



massmove i regioni un objet



imal standards europeo per lo sviluppo regionale

Lo. Sechs Reg for the compilation of hazard maps Ð Italien · Östeof landslidestand rock fall



GUIDELINES OF GEOLOGICAL LANDSLIDE SUSCEPTIBILITY / HAZARD MAPPING

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PART A: INTRODUCTION

1. Introduction

As a result of progressive settlement in alpine areas, as well as the fact that in modern times mountain areas are used increasingly for recreational and touristic

activities, land use in these areas has changed greatly in comparison to the past. These manmade changes overlap with climate change, therefore increasing the vulnerability of alpine regions and with this the people living there.

For ensuring the safety of people and infrastructure, as well as for a foundation for adequate territorial and land use planning, it is



essential to gain knowledge about areas prone to landsliding.

Landslide related maps greatly differ between countries, and also between regions within the same country regarding scale, considered landslide type and purpose. In this context, this handbook as a final conclusion of the MassMove project is an attempt to provide a tool for landslide susceptibility and hazard mapping towards a unique identification and classification of hazard areas regarding rock fall and (shallow) landslides.

2. Purpose of the guidelines

The guidelines are an operative tool for the generation of susceptibility and hazard maps. It states in short the necessary parameters that have to be collected

for the aimed purpose (regional or local) and illustrates how to progress and reach the intended target, depending on the intended scale of the project. It also states clearly the minimal results that need to be achieved to fulfill the task. The guidelines provide a framework to be applied by the authors of susceptibility and hazard maps (e.g. geologists, civil engineers, etc.). Thus generated maps intend

> to supply regional/ territorial planners and stakeholders with fundamental information, so that appropriate spatial or action planning can be carried out.



3. Aim of the guidelines

Natural hazards like floods, avalanches, landslides and rock fall are causing great damages in the alpine regions. Due to the geological hazards and the associated damages the reduction of the risk potential is a necessity.

Landslide susceptibility maps and hazard maps represent a powerful instrument for this.

Because of the restrictions (prohibitions and regulations) concerning land use in hazard zones, the process of map compilation must be transparent and comprehensible to get acceptance by affected land owners and stakeholders. That means minimal requirements for susceptibility/ hazard mapping must be defined, guidelines for landslide susceptibility/ hazard mapping should be created. Minimal requirements for hazard mapping are necessary for objective comparability of the maps created by different persons or institutions.

For alpine hazards such as floods and avalanches in Italy and in Austria guidelines for hazard mapping already exist.

For the evaluation of the hazard potential (individual case evaluation) of landslides and rock fall different approaches are in practice: in Austria no regulations are available, in Italy hazard mapping is regulated by law; in Veneto and Friuli Venezia Giulia a modified BUWAL method for hazard assessment is in practice (Bäk et al. 2011).

In the partner regions (Carinthia, Friuli Venezia Giulia, Veneto) geological information systems are established: In the geological information system of Carinthia the event documentation is supplemented by a landslide inventory map; in connection with the event documentation a general susceptibility map was created. However, this general map is insufficient due to the quality of the available data for the hazard assessment. More detailed susceptibility/ hazard maps should be provided to assess the hazard potential to infrastructure and the need of measurements.

The GIS based system to inventory mass movements in Veneto and Friuli Venezia Giulia takes part in the national inventory landslide project IFFI (Kranitz et al. 2007, Baglioni et al. 2007). In Veneto and Friuli Venezia Giulia geological hazard assessment is made in accordance with the National authority for river basins. Because of the effects of landslides to roads, villages and infrastructures, a methodology to evaluate hazard in more detail is necessary for land use planning and protection measurements.

In Friuli Venezia Giulia the collection and classification of data on landslides, avalanches and floods was carried out by different entities: the regional departments, municipalities, mountain communities, etc. Each of these offices used their specific systems for collecting, organizing and storing information. Since the second half of 2010 an information system called SIDS has been implemented to homogenize the various information and databases to make the data available for regional hazard management.

A guideline of minimal requirements for landslide susceptibility/ hazard mapping should be a tool for reduction of the risk potential under consideration of hazards in land use planning and planning of preventive measurements: The minimal requi-



rements for the input data (necessary for the description of the phenomena of the mass movements) and for the results (evaluation of the hazard potential, spatial description of hazard by maps) were derived from the insights gained by the systematic investigations in the model areas.

4. Scope of investigation

The idea is to provide a simple Toolbox in the form of a table-driven "expert system", for the definition of minimal data requirements and methodologies.

By definition a set of minimal requirements defines the lowest acceptable level of investigation for a consistent landslide susceptibility/ hazard assessment.

In this paper the minimal requirements are defined regarding

- The collection of basic data and parameters for the categories geology, geomorphology, topography, hydrogeology, vegetation and anthropogenic influence;
- The evaluation of the hazard potential;
- The products: landslide inventory maps, susceptibility maps, hazard maps.

The basic elements considered and illustrated in the following are:

- A minimal susceptibility/ hazard assessment methodology should provide results sound enough for a given scale and scope of the landslide study;
- 2. Each methodology suggested in the guidelines can be implemented using different tools for landslide onset and runout simulation or estimation, provided that they satisfy the minimum requirements;
- 3. Each methodology requires specific input and validation data that can be collected using different approaches depending on the required accuracy.

Data for a specific area can be available at very different scales and levels of quality. In any case when data with higher resolution than the standard fixed in the minimal requirements are available, these data should be the input data to be used for the analyses at any level. This approach will guarantee that the study is always considering the most up-to-date and high quality information available for

the study area.

Validation of the produced maps and studies is mandatory. Validation and verification of reports and maps regarding landslide susceptibility and hazard fulfill their intended purpose to confirm the adaptation of the products to the needs of the stakeholders and users. Data validation is suggested to ensure that data introduced into a model or used for an analysis satisfies defined formats and other input criteria.

Finally, to the aims of these guidelines it is considered fundamental to define clearly the minimal requirements to reach the demanded results.



