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A Guide to Processing Rock-fall Hazard from Field Data

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ABSTRACT: The assessment of rock-fall hazard in appointed regions of the Bavarian Alps involves the evaluation of occurrence probability and intensity of the potential events. A systematic approach is presented, which allows to establish a regional comparability of the rock-fall hazard determinations. This method is based on simple field-geological data and observations. The rock-fall probability, on the one hand, can be estimated by classifying the rock-fall disposition of the detachment areas and their degree of activity. The rock-fall disposition is the total of geological and geomechanical criteria, that influence the likelihood of rock-fall processes. Furthermore, the role of external influences, like earthquakes and extreme precipitation by heavy rainfalls, and their likelihood as triggering events are discussed. The combination of the above parameters and the quantification procedure for the probability assessment follow mathematical models which are similar to those used in rock mass classifications. On the other hand, the intensity of potential rock-falls, which can be defined by the rock volume and its kinematics, is subdivided into four categories. Finally, the combination of probability and intensity leads to a matrix model, which distinguishes different types of hazards. Without applying complex numerical models, the presented rock-fall matrix model resembles a practical method enabling reasonable and reproducible determinations of rock-fall probability and intensity based on geological field expertise.

Keywords: Rock-fall, slope, discontinuity, activity, matrix

1 INTRODUCTION

Within the broad range of sedimentary processes, the simplest case of mass movement is that of rock fragments falling by gravity off a cliff or down a slope. Rock-falls are rapid depositional phenomena which involve erosion of particles from rock faces, transport in free fall with subsequent bouncing, rolling or sliding and final sedimentation as scree. The term “rock-fall” in this article does not distinguish any volume, but generally refers to phenomena in the range of single falling blocks of few dm^3 to rock volumes of more than 10.000 m^3.

Rock-falls are difficult to predict in their timing and dimension, especially without any extensive instrumentation. In densly populated mountainous regions falling rocks constitute a major hazard that can give rise to casualties, damage and injuries. As a consequence, the assessment of hazards in rock-fall prone areas has become a major research task worldwide (e.g. Budetta 2004, Corominas et al. 2003, Lateltin 1997).

Hazard analysis is a highly complex operation requiring several steps, starting with the regional detection of detachment areas and an exact assessment of run out parameters of falling rocks to determine the endangered areas (e.g. Evans and Hungr 1993, Meißl 1998).

Further steps, which we will discuss in this article, involve the estimation of occurrence probability and intensity of potential rock-fall incidents to assign specific hazard values to the affected areas.

In the present paper, we outline the interplay of the physical principles of rock-fall processes with their preconditions and triggers, on the one hand, and the assessment of probability and intensity on the other. Furthermore, we will propose a semi-quantitative rating method to estimate and describe rock-fall hazard and point out limits and advantages of field-based geological analysis.

During the hazard assessment procedure a variety of parameters have to be examined, quantified and combined with each other as shown in Figs. 1 and 4 and which will be explained in the following chapters.

2 BACKGROUND

In the scope of the project "CatchRisk" of the European Union, regional rock-fall hazard assessment was carried out for the Bavarian Alps. Detachment areas are well documented in the GeoRisk-database of the LfU of Bavaria, modelling of depositional areas was accomplished at the LfU applying a GIS.

Our task was to distinguish these depositional areas in respect to rock-fall hazard. Probability and intensity were processed with a method based on field observations, largely available in the GeoRisk-database. The involved field parameters comprise fundamental rock slope properties, which allow application of the system also independant from the mentioned database and thus in every mountaineous region beyond the Bavarian Alps. The principle concept is presented in Fig. 1. Tab. 1 is an evaluation form sheet providing the total procedure.

