SRC International Cooperation

Rock fall hazard analysis

Swiss Red Cross

Introduction

Why this manual is necessary

The Swiss Red Cross (SRC) supports its partner organizations worldwide in disaster risk management (DRM) to strengthen the resilience of vulnerable people. This includes relief both in emergencies and during reconstruction phases, as well as strengthening prevention and preparedness to mitigate natural hazard risk. A sound knowledge of existing natural hazards is an important prerequisite for DRM, both for landuse planning and for the planning of mitigation measures. For this reason, the SRC developed the methodological guide “Natural Hazard Analysis” (see https://www.hazard-risk.com), a practical manual for determining areas prone to flood, debris flow, landslide and rockfall, specifying frequency and intensity of occurrence of future events. This guide is intended to complement the VCA methodology of the International Federation of Red Cross and Red Crescent Societies (IFRC), with simple geomorphological and quantitative methods to improve the quality of hazard analyses.

In mountain areas, rockfall processes often pose additional hazards to settlement areas and infrastructure facilities. For this reason, the SRC methodological guide has been enriched with this rockfall hazard analysis manual.

Who the manual is for

The "Rockfall Hazard Analysis" manual describes the minimum requirements for natural hazard analyses in SRC projects. Quantitative analyses and the use of numerical models were deliberately avoided so that even institutions without in-depth specialized knowledge can apply the analysis methods. This document is intended for DRM managers of the Red Cross societies and externally mandated consultants.

How the manual is structured

This manual is divided into three parts. The first part explains the definitions of the different types of rockfalls. The second contains instructions for the 5-step hazard analysis according to Figure 2. The third shows the procedure for hazard mapping.

Part 1 - Definitions

The generic term "rockfall processes" describes the detachment of stones and blocks from a rock wall or a natural steep slope of loose material by which the falling components are moved valley side in a free fall, jumping, sliding, or rolling. Rockfall processes can be triggered both naturally (earthquakes, rainfall, temperature changes) and artificially (e.g. excavations on slopes). Topography as well as geological and climatic conditions are basic prerequisites for rockfall processes to occur.

As for **stone- and block-fall processes**, individual stones (diameter < 0.5 m) or individual blocks (diameter > 0.5 m) fall downslope and can reach velocities as fast as 30 m/s (100 km/h). The total volume per event is less than 100 m^3. Along the way, stones and blocks generally lose energy and begin to slow down on slopes below 30° - 35°.

Illustration 1: Examples of rockfall processes. Source: Geographyeducation.org

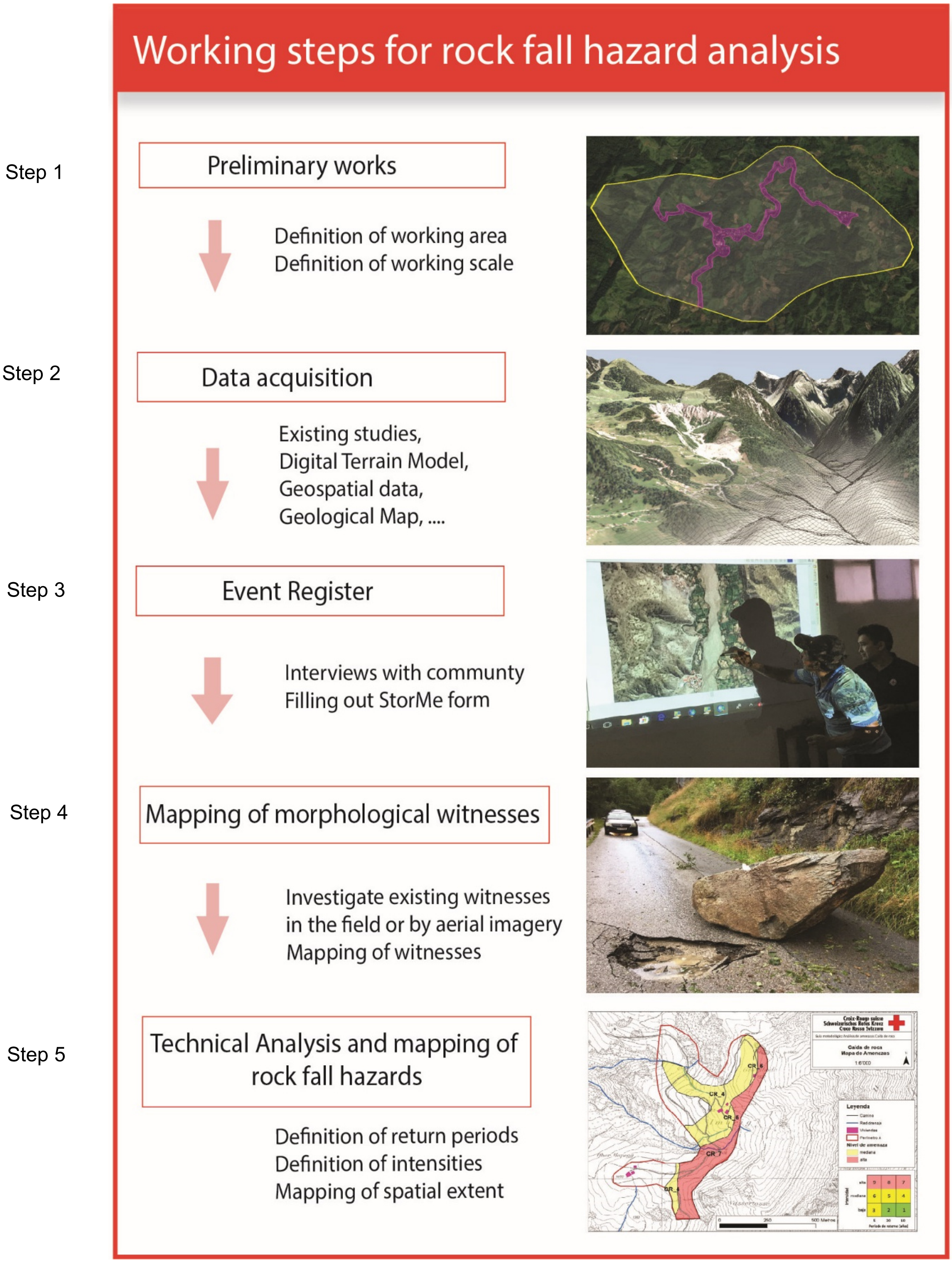
Rockfall volumes greater than 100 m^3 belong to the category of **rock avalanches**. The impact energy is so significant that organizational planning measures must be taken instead of structural measures to protect housing or infrastructure (landuse planning).