5. Basis of the guideline

To define the minimal requirements for creating susceptibility/ hazard maps, the partner regions Carinthia, Friuli Venezia Giulia and Veneto investigated model areas systematically. The cooperation was funded by INTERREG IV A program Italy/ Austria 2007 - 2013.

The systematic investigations of 12 model areas in the partner regions are the basis for the conclusions documented in this issue. The guidelines are supplemen-

ted by literature studies, comparison of existing data structures and examples of maps. Experiences from other INTERREG projects (Falaises, AdaptAlp) were incorporated.

A project glossary of relevant terms has been I created for better understanding (Annex 1).



6. Method of project operation

At the beginning of the project the model areas tending to landslides and rock fall were chosen. Susceptibility to landslides and rock fall results from geological and geomorphologic conditions in these areas. The parameters useful to describe mass movements were defined in categories: geology, geomorphology, topography, hydrogeology, vegetation and anthropogenic influence. The availability of these parameters for hazard assessment was examined by systematic investigations in the model areas (data acquisition, field work, remote sensing and simulation).

In the partner regions landslide inventories (inventory maps) exist. Susceptibility maps at different scales and contents are in use. One of the project activities was the comparison of existing data structures. This contributes to the project objective – development of minimal requirements regarding susceptibility/ hazard mapping.

After the collection of basic data (DTM, topography including slope inclination classes, exposition, cliffs, land use, geological maps, process index maps a.s.o.) the possible processes were evaluated with the aid of recorded events of the past (e.g. causes, effects) using the landslide in-

massmove

ME PROJECT DESCRIPTION PROJECTORGANISATION PROJECTSTATUS DOWNLOADS FORUM

Minimal standards for compilation of danger maps like landslides and rock fall as a tool for disaster prevention Mindeststandards zur Erstellung von Gefahrenkarten zu Rutschungen und Steinschlägen als Werkzeug für vorbeugende Katastrophenvermeidung

Standard minimi per la stesura di carte di pericolosità per frane di scivolamento e di crollo quale strumento per la prevenzione dei dissestifranosi

MassMove

In this INTERREG IV A project partners from Italy (Regione Friuli Venezia Giulia and Veneto) and Austria (Carinthia) are investigating model areas regarding geological hazards (rock fall and shallow landslides). Results of the investigations should be susceptibility and hazard maps as a basis to define minimal standards for susceptibility and hazard maps.



ventories supplemented by the local authorities. For DTM airborne laser scan and terrestrial laser scan was be used.

Systematic investigations in model areas included geological mapping under consideration of mass movement aspects and lithology, remote sensing using laser scan data and aerial photographs as well as simulations using different software. Susceptibility/ hazard maps of model areas are the final results of the investiga-

tions. The technical reports to the model areas and the common report will be available by download from the project homepage www. massmove.at or the homepages of the partner regions' administrations in the future.

The results of the systematic investigations of the model areas can be the basis for an improvement of hazard assessment rules in both countries.

7. Model areas - Geological/Geotechnical situation

The selection of the study areas had to be adjusted between the priorities of the partners and the common goal of the project, the guideline. Also as many phenomena and processes as possible had to be taken into account. The selection of the study areas was based on the following criteria: The areas had to be adjusted to the variability of the phenomena (e.g. shallow landslides, earth flows, rock fall), to documented events and geological structures of old events, to different geological formations, to different processes, effects and existing informations (e.g. remote sensing).

In Carinthia two model areas were investigated. In one area (Auental) landslides were worked on predominantly, whereas in the second area (Mölltal) falling processes prevailed.

In Friuli Venezia Giulia two partners worked on different processes: One partner worked exclusively on shallow landslides. For this purpose three areas (in the municipal territories of Paularo, Pontebba and Castelnovo del Friuli) have been chosen. The second partner studied rock fall phenomena in 3 study areas (in the municipal territories of Paluzza, Venzone and Villa Santina-Tolmezzo).

In Veneto rock fall was studied in four model areas (Perarolo di Cadore e Valle di Cadore (Belluno), Alleghe and Colle S. Lucia (Belluno), Rocca Pietore (Belluno) and Valstagna (Vicenza).



7.1 Carinthia

Both investigation areas are situated in metamorphic rocks that are tectonically stressed and therefore severely disjointed. Also an alternate bedding of competent and incompetent rocks is developed in large areas.

Auental

Situated in the Northeast of Carinthia the main topic of investigation in this area (around 50 km2) was the assessment of hazard due to landslides. Many small shallow landslides occurred in the region during the last 50 years; one of the known old landslides was reactivated in 2005. Rock fall happens only rarely in this region. The underground consists mainly of mica schist with layers of marble weakened by weathering to greater depth.

Auental mapped massmoves



Mölltal

Situated in the Northwest of Carinthia the main topic of investigation of this area (approximately 100 km2) was the assessment of hazard due to rock fall. Old huge rock fall events are documented in the process index map. Rock fall events also occurred in the recent past.



There are high cliffs with rock fall potential in the area. Some old huge landslides with deep slide surfaces are known. The underground consists of metamorphic rocks with deep disaggregation in consequence of glacial debuttressing.

7.2 Friuli Venezia Giulia

Paularo

In this region two areas tend to shallow landslides. The affected slope is formed by alterated Permian sandstone and moraine deposits. One area is already defined as a P2 hazard level (within a scale ranging from P1, lowest, to P4, highest). There is a good documentation of alluvial events on September 11, 1983 and June 22, 1996, that triggered many shallow landslides.

Studena (Pontebba)

This test site was affected by many shallow landslides during two quite welldocumented alluvial events on June 22, 1996 and August 29, 2003; another little event occurred on September 4, 2009. The "moving" material is formed by the alteration of carbonatic rocks from the Werfen Formation (Scythian stage, Triassic) and

carbonatic and conglomeratic rocks from Serla, Ugovizza and Sciliar Formations (from Anisic to Ladinic stage, Triassic): these formations are in tectonic contact. The test site is shaped into two areas with different exposures, with defined hazard levels of P2 and P3 respectively.