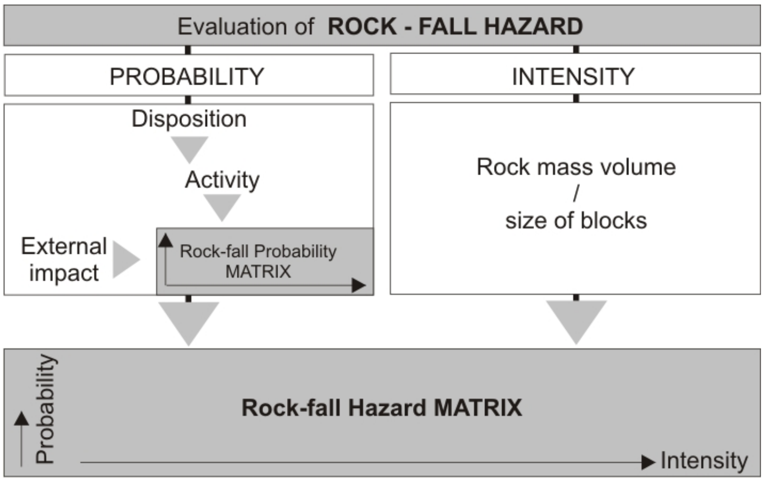


Figure 1. Simplified procedure of rock-fall hazard analysis.

3 ROCK-FALL PROBABILITY

The major task is to find out how close a rock or rock mass is to falling over. Each rock wall poses a hazard and thus a prior probability for falling rocks, otherwise the region would not be considered. These prior probabilities are of a quite general nature and must be updated to enable reasonable and regionally comparable estimations. Different approaches exist (e.g. Einstein 1988). Statistical analysis of past rock-falls is a powerful tool (e.g. Dussauge-Peisser et al. 2002), but depends largely on the quality of historical data sets (archives) or geological indications of previous rock-falls. Frequencies are mostly referred to as annualties or as probabilistic percentage during defined periods of time. Mostly, however, the historical archive is missing and frequencies are only a paraphrase to describe subjective estimations of rock-fall probabilities.

Based on geoscientific know-how, it can be attempted to reproduce and quantify subjective estimations. The basic approach is to include all seizable natural parameters, which not only account for rock-falls but also influence the likelihood. Probability depends on several factors comprising three categories: the rock-fall disposition of the detachment zones (susceptibility), the activity in this region and the external influences acting on the system under consideration (Fig. 1, 4). These must be set in causal relationship, ordered hierarchically and quantified in the following.

3.1 *Disposition for rock-fall processes*

The first step is to make an inventory of the geological, structural, lithological and stratigraphical properties of a slope that influence its susceptibility for failure and thus summarizes all geotechnical preconditions for falls (e.g. loosening, toppling etc.). This inventory is best defined as rock-fall disposition, and comprises static properties (e.g. joint orientation) as well as very slow, quasi-static, processes (e.g. weathering) acting in a rock slope or cliff (rock mechanical characteristics of the detachment zone), as well as large-scale factors, like sagging (regional geomechanical environment).

In principle, geometry and height of detachment areas are critical disposition parameters. However, these must be neglected in probability assessment, since they are already included in the computation of run-out parameters and depositional areas.

The bulk of parameters is related to the structural composition of the rock mass. For regional comparison discontinuities and their properties are described based on international classifications (e.g. ISRM, IAEG).

3.1.1 *Rock-mechanics of the detachment zone*

Specific rock-fall susceptibilities of detachment areas are characterized by the interaction of a set of rock mechanical parameters. These can be summarized as follows:

Orientation of discontinuities: Analyses of discontinuity sets can be highly complex. For rock-fall hazard assessment the critical question arises, whether joints or bedding planes have favourable, random or adverse orientation considering a rock cliff. Adverse joints and also unfavourable cuttings of discontinuities are those that cause block, wedge or toppling failures.

Degree of weathering: Long-term deterioration due to weathering can lead to a reduction of shear strength of discontinuity planes (reduced friction angle and cohesion). The degree of weathering must be quantified, e.g. according to ISRM and IAEG classifications.