Illustration 2: Rockfall in Evolène, Switzerland. Source: Community of Evolène.

Rockfall often occur suddenly. The forewarning time is minimal, so there is hardly time for evacuation. Early warning systems are usually not effective in this case. On the other hand, a rock avalanche of larger volume is sometimes noticed several days or weeks in advance through increased rockfall activity with small volumes. In this way, appropriate emergency measures can be taken.

The probability of rockfalls greater than 100 m^3 in settlement areas is usually low. Therefore, this manual exclusively describes the analytical steps for assessing rockfall hazards that often put buildings and infrastructure facilities at risk.

Part 2 – Analysis steps



Working steps for rock fall hazard analysis

Step 1

Preliminary works

Definition of working area
Definition of working scale

Step 2

Data acquisition

Existing studies,
Digital Terrain Model,
Geospatial data,
Geological Map, ...

Step 3

Event Register

Interviews with communty
Filling out StorMe form

Step 4

Mapping of morphological witnesses

Investigate existing witnesses
in the field or by aerial imagery
Mapping of witnesses

Step 5

Technical Analysis and mapping of rock fall hazards

Definition of return periods
Definition of intensities
Mapping of spatial extent

Illustration 3: Working steps for the analysis of rockfall hazards. Source: SRC.

Step 1 – Preparatory Work

Definition of the perimeter and the level of detail of the analysis

Before starting a hazard analysis, the study area should be spatially defined and captured on a map. As a general rule, the perimeter of hazard mapping is smaller than the study area and includes current (or planned) areas for settlements, infrastructure facilities and important livelihoods. Therefore, the perimeter of the hazard mapping must be limited to these existing or designated areas (perimeter „A“). By limiting the perimeter to relevant areas, it is possible to save time and costs. Areas outside this perimeter should also be explored if they affect this perimeter. Illustration 3 shows the project area (in yellow) and perimeter „A” of a hazard mapping (in purple). The perimeter „A“ is defined jointly by the communities and competent authorities. In tenders for hazard mapping, the perimeter „A“ must be defined in the terms of reference. The detail level of the analysis must also be determined. Scale accuracy between 1:5,000 and 1:10,000 is appropriate for land use and mitigation measure planning at the municipal level.