Castelnovo del Friuli

This choice was dictated by the fact that almost every year this area is affected by various phenomena of shallow landslides. The hilly territory of this municipality is located in front of the chain of the Carnian Prealps. The bedrock consists of conglomerates, sandstones and marls of the Miocene, often intensely folded and fractured by the presence of an important thrust to the North; this thrust positioned the limestones of the Cretaceous onto ductile lithologies of the Miocene.

The system of forces resulted in the formation of a series of anticlines, synclines and secondary faults that fractured the involved lithologies, predisposing them for landslide phenomena.

Timau (Paluzza)

In the area of Timau, massive limestone (upper Devonian), and in the northwestern part of the area Quartz-rich sandstones (Carboniferous sup.) can be found. Protection measurements like embankments and elastic barriers have been realized. Based on the actual method of hazard assessment hazard zone was reduced by these protection measurements.

Venzone

This area consists of m-thick stratified dolomites, interstratified with dm-thick stromatolithic dolomites ("Dolomia Principale", upper Trias). Especially during the earthquakes in 1976 rock fall was triggered. Several protection measurements have been realized such as embankments, elastic barriers and road tunnelling. Based on the actual method of hazard assessment the hazard zone has not been reduced by these measurements.

Villa Santina – Caneva di Tolmezzo

The slope between Villa Santina and Caneva di Tolmezzo consists of massive or well stratified dolomites ("Dolomia dello Schlern", upper Trias). The main rock fall of this area was activated by the earthquakes in 1976. Several protection measurements such as reinforced concrete walls, embankments and high energy absorbing elastic barriers has been built. Actually two high hazard areas are identified. Between these two areas, there is a rocky slope with the same morphological condition, but no event has ever been documented there up to now.



7.3 Veneto

Pilot areas of Veneto Region have different geological geomorphological and lithological features, but represent the regional problem very well concerning rock fall.

Perarolo di Cadore and Valle di Cadore (Belluno)

This area is located in Boite basin in the municipality Perarolo di Cadore affected by rock fall. Characterized by a complex tectonic system the rock mass (massive dolomites from the upper Triassic) is intense fractured. Recently a rock fall of 4.000m3 occurred in this area. The geological hazard is very high (P4), especially along an old district road "la Cavallera", used for local traffic.

Alleghe and Colle S. Lucia (Belluno)

This area is located in Cordevole basin in the municipality Alleghe. Volcanic rocks (Middle-Triassic) form the cliff above the village, the geological hazard in view of rock fall is very high (P4) and affects both the village road and the provincial road.

Rocca Pietore (Belluno)

This area includes the SE oriented cliff of Pizzo - Serrauta and the SW oriented cliff of Monte Guda, consisting of calcareous and volcanic rocks of triassic age. Related to the rock fall hazard a camping area below the cliffs is threatened by debris flow.

Valstagna (Vicenza)

This area is located in Valbrenta in the municipality Valstagna. The glacial formed Valbrenta valley has an high difference in altitude between bottom and the top of the rocky wall. The proximity of Valsugana thrust locally causes intense fracturing (dolomites – upper Triassic and in the upper part jurrasic limestone). Rock fall phenomena are frequent and widely spread, the test area is classified with a very high degree of geological hazard (P4). This area was suitable for the planned analyses

(laser scanning, infrared analysis, back analysis, etc.) in view of morphological and geological features as well as of available historical data.





PART B : HANDBOOK FOR LANDSLIDES

Susceptibility/Hazard Mapping

Preface

This Guideline provides a flexible, hands-on framework, a definition of data quality and choice of assessment methods for creation of landslide susceptibility/hazard maps as a function of the scale related accuracy of the results. It defines the minimum requirements in terms of

- minimum required level of accuracy of input data and
- most cost and time effective methodology to guarantee the required scale related accuracy.

A landslide system may be decomposed into three components: an initiation zone (onset), a transport and a deposition zone (collectively termed "runout" in the following sections).

The basic conditions are:

- A minimal susceptibility/hazard assessment methodology should provide results accurate enough for a given scale and scope of the rockfall and landslide study.
- 2. Each minimal methodology suggested in the handbook can be implemented using different tools for rockfall/landslide onset and runout simulation or estimation, on condition that they satisfy some minimum requirements.
- 3. Each minimal methodology requires specific input and validate data, that can be collected using different approaches depending on the required accuracy.

The quality of hazard analysis depends on the data quality and processing depth (Table 1): Data quality is content-related and spatially, that means for hazard maps greater than for susceptibility maps.

It is very important and also essential for the authorities to have appropriate maps describing landslide/rockfall hazard. The expressiveness of output maps depends on the chosen scale of investigation.

Data quality	(R) Regional scale	(L) Local scale	(S) Site specific scale	
ic data	low / low	low / low	low / low	
/ Basi	low / medium	low / medium	low / medium	
data	medium / low	medium / low	medium / low	
Process	high / high	high / high	high / high	

obligatory for susceptibility assessment

is also suitable, but an economic choice is necessary

not recommended

Table 1: Data quality

B.1. Handbook for landslides

1.1 Toolbox for landslide susceptibility and hazard mapping (range of validity)

The proposed methodology brings the user through some tables, which define the minimal methodology which should be used. Each methodology is a specific combination of:

- a landslide onset modelling method •
- a landslide runout modelling method ۲
- a method to combine the two components for susceptibility zonation ٠
- a method to introduce temporal probability for hazard zonation •

Use of the toolbox requires the following steps:

- choose a scale and a scope for the analysis according to the following table 2. 1.
- for each scale, choose the analysis level (minimal or advanced) according to 2.

assessment methodologies (and related zonation), runout modelling methodologies, susceptibility zonation methodologies, and hazard zonation methodologies. Each methodology is referred to a short acronym;

4. for each acronym, a brief explanation of basics, related procedures and available tools, required data, and suitability for different applications is provided in chapter B 1.2, B 1.3, B 1.4 and in Annex 3 (Methodologies). The suitability of different methodologies for specific applications (e.g. susceptibility for landuse planning, linear infrastructures, countermeasure design, very detailed hazard zonation etc.) is also reported in Annex 3. Only the essential information is given in the guideline, and the user will refer to the cited references for the practical details of the adopted procedures.