Structural configuration: This field comprises the degree of transection of joints, their persistence (length), opening widths (aperture) and the condition of the joint surfaces. The friction along a joint, bedding plane or any other discontinuity is governed by the macro and micro roughness of the surface (degree of undulation and the texture of the surface). Additionally, fault gauge and slickensides are highly significant for surface friction and thus for rock-fall probability estimations.

The spacing of joints, in contrast, is only critical regarding volume of falling masses and their mechanical behaviour. It does not influence probability, since one unfavourable joint is sufficient for failure.

Increasing probability is indicated by high degree of transection of discontinuities, high persistence, open joints and even, smooth surfaces (e.g. slickensides). These parameters presuppose a high mobility of blocks.

Degree of loosening: The above parameters account for the degree of loosening of a slope. Often no detail indications are available for detail structural evaluations and ratings like above. Nevertheless, general observations of symptoms of movements are at hand, like information about open fractures and neck valleys. This point can be seen as parallel estimation of the structural configuration, with minor degree of significance (valuation, see Fig. 4 and chapter 3.4.1).

3.1.2 *Regional geomechanical environment*

The overall geological and morphological situation of a detachment zone and its surrounding mountain slopes (geomechanical environment) has to be considered. The following points must be mentioned:

Type of basement: The type of basement formation influences the state of stress in a rock slope. Dissolvable rocks or clayey, marly beds with highly plastic behaviour must be regarded as unfavourable.

Large-scale, deep-seated deformations: The implications of long-term, large-scale slope deformations on a regional scale (e.g. sagging of mountain slopes, large landslide processes) are difficult to interpret. In principle, these processes imply changes of stress and thus influence stability in the detachment zone.

Mass movements in the foot of slope: Also active creeping or sliding processes in the foot of slope most likely influence the stability of the detachment zone. The effects in detail, however, are not always clear.

The valuation of such processes (regional geomechanical environment) for rock-fall hazard is still in debate. Nevertheless, in Fig. 4 and Tab. 1 we propose a way to include factors.

3.2 *Activity*

Activity is defined as the total of movements occurring within a detachment area and talus slope. The degree of activity results from the general rock-fall disposition and can be identified in the field by evaluating activity indicators (Fig. 3). These indicators give direct proof of recent movements, e.g. fresh impact marks. For probabilistic evaluations of rock-fall processes, activity has to be distinguished as follows.

3.2.1 *Activity in advance of rock-falls (initial activity)*

Activity in advance of rock-falls comprises loosening processes in the detachment area, indicated by e.g. fresh and open joints or strained roots. Proof for or against active movement are critical for probability estimations. The rock-fall disposition mirrors the current condition of the detachment zone, whereas the activity indicators helps to estimate whether the system actually approaches the point of failure or not (Fig. 2).

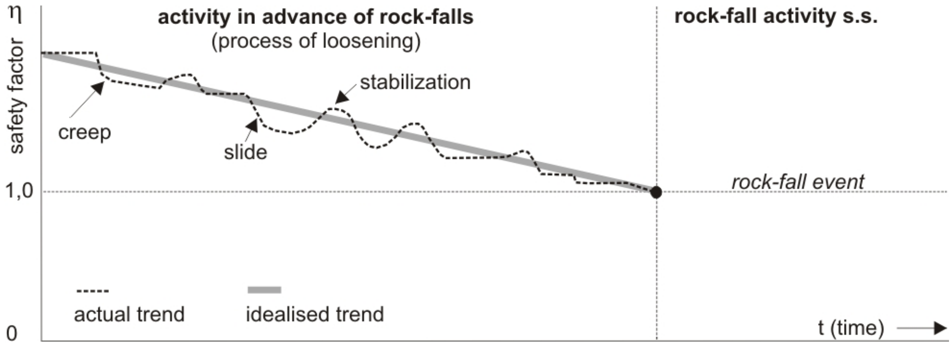


Figure 2. Interpretation of activity of slopes.