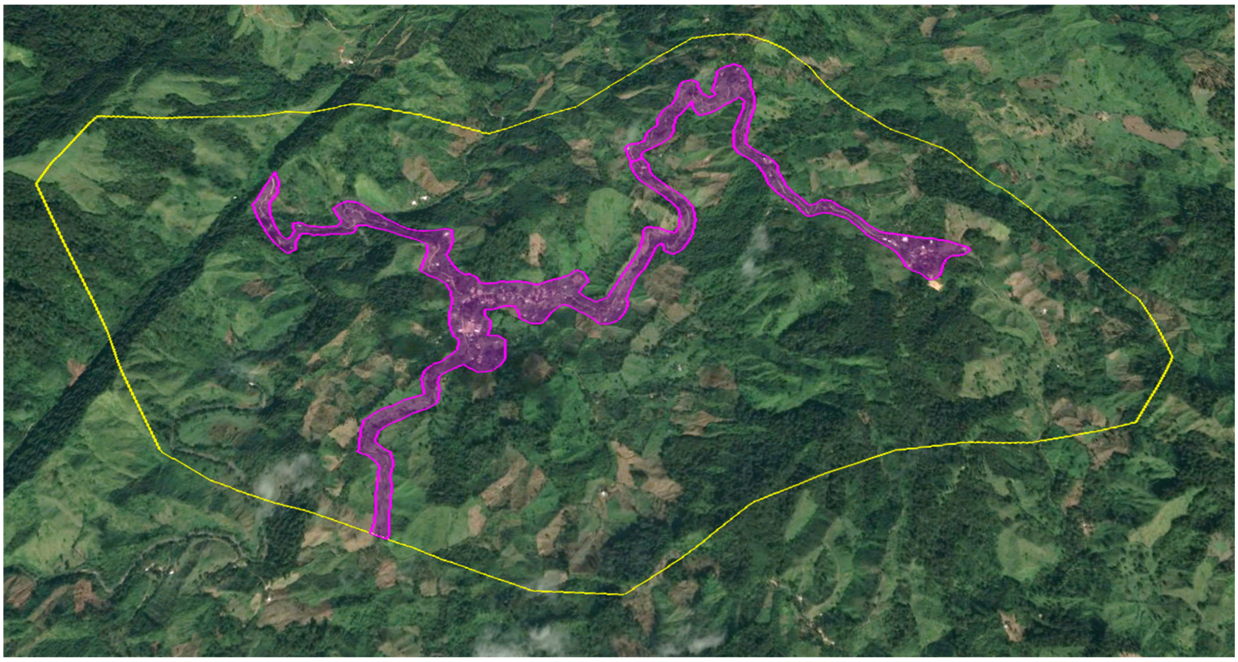


Illustration 4: Drawing of a project perimeter (yellow area) and perimeter „A“ of a hazard map (purple area).

Precheck of the relevance of rockfall processes for perimeter "A”

Before starting an analysis of rockfall hazards, it is recommended to do a simple check to determine if they may exist in perimeter A and, therefore, if an analysis is justified. An examination is recommended under the following conditions:

- Fractured rocks or deconsolidated stones/blocks of rocky outcrops or debris from steep slopes are found in or near the perimeter “A”. In both cases, the overall gradient is greater than 28°. The overall gradient describes the gradient of an imaginary line between the highest point of a rocky wall and the highest point of perimeter “A” in the fall direction (see Illustration 5).

- There are no significant morphological depressions or embankments in the fall direction that can stop the falling of stones/blocks.

These preliminary clarifications are best carried out in the field. Complementarily, it is possible to use desk-based research providing high-resolution digital terrain models and aerial imagery.

Illustration 5: Outline of the overall gradient concept. Source: SRC.

Recommended equipment for analysis

Rockfall hazard analysis is mainly performed in the field using the following equipment:

- Clinometer (to measure slope angle, for ex. from Suunto, or Smartphone application)

- Binoculars

- Measuring tape

- Geological compass

- Topographic map

Definition of scenarios

It is recommended to consider three research scenarios. These are often applied with return periods of 10, 30 and 100 years, equivalent to a very frequent event, a generational event and an extreme event, respectively (see Table 1).

Table 1: Scenarios and their return periods. Source: SRC.

	Frequent event	**Generational event**	**Extreme Event**
Name of scenario	„10-year”	„30-year”	„100-year”
Return period	≤ 10 years	10 – 30 years	30 – 100 years
Frequency of occurrence within 30 years	> 3 times	1 – 3 times	< 1 time

Step 2 – Basic Data

The following list represents frequently used base line data. The quality of a hazard assessment relies primarily on the availability of data:

- Topographic map or satellite photos as a cartographic database
- Geological map
- Local reports from previous events (VCA, etc.)
- Photos of events and damage occurred
- Press reports
- Georeferenced aerial photos from different dates
- Digital Terrain Model (DTM)
- Digital drainage system
- Studies of works carried out
- Previous hazard studies

Step 3 – Event Register

The analysis of past events is a core component of the hazard analysis. Particularly for very short return periods (< 10 years), the information obtained may be sufficient to describe the hazards for this scenario. For scenarios with long return periods (extreme events), data serve to verify the results of technical analyses. The documentation process of previous events allows for taking into account the local population‘s knowledge on natural hazards. It also serves to raise awareness and help the population to take ownership for the implementation of the hazard map.

The IFRC‘s VCA methodology describes methods and tools to collect information from past events in a participatory manner. All information obtained is recorded on the StorMe form (Annex in https://www.hazard-risk.com).

Two pragmatic data collection approaches are presented below:

Aerial Photo-based Approach

- A facilitator projects an aerial photography of the perimeter of interest (GoogleEarth or drone made orthophoto) on a white paper (Illustration 6).
- Through an exercise with the plenary, the facilitator ensures that all participants can orient themselves using aerial photography.
- In a participatory procedure, the spatial extent of previous events is marked on the white paper. Each event area is assigned with the date of the related event (event index). This is linked to the StorMe forms attached to each documented event.
- In the plenary, known damage and event information are compiled into the StorMe form. For this, the facilitator appoints someone who has previously become familiar with the form so that he/she can be responsible of the protocol. The StorMe form is referenced with the event index on the photo displayed.