	the require		-				Table 2: Definition of
	ments of the	Analysis Scale	Scope	Type of maps	Map scale	DEM cell size	study scale and scope
-	assignment.	R	Recognition of potentially	Inventory maps /	1:50.000 - 1:10.000	≤ 30 m	
3.	for each sca-	Regional	endangered areas	Susceptionity maps			
	le and level,	L		Susceptibility maps /			
	tables pro-	Local	Land-use planning	Landslide susceptibility	1:10.000 - 1:5.000	≤ 5 m	
	vide a com-	(e.g. municipality)		maps			
	bination of	S	Hazard and risk	Hazard man /			
	onset su-	Specific areas or slope-scale	analysis, design of	Hazard zone mans	1:5.000 - 1:500	≤ 2 m	
	sceptibility	(site specific study)	countermeasures				

Methodology	Advantage			Onset			Runout	
methodology	Advantage	Disadvantage	Regional	Local	Specified study	Regional	Local	Specified study
Geomorphological field analysis	Analysis of many parameters; detailed	Very subjective and time consuming	-	x	x	_	x	x
Index Method	Standardisation	Subjective indexing	х	x	х		х	x
Statistics	Objective, automation, standardisation	Extensive data collection and processing	x	x	(x)	-	-	-
Process-based	Objective, quantitative	Very detailed knowledge of area neccesary	x	x	x	-	x	x

Table 3: Scales and usability of the methodologies

The use of the proposed methodology (Table 3) depends on the scale of analysis

(Table 2).

	ONSET	RUNOUT	SUSCEPTIBILITY ZONING	HAZARD
Minimum: characterisation of landslide susceptibility with ranking into 2 classes	R_01	R_R1	R_S1	-
Advanced: characterisation of landslide susceptibility with ranking into >2 classes	R_02	R_R1	R_S2	-

Table 4: Methodologies for regional-scale landslide assessment

RUNOUT

 R_R1: susceptibility for shallow landslides on base of simulation under using cell size < 20 m (topography)

ONSET

- **R_O1:** susceptibility to landslide *on the basis of topography, lithology and landuse*
- R_O2: susceptibility to landslide on the basis of topography, lithology, landuse and inventory maps (event map, event cadastre, landslide inventory map)

<u>Check point:</u> Both end products will be verified against inventories of observed landslides testing the quality of the product both on observed landslides and on non-failing areas.

SUSCEPTIBILITY ZONING

 R_S1 only for shallow landslides on base of cell size < 20 m

	ONSET	RUNOUT	SUSCEPTIBILITY ZONING	HAZARD
Minimum: characterisation of source and runout susceptibility			L_S1	-
Advanced: characterisation of source and runout susceptibility + susceptibility zoning based on field mapping	L_0	L_R	L_S2	-

Table 5: Methodologies for local-scale landslide assessment

RUNOUT

 L_R: Simulation of shallow landslide trajectories, runout map

SUSCEPTIBILITY ZONING

- L_S1: Simple combination based on superimposing layers of onset and runout,
- L_S2: Combination of onset and runout information with the support from engineering mapping. The intersection of susceptibility map and runout map with "layer of assets" which should be protected (roads, settlements) may be used to indicate endangered areas under consideration of mapped and known deposition areas; at least ranking to endangered, possible endangered and not endangered areas.

<u>Check point:</u> End products of onset susceptibility will be verified against inventories of observed landslides testing the quality of the product both on observed landslides and on non-failing areas. The output for the runout assessment should be checked with field evidences.

ONSET

 L_O: On the basis of event register, engineering geology parameters, topography, lithology and landuse;

1.4 Site specific (slope) scale study

Table 6: Methodologies for site-specific landslide assessment

Standard:SusceptibilityandhazardS_0S_R-HAZARDSconingS_0S_R-S_H

RUNOUT

• S_R: Dynamic modelling

<u>Check point:</u> The output from the dynamic modelling should be checked with field evidences.

The difference between local and site specific scales will be mostly on the density of the information to be surveyed.

ONSET

• S_O: On the basis of event register, engineering geology parameters, topography, lithology, landuse and temporal information. It will provide information about volume of mass movements linked to return time for a certain site.

<u>Check point:</u> End products of onset susceptibility will be verified against inventories of observed landslides (in a wider area than the study area where enough observed landsides have been surveyed) testing the quality of the product both on observed landslides and on non-failing areas. Volume estimation bases on statistic analysis.

SUSCEPTIBILITY ZONING

No susceptibility analysis because of hazard analysis directly

HAZARD

 S-H: Hazard zoning on the basis of onset and runout analysis where a certain volume of sediment will occur and will be deposited within the recurrence period

1.5 Basic data and parameter

1.5.1 Regional scale study

For landslide analysis (susceptibility map) the usage of the following data are necessary as minimal requirement:

DEM (30 m or better) derived parameter maps: Slope inclination map (10° or 5°), Slope aspect map, curvature

Geological map (1:50.000 – 1:10:000) derived parameter map: Lithological map

Landuse map (at least differentiation of forest and grassland)

1.5.2 Local scale study

Input data:

DEM (5 m or better) derived parameter maps: Slope inclination map (10° or 5°), Slope aspect map, curvature

Geological map (1:10.000 – 1:5:000) derived parameter map: Lithological map

Landuse map (at least differentiation of forest and grassland)

Engineering geological mapping At least mapping representative areas.

Parameters to be collected are given in table 7

For local scale, information may be sampled based on maps of homogenous soil/ land use classes.