3.2.2 *Rock-fall activity s.s.*

Examples of indicators for recent rock-fall activity (activity s.s.) are fresh detachments and scars in the rock slope/cliff or fresh blocks and impact marks in the depositional area. These resemble direct evidence of falls.

The question arises how to valuate the activity in the scope of probability assessment. Fresh marks can indicate subsequent incidences with progressing erosion and the creation of even more unsupported or oversteepened slope conditions, but also hint at a geomechanical stabilization of the system after the event (temporary dormancy). From this point of view it becomes evident, that the initial activity s.l. mentioned above must be emphasized to answer this question. Furthermore, different types of events with distinct probabilities must be taken into account (varying rock-fall intensities with specific likelihoods in one and the same depositional area).

Figure 3. Examples of indicators. Left: Fresh damage of a tree caused by bouncing rock fragments (activity s.s.). Middle and right image: Wide open fractures, partly with stressed vegetation, indicating active loosening and instable conditions in the detachment zone.

3.3 *External impact*

The rock-fall potential must also be considered through assessment of the probability that rocks would fall if large rainfalls or earthquakes occurred. Also other meteorological influence should be regarded if existent, like freeze/thaw cycles, which can dislodge blocks and wedges. In this regional assessment process focus is given to major impacts, for which also reliable probabilistic data are available.

3.3.1 *Significance of earthquakes*

High-intensity short duration forces or vibrations act on rock slopes and their basements. The rock structure can be loosened and blocks and wedges which are at risk can move. Rock-falls can either be prepapered or actually be triggered by these forces. The detail impact of horizontal earthquake acceleration, however, is complicated.

The earthquake zonation provided in German Code DIN 4149 is based on the "Seismic hazard map of the D-A-CH countries". This probabilistic map distinguishes areas of macroseismic intensities with the internationally used recurrence period of 475 years. In DIN 4149, the Bavarian Alps include the warning zone 0, earthquake zone 1 as well as, locally, zone 2, which will be used for probabilistic differentiation.

3.3.2 *Heavy precipitation*

Statistic analyses (e.g. Sandersen et al. 1996) shows, that rock-fall frequencies increase during periods of heavy rainfalls or snow melt. Detail regional distinction of heavy precipitation is provided in the KOSTRA-Atlas of the DWD (Deutscher Wetterdienst; KOordinierte STarkniederschlags – Regionalisierungs – Auswertungen; Bartels et al. 1997). Probabilistic heights of heavy precipitation are supplied for different durations and recurrence intervals, based on 30 year old test series, in an areal pattern of $70km^2$. For rock-fall probability estimations, we propose to consider the most intense events with highest durations: 72hrs, 100-years recurrence period.

3.4 *Models for rock-fall probability rating*

In order to assess the exposition to hazards associated with rock-falls we developed a classification scheme designed specifically for detail local evaluations, but also applicable for regional analyses by statistic accumulation.

The following chart shows the simplified way for probability assessment. In Table 1 the detail assessment process is shown.

Rating criteria			Rating	Valuation
Rock-Fall Disposition	Rock mechanics of the Detachment Zone	Orientation of discontinuities	0 — 500 (favourable - unfavourable)	17%
		+ Degree of weathering	0 — 200	7%
		+ Structural Configuration		
		Degree of transection	0 — 200	7%
		Persistence (length)	0 — 200	7%
		Opening width (aperture)	0 — 200	7%
		Condition of surfaces	0 — 200	7%
		or		
		Degree of loosening	0 — 800	28%
	Regional Geomecanical Environment	+ Type of basement	0 — 600	20%
		+ Large-scale, deep-seated deformations	0 — 200	7%
		+ Active movement in the foot of slope	0 — 200	7%
Activity		+ Activity in advance of potential rock falls	0 — 500	14%
= Score		low <800	moderate 800 - 1900	high 1900 - 3000
External Impact		In case probabilistic data available		
		Earthquake zonation	0 — 50	
		Heavy precipitation	0 — 50	
= Impact		weak <30	medium 30 - 60	strong >60

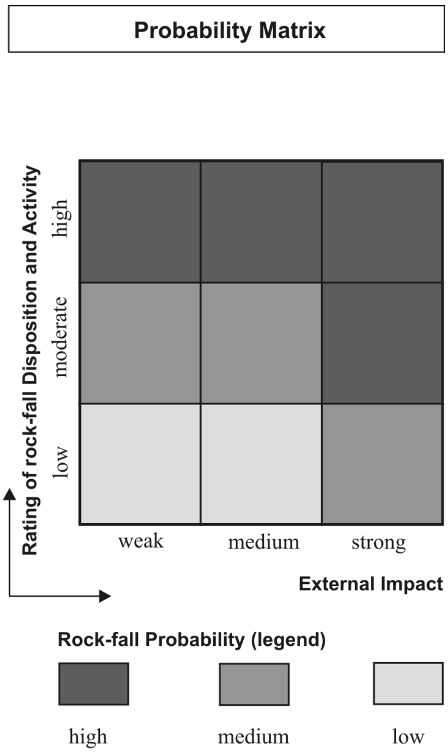


Figure 4. Simplified flow-chart for rock-fall probability rating, with hypothetical rating and valuation indices (see also Fig.1).

3.4.1 *Classification of rock-fall disposition*
Rock-fall disposition, which is the degree of the exposition to the hazard, must be transferred into a stochastic value. Several "rating systems" have been developed in rock mechanics. In our study, we want to present a method, which is mainly based on the ideas of the Rock Mass Rating System of Bienawski (1989) in engineering geology. The principle is presented in Fig. 4. The evaluated properties are rated according to their probabilistic impact and added to a total score. The system is easy to apply and adjustable. The rating procedure is carried out in two steps, assessment of the geological field data (disposition, activity) and assessment of external impact. The second step, however, is only performed when probabilistic data are available.

Rating

The properties mentioned in the fields "Rock mechanics of the detachment zone" and "Regional geomechnaical environment" are referenced with simple numerical scales. Different probabilistic conditions of a property can be expressed with low values indicating advantageous (favourable) conditions and high values indicating disadvantageous (unfavourable) conditions. The rock-fall disposition is finally assessed through the combination of the numerical scores of all evaluated categories.

Some categories require a more subjective evaluation, whereas others can be directly measured and then scored. Also the resulting total score is subject to an artificial probabilistic scale (see Tab. 1), which must be adjusted by personal expertise on the one hand, and experience from regional evaluations on the other.

Valuation of categories (significance)

The valuation of each mentioned property category denotes the degree of importance for probabilistic assessment. Often not all required data are available, especially in comprehensive regional evaluations, and thus cannot be involved in the rating process. In such cases, in general, unfavourable conditions must be assumed in the rating process (highest value). With missing data input the final score looses reliability. The degree of reliability of the result can be provided by including the valuation in addition to the final rating. The total valuation of 100% is decreased by the valuation of the missing category, e.g. 7% for the persistence of joints. Thus the degree of reliability of the result can be easily recognized.

3.4.2 *Classification of activity*
The significance of activity is mentioned in chapter 3.2. Activity in advance of rock-falls gives an important clue to understand the system behavior. A digital distinction between active and non-active detachment zones can be carried out. Active zones have a higher rock-fall probability.

The actual rock-fall activity s.s. helps to verify the assumptions and to differentiate different types of hazards (e.g. frequent falls of single blocks and the hazard of a large rock-fall in on and the same area).

3.4.3 *Classification according to external impact*
Further probabilistic input comes from the evaluation of earthquake zones and high precipitation maps. The mentioned parameters are rated, similar to disposition, giving a total score (see Tab. 1). The total scores of disposition and activity rating on the one hand, and the rating of external impact on the other are combined in a probability matrix and provide the final probability result (Fig. 1 and Tab. 1).

4 ROCK-FALL INTENSITY

Intensity or magnitude describes the energy occurring in a rock-fall event. Different approaches for definition exist in literature including e.g. velocity, energy levels, or the degree of destruction.

In this study, we refer to the block size (single falling blocks) or rock volume (falling rock masses) as a simple measurement which is representative of whichever type of rock-fall event is most likely to occur. This can be determined from geometry and geomechanical inventory of the detachment area or from the maintenance history if available. Other properties, like block shape, fracturing and subsequent defragmentation of rock masses, rock strength and the absorption coefficient of the foot of slope are important, however, mostly hard or impossible to acquire. Thus we confine ourselves to investigate the volume. This measurement is also required for determining remedial measures.

The distinguished categories (see Tab. 1) include, on the one hand, low-magnitude events, which are generally assumed as the classical rock-fall type. They range from single falling blocks to rock mass volumes up to 10000m^3. On the other hand, also high-magnitude events are encompassed in our hazard analyses, which mostly are referred to as large rock-slides, rock avalanches or even have the dimension of a landslide.

5 DEFINING ROCK-FALL HAZARD BY A MATRIX MODEL

The final result (hazard) of the entire investigations and evaluations can be obtained from the rock-fall hazard matrix (Tab. 1 bottom). The matrix combines three likelihood categories with four intensity categories. Different colours or grey shades of the matrix fields can help differentiate the resulting degrees of intensity, whereas varying styles of hatching reflect probabilities. Thus it is possible to present different rock-fall hazard types in regional hazard maps. Table 1 is a form sheet which summarizes the entire evaluation process discussed in this article.

Table 1. Detail flow chart for rock-fall probability rating, rock-fall hazard matrix.

Occurrence Probability of Rock-fall

➔ *Assessment of Disposition and Activity*

1: Orientation of Discontinuities	**unfavourable**	**fair**	**favourable**
Dip direction of a prominent discontinuity set	adverse or slope-parallel	horizontal	inward or vertical
System of two or more discontinuity sets with similar geomechanical properties	mostly sliding wedges	--------------------------	------------------------
Probability estimation	high	medium	low
Rating (Valuation 17%)	500	200	0

2: Weathering degree of joints in the detachment area	**medium to strong weathering**	**fresh to slight weathering**
Grades according to ISRM-IAEG	V4-5	V1-3
Probability estimation	high	low
Rating (Valuation 7%)	200	0

3: Structural Configuration of Discontinuities			
Persistence	large discontinuities (area > 100m², extent > 10m)	medium-scale disc. (area 10-100m², extent 1-10m)	small discontinuities (area < 10m², extent < 1m)
Rating (Valuation 7%)	200	100	0
Degree of Transection	no or subordinate mineral bonds		mineral bonds existent
Rating (Valuation 7%)	200		0
Opening width / Aperture	open (> 1 cm)	slightly open (0,5 mm bis 1 cm)	closed (< 0,5 mm)
Rating (Valuation 7%)	200	100	0
Condition of surfaces	slickensides		no slickensides
Rating (Valuation 7%)	200		0

4 (alternativ for category 3): Degree of Loosening	**high**	**low**	**no indication**
General description	clear indications available: -wide open gaps and fractures -neck valleys etc.	only subordinate indications	no indications given
Probability estimation	high	medium	low
Rating (Valuation 28%)	800	400	0
Total – Rock mechanics of the Detachment Zone [Category 1 + 2+ (3 or 4)]			

5: Type of Basement	**very unfavourable**	**unfavourable**	**favourable**
Type of formation	dissolvable rocks/formations (cavities and/or highly plastic behaviour)	clayey-marly formations (plastic behaviour)	other formations
Probability estimation	high	medium	low
Rating (Valuation 20%)	600	200	0

6: Large-scale, deep-seated deformations (e.g. sagging of mountain slopes, major landslides)	**yes** (detachment area influenced by large-scale slope deformations)	**no** (no large-scale slope deformations)
Probability estimation	high	low
Rating (Valuation 7%)	200	0
7: Active mass movements in the foot of slope	**serious indications for mass movements**	**no or subordinate indications for mass movements**
Probability estimation	high	low
Rating (Valuation 7%)	200	0
Total – Regional Geomechanical Environment [Categories 5 to 7]		

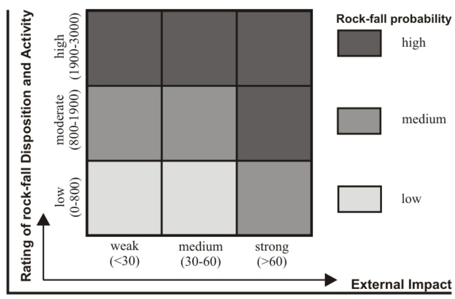
8: Activity			
Initial Activity	active		not active
Rating (Valuation 14%)	500		0
Rock-fall activity s.s.	active (in the range of the assessed maximum intensity)	active (in minor volumes compared to maximum assessed intensities)	not active
Probability estimation	**high**	t indicator of **initial activity**	no consideration
Final valuation in hazard matrix	**very likely**	----------------	----------------
Total – Activity [category 8]			

Total – Disposition and Activity	1) + 2) + [3) or 4)] +5) + 6) + 7) +8) =		
Probability estimation	high	medium	low
Classification	3000 to 1900	1900 to 800	800 to 0

➔ *Assessment of External Impact*

1: Earthquake Zonation	**Zone 2**	**Zone 1**	**Zone 0**
Probability estimation	high	medium	low
Rating	50	20	0
2: Heavy Precipitation	**> 310 mm**	**230 – 310 mm**	**< 230 mm**
Probability estimation	high	medium	low
Rating	50	20	0
Total – External Impact	1) + 2) =		
Probability estimation and classification	high > 60	medium 60 to 30	low < 30
Degree of impact	strong	medium	weak

➔ *Probability Matrix*



RESULT	**Rock-Fall Probability =**

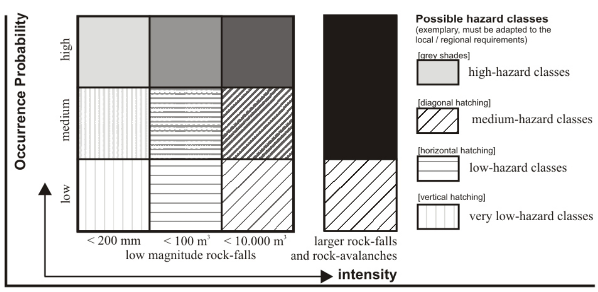
INTENSITY of potential Rock-falls

➔ *Classification*

Intensity	**High-magnitude Rock-falls**		**Low-magnitude Rock-falls**		
Volume	**Rock avalanche**	**Large Rock-fall**	**Medium Rock-fall**	**Small Rock-fall**	**Single blocks**
Distinction	total rock mass volume > 1 Mio m³	total rock mass volume of up to 1 Mio m³	total rock mass volume of up to 10.000 m³	rock fragments with more than > 200 mm diameter and/or a rock mass total volume of up to 100 m³	one or few single fragments (< 200 mm)

ASSESSMENT of Rock-fall Hazard

➔ *Hazard Matrix*



This assessments concept must be seen as a prototype for discussion, testing and development. It distinguishes hazard degrees in a descriptive way, parameters are quantified and combined, the process is also comprehensive and reproducible. Nevertheless, adjustments have to be carried out regarding the graduation/scales of disposition and activity as well as of external impacts. This graduation mainly depends on regional project requirements. In this article we give proposals in numbers, but these must be verified in future application.

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