Illustration 6: Mapping carried out by the population on areas affected by previous events (Poco Poco, Bolivia). Source: SRC.

“Field Tour” Approach

After a meeting with community representatives or when participants cannot orient themselves with an aerial photo, they are invited to tour the area of interest. The information collected in the field about events occurred is entered into the StorMe form. Of particular interest in data collection is the frequency and distance covered by rockfalls. In addition, the block shape and diameter can be recorded using the StorMe form.

Illustration 7: Data collection of slope of rockfall events in Honduras using a clinometer. Source: SRC.

Step 4 – Morphological Silent Witnesses

Recording morphological silent witnesses of previous rockfall deposits allows us to draw similar conclusions about future events in terms of potential hazard areas, intensity and frequency of occurrence. Witnesses of previous events can often be found, for example deposits, traces that left tangled blocks, wounds in the bark of trees, or holes in paved roads left by the stones on impact. The mapping of morphological witnesses is mainly carried out through on-site inspections, but can also be complemented with high-precision aerial photography information. A scale of 1:10,000 is recommended for the mapping, which is carried out using the symbolism in the Annex of https://www.hazard-risk.com).

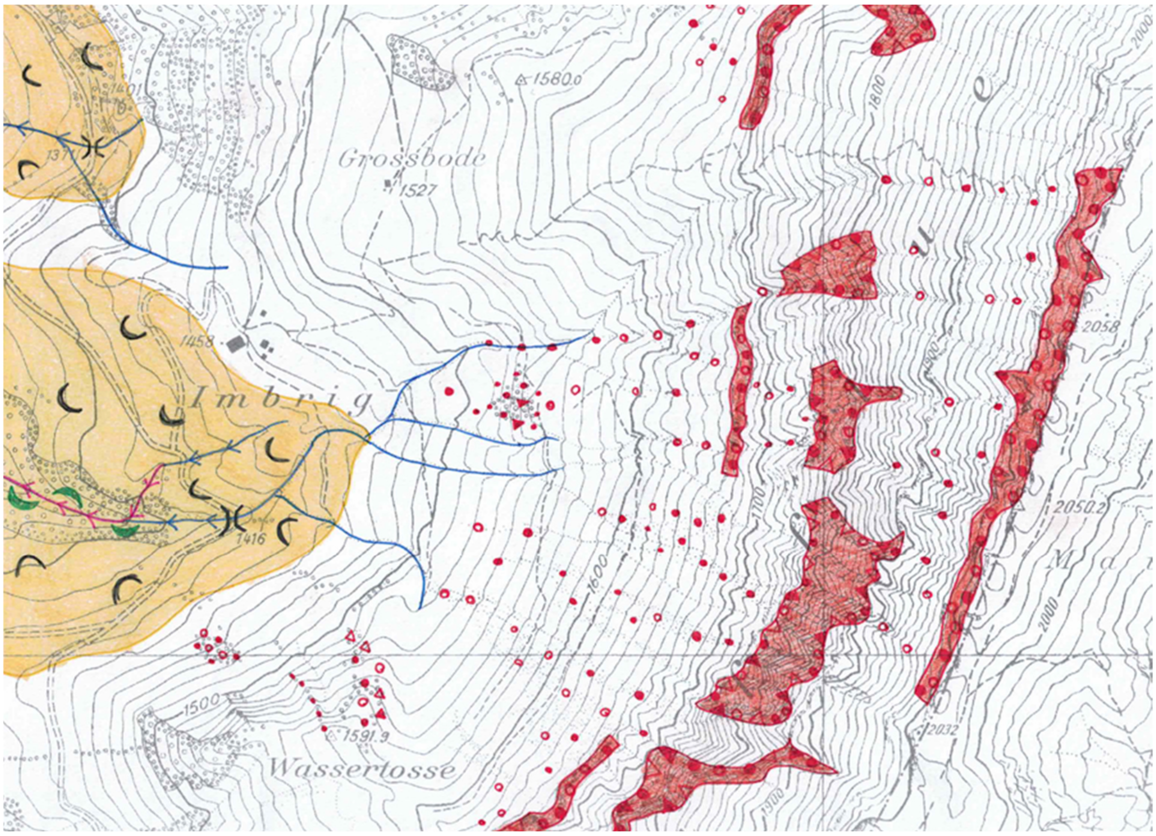


Illustration 8: Morphological silent witnesses map in Schangnau, Switzerland. The red areas represent sectors of stone and block detachment, the circles and triangles represent deposits on the cone. The black lines represent contour lines. The symbols can be found in Annex from https://www.hazard-risk.com) Source: SRC.

Examples of morphological traces of rockfalls are the following:

Illustration 9: Dejection cone on a steep slope with deposits of stones and larger blocks. The area of detachment can be seen in the background (Valle del Maipo, Chile).

Source: Geotest Chile SpA

Illustration 10: Cone with block deposits behind cowsheds on steep slopes (Kandersteg, Switzerland).

Source: SRC

Illustration 11: Deposits of stones and blocks from different dates/events. The blocks covered by lichen vegetation represent deposits of old events. The bare white block at the center of the photo is from the same lithology. The lack of vegetation succession shows that it is witness to a recent event (Bregaglia, Switzerland)

Source: SRC

Illustration 12: Trace of a rolled block that uprooted bushes and followed its course in the direction of the buildings shown in the background of the photo (Valle Colorado).

Source: Geotest Chile SpA

Illustration 13: Fresh injuries caused by stones on tree bark (Valle del Maule, Chile)

Source: Geotest Chile SpA

Illustration 14: The stone lifted covers the vegetation, evidencing a recent rockfall event (Hohgant, Switzerland).

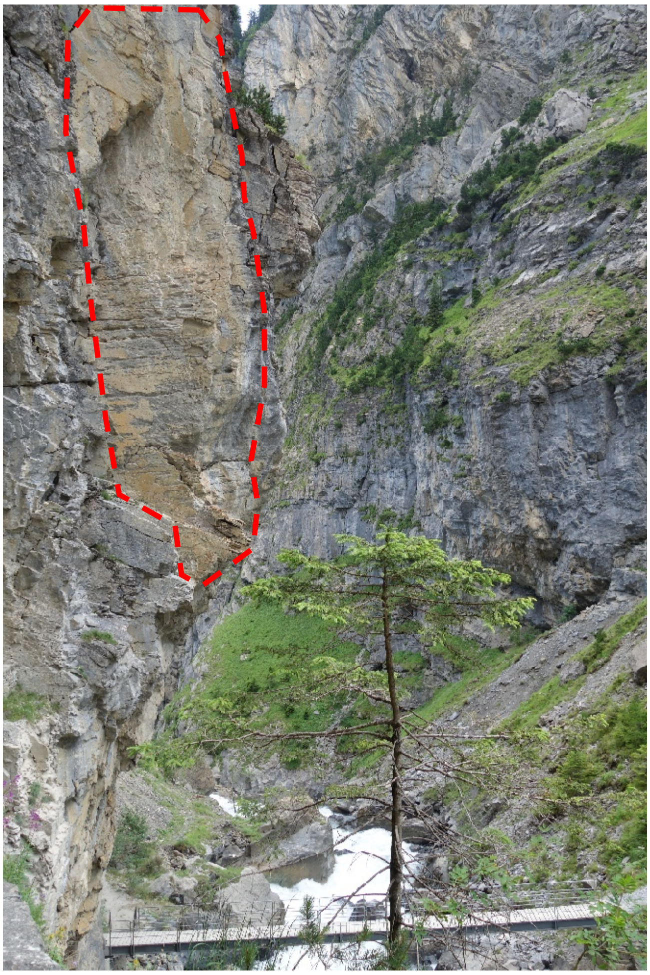
Source: SRC

Illustration 15: Hole in the pavement left by a block upon impacting this road.

Source: meinbezirk.at

Illustration 16: Stone detachment area. The change in the rock's color indicates a recent rockfall event (Gasterntal, Switzerland)

Source: SRC



Step 5 – Technical Analysis of Rockfalls

Analysis of the detachment area

During site inspections, potential detachment sectors (rocky outcrops or banks of loose material such as moraines) are located, and the kinetic energy "E" of potential rockfall is defined. On the one hand, the maximum vertical height of rockfall is determined. On the other hand, the mass of potential blocks falling is determined through research on the bedrock stratification and the transversal or perpendicular cracks (surface analysis, see Illustration 17)[1]. The kinetic energy "E" is estimated in a simplified way by the following basic formula:

$$E\ [kJ] = m * g * h, \qquad \text{where}$$

E = Kinetic energy in Kilojoule [kJ]

m = Mass of the block (length * width * height in meters multiplied by 2,75) [t]

g = Gravitation (~ 10) [m/s^2]

h = Vertical height of the fall [m]

Alternatively, the kinetic energy of a vertically falling block can be estimated from its velocity and mass, as shown in

Table 2. The velocity v can be approximated with the following formula:

$$v = (2 * g * h)^{0.5} \qquad \text{[m/s]}$$

Table 2: Examples of kinetic energy resulting from the vertical fall height (h), the velocity of motion (v) and the mass (m) that respectively correlates with the volume (Vo) of the fall components. Source: Schutz vor Naturgefahren.ch.

Mass m [kg]	**Volume Vo [m3]**	**h: 0.3 [m]**	**h: 1 [m]**	**h: 5 [m]**	**h: 12 [m]**	**h: 20 [m]**	**h: 32 [m]**
		v: 2.5 [m/s]	**v: 5 [m/s]**	**v: 10 [m/s]**	**v: 15 [m/s]**	**v: 20 [m/s]**	**v: 25 [m/s]**
20	0.01	0.0 [kJ]	0.1 [kJ]	0.5 [kJ]	1 [kJ]	2 [kJ]	3 [kJ]
50	0.02	0.2 [kJ]	0.6 [kJ]	3 [kJ]	6 [kJ]	10 [kJ]	16 [kJ]
100	0.04	0.3 [kJ]	1 [kJ]	5 [kJ]	11 [kJ]	20 [kJ]	31 [kJ]
170	0.07	0.5 [kJ]	2 [kJ]	9 [kJ]	19 [kJ]	34 [kJ]	53 [kJ]
250	0.09	0.8 [kJ]	3 [kJ]	13 [kJ]	28 [kJ]	50 [kJ]	78 [kJ]
500	0.18	2 [kJ]	6 [kJ]	25 [kJ]	56 [kJ]	100 [kJ]	156 [kJ]
1000	0.38	3 [kJ]	13 [kJ]	50 [kJ]	113 [kJ]	200 [kJ]	313 [kJ]
1400	0.52	4 [kJ]	18 [kJ]	70 [kJ]	158 [kJ]	280 [kJ]	438 [kJ]
2000	0.74	6 [kJ]	25 [kJ]	100 [kJ]	225 [kJ]	400 [kJ]	625 [kJ]
3000	1.15	9 [kJ]	38 [kJ]	150 [kJ]	338 [kJ]	600 [kJ]	938 [kJ]
4000	1.50	13 [kJ]	50 [kJ]	200 [kJ]	450 [kJ]	800 [kJ]	1250 [kJ]

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[1] The relevant parameters to be studied are the thickness of the layers [m] and the separation and length of the fissures [m] that cross the layers. This results in possible block sizes (e.g. layer thickness: 0.5 m; distance between fissures). The distance between fissures 1: 0.5 m; and the distance between fissures 2: 1 m; equals a block size of 0.5 x 0.5 x 1 m = 0.25 m^3).

For the sake of simplicity, it is assumed that the energy of the fall in the detachment area also remains in the transit zone and abruptly decreases only a few meters before the critical angle of the overall slope is reached (see Table 3).

If lithology is uniform, color differences in the rock surfaces can provide information about the frequency of falls. The degree of weathering of the rock surface can also provide information on the frequency of falls.

Illustration 17: Analysis of the rocky surfaces. The rock face has a very steep stratification parallel to the slope (left side). The right portion of the photo shows the fractures that cross the strata and, therefore, define the size of the rockfall components.

Illustration 18: Analysis of the rock surfaces. At the right side of the photo there is an enlarged section of a rock face at the entrance of a tunnel. The orientation of the fissures (red lines) define the diameters of blocks and stones prone to rockfall. Source: SRC.

Analysis in the transit area

The area between the detachment sector and the deposition sector represents the transit zone. Roughness and topography define the reduced kinetic energy of the falls and, therefore, their long path in the cone[2].

When the cone has a stretched length profile, the following values of the overall gradient can be used to define the length of the fall path.

Table 3: Critical global slope to define maximum distance or spatial extent of falls.

	Critical overall gradient based on surface roughness in the transit area		
	Diameter of blocks	Forest or high roughness by blocks in the cone	Smooth surface/low roughness
Rockfall	< 0.5 m	35°	30°
Blockfall	> 0.5 m	32°	28°

If the length profile of the transit area is abruptly concave (e.g., by a road crossing the transit area) or when there are counter-gradients (e.g., transverse embankments), the fall extent can be considerably smaller. In addition, the extent of falls is usually less than those shown in Table 3, for non-uniform fall components in terms of their length/width/height.

Analysis in the deposition area

The stones and blocks in the deposition area provide important information about the size and extent of the falls, as well as the frequency of events (see Step 4). In addition to the information obtained from the event register, the broken edges of the blocks and the vegetation pattern under and around the falls usually provide reliable information of the frequency of events (see Step 3).

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[2] For the sake of simplicity, the influence of shock absorption in the transit area that reduces kinetic energy is not addressed in this manual.

Part 3 – Hazard Mapping

Following Step 1 ("scenario definition"), hazard is defined on the basis of three scenarios for which three intensity maps will be developed, according to Illustration 23. Three levels of intensity are shown in each map as presented in Table 4. It is possible that an area is not considered a hazard in either the "10-year" or the "30-year" scenario. In this case, only the intensity map for the 100-year scenario would be produced.

Table 4: Differentiation of the intensity of falls according to their kinetic energies[3]

	Intensity		
	Low	**Medium**	**High**
Kinetic energy [kJ]	< 10 kJ	10 – 30 kJ	> 30 kJ
Destructive potential	Destruction of adobe and wooden house walls (simple construction)	Destruction of brick or wooden walls with 20 cm thickness	Destruction of concrete walls of 20 cm 20 cm (< 100 kJ) or 50 cm (< 300 kJ) thickness
People affected in homes	People inside buildings are not threatened	People inside buildings of simple construction are threatened	People inside buildings are threatened

Low intensity: Falling stones can cause damage to the masonry. People and animals are generally not threatened inside buildings. Outside of buildings, people and animals can be injured.

Illustration 19: Low intensity fall deposits. Source: kfv.at

Medium intensity: The impact of boulders causes greater damage, depending on the structural characteristics of buildings. Simple adobe and wooden constructions can be completely destroyed. Reinforced concrete walls can be damaged without affecting the overall stability of the building.

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[3] Classification is based on the regular types of residential building construction in the rural areas of Latin America.

Risks to people and animals in the buildings depend largely on the type of construction of the building. Roads and above-ground pipes can be damaged and interrupted.

Illustration 20: Deposits of medium intensity falls. Source: vkf.ch

High intensity: The impact of blocks produces irreversible damage or even leads to the complete destruction of buildings. People and animals are also at great risk inside buildings. The deposition of boulders can cause small waterways to be dammed and consequently lead to blockages, creating local flooding when the blockages are broken. Fall processes can disrupt infrastructure facilities (e.g. roads and power lines).

Illustration 21: Deposits of high intensity falls. Source: RCN Radio, Colombia.

Hazard mapping

Intensity maps are drawn according to the matrix in Illustration 22. This 9-field matrix shows the three intensity levels for the three hazard scenarios, and assign them indexes between 1 and 9. A red area with an index of 9 means, for example, that in the corresponding area it is to be expected that high intensity rockfall events will occur more frequently than every 10 years (kinetic energy of ≥ 30 kJ).

As discussed in detail in this chapter, in a first step intensity maps are created for the three scenarios. These are internal working documents that don't have to be published. The three intensity maps will then be combined to produce the hazard map, which, together with the technical report, represent the final product of the analysis. The combination is done either through a GIS

(Geographic Information System) or manually. The combination process is described in the SRC methodological guide (https://www.hazard-risk.com). Each hazard zone is assigned a corresponding index to clearly identify the hazard in terms of the event return period and intensity. Illustration 24 shows the rockfall hazard map for the "Imbrig" area, which was derived from the intensity maps in Illustration 23.

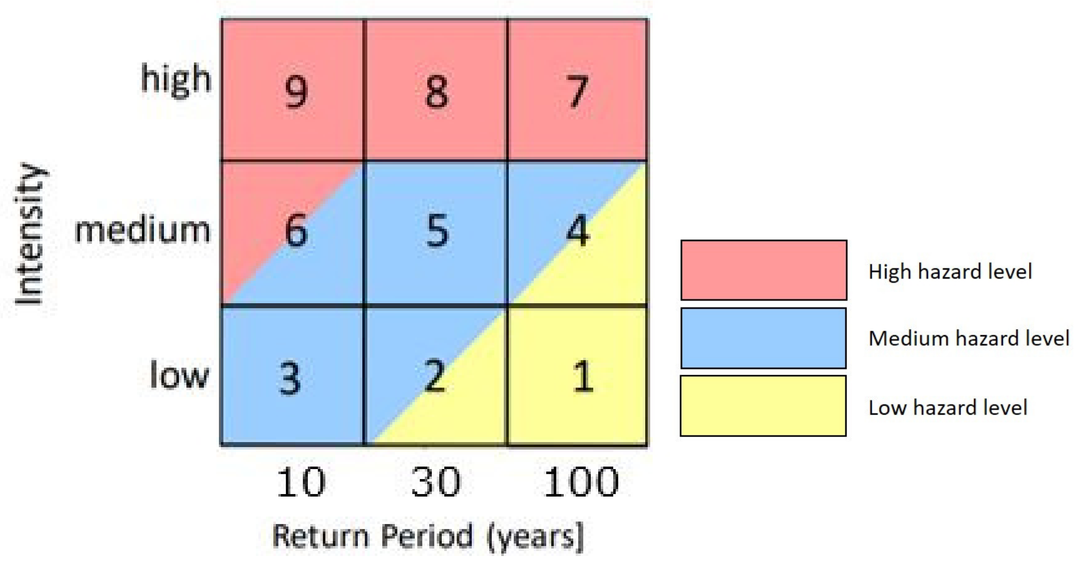
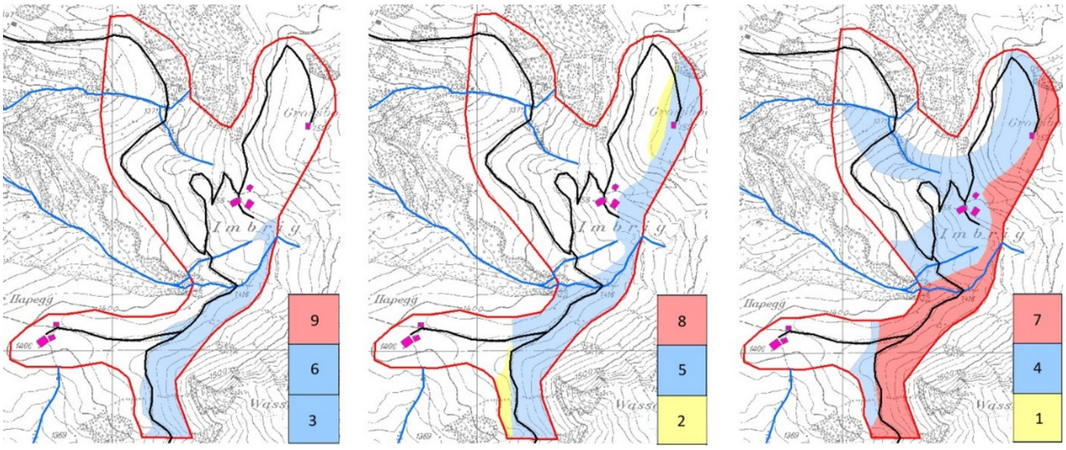


Illustration 22: Diagram of hazard levels for rockfall with their indexes (left). The hazard levels are presented at the right side. The color code corresponds to the Honduran national specifications. Source: PLANAT, modified.



Intensity mapping, 10-year scenario

Intensity mapping, 30-year scenario

Intensity mapping, 100-year scenario

Illustration 23: Intensity maps of frequent events (10-year scenario), infrequent events (30-year scenario) and extreme events (100-year scenario) using Illustration 22.

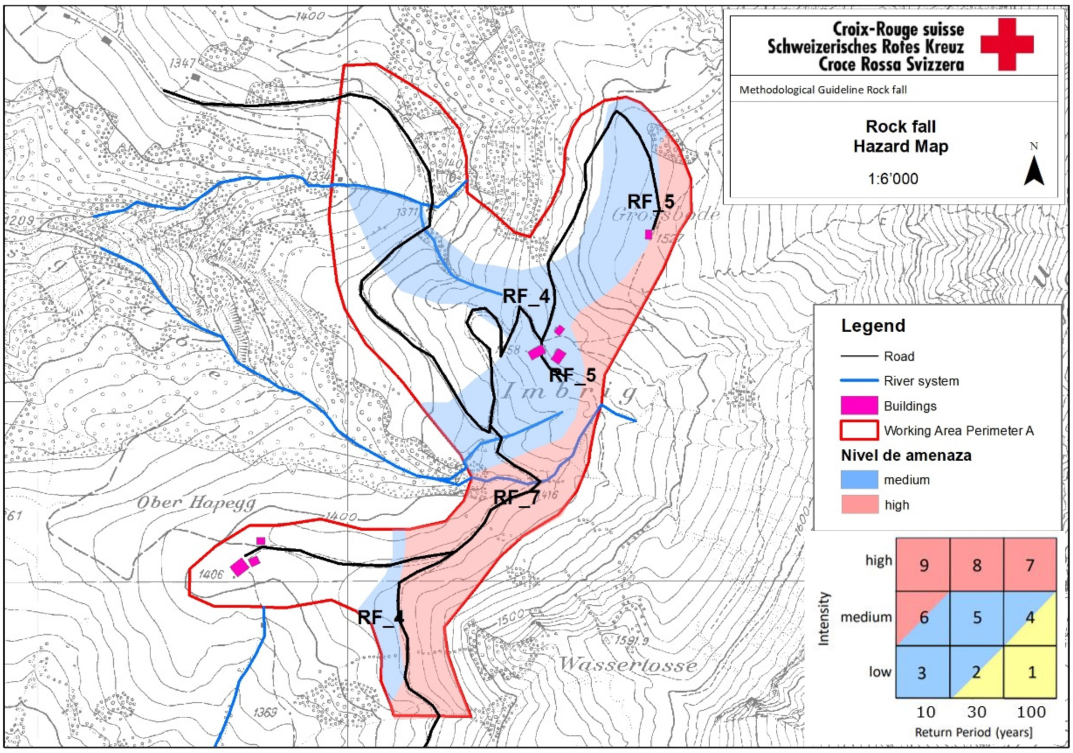


Illustration 24: Rockfall Hazard Map compiled from the three intensity maps. The "RF_x" indexes inform about the dangerous process (RF = Rock Fall), the frequency and the intensity of future falls. Source: SRC.

Meaning of hazard levels

Table 5: Definition of hazard levels. Source: SRC.

Hazard Level		**Meaning**
red	High hazard	People are threatened both inside and outside buildings. Destruction of buildings and infrastructure is to be expected.
blue	Medium hazard	Area under high frequency and low intensity hazard, or medium/low frequency and medium intensity hazard. Significant damage to buildings and infrastructure is to be expected. Destruction of buildings cannot be ruled out for simple constructions (wood or adobe buildings).
yellow	Low hazard	Buildings and infrastructure may suffer minor damage. People are not threatened inside or outside of buildings. Fall frequency is medium to low.
white	No hazards are expected	

Quality control

Quality control of the hazard study is done through a comparison of the results of the three analysis steps:

- Event register (Step 3)
- Analysis of morphological phenomena in the detachment and deposit area (Step 4)
- Technical hazard analysis (Step 5)

If a comparison of these results provides a coherent picture of the hazard, a qualitatively satisfactory analysis can be assumed. Any contradictions should be clarified and presented in the technical report.

Climate changes can trigger a shift in the hazard, which may not be detected by the event register and morphological witness analysis. In such cases, the analysis is mainly based on the technical analysis (Step 5). Such climate-related system changes are possible especially in high mountain regions, in connection with melting permafrost and retreating glaciers. For these conditions, it is recommended to hire specialists.