Events: Collection of documented landslide events, literature, reports

"layer of assets" (e.g. settlements, roads, railways, infrastructure)

Table 7: Engineering geological mapping – parameters and weight of importance

General information	General setting
bject number	altitude [m asl]
nunicipality	geological unit
oordinates of scarp	reason of massmove event
ate of survey	anthropogenic influence
urveyor	
ate of massmove event	Geomorphology and topography
	shape of terrain
Scarp and deposition area	gradient [°]
lard rock underground	aspect
ock / colour	length of slope (watershed - local foot of erosion) [m]
tructure, texture, weathering	altitude of scarp above local foot of erosion [m]
nain joints	width of massmove [m]
pening of joints]mm]	length of massmove [m]
ransection	thickness of massmove [m]
lling of fissures	shape of scarp
onnectivity	activity
issolutions	
roundwater condition	Vegetation
	type of use
Soft rock underground	kind of trees
ock / colour	inclination of trees [°]
rain-size distribution	damage of vegetation
exture / compactness	colour
riction angle [°]	moisture-indicating plants
ohesion	
lasticity	damage to infrastructure and buildings
rain shape	
omogenity	
roundwater condition	
nickness above hard rock [m]	



minimal standard local scale

additional information to be collected if possible

parameters with low importance

Additional data for verification and/or interpretation (plausibility check)

Topographic map, Orthophotos: GIS-analyses of DEM (morphological discontinuities) will produce anthropogenic lineaments too, which should be verified with topographic maps and orthophotos.

Digital cadastral map: This maps may provide additional information to the "layer of assets".

Digital road path: This layer can help to eliminate anthropogenic lineaments (roads).

Derived data from input data

Slope inclination – parameter map (indexed for steps 5° or 10°), necessary

Slope aspect – parameter map (indexed for steps 45°), optional

Curvature

Contributing area

Lithological map – (indexed for lithological units)

Landslide inventory map – from documented and mapped events used for statistical analysis and check of the quality of results

Land use map (indexed for land use classes)

Output data

For traceability of the results the used input data and derived data should be documented

Slope inclination map (classified): Classified slope map (raster data or polygons) in digital format in the required scale

Slope aspect map (classified): Classified aspect map in digital format in the re-

quired scale, optional

Lithological map – Map of lithological units derived from the geological map (raster data or polygons) in digital format with the used map scale

Land use map – Map of land use classes derived from the land use map (raster data or polygons) in digital format in the required scale

Landslide inventory map – Map of the documented landslides (mapped and from the event cadastre)

Landslide susceptibility map – Combination of onset and runout susceptibility (susceptibility zoning, raster data or polygons) in digital format

Runout map (modelling result) – map of modelling results (raster data or polygons) in digital format)

Map of endangered areas - intersection of onset susceptibility map and runout susceptibility map with layer of assets (raster data or polygons) in digital format

1.5.3 Site specific scale study

Input data:

DEM (2 m or better) derived parameter maps: Slope inclination map (10° or 5°), slope aspect map, curvature

Geological map (≥ 1:5:000) derived parameter map: Lithological map

Land use map (at least differentiation of forest and grassland)

Engineering geological mapping: Parameters to be collected are given in table 8

The difference between local and site specific scales will be mostly on the density of the information to be surveyed.

Checking the quality of the classification into homogenous soil classes is required.

Events: Collection of documented landslide events, literature, reports

"layer of assets" (e.g. settlements, roads, railways, infrastructure)

Additional data for verification and/or interpretation (plausibility check)

Plausibility check by engineering geological mapping

Derived data from input data

Slope inclination map (indexed for steps 5° or 10°), necessary

Slope aspect map (indexed for steps 45°), optional

Curvature

Contributing area

Lithological map – (indexed for lithological units)

Landslide inventory map - from documented and mapped events used for statisti-

Table 8: Engineering geological mapping – parameters and weight of importance

General information	General setting
object number	altitude [m asl]
municipality	geological unit
coordinates of scarp	reason of massmove event
date of survey	anthropogenic influence
surveyor	
date of massmove event	Geomorphology and topography
	shape of terrain
Scarp and deposition area	gradient [°]
Hard rock underground	aspect
rock / colour	length of slope (watershed - local foot of erosion) [m]
structure, texture, weathering	altitude of scarp above local foot of erosion [m]
main joints	width of massmove [m]
opening of joints]mm]	length of massmove [m]
transection	thickness of massmove [m]
filling of fissures	shape of scarp
connectivity	activity
dissolutions	
groundwater condition	Vegetation
	type of use
Soft rock underground	kind of trees
rock / colour	inclination of trees [°]
grain-size distribution	damage of vegetation
texture / compactness	colour
friction angle [°]	moisture-indicating plants
cohesion	b
plasticity	damage to infrastructure and buildings
grain shape	
homogenity	
groundwater condition	
thickness above hard rock [m]	



minimal standard local scale



additional information to be collected if possible

parameters with low importance

cal analysis and checking of quality of results

Land use map (indexed for land use classes)

Output data

For traceability of the results the used input data and derived data should be documented

Slope inclination map (classified) – Classified slope map in digital format in the required scale (raster data or polygons)

Legend:

Slope aspect map (classified) -. Classified aspect map in digital format in the required scale (raster data or polygons) Lithological map – Map of lithological units derived from the geological map in digital format in the required scale (raster data or polygons)

Land use map – Map of used land use classes derived from the land use map in digital format in the required scale (raster data or polygons)

Landslide inventory map – Map of the documented landslides (mapped and from event cadastre)

Landslide susceptibility map – Combination of onset and runout susceptibility in digital format (raster data or polygons)

Runout map – map of modelling results in digital format (raster data or polygons)

Map of endangered areas (intersection of landslide susceptibility map with layer of assets) in digital format (raster data or polygons)

Slope Angle Distribution Analysis Moertschach (DEM 1m)



			Suso	ceptibility	Map,	Suscept	ptibility zoning		
	Minimum Requirements for Landslide Processes			R		L		s	Hazard
				al extent	Local	extent	Slope extent		Zoning
			Onset	Runout	Onset	Runout	Onset	Runout	1
		lithology						J	
	Coological Information	hard rock underground, orientation of discontinuities, dipping							
	Geological Information	soft rock underground, soil information							
		tectonic structures /lineaments							
		archive data on past and current events							
		field work data							
Basic Data	Topographic data	optical, aerial photos, topographic maps							
	Digital Elevation Model	cell size ≤ 30m							
	(DEM)	cell size ≤ 5m							
		cell size $\leq 2m$							
	Land use map	scale ≥1:50.000							
		scale 1:25.000 - 1:5.000							
		scale ≥1:5.000							
	-	low							
Duran data	Source area	low -medium							
Process data		high - excellent							
quality	Transport and runout	low							
		low - medium							
	alca	high - excellent							
	-	information							
	Scope	advisory							
		statutory basis - design							
		geomorph. method							
Modelling Approach		index method							
	0 11	statistical methods							
		process based methods							
		Evaluation							
		Element at risk							



necessary (red)

recommended (yellow)

auxiliary information for advanced study (green)

white: not relevant

Table 9: Minimum Requirements for Landslide processes

B.2. Handbook for rockfall

2.1 Toolbox for rockfall susceptibility and hazard mapping

The proposed methodology brings the user through some tables, which define the minimal methodology which should be used. Each methodology is a specific combination of:

- a rockfall onset modelling method
- a rockfall runout modelling method
- a method to combine the two components for susceptibility zonation
- a method to introduce temporal probability for hazard zonation

Use of the toolbox requires the following **steps**:

- choose a scale and a scope for the analysis according to the following table 10;
- 2. for each scale, **choose the analysis level** (minimal or advanced) according to the requirements of the as-

for each scale and level, tables provide a combination of onset susceptibility assessment methodology (and related zonation), runout modelling methodology, susceptibility zonation methodology, and hazard zona-

signment;

Analysis Scale	Scope	Type of maps	Map scale	DEM cell size
R Regional	Recognition of potentially endangered areas	Inventory maps / Susceptibility maps	1:50.000 - 1:10.000	≤ 30 m
L Local (e.g. municipality)	Land-use planning	Susceptibility maps / Landslide susceptibility maps	1:10.000 - 1:5.000	≤ 5 m
S Specific areas or slope-scale (site specific study)	Hazard and risk analysis, design of countermeasures	Hazard map / Hazard zone maps	1:5.000 - 1:500	≤ 2 m

tion methodology. Each methodology is referred to a short acronym;

4. for each acronym, a brief explanation of basics, related procedures and available tools, required data, and suitability for different applications is provided in chapter B 2.2, B 2.3, B 2.4 and in **Annex 3 (Methodologies)**. The suitability of different methodologies for specific applications (e.g. susceptibility for land-use planning, linear infrastructures, countermeasure design, very detailed hazard zonation, etc.) is also reported in **Annex 3**. Only the essential information is given in the guideline, and the user will refer to the cited references for the practical details of the adopted procedures.

Table 10: Definition of study scale and scopes

Methodology Advantage		Disadvantage		Onset		Runout			
wethodology	Advantage	Disadvantage	Regional	Local	Specified study	Regional	Local	Specified study	
Geomorphological field analysis	Analysis of many parameters; detailed	Very subjective and time consuming	-	х	x	-	х	(x)	
Index Method	Simple	Subjective indexing	х	х	(x)	-	-	-	
Empirical approach	Simple	-	-	-	-	х	х		
Statistics	Objectiv, automation	Extensive data collection and processing	x	х	-	х	-	-	
Process-based	Objectiv, deterministic or stochastic	Detailed knowledge required	(x)	х	х	-	х	х	

Table 11: Scales and usability of the methods

ANALYSIS LEVEL	ONSET	RUNOUT	SUSCEPTIBILITY ZONING	HAZARD
Minimal:susceptibilitywithsourceareasidentification+mostconservativerunout	R_01	R_R1	R_S1	-
Advanced:susceptibilityzoningwithonsetsusceptibility+transitsusceptibility	R_02	R_R1	R_S2	-

ONSET

- R_O1 rockfall sources: identification based geomorphological mapping, location and height of cliffs
- R_O2 rockfall source ranking: categorisation of the cliffs in terms of rock fall potential (potential processes, rockfall inventories))

SUSCEPTIBILITY ZONING

- R_S1: maximum runout and recognition of potential conflicts between rockfall processes and human activities steering the more detailed investigation
- R_S2: run-out reclassified according to transit frequency of boulders or nr. of simulated deposited blocks, also considering rockfall source ranking

Table 12: Methodologies for regional-scale rockfall assessment

RUNOUT

- R_R1 conservative runout: map of the maximal run-out zone using simple methods (e.g. energy line principle, shadow angle)
- R_R2 runout with transit frequency: intersection of the max run out zone with the location of blocks from past events and/or 3D run-out modelling at regional-scale resolution with assessment of transit frequency

2.3 Local scale study (L)

	ONSET	RUNOUT	SUSCEPTIBILITY ZONING	HAZARD
Minimal: hazard with onset and transit probability for a certain intensity	L_01			L_H1
Advanced: hazard with onset and transit probability for a certain intensity (based on stability calculations)	L_02	L_R	L_S	L_H2

ONSET

- L_O1 rockfall source ranking: categorisation of the cliffs in terms of rock fall potential (potential processes, rockfall inventories)
- L_O2 rockfall source ranking based on rockslope stability analysis: assessment of failure mechanism (sliding, falling and/or toppling) an stability analysis with cinematic or limitequilibrium methods

Table 13: Methodologies for local-scale rockfall assessment

RUNOUT

 L_R runout with transit frequency and kinetic energy: 3D (for any extent) or 2D (for small areas e.g. few km2 and simple slope morphologies) run-out modelling with assessment of transit frequency and kinetic energy

SUSCEPTIBILITY ZONING

 L_S: run-out reclassified according to transit frequency of boulders or nr. of simulated deposited blocks, also considering rockfall source ranking.

HAZARD

 L_H1-2: run out reclassified according to expected frequency obtained by rescaling the probability of a reference scenario with susceptibility + kinetic energies

2.4 Site specific study (S)

	ONSET	RUNOUT	SUSCEPTIBILITY ZONING	HAZARD
Minimal: source and runout susceptibility classified by intensity (with onset and runout susceptibility ranking)	S_01		-	S_H1
Advanced:sourceandrunoutsusceptibilityclassifiedbyintensity-"probabilistic"hazard(withonsetandrunoutsusceptibilityranking)	S_02	S_R	-	S_H2

Table 14: Methodologies for site-specific rockfall assessment

ONSET

- S_O1 rockfall source ranking: categorisation of the cliffs in terms of rock fall potential (potential processes, rockfall inventories)
- S_O2 rockfall source ranking based on rock-slope stability analysis: assessment of failure mechanism (sliding, falling and/or toppling) an stability analysis with cinematic or limitequilibrium methods

RUNOUT

 S_R runout with transit frequency and kinetic energy: 3D (for any extent) or 2D (for small areas e.g. few km2 and simple slope morphologies) run-out modelling with assessment of transit frequency and kinetic energy

HAZARD

- S_H1: run out reclassified according to expected frequency obtained by rescaling the probability of a reference scenario with susceptibility + kinetic energies
- S_H2: Magnitude dependent frequency combined with onset susceptibility ranking

2.5 Basic data and parameter

2.5.1 Regional scale study

Input data:

DEM (\leq 30 m), generated from optical aerial photos (DTM – DSM cell size \leq 10 m)

Orthophotos.

Geologic and tectonic maps (scale \geq 1:50.000)

Collection of documented rock fall past events, literature, reports

Output data (derived parameter maps and documents):

Slope angle and slope aspect maps from DTM; Land use (differentiation of forest and grassland) and soil texture maps from DSM and orthophotos.

Lithologic, tectonic, geomorphologic and out crop / soil type maps from DTM, DSM, orthophotos, geologic and tectonic maps.

Documented data base of major rock fall past events in data sheets and/or GIS environment.

2.5.2 Local scale study

Input data:

DEM (\leq 5 m), generated from optical aerial photos and LIDAR Approach (DTM – DSM cell size \leq 5m)

Orthophotos.

Geological and tectonic maps (scale \geq 1:10.000)

Collection of documented rock fall past events, literature, reports.

Geomechanical survey in the field and with ALS oblique.

Main existing rock fall protection methods collection and mapping.

Output data, derived parameter maps and documents (scale \ge 1:10.000) in digital format (GIS) (raster data or polygons/shape files):

Slope angle (indexed for steps 5° or 10°) and slope aspect maps (indexed for steps 10° or 30°) from DTM.

Cross sections from DTM from the source area ending beyond the runout / impact zone.

Land use (differentiation of main forest and grassland types) and soil texture maps from DSM and orthophotos.

Lithologic map with lithologic description (indexed for geotechnical lithotype units).

Tectonic map with main tectonic lineaments.

Geomorphologic and out crop / soil type maps with active processes and form, talus / scree characteristics maps from GIS-analyses of DTM, DSM, orthophotos, geologic and tectonic maps, on site investigation.

Rock mass characterisation from on site geomechanical investigation with assessment of main structural domains, block shape and volume identification and rock mass classification (BRMR and GSI indexes).

Kinematic rock mass slope stability analysis.

Rock fall source area (scarp) and potentially critical volumes assessment and data sheets compilation.

Rock fall inventory map from documented and mapped events used for back analysis and check of the quality of results Main existing rock fall protection methods inventory map, assessment of their effectiveness in rock fall mitigation.

Rockfall susceptibility map – Combination of onset and runout susceptibility (susceptibility zoning)

Runout map (modelling result) – map of modelling results

Map of endangered areas - intersection of onset susceptibility map and runout susceptibility map with layer of assets

2.5.3 Site specific scale study

Input data:

DEM (\leq 2 m), generated from optical aerial photos and LIDAR Approach: airborne nadiral and oblique (ALS) and terrestrial TLS (DTM – DSM cell size \leq 2m).

Orthophotos.

Geological and tectonic maps (scale \geq 1:5.000)

Collection of documented rock fall past events, literature, reports.

Geomechanical survey in the field, with ALS oblique and TLS.

Main existing rock fall protection methods collection and mapping.

Output data, derived parameter maps and documents (scale \geq 1:5.000) in digital format (GIS) (raster data or polygons/shape files):

Slope angle (indexed for steps 5° or 10°) and slope aspect maps (indexed for steps 10° or 30°) from DTM.

Cross sections from DTM from the source area ending beyond the runout / impact zone. Land use (differentiation of main forest and grassland types) and soil texture maps from

DSM and orthophotos.

Lithologic map with lithologic description (indexed for geotechnical lithotype units).

Tectonic map with main tectonic lineaments.

Geomorphologic and out crop / soil type maps with active processes and form, talus / scree characteristics maps from GIS-analyses of DTM, DSM, orthophotos, geologic and tectonic maps, on site investigation.

Rock fall inventory map from documented and mapped events used for back analysis and check of the quality of results

Rock mass characterisation from on site geomechanical investigation with assessment of main structural domains, block shape and volume identification and rock mass classification (BRMR and GSI indexes) leading to detailed geological and engineering geological maps.

Geomechanical slope face analysis: potentially critical volumes characterization (block geometrical reconstruction and position)

Kinematic rock mass slope stability analysis

Kinetic rock mass slope stability considering water pressure and seismic force effects.

Rock fall source area (scarp) and potentially critical volumes assessment and data sheets compilation.

Main existing rock fall protection methods inventory map, assessment of their effectiveness and effectiveness in rock fall mitigation.

Rockfall susceptibility map – Combination of onset and runout susceptibility (susceptibility zoning)

Runout map (modelling result) – map of modelling results

Map of endangered areas - intersection of onset susceptibility map and runout susceptibility map with layer of assets

Minimum Requirements for Rockfall Processes			Susceptibility Map									
				R		L			S			
			1	Regional extent		Local extent			Slope extent			
			Onset	Runout	Suscept. zoning	Onset	Runout	Suscept. zoning	Onset	Runout	Hazard zoning	
		lithology (GTL)										
	Geology	orientation of discontinuities, type of rock mass structure										
		tectonic structures / lineaments		_								
	Rockfall	archive data on past and current events										
	inventorv	field work data										
	Topography	aerial photos, top	oographic maps									
Dat		LIDAR-airborne	inclined image									-
U U		scanning	vertical image									
asi		LIDAR -terrestrial										
	Digital	cell size \leq 30m										
	Elevation	cell size ≤ 5m								_		
	Model	cell size ≤ 2m										
		scale ≥1:50.000										
	Land use	scale 1:25.000	- 1:5.000									
		scale ≥1:5.000										
	s data lity	source area	low									
			low - medium									
			high - excellent									
	Process qua	run-out area	low									
			low - medium									
			high - excellent									
		information - screening										
Scope		land planning										
		countermeasure design										
		E	valuation									

necessary (red)

recommended (yellow)

auxiliary information for advanced study (green)

white: not relevant

Table 15: Minimum requirements for rockfall processes



Accumulation (Ablagerung, Accumulo): The volume of the displaced material, which lies above the original ground surface. (Cruden, 1993).

Disaster (Katastrophe, Disastro): An event in which a society incurs, or is threatened to incur, such losses to persons and/or property that the entire society is affected and extraordinary resources and skills are required, some of which must come from other nations.

Crown (Krone, Coronamento): The practically undisplaced material still in place and adjacent to the highest parts of the main scarp. (Cruden, 1993).

Danger (Gefahr, Pericolo): The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The danger can be an existing one (such as a creeping slope) or a potential one (such as a rockfall). The characterisation of a danger or threat does not include any forecasting. (Hungr et al, 2005).

Depleted mass (Gleitmasse, Massa asportata): The volume of the displaced material, which overlies the rupture surface but underlies the original ground surface. (Cruden, 1993).

Displaced material (Verlagertes Material, Materiale spostato): Material displaced from its original position on the slope by movement of the landslide. It forms both the depleted mass and the accumulation. (Cruden, 1993).

Element at risk (Gefährdetes Element, Elemento a rischio): Population, property, economic activity, public services or environmental goods situated in a location exposed to risk.

Event map (Ereigniskarte, Inventario di evento – componente geometrica): Event maps exclusively comprise process information which has a known date assigned to it. They mostly cover damage-related information and details on the area affected, based on the 5 key questions of event inquiries (who-what-whe-re-when-why). Redundant information of one event, such as that obtained when dealing with inconsistent sources, is compiled.

Event registers (Ereigniskataster, Inventario di evento – componente logica): According to event maps, event registers only cover process information for which a date is known. They mostly cover damage-related information and details on the area affected, based on the 5 key questions of event inquiries (who-what-where-when-why). As opposed to event maps, however, event registers are independent of scale and can include non-locatable information.

Foot (Rutschungsfuß, Piede): The portion of the landslide that has moved beyond the toe of the surface of rupture and overlies the original ground surface. (Cruden, 1993).

Frequency (Häufigkeit, Frequenza): A measure of likelihood expressed as the number of occurrences of an event in a given time or in a given number of trials (see also probability) (Hungr et al, 2005).

Gravitational mass movement (Gravitative Massenbewegung, Movimento in massa gravitativo): Gravitational mass movement refers to all those processes by which soil, debris, and rock move downslope discontinuous or continuous under the force of gravity, neglecting a transport medium (water, ice, air).

Hazard (Gefahr, Pericolosità):

- Probability of occurrence of a landslide of a given magnitude, in a given period of time, and within a given area (Varnes et al., 1984; Fell, 1994; Fell and Hartford, 1997; Guzzetti et al., 1999). The description of landslide hazard should include the classification, location, intensity and the probability of their occurrence within a given period of time (Fell et al., 2008). Different intensity descriptors (e.g. volume, area, velocity, energy) can be used depending on the landslide type and the expected runout potential.
- Probability that a specific location on a slope is reached/affected by a landslide of given intensity (volume and/or energy) and temporal probability of occurrence.

Hazard map (Gefahrenkarte, Carta della pericolosità): Map portraying, for each considered slope unit (pixel, unique condition unit, basin), a quantitative description of either the probability of reach/occurrence
of landslides of given magnitude and temporal probability of occurrence, or their intensity.

Hazard zone map (Gefahrenzonenkarte, Carta di zonazione della pericolosità): Map portraying the geographical location of zones of different intensity of effects by a given hazard (given magnitude and frequency of events).

Head (Rutschungskopf, Testata): The upper parts of the landslide along the contact between the displaced material and the main scarp. (Cruden, 1993).

Inventory map > Landslide inventory map

Intensity > Landslide Intensity

Landslide (Rutschung, Frana): It is a geological phenomenon which includes a wide range of ground movement, such as rock falls, deep failure of slopes and shallow debris flows, which can occur in offshore, coastal and onshore environments. Although the action of gravity is the primary driving force for a landslide to occur, there are other contributing factors affecting the original slope stability. Typically, pre-conditional factors build up specific sub-surface conditions that make the area/slope prone to failure, whereas the actual landslide often requires a trigger before being released.

Landslide Intensity: (Intensität, Intensità di frana): synonym of, or a proxy for, landslide magnitude is a measure of the destructive potential of a landslide, based on a set of physical parameters, such as downslope velocity, thickness of the landslide debris, volume, energy and impact forces, total and differential displacement, peak discharge per unit width, kinetic energy per unit area. Intensity can be expressed qualitatively or quantitatively. Intensity varies with location along and across the path of the landslide and it should ideally be described using a spatial distribution function or an appropriate map. In geomorphological risk assessment, it is defined as a function of the landslide volume and of the landslide velocity.

Landslide inventory (Rutschungskataster, inventario delle frane – componente logica): An inventory for landslides (slides, debris flows, rock falls and other mass movements) is a collection of data on past and current landslide occurrences. Content, symbology (map representation) and scale of available landslide inventories differ significantly (Schweigl & Hervas, 2009).

Landslide inventory map (Karte der Phänomene, inventario delle frane – componente geometrica): The inventory map shows the location of occurrences of landslides and rockfalls of the landslide inventory at different scales.

Landslide magnitude (Magnitude, Magnitudo della frana): A synonym of landslide intensity. Measured by the size (area or volume), speed, momentum or destructiveness of the landslide. **Landslide susceptibility** (Rutschungsanfälligkeit, Suscettibilità da frana): Spatial probability (susceptibility; Brabb, 1984) that any given slope unit will be affected by the occurrence of a landslide of given type, given a set of conditions including topography, geology, hydrogeology, landuse, vegetation, geomechanