall
RRC for local damage:		no units	Considered for destruction of a central column
RRC for partial collapse		no units	Considered for destruction of a corner column
RRC for total collapse		no units	Considered for destruction of more that 2 columns
Velocity considered for fragility curves (m/s)	v	m/s	

2.3 OUTPUTS

Through the elaboration of the input data, the main outputs that are obtained are:

1. The vulnerability of a reinforced-concrete building that may potentially be impacted at its base by rockfalls. The vulnerability index is representative of the potential for damage for a building impacted by a fragmental rockfall, it is in accordance with the most common vulnerability definitions and does not require a record of previous events. It considers the rock block motion properties as well as the building's response to them after the block impact and it is given by:

$$V(R_{ij}) = \sum_{k=1}^{k} (P_{e,k} \, x \, RRC_k) \leq 1 \quad (2.1)$$

where,

$V(R_{ij})$: vulnerability for a rock block with a magnitude "i" and velocity "j",

$P_{e,k}$: encounter probability of a rock with a possible structural and non-structural element of the building " k" that may be struck by a rock block of magnitude "i",

RRC_k: relative recovery cost that corresponds to the struck of a possible structural and non structural element of the building "k" by a rock block of magnitude "i" and velocity "j".

The calculated vulnerability is non-linear with a range from 0 to 1, where increasing values indicate increasing potential for higher damage. It can be used directly as a input for the quantification of the rockfall risk. It is probabilistic and the considered uncertainty is the location of the rock impact on the building (Figure 2.1).

Vulnerability

$$V_{ij} = \sum_{i=1}^{i}\sum_{j=1}^{j}(P_e \, x \, RRC)$$

Block Diameters d (m)	Volume (m3)	Mass (kg) \ Velocities (m/s)	0,5	1,0	1,5	2,0	2,5	3,0	3,5	4,0	4,5	5,0	5,5	6,0	6,5	7,0	7,5
0,500	0,0654	164	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1,000	0,5233	1308	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,11	0,11	0,11	0,11	0,26	0,26
1,500	1,7663	4416	0,01	0,01	0,01	0,01	0,01	0,15	0,15	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36
2,000	4,1867	10467	0,01	0,01	0,01	0,19	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45	0,45
2,500	8,1771	20443	0,01	0,01	0,22	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54
3,000	14,1300	35325	0,01	0,26	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64
3,500	22,4379	56095	0,01	0,30	0,73	0,73	0,73	0,73	0,73	0,73	0,73	0,73	0,73	0,73	0,73	0,73	0,73
4,000	33,4933	83733	0,01	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82
4,500	47,6888	119222	0,37	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92
5,000	65,4167	163542	0,41	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

Figure 2.1 Vulnerability of a building to rockalls for a range of rock block velocities and diameters

2. Additional outputs are the fragility curves sets for a building, considering increasing diameters of the rock block. The definition of the rock block velocity is required by the user. The provided information consists in the probability of exceeding a given damage state (i.e. low, moderate, high and very high) for certain rock block motion properties. The fragility curves are generated based on analytical results using the methodologies by Mavrouli and Corominas (2010a, 2010b) for the evaluation of the response of the structure and the calculation of fragility curves for rockfalls.

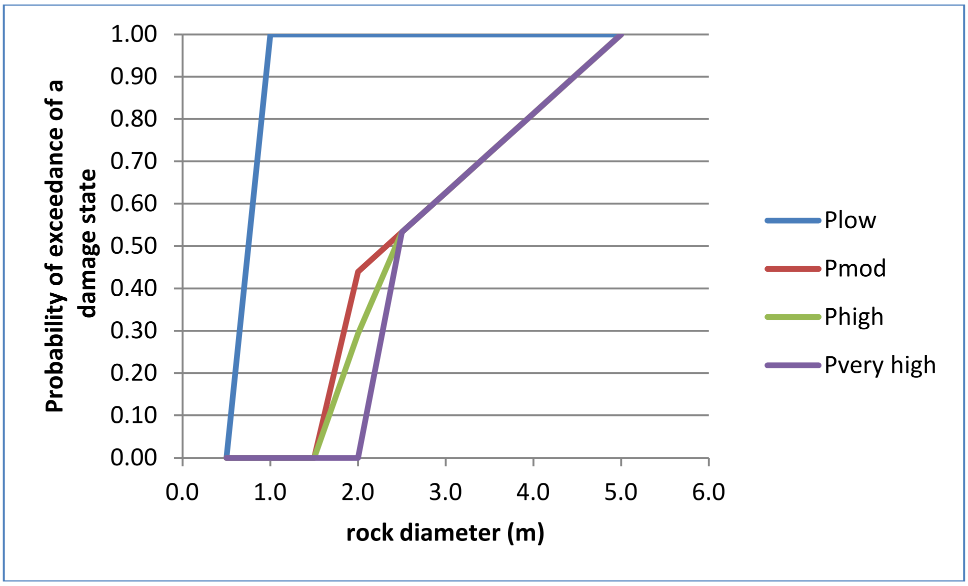

Figure 2.2 Fragility curves for a given rock block velocity and a given building

More details for the calculation of the outputs are given in the description of the used methodology for the toolbox.
Several parameters are additionally calculated, in the intermediate, in order to acquire the vulnerability and the fragility curves. The most important of them are the kinetic energy of the rock block (E_{kin}), the probability of impact of the rock block on the column or on the walls of the building, here called probability of encounter with a structural or non-structural element ($P_{e,k}$), and energy capacity of the building's columns to the rock block impact.

2.4 METHODOLOGY

The steps of the methodology that is used for the developement of the toolbox are explained in the following.
The methodology applies to reinforced concrete (RC) frame structures as the one seen in Figure 2.3 which are impacted by single fragmented rocks at their base, according to Mavrouli and Corominas (2010a and 2010b). It is analytical and it includes:

- evaluation of the structural response of RC buildings to rockfalls,
- the quantification of the vulnerability using a vulnerability index for rockfalls,
- the development of fragility curves for RC buildings impacted by rockfalls

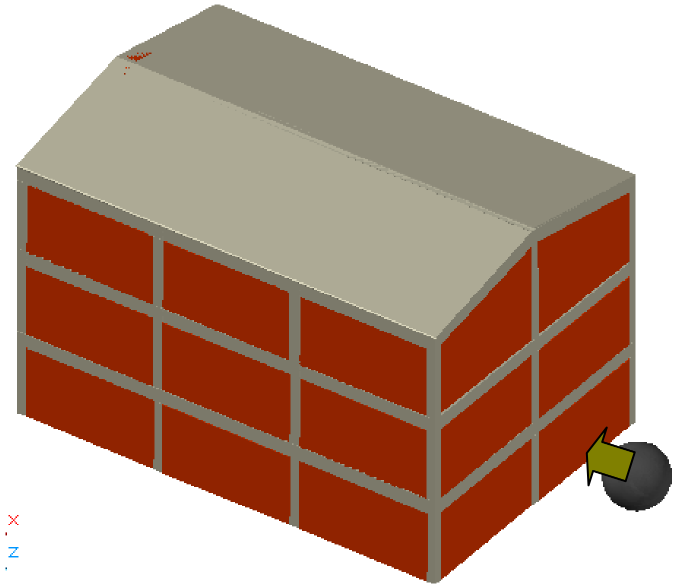

Figure 2.3 Rockfall impact on the basement of reinforce concrete frame structures

The evaluation of the structural response of RC buildings to rockfalls includes the following steps:

- Evaluation of whether the impacted element(s) is/are destroyed:
  - Calculation of the energy capacity of the impacted element(s):

The piecewise linear lateral load-shear displacement model developed by Sezen (2008) is used to predict the column's response to the rockfall impact. The model is presented in Figure 2.5 and it provided the energy capacity of the column. The critical points identified in the proposed model include: Point A (displacement: Δ_{cr}, lateral load: V_{cr}) which represents the conditions under which the first diagonal cracking in concrete due to shear occurs. After the formation of the first crack the stiffness of the column is lower than the initial one, up to point B (displacement: Δ_{n}, lateral load: V_{n}), where the stress resistance is reached. Under the maximum shear stress the column is deformed up to point C (displacement: Δ_{u}, lateral load: V_{n}), where from the shear strength degrades (due to extensive cracking). During this phase, the column experiences additional shear deformations. The ultimate shear deformation is represented by Point D (displacement: Δ_{af}, lateral load=0) where the axial-load carrying capacity of the column is lost.

The high strain-rate effect enhances the strength and ductility of reinforced concrete and to take the associated dynamic effect into account, resistance should be multiplied with a Dynamic Increase Factor DIF of the order of 1.3 (Tsang and Lam 2008; and CEB 1990).

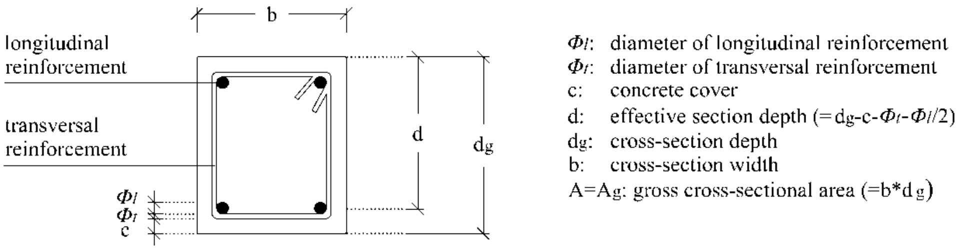

Figure 2.4 Cross section of the column

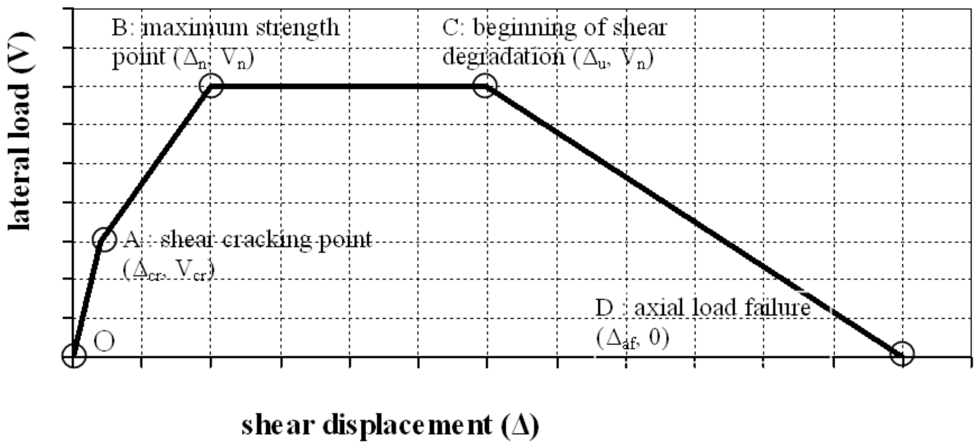

Figure 2.5 Sezen's monotonic lateral load-shear displacement relationship

The critical points are calculated using Equations (2.2) to (2.7).

Point A: Shear cracking initiation (lateral load: V_{cr}, displacement: Δ_{cr})

$$V_{cr} = \left(\frac{P}{2 * f_c' * A_g} + 0.10 \right) \frac{G*A}{L} \tag{2.2}$$

$$\Delta_{cr} = \frac{V_{cr} * L}{G * A_g} \tag{2.3}$$

Point B: Maximum strength point (lateral load: V_n, displacement: Δ_n)

$$V_n = V_s + V_c = k \frac{A_v * f_{yv} * d}{s} + k * \left(\frac{0.5 * \sqrt{f_c'}}{a/d} \sqrt{1 + \frac{P}{0.5 * \sqrt{f_c'} A_g}} \right) * 0.8 * A_g \tag{2.4}$$

$$\Delta_n = \left(\frac{1}{25000} * \frac{\left(a/d\right) * f_{yt} * \rho_v}{\sqrt{\frac{P}{A_g f_c'}}} - 0.0011 \right) * L \tag{2.5}$$

Point C: Beginning of shear degradation (lateral load: V_n, displacement: Δ_u)

$$\Delta_u = (4 - 12\frac{v_n}{f_c^{'}}) * \gamma_n * L \tag{2.6}$$

Point D: Ultimate shear deformation until the lost of the axial-load capacity (lateral load= 0, displacement: Δ_{af})

$$\Delta_{af} = L * \frac{4}{100} * \frac{1 + \tan^2\theta}{\tan\theta + P * (\frac{s}{A_v * f_{yv} * d_c * \tan\theta})} \tag{2.7}$$

where P: axial load, fc´: concrete compressive strength, A: gross cross-sectional area (Fig. 2.4), L: column length, G: shear modulus, Ag: gross cross-sectional area, Av: cross sectional area of transverse reinforcement oriented parallel to the applied shear, s: longitudinal spacing between transverse reinforcement, k: constant varying according to displacement ductility (1.00 for ductility less than 2), f_{yv}: transverse steel yield strength, a: shear span, d: effective section depth, f_{yt}: longitudinal steel yield strength, ρ_v: transverse steel reinforcement ratio, v_n=Vn/(b*d), b: width of the cross section, θ: angle of the shear crack and dc: depth of the core concrete, measured to the centerlines of the transverse reinforcement.

Using this model, the energy capacity of a single column is calculated.

- Consideration of the column destruction when the energy capacity is exceeded during the impact:

From the safety side, elastic collision and full transmission of the kinetic energy of the block to the impacted element is considered. When the kinetic energy of the rock block is higher than the energy capacity of the columns, destruction of the latter is considered.

- Evaluation of the potential damage of the building:

The destruction of one or more basement column(s) may initiate a cascade of failures leading to extensive progressive collapse. The response of the building depends on its particular characteristics and can be evaluated analytically using the methodology developed by Mavrouli and Corominas (2010a). To simplify by taking into consideration some results from this work it can be considered that the importance of a lateral column for the stability of the building can be higher than of a central column on the façade, leading to increased repair cost in the first case. However this assumption depends on the particular characteristics of the building and detailed analysis is recommended for the establishment of the damage extent and the respective repair costs in each case.
The damage extent is here expressed by the respective relative repair cost which is given by:

$$RRC = \frac{\text{recovery cost}}{\text{value of building}} = \text{f}\ (RRC) \leq 1 \tag{2.8}$$

Further recommendations for its calculation are also given at Mavrouli and Corominas (2010a). In case of lack analytical data, the RRC can be evaluated judgmentally or empirically.
Furthermore, the probability of encounter $P_{e,k}$ for every impact location has to be evaluated. The probability of encounter with a lateral column P_{elc} is the double of the probability of encounter with a central column P_{ecc}. It is:

$$P_{elc} = min(\frac{2}{n}\frac{l_c + d}{l_c + l_w}, 1) \quad [3.9]$$

$$P_{ecc} = min(\frac{n-2}{n}\frac{l_c + d}{l_c + l_w}, 1) \quad [3.10]$$

$$P_{ew} = min(\frac{l_w + d}{l_c + l_w}, 1) \quad [3.11]$$

where,
P_{elc}: encounter probability of a rock with a lateral column,
P_{ecc}: encounter probability of a rock with a central column,
P_{ew}: encounter probability of a rock with a wall only,
n: number of column on the façade of the building

− Vulnerability calculation:

The quantification of the vulnerability is made using the index:

$$V(R_{ij}) = \sum_{k=1}^{k}(P_{e,k}\ x\ RRC_k) \leq 1 \quad (2.9)$$

where,
$V(R_{ij})$: vulnerability for a rock block with a magnitude “i” and velocity “j”,

$P_{e,k}$: encounter probability of a rock with a possible structural and non-structural element of the building “ k” that may be struck by a rock block of magnitude “i”,

RRC_k: relative recovery cost that corresponds to the struck of a possible structural and non structural element of the building “k” by a rock block of magnitude “i” and velocity “j”.

− Fragility curves calculation:

The methodology that is used for the calculation of the fragility curves is shown in the Figure 2.6.

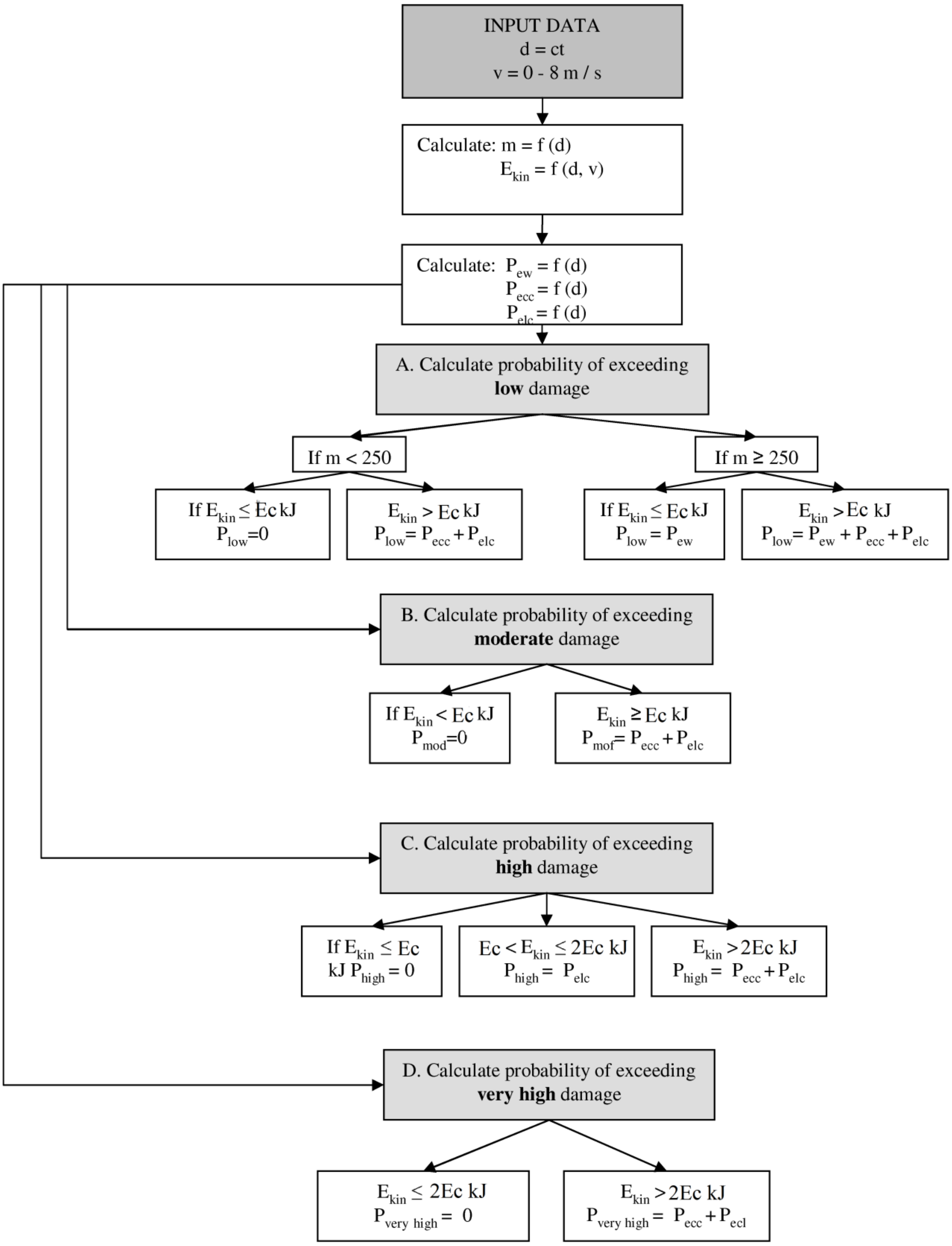

Figure 2.6 Rockfall impact on the basement of reinforce concrete frame structures

The following damage states are proposed.

Table 2.2 Proposed damaged states for the calculation of fragility curves

Damage State	Description
Low	Non-structural damage
Moderate	Local damage on a structural element
High	Partial collapse due to damage of a key-structural element (i.e. a corner column)
Very high	Extensive to total collapse due to damage of more than one structural elements

2.5 LIMITATIONS

The toolbox can be used for reinforced concrete frame structures which are impacted at their base by a single rock block. The simultaneous impact of several blocks or on other impact locations (i.e.roof) is not considered here.
The toolbox maybe applied for the calculation of the vulnerability of an individual building, at site-specific or local scale.
The evaluation of RRC (relative repair costs) and of the damage states are key-issues for the results.

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3 QUANTITATIVE ANALYSIS OF RISK DUE TO ROCKFALL EVENTS ON ROCKFALL PROTECTION GALLERIES

(ETHZ)

3.1 INTRODUCTION

This chapter illustrates the use of RiskNow – Falling Rocks, a generic and probabilistic Microsoft Excel®-based software tool which allows the calculation and analysis of the risk due to rockfall events on rockfall protection galleries. The software tool has been developed as part of a project sponsored by the Swiss Federal Roads Office (Bundesamt für Strassen – ASTRA).
The analysis takes into account the site- and object-specific characteristics of the gallery, the slope, the geology and the road traffic. Using the input from the special characteristics of the problem, the risk and the distribution of the risk are calculated – both in an aggregated form and separately for the different types of risks such as property damage or expected fatalities. The detachment process of the rock mass, the falling process, the failure of the gallery and the consequence model are systematically modelled. The probabilistic analysis of the failure arising from the rockfall events is carried out using a Bayesian Probabilistic Networks (BPN). This analysis runs in the background; therefore, almost no expertise in the field of probabilistic modelling is required by the user.
The use of this software also illustrates how generic probabilistic models can be developed in safety-relevant fields in order to support decision making.

3.2 GENERAL DESCRIPTION OF THE PROGRAM

3.2.1 Technical information

The program is written using Microsoft ® Visual Basic programming language in a Microsoft ® Office Excel 2007 environment. The detailed technical documentation (in German) for the program can be downloaded from: http://partnershop.vss.ch/downloadAnhang.aspx?ID=3a022cc2-100f-4ce6-8222-1d8d3fe512e0&ID_Sprache=1

3.2.2 Steps

The program is designed following the general procedure for risk assessment and analysis described in a guideline document (JCSS 2008) containing the framework and principles for risk based engineering decision making developed by the Joint Committee on Structural Safety (JCSS).

The program includes the following steps:
- System definition
- Description of exposure

  - Modelling of the detachment process
  - Modelling of the case process
- Description of vulnerability
  - Modelling of failure probability of the gallery
  - Modelling the impact probabilities of vehicles
  - Modelling the probabilities of death
- Modelling of the consequences
- Calculation and presentation of risk

3.3 DESCRIPTION OF THE METHODOLOGY, INPUTS AND OUTPUTS

3.3.1 System definition

The totality of all objects, events, consequences, assumptions and conditions which are necessary for a particular risk assessment form the considered system for analysis. In this definition, the system is defined and described by all the relevant information, data, expertise and models. The delimitation and characterisation of the system depends on the decision-makers. A screenshot from the program showing the system definition page is shown in Figure 3.1; information pertaining to three categories is requested – project (administrative), characteristics of the rockfall protection gallery and the characteristics of the traffic.

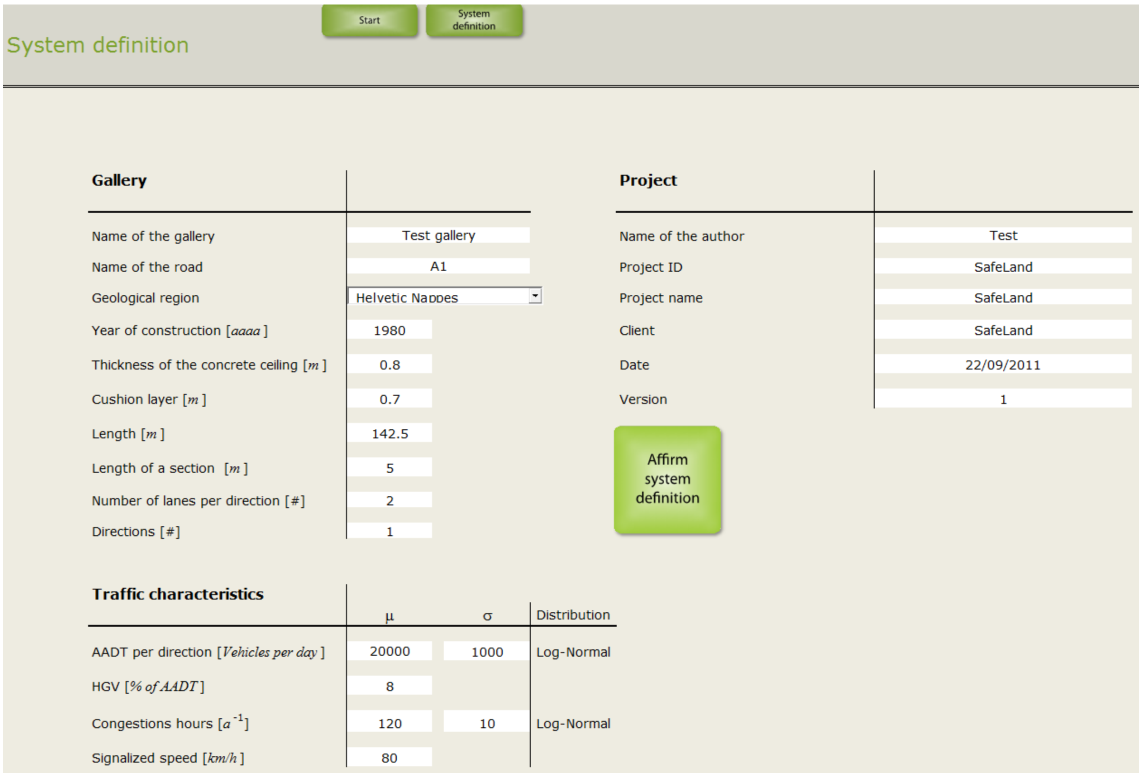


Figure 3.1 System definition

Project
All entries in this category are of purely informative character and useful for documentation purposes.

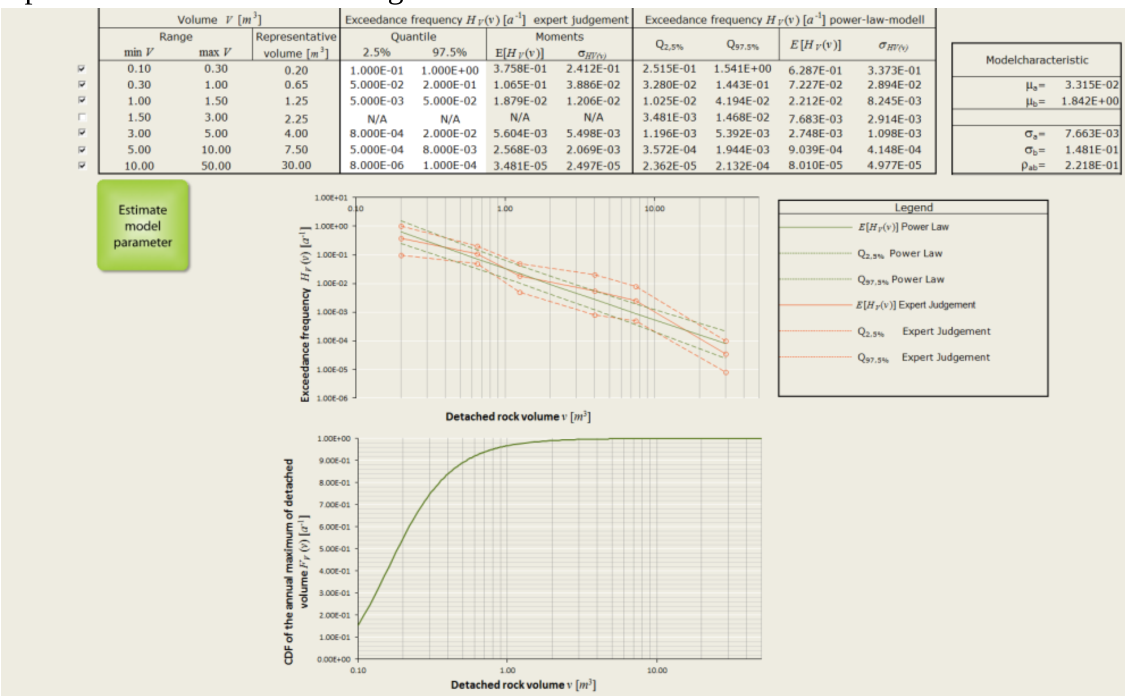
Gallery
First, information about the name of the rockfall protection gallery and the name of the road on which it is located is sought for referencing purposes. Then, the geological region in which the gallery is located is requested; this is used as an indicator of the present rock and slope characteristics. A choice between the following four regions – Helvetic nappes, Penninic nappes, Gotthard & the Aare massif and others is provided. This information is required in calculating the trajectories of rocks in order to take into account the energy loss in the process. These regions have been used to describe the geology and tectonic areas relevant for Switzerland. The superposition of the geological and tectonic maps of Switzerland shows that this categorization of the geological features in the areas at risk of rockfall in Switzerland is well covered.
Next, the year of construction of the gallery is required; this serves as an indicator for the vulnerability model for the gallery and also in some cases provides an indication of the type of materials used for the construction of the gallery based on the prevailing practices and standards at the time of construction. Then, the thickness of the gallery ceiling and the height of the cushion layer (roof covering) are required. This information may be essential to account for the amount of the resistance and the failure mechanism of the gallery during the impact of a stone. Next, the length indicator takes into account the length of the gallery not considered in the risk analysis and has only informative character. The length of the section in the gallery necessary for risk analysis can also be specified, which usually corresponds to the column spacing. After a failure event, it is considered that only the affected section is replaced. To describe the road protected by the gallery, the number of lanes per direction and the number of directions are required. These indicators are used to determine the direct and indirect impact probabilities of vehicles, when the gallery fails due to a rockfall event.

Traffic
The traffic is described by four indicators. First, the annual average daily traffic (AADT) on the road in each direction is modelled following the Lognormal probability distribution. The mean and the standard deviation are required. Next, the proportion of Heavy Good Vehicles (HGV) is inputted as a percentage of the AADT. Then, the congestion hours on the road per year is required as this can affect the probability of a vehicle using the road section during a rockfall event that can lead to failure of the gallery. The uncertainty in the congestion hours is considered by modelling the variable as a Lognormal random variable. Finally, the signalized speed is required; this serves as an indicator of the speed and also affects the direct and indirect impact processes, and in particular the probability of death in rockfall events.

3.3.2 Detachment model

Figure 3.2 shows a screenshot of the detachment model section of the program. The exposure model describes the frequency of rockfall events from the detachment point. In a given slope, there exist several possible transfer zones in which the rockfall trajectory can proceed. Assuming that the transfer events in the slopes are stochastically independent, the analysis can be performed separately for each zone and the results can be aggregated subsequently.

The model considers only rocks with a certain volume. It is assumed that rocks smaller than 0.1 m^3 do not endanger the galleries. Rockfall events involving rock volumes larger than 50 m^3 are considered to represent events that are too large for the rockfall galleries to be able to offer effective protection. The volume range considered is therefore between 0.1 to 50 m^3 which is then divided into seven intervals. Here, since generally more information is available over the lower volume range, this is discretized more finely than the larger volume intervals in which events occur rarely. The representative volume corresponds to the mean between the minimum and maximum volume in the respective interval. For each of the defined volume ranges, the exceedance frequency in terms of 2.5% and 97.5% quantile values needs to be specified. These values are generally estimated through expert judgment and experience or through the use of the power-law model. For the former, it is considered that exceedance frequency in each volume range follows a Lognormal distribution. Following this, the parameters of the detachment model are estimated using both the expert judgement and the power law approaches and relationships between the detached rock volume and the exceedance frequency are obtained and illustrated in graphical representations as shown in Figure 3.2.



Volume V [m^3]			Exceedance frequency $H_V(v)$ [a^{-1}] expert judgement				Exceedance frequency $H_V(v)$ [a^{-1}] power-law-modell			
Range		Representative	Quantile		Moments					
min V	max V	volume [m^3]	2.5%	97.5%	$E[H_V(v)]$	$\sigma_{HV(v)}$	$Q_{2,5\%}$	$Q_{97.5\%}$	$E[H_V(v)]$	$\sigma_{HV(v)}$
0.10	0.30	0.20	1.000E-01	1.000E+00	3.758E-01	2.412E-01	2.515E-01	1.541E+00	6.287E-01	3.373E-01
0.30	1.00	0.65	5.000E-02	2.000E-01	1.065E-01	3.886E-02	3.280E-02	1.443E-01	7.227E-02	2.894E-02
1.00	1.50	1.25	5.000E-03	5.000E-02	1.879E-02	1.206E-02	1.025E-02	4.194E-02	2.212E-02	8.245E-03
1.50	3.00	2.25	N/A	N/A	N/A	N/A	3.481E-03	1.468E-02	7.683E-03	2.914E-03
3.00	5.00	4.00	8.000E-04	2.000E-02	5.604E-03	5.498E-03	1.196E-03	5.392E-03	2.748E-03	1.098E-03
5.00	10.00	7.50	5.000E-04	8.000E-03	2.568E-03	2.069E-03	3.572E-04	1.944E-03	9.039E-04	4.148E-04
10.00	50.00	30.00	8.000E-06	1.000E-04	3.481E-05	2.497E-05	2.362E-05	2.132E-04	8.010E-05	4.977E-05

Modelcharacteristic	
μ_a=	3.315E-02
μ_b=	1.842E+00
σ_a=	7.663E-03
σ_b=	1.481E-01
ρ_{ab}=	2.218E-01

Figure 3.2 Detachment model

In order to estimate the failure probability of the rockfall gallery, the quantity of interest is the description of the biggest event in a given period and generally not the description of the frequency of an event. Further, failure events in the built environment are typically expressed in terms of annual risk with the corresponding probabilities expressed as annual values. From the exceedance probability relationships, the distribution of the annual maximum detached volume is calculated. This forms the basis for calculating the failure probability of the gallery.

3.3.3 Generic trajectory model

Usually the process of a rockfall event is modelled using trajectory models. Due to the highly site specific nature of rockfall events, it is not possible to provide general solutions for use. For the development of trajectory models, information concerning the topography in the form of a high resolution digital elevation model is generally required. In addition, the rock types that occur in the slope, the type of vegetation and the roughness of the surface must be known to describe the energy loss during the rockfall. In this program, pre-computed values stored in a database for different selected generic cases can be used for the different specific applications in order to describe the rockfall process. This database can be seen as a first and possibly crude approximation of the real physical situation and can therefore help to make a first estimation of the risk level. In the program, it is also possible to consider more detailed and site specific results of simulations performed by using 2D or 3D trajectory models, if such information is available. In this case, the results from these models and analyses can be manually inserted in the program, thus providing the user the freedom to consider and use more accurate results when available.

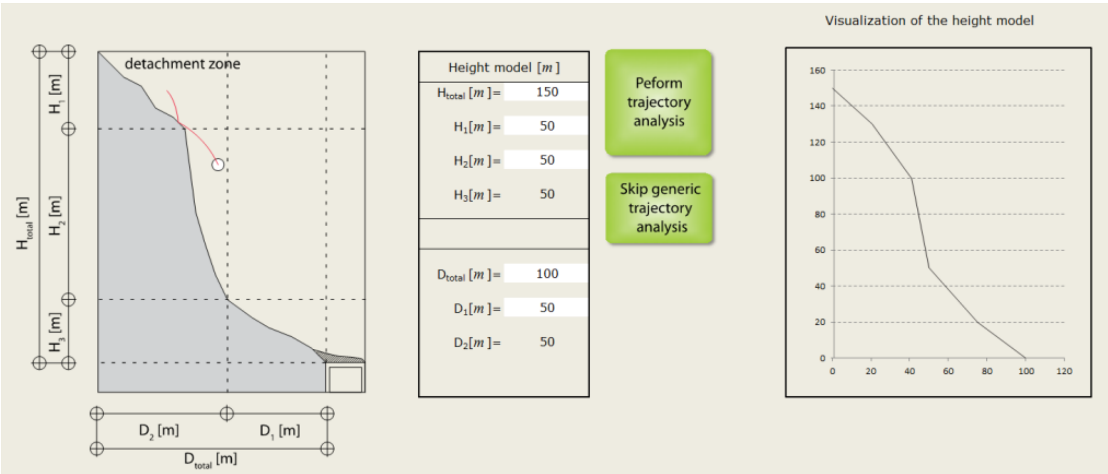


Figure 3.3 Generic trajectory analysis

The slope, as illustrated in Figure 3.3, is divided into three segments; the upper part H_1 (that begins at the detachment point), a central part H_2 (consisting of a steep slope section with a slope of about 80˚) and a lower part H_3 (the run-off area of the rockfall). In the horizontal direction, the topography is divided into two parts, and is described by specifying the total orthogonal distance between the gallery roof and the detachment point and the horizontal distance of the run-off area. With this information, the trajectory analysis can now be performed. For the appropriate slope corresponding to the characterization, the probability density function of the impact velocity of the rock mass on the roof of the gallery is loaded and the likelihood that the gallery is hit during a rockfall is calculated. The results for the different generic slope cases have been generated using the commercial software RocFall. The results from the trajectory analysis are shown in Figure 3.4.

Affirm distribution of the impact velocity

Impact velocity

Interval [m/s] min	max	Frequency	Frequency
0	1	5.017E-04	0.00200682
1	2	1.505E-03	
2	3	4.515E-03	0.01555288
3	4	1.104E-02	
4	5	2.498E-02	0.08207907
5	6	5.709E-02	
6	7	1.126E-01	0.2934979
7	8	1.809E-01	
8	9	1.826E-01	0.33985551
9	10	1.572E-01	
10	11	1.108E-01	0.18412603
11	12	7.335E-02	
12	13	4.124E-02	0.06331527
13	14	2.208E-02	
14	15	1.104E-02	0.01515152
15	16	4.114E-03	
16	17	2.609E-03	0.00371262
17	18	1.104E-03	
18	19	0.000E+00	0.00020068
19	20	2.007E-04	
20	21	2.007E-04	0.00040136
21	22	2.007E-04	
22	23	0.000E+00	0
23	24	0.000E+00	
24	25	1.003E-04	0.00010034
25	26	0.000E+00	
26	27	0.000E+00	0
27	28	0.000E+00	
28	29	0.000E+00	0
29	30	0.000E+00	
30	31	0.000E+00	0
31	32	0.000E+00	
32	33	0.000E+00	0
33	34	0.000E+00	
34	35	0.000E+00	0
35	36	0.000E+00	
36	37	0.000E+00	0
37	38	0.000E+00	
38	39	0.000E+00	0
39	40	0.000E+00	
40	41	0.000E+00	0
41	42	0.000E+00	
42	43	0.000E+00	0
43	44	0.000E+00	
44	45	0.000E+00	0
45	50	0.000E+00	

Conditional impact probability = 0.997 [-]

$\mu_{impact\ velocity}$ = 8.73469639 [m/s]

$\sigma_{impact\ velocity}$ = 2.33974719 [m/s]

$CoV_{impact\ velocity}$ = [-]

Figure 3.4 Results from trajectory analysis

The distribution of the impact velocity of the rocks is used to calculate the failure probability in this case. It is usual in many cases to use the kinetic impact energy as an indicator of risk. The kinetic energy represents an aggregate measure and is therefore particularly suitable for communication because the two components of velocity and mass are converted into a one-dimensional measure. At the same time, it must be realised that each type of aggregation is a loss of information. In this case, there are infinitely many combinations of mass and velocity, leading to the same energy. The mode of failure of the protective galleries differs among the various combinations of mass and velocity. At galleries where a large rockfall event with a relatively more likely lower speed occurs, a bending failure of the gallery ceiling is more likely whereas small rockfall events occurring with a high speed are more likely to lead to a punching failure. Both failure modes are physically completely different. Therefore, instead of an aggregated measure it is useful to explicitly model the impact velocity and the mass of the rock. This gives a two-dimensional distribution of mass and velocity. As shown in Figure 3.4, the distribution of the impact velocity of the rock mass is provided. In addition to the impact velocity, the conditional impact probability of the rock mass impacting the gallery is also calculated. This probability is calculated conditional on the event that a stone is detached. This can also be determined directly from the trajectory analysis.

3.3.4 Probability of failure

Once the above described steps are completed, the probability of failure of the rockfall protection gallery is computed based on a Bayesian Probabilistic Network (BPN) approach. The BPN used for the analysis and a screenshot from the program showing the results from the probability of failure analysis are shown in Figure 3.5. The expected value of the unconditional probability of failure $E[P(F)]$ is estimated as:

$$E[P(F)] = E[P(F \mid impact)P(impact \mid detachment)P(detachment)]$$

where $P(F \mid impact)$ is the conditional probability of failure of the rockfall protection gallery given the impact of a rock mass, $P(impact \mid detachment)$ is the conditional probability of the rock mass reaching the gallery given that it has detached and $P(detachment)$ is the annual detachment probability.

As mentioned in the introduction section of this chapter, the probabilistic analysis using a BPN approach runs in the background; therefore, almost no expertise in the field of probabilistic modelling is required by the user.

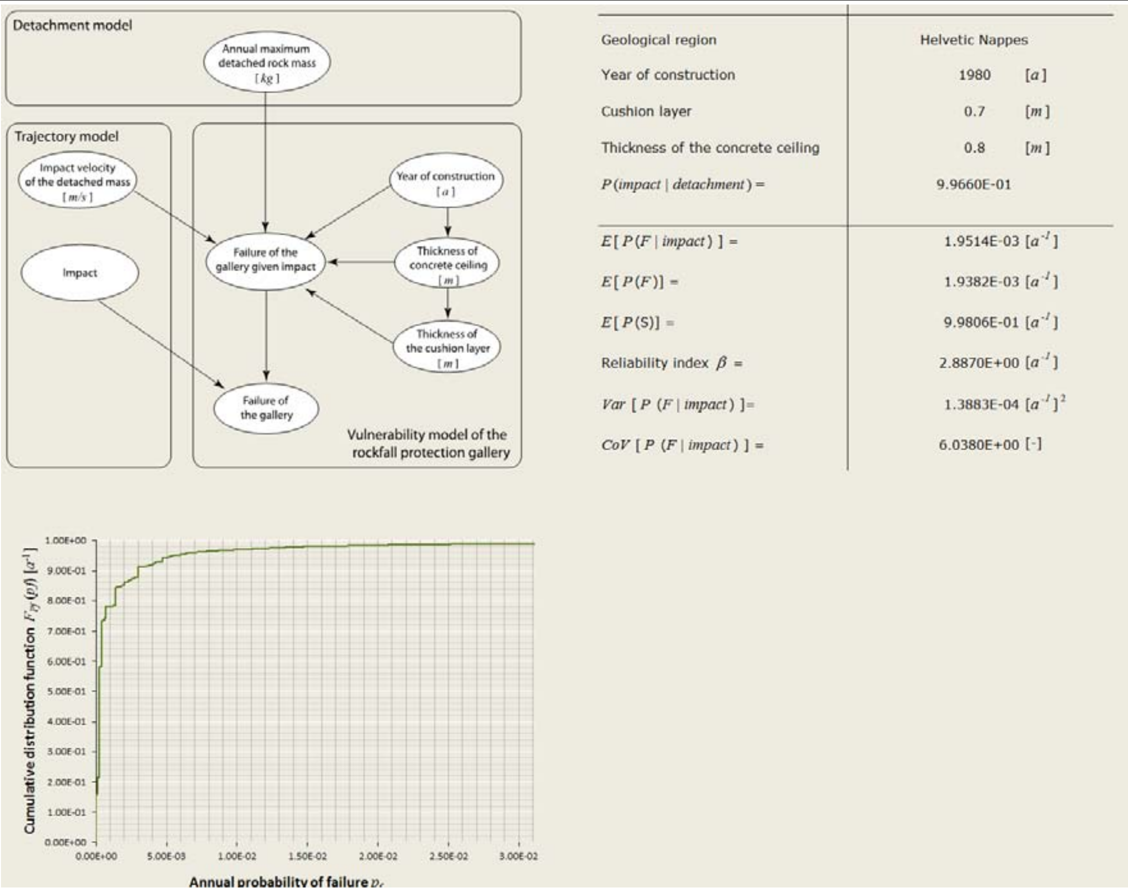


Figure 3.5 Bayesian Probabilistic Network (BPN) for the probability of failure

3.3.5 Modelling of consequences

The consequences to be considered in the risk analysis process can be associated with loss of lives and injuries, damages to the qualities of the environment and economic losses with varying degrees of importance. A screenshot from the consequences section of the program is shown in Figure 3.6. Distribution parameters are required for the listed categories of costs. Apart from the consequences listed in the program, other consequences appropriate for the analysis can be added.

Damage Gallery	μ	σ	Distribution
Property damage gallery [*CHF/m*]	18000	2700	*Normal*
Property damage road [*CHF/m*]	2700	300	*Normal*
Administration costs [*CHF*]	25000	7000	*Normal*
Clean-up costs [*CHF/m*]	1000	200	*Normal*
Compensation Costs			
Cost per fatality [*CHF*]	1.80E+06	3.60E+05	*Normal*
Cost per HGV [*CHF*]	100000	20000	*Normal*
Cost per car [*CHF*]	20000	4000	*Normal*
Societal Costs			
Days of closed road	23	15	*Log-Normal*
Detour Length [*km*]	20	3	*Log-Normal*
Detour velocity [*km/h*]	100	15	*Log-Normal*
User costs [*CHF/(h vehicle)*]	35	7	*Log-Normal*
Marginal costs for a fatality [*CHF*]	3.88E+06		*Deterministic*

Affirm consequence model

Figure 3.6 Modelling of consequences

3.3.6 Risk analysis

Figures 3.7a and 3.7b show the results obtained from the risk analysis. The results are provided in two different formats – in terms of the expected value or mean and in terms of the distribution and are expressed in the units in which the consequences are specified (e.g. Swiss Francs per year as shown in the example in Figures 3.7a and 3.7b). The mean values provide an indication of the contribution to risk from the different sources. The dispersion of the expectation value contains information that is particular to portfolio analysis where the aggregation of risks is important.

Risk	μ	σ	CoV	Type of risk	
Expected property damage gallery [CHF/a]	174.2	1082.8	6.216	*direct*	*internal*
Expected property damage road [CHF/a]	26.2	164.5	6.292	*direct*	*internal*
Expected administration costs [CHF/a]	48.7	325.1	6.671	*direct*	*internal*
Expected clean-up costs [CHF/a]	9.6	60.1	6.234	*direct*	*internal*
Expected property damage cars [CHF/a]	21.4	173.2	8.090	*indirect*	*external*
Expected property damage HGV [CHF/a]	11.8	91.2	7.724	*indirect*	*external*
Expected number fatalities [$1/a$]	5.1230E-04	3.7733E-03	7.365	*indirect*	*external*
Expected compensation costs for fatalities [CHF/a]	923.9	7086.8	7.670	*indirect*	*internal*
Expected days of road closure [$days/a$]	4.3672E-02	2.8917E-01	6.621	*indirect*	*external*
Expected user costs [CHF/a]	6311.4	62381.9	9.884	*indirect*	*external*
Expected societal costs for fatalities [CHF/a]	1987.7	14640.4	7.365	*indirect*	*external*

Aggregated Risk	μ	σ	CoV
Direct internal risk [CHF/a]	258.7	1619.0	6.258
Indirect internal risk [CHF/a]	923.9	7086.8	7.670
Indirect external risk [CHF/a]	8332.3	74802.6	8.977
Total internal risk [CHF/a]	**1182.6**	8416.9	7.117
Total external risk [CHF/a]	**8332.3**	74802.6	8.977
Total risk [CHF/a]	**9515.0**		

Figure 3.7a Results from risk analysis

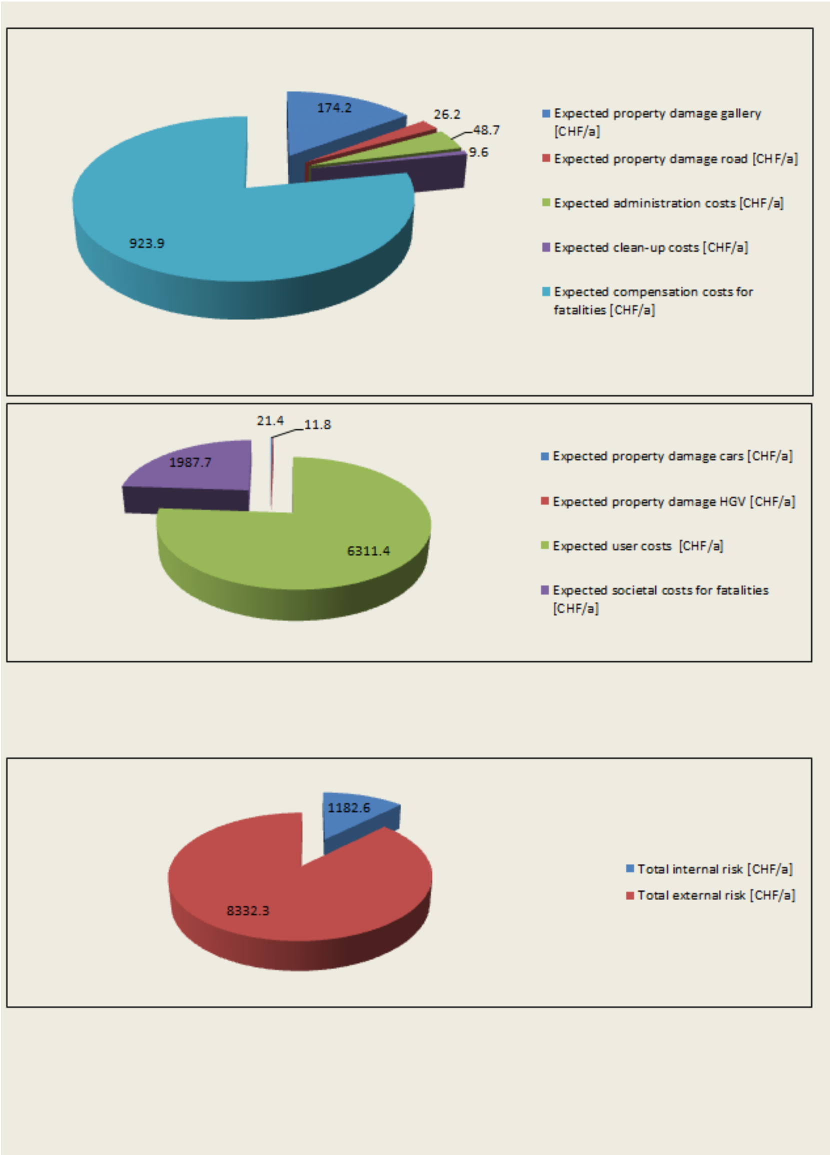


Figure 3.8b Results from risk analysis

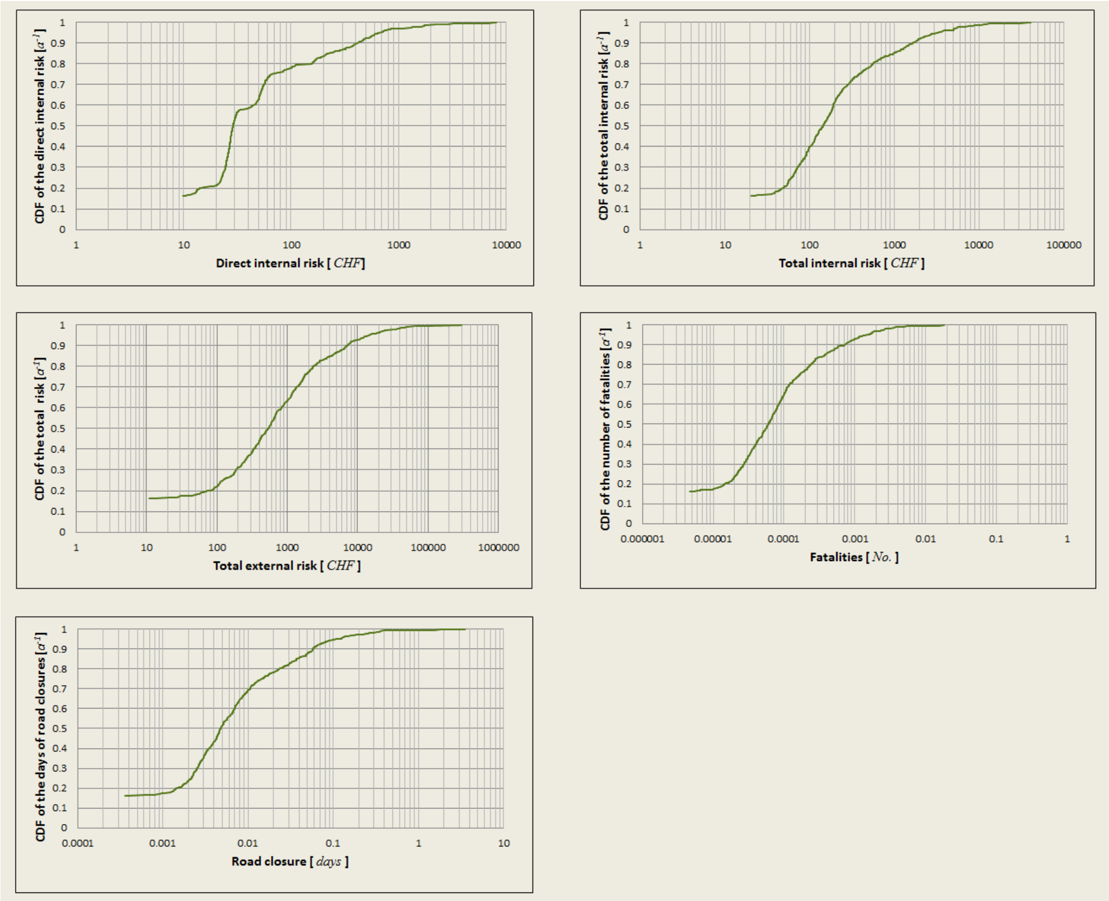


Figure 3.9 Distribution of risk

Generally, different types of risks can be distinguished – direct, indirect, internal and external risks as well as combinations. The internal consequences leading to internal risks will be borne by the decision makers themselves while the external consequences may be borne by third parties. Direct consequences are those implications that arise directly from the rockfall event. The follow-up consequences which go beyond the gallery structure and the direct consequences are called indirect consequences. The breakdown of direct and indirect consequences of consequences allows the conscious use of the various consequences and their sources. In addition to the detailed statement showing the contribution of risks, the risks are also given in aggregate form under direct internal risks, indirect internal risks and external risks and finally the total internal risks and external risks. Further, the distribution functions for the various components of risk are also shown as illustrated in Figure 3.8. The knowledge of the distribution of risks may be important, particularly for further aggregation of risk.

3.3.7 Limitations

For many decision problems, all the necessary information to be able to perform a risk analysis may not available. In this software tool, suitable a priori distributions are used when some information is missing. This makes it possible to perform the analysis even in the absence of information. However the underlying uncertainties may be greater in this case. The user can reduce the uncertainties through the collection of more information, whenever possible.

Presently, material characteristics and procedures from the codes and standards used in Switzerland are considered in the vulnerability model while estimating the probability of failure. For use outside Switzerland, this may generally represent the situation in other countries but this needs to be confirmed on a case-by-case basis.

REFERENCES

RiskNow - Falling Rocks Excel®-basiertes Werkzeug zur Risikoermittlung bei Steinschlagschutzgalerien (RiskNow-Falling Rocks Excel®-based tool for the risk analysis of rockfall protection galleries) 2010. Available from http://partnershop.vss.ch/downloadAnhang.aspx?ID=3a022cc2-100f-4ce6-8222-1d8d3fe512e0&ID_Sprache=1

JCSS 2008. Risk Assessment in Engineering. Internet Publication: http://www.jcss.ethz.ch/publications/JCSS_RiskAssessment.pdf

APPENDIX-LIST OF INPUT AND OUTPUT PARAMETERS

Name of parameter	Symbol used (if any)	Units
SYSTEM DEFINITION – INPUT PARAMETERS		
Information about the project (administrative)		
Name of the author/user		
Project ID		
Project name		
Client		
Date		
Version		
Information about the rockfall protection gallery		
Name of the gallery		
Name of the road		
Geological region		
Year of construction		
Thickness of the concrete ceiling		metres
Cushion layer		metres
Length of the overall gallery		metres
Length of the section in the gallery (necessary for risk analysis)		metres
Number of lanes per direction		
Number of directions		
Information about the traffic		
Annual average daily traffic	AADT	vehicles per day
Proportion of heavy good vehicles	HGV	% of AADT
Congestion hours on the road per year		hours per

		year
Signalised speed		km/hr
DETACHMENT MODEL – INPUT PARAMETERS		
Exceedance frequency (based on expert judgement) for different rock volumes – 2.5% and 97.5% quantile values	H_V	per year
DETACHMENT MODEL – OUTPUT PARAMETERS		
Exceedance frequency (based on power law model) for different rock volumes – 2.5% and 97.5% quantile values	H_V	per year
Mean and standard deviation of model parameters *a* and *b* based on power law relation $H_V = av^{-b}$, where *v* is the rock volume in m^3	μ_a, σ_a μ_b, σ_b	
TRAJECTORY MODEL – INPUT PARAMETERS		
Total height of slope	H_{total}	metres
Upper part (beginning at the detachment point)	H_1	metres
Central part (steep slope section with a slope of about 80°)	H_2	metres
Total orthogonal distance between gallery roof and detachment point	D_{total}	metres
Horizontal distance of the run-off area	D_1	metres
Distribution of impact velocity (manually defined by user if the generic trajectory analysis carried out by the software is not used)		(frequency)
TRAJECTORY MODEL – OUTPUT PARAMETERS		
Mean and standard deviation of impact velocity	$\mu_{impact\ velocity}$ $\sigma_{impact\ velocity}$	m/s
Conditional probability of rock mass impacting the gallery (conditional on the event that the rock mass is detached)		
PROBABILITY OF FAILURE – OUTPUT PARAMETERS		
Probability of failure of the rockfall protection gallery	$P(F)$	
Conditional probability of failure of the gallery given the impact of a rock mass	$P(F \mid impact)$	
Conditional probability of the rock mass impacting the gallery given that it has detached	$P(impact \mid detachment)$	
Annual detachment probability	$P(detachment)$	
MODELLING OF CONSEQUENCES – INPUT PARAMETERS Mean and standard deviation values for different consequence categories (choice of pre-defined values provided by software or user defined values)		
Damage to gallery		
Property damage to gallery		Swiss Francs/m
Property damage to road		Swiss Francs/m
Administration costs		Swiss

		Francs
Clean-up costs		Swiss Francs
Compensation costs		
Cost per fatality		Swiss Francs
Cost per HGV		Swiss Francs
Cost per car		Swiss Francs
Societal costs		
Number of days of road closure		days
Detour length due to road closure		km
Detour velocity due to road closure		km/hr
User costs		Swiss Francs per vehicle
Marginal costs for a fatality		Swiss Francs
RISK ANALYSIS – OUTPUT PARAMETERS (Mean, standard deviation and distribution)		
Categorised risks		
Expected property damage to gallery		Swiss Francs per year
Expected property damage to road		Swiss Francs per year
Expected administration costs		Swiss Francs per year
Expected clean-up costs		Swiss Francs per year
Expected property damage to cars		Swiss Francs per year
Expected property damage to HGVs		Swiss Francs per year
Expected number of fatalities		per year
Expected compensation costs for fatalities		Swiss Francs per year
Expected days of road closure		days per year
Expected user costs		Swiss Francs per year

Expected societal costs for fatalities		Swiss Francs per year
Aggregated risks		
Direct internal risk		Swiss Francs per year
Indirect internal risk		Swiss Francs per year
Indirect external risk		Swiss Francs per year
Total internal risk		Swiss Francs per year
Total external risk		Swiss Francs per year
Total risk		Swiss Francs per year

4 RISK ASSESSMENT FOR ROCKFALLS

(UNIMIB)

4.1 THEORETICAL FRAMEWORK

The QuRAR spreadsheet has been conceived as a simple tool to illustrate how rockfall risk can be quantitatively defined and evaluated, and how different involved parameters interplay (see Section 4.3 “Conditions of Use” below).
The Quantitative Risk Assessment methodology implemented in the QuRAR spreadsheet is based on that proposed by Agliardi et al. (2009). Users are thus encouraged to refer to the original paper or to the detailed discussion included in the Safeland Deliverable 2.11. The latter can be considered as a companion document to the present one.

QuRAR has been implemented under the following assumptions and restrictions:

1) it calculates rockfall risk in terms of annual expected cost (in Euro) for individual buildings or structures, i.e. elements at risk of limited extent characterised by unit exposure (static elements). The tool does not apply to risk analysis for linear elements as roads, railways, etc., for which other methodologies are available in the literature (e.g. Bunce et al., 1997; Hungr et al., 1999);
2) it does not calculate individual or societal risk (e.g. Loss of Life, LoL) for people inside or outside the considered structures (e.g. people walking or driving);
3) it considers a single protection scenario (see Agliardi et al., 2009 for details) and limited numbers of event magnitude scenarios (5) and exposed elements at risk (10). These restrictions have been introduced for the sake of simplicity. Nonetheless, the users are allowed to freely implement and modify the spreadsheet.

According to the adopted approach (Hungr et al., 1999; Fell et al., 2005; Agliardi et al., 2009) and considering the aforementioned assumptions, rockfall risk for static elements (e.g. buildings) can be practically evaluated according to the following equation:

$$R = \sum_{i=1}^{I} \sum_{j=1}^{J} N_j \cdot P(T|L)_{ij} \cdot V_{ij} \cdot W_i \tag{4.1}$$

where:

N_j: annual frequency of rockfall events in the magnitude (volume) class j;
$P(T|L)_{ij}$: probability of reach (i.e. for block in magnitude class j to reach the element i);
V_{ij}: vulnerability (i.e. expected degree of loss) of a given element at risk i to the impact of a block in the magnitude class j;
W_i: economic value of the element at risk i (building and people inside).

The temporal spatial probability, or exposure, $P(I|T)_i$ (see Agliardi et al., 2009) is not explicitly included in the equation since it equals 1 for static elements as those considered.

Annual frequency of rockfall events in the magnitude (volume) class j, Nj

In the adopted approach, the annual frequency of rockfall events is evaluated starting from magnitude-cumulative frequency (MCF) relationships in the form (Dussauge et al., 2003):

$$N_j = \frac{N_0}{T}\left(\frac{v_j}{v_0}\right)^{-b} \tag{4.2}$$

where:

N_0:	the total number of rockfall events larger than V_0 (see below) occurring in the study area over a reference time interval T (see below);
T:	the reference time (in years) covered by the available event dataset.
v_j:	maximum block volume in the magnitude (volume) class j;
v_0:	the minimum volume of individual blocks in the study area. This value strongly affects the shape of the MCF curve (i.e. the volume range over which the total number of event is distributed), thus it should be related to the minimum volume significant to the rockfall problem;
b:	the MCF power-law exponent b (positive value);

MCF relationships allow deriving the incremental frequency (number/year) of rockfall events within different magnitude (volume) classes j (Tab. 4.1). These provide “event magnitude scenarios” resulting in different “risk scenarios”, which are evaluated separately in the following and then combined according to Eq. 4.1.

Table 4.1. Event magnitude (volume) classes considered in QuRAR.

Magnitude class, j	Volume (range, m^3)	Volume (upper limit, m^3)
1	0.001 - 0.01	0.01
2	0.01 - 0.1	0.1
3	0.1 - 1	1
4	1 - 10	10
5	10 - 100	100

Depending on the available information, field evidence, and project budget, these parameters may be derived from historical databases of rockfall events (Hungr et al., 1999; Dussauge et al., 2003), estimated from geomorphological / event data, or assumed from the literature. If an inventory of historical rockfall events is used, parameter T should be the time interval covered by the inventory. If the analysis is based on literature values of b, T will usually equal 1 year, and N_0 will be an estimate of the total annual number of events with volume > V_0 in the study area.

Probability of reach $P(T|L)_{ij}$

The probability of reach (or propagation) is the probability that a block in the magnitude class j reach the element at risk i, given that a rockfall event in the magnitude class j has occurred. In the present approach, this probability is derived from the results of rockfall mathematical modelling (performed outside QuRAR for each magnitude class separately). Agliardi et al. (2009) used the 3D simulation model Hy-Stone to implement the methodology. Nevertheless, any simulation tool able to provide the following data to QuRAR can be used:

1) total number of rockfall trajectories (or blocks) simulated in the study area;
2) the number of blocks reaching (i.e. impacting or stopping inside) each element at risk;
3) the distribution of kinetic energy of blocks reaching each element at risk (see below).

For each element at risk i, the probability of reach is easily calculated as the ratio between the total number of blocks reaching the element and the total number of simulated trajectories (see Agliardi et al., 2009 for details).

Since in real-world applications multiple, spatially-distributed rockfall sources may contribute to risk for a given element at risk, a robust definition of the probability of reach requires the use of 3D modelling tools.
The probability of reach allows calculating the "probability of impact" of a rock fall in the magnitude class j on the element i, which for elements with unit exposure is:

$$P(I)_{ij} = N_j \cdot P(T|L)_{ij} \qquad (4.3)$$

Vulnerability, V_{ij}

The physical vulnerability (i.e. expected degree of loss) of a given element at risk i to the impact of a block in the magnitude class j is a function of the kinetic energy of blocks at impact, in turn depending on block size and dynamics. In the approach implemented in QuRAR, the vulnerability of each element at risk i in each event magnitude scenario j is evaluated using an empirical, sigmoidal vulnerability function of general form:

$$V = \frac{A_1 - A_2}{1 + e^{\frac{(E - x_0)}{dx}}} + A_2 \qquad (4.4)$$

where:

V: expected degree of loss;
E: kinetic energy of the block impacting the element at risk (in Joule);
A_1, A_2, x_0 and dx: empirical constants

Default values of the empirical constants have been obtained by Agliardi et al. (2009) by combining site-specific numerical modelling results and field data for buildings impacted by rockfalls, and can be modified by the users.
In order to compute the expected degree of loss suffered by each element at risk i for each event magnitude scenario j using Eq. 4.4, the distribution of the kinetic energy values of blocks reaching each element at risk i must be derived from numerical modelling (performed outside QuRAR for each magnitude class separately). Also in this case, 3D simulation tools should be used to obtain consistent values when multiple rockfall sources are expected to contribute to the same element at risk. The descriptor of kinetic energy to be used in the analysis (e.g. mean, maximum, median, quantile) must be selected by the users depending on the scope of risk analysis and/or specific regulatory or management issues.

Economic value of elements at risk, W_i

The value of individual elements at risk can be derived from existing databases or cadastral surveys/documentation, or estimated from real-estate market information or previous loss reports, depending on structure destination (e.g. housing, commercial), type (e.g. masonry walls, reinforced concrete frame), and size (e.g. height, plan area, number of storeys).

4.2 TOOL DESCRIPTION

QuRAR has a very simple structure, and is made of two worksheets:

1) 01_in-out: main user interface, where all the required input data are provided to the tool and results (i.e. risk, or the annual expected cost for each element at risk) are summarized;
2) 02_calculations: includes all calculation steps and intermediate results (e.g. probability of reach, probability of impact, vulnerability/degree of loss, and specific risks).

The following general conventions apply:

1) green cells indicate input parameters, required to perform risk analysis;
2) white cells contain calculations;
3) yellow cells contain results (intermediate calculation steps and risk).

All cells except input (green) ones are protected in order to prevent accidental modifications or formatting change. Users are free to unprotect the worksheets.

4.2.1 Inputs and outputs

This worksheet includes four sections, which are illustrated in detail below. Input and output data required or produced by the QuRAR tool, as well as their units and symbols are summarised in the following Table 4.2.

Table 4.2. QuRAR input and output data: list of symbols

Parameter description	Symbol	Units	Note
Input data			
Total number of rockfall events	N	-	from inventories or geomorphology
Minimum block volume	v_0	m^3	to be selected carefully
Power-law exponent	b	-	insert positive (absolute) value
Reference time	T	years	
Total number of simulated traj.	-	-	from rockfall modelling
Value of elements at risk (EAR)	W_i	Euro	for each element at risk (EAR)
numbers of impacting blocks	-	-	for each EAR and volume class j
impact kinetic energies	-	Joule	for each EAR and volume class j
vulnerability empirical constant 1	A1	-	default after Agliardi et al. (2009)
vulnerability empirical constant 2	A2	-	default after Agliardi et al. (2009)
vulnerability empirical constant 3	x_0	-	default after Agliardi et al. (2009)
vulnerability empirical constant 4	dx	-	default after Agliardi et al. (2009)
Output data			
Annual # events in volume class j	N_j	-	from MCF relationship
Probabilities of reach on EAR	$P(T \mid L)_{ij}$	-	for each EAR and volume class j
Probabilities of impact on EAR	$P(I)_{ij}$	-	for each EAR and volume class j
Degree of loss	V_{ij}	-	for each EAR and volume class j
Total risk (annual expected loss)	R_i	Euro	for each element at risk (EAR)

4.2.2 Worksheet “01_in-out”

This worksheet includes four sections:

1) Input 1. Annual frequency of rockfall events: here the inputs required to calculate the different probabilities (onset, reach, impact) are provided to the tool. Inputs include MCF curve parameters (the resulting MCF power law is plotted and automatically updated on the right) and the total number of simulated trajectories (from rockfall modelling, assuming that the same total number of trajectories is simulated for each model run – one for each magnitude class j). Both cumulative and incremental frequencies of rockfalls computed for each magnitude class j are reported in the bottom table;

INPUT 1. Annual frequency of rockfall events, Nj ***(after Dussauge et al., 2003)***

Total number of events, N_0	**10**
Minimum block volume, V_0	**0.001**
Power-law exponent, **b**	**0.41**
Reference time, **T**	**1**

Total number of simulated trajectories	**10000**

Magnitude class, j	Volume (m^3) range	Volume (m^3) upper limit	Cumulative frequency (# events / year)	Incremental frequency, Nj (# events / year)
			10.00	
1	0.001 - 0.01	0.01	3.89	**6.11**
2	0.01 - 0.1	0.1	1.51	**2.38**
3	0.1 - 1	1	0.59	**0.92**
4	1 - 10	10	0.23	**0.36**
5	10 - 100	100	0.09	**0.14**

Figure 4.1 Worksheet "01_in-out": detail of Input 1 section

2) Input 2. Elements at risk: in this section, up to ten elements at risk can be listed and characterised with respect to: economic value (in Euro), number of impacting blocks and impact kinetic energy (in Joule). These are derived from rockfall modelling performed separately for each magnitude class j;

INPUT 2. Elements at risk, EARi

EAR ID, i (-)	Value, Wi (Euro)	# impacting blocks (magnitude class j=1)	# impacting blocks (magnitude class j=2)	# impacting blocks (magnitude class j=3)
1	606000	5	5	5
2	333000	5	5	5
3	498000	5	5	5
4	318000	5	5	5
5	270000	5	5	5
6	318000	5	5	5
7	924000	5	5	5
8	534000	5	5	5
9	504000	5	5	5
10	960000	5	5	5

EAR ID, i (-)	kinetic energy (Joule) (magnitude class j=1)	kinetic energy (Joule) (magnitude class j=2)	kinetic energy (Joule) (magnitude class j=3)
1	1000	15000	150000
2	1000	15000	150000
3	1000	15000	150000
4	1000	15000	150000
5	1000	15000	150000
6	1000	15000	150000
7	1000	15000	150000
8	1000	15000	150000
9	1000	15000	150000
10	1000	15000	150000

Figure 4.2 Worksheet "01_in-out": detail of Input 2 section.

3) Input 3. Vulnerability: input data required in this section allow to set up the empirical, sigmoidal vulnerability function used in the Worksheet "02_calculations"

to compute the expected degree of loss for each element at risk i, depending of the kinetic energy values provided to the tool for each magnitude class j;

INPUT 3. Vulnerability, Vij

Empirical constant, **A1**	**-0.358**
Empirical constant, **A2**	**1**
Empirical constant, **x_0**	**129000**
Empirical constant, **dx**	**120300**

$$V = \frac{A_1 - A_2}{1 + e^{\frac{(E - x_0)}{dx}}} + A_2$$

after Agliardi et al. (2009)

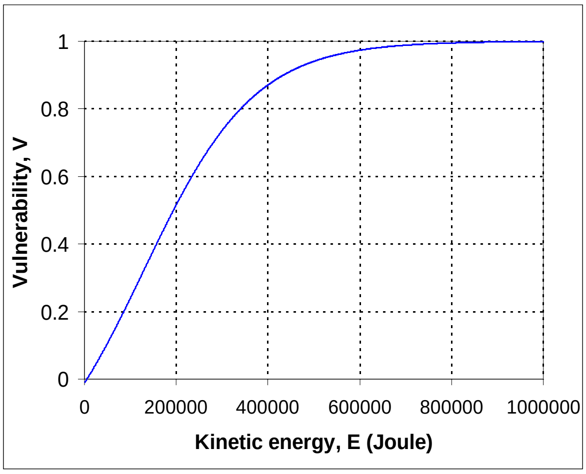


Figure 4.3 Worksheet "01_in-out": Input 3 section.

4) Output. Risk: this section provide a summary of the annual expected costs (risk) computed in the Worksheet "02_calculations" for each element at risk i.

4.2.3 Worksheet "02_calculations"

In this worksheet, the entire calculation sequence required to compute risk according to Eq. 4.1 is performed and summarized (Fig. 4.4).
For each element at risk i and for each magnitude class j, the sequence include the following calculation steps: 1) incremental frequency of rockfall events (copied from "01_in-out"); 2) probability of reach; 3) probability of impact; 4) kinetic energy of impact (copied from "01_in-out"); 5) degree of loss; 6) specific risk; 7) total risk.

	Incremental frequency (# events / year), Nj				
EAR ID	**Magnitude class j=1**	**Magnitude class j=2**	**Magnitude class j=3**	**Magnitude class j=4**	**Magnitude class j=5**
1	6.11	2.38	0.92	0.36	0.14
2	6.11	2.38	0.92	0.36	0.14
3	6.11	2.38	0.92	0.36	0.14
4	6.11	2.38	0.92	0.36	0.14
5	6.11	2.38	0.92	0.36	0.14
6	6.11	2.38	0.92	0.36	0.14
7	6.11	2.38	0.92	0.36	0.14
8	6.11	2.38	0.92	0.36	0.14
9	6.11	2.38	0.92	0.36	0.14
10	6.11	2.38	0.92	0.36	0.14

	Probability of reach				
EAR ID	**Magnitude class j=1**	**Magnitude class j=2**	**Magnitude class j=3**	**Magnitude class j=4**	**Magnitude class j=5**
1	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04
2	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04
3	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04
4	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04
5	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04
6	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04
7	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04
8	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04
9	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04
10	5.00E-04	5.00E-04	5.00E-04	5.00E-04	5.00E-04

	Probability of impact for magnitude classes, P(I)ij				
EAR ID	**Magnitude class j=1**	**Magnitude class j=2**	**Magnitude class j=3**	**Magnitude class j=4**	**Magnitude class j=5**
1	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05
2	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05
3	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05
4	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05
5	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05
6	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05
7	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05
8	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05
9	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05
10	3.1E-03	1.2E-03	4.6E-04	1.8E-04	7.0E-05

	Kinetic energy for magnitude classes (Joule)				
EAR ID	**Magnitude class j=1**	**Magnitude class j=2**	**Magnitude class j=3**	**Magnitude class j=4**	**Magnitude class j=5**
1	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07
2	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07
3	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07
4	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07
5	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07
6	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07
7	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07
8	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07
9	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07
10	1.0E+03	1.5E+04	1.5E+05	1.5E+06	1.5E+07

	Degree of loss for magnitude classes, Vij				
EAR ID	**Magnitude class j=1**	**Magnitude class j=2**	**Magnitude class j=3**	**Magnitude class j=4**	**Magnitude class j=5**
1	0.000	0.021	0.380	1.000	1.000
2	0.000	0.021	0.380	1.000	1.000
3	0.000	0.021	0.380	1.000	1.000
4	0.000	0.021	0.380	1.000	1.000
5	0.000	0.021	0.380	1.000	1.000
6	0.000	0.021	0.380	1.000	1.000
7	0.000	0.021	0.380	1.000	1.000
8	0.000	0.021	0.380	1.000	1.000
9	0.000	0.021	0.380	1.000	1.000
10	0.000	0.021	0.380	1.000	1.000

	Specific risk for magnitude classes, Rsij					Total risk, Ri (Euro)
EAR ID	**Magnitude class j=1**	**Magnitude class j=2**	**Magnitude class j=3**	**Magnitude class j=4**	**Magnitude class j=5**	
1	0.00E+00	2.54E-05	1.76E-04	1.80E-04	7.00E-05	**273**
2	0.00E+00	2.54E-05	1.76E-04	1.80E-04	7.00E-05	**150**
3	0.00E+00	2.54E-05	1.76E-04	1.80E-04	7.00E-05	**225**
4	0.00E+00	2.54E-05	1.76E-04	1.80E-04	7.00E-05	**143**
5	0.00E+00	2.54E-05	1.76E-04	1.80E-04	7.00E-05	**122**
6	0.00E+00	2.54E-05	1.76E-04	1.80E-04	7.00E-05	**143**

Figure 4.4 Worksheet “02_calculations”

4.3 CONDITIONS OF USE

The ”QuRAR” spreadsheet can be freely downloaded, used, copied, distributed and modified. All spreadsheet cells can be accessed and modified without limitations, allowing users to explore and implement the tool according to their needs.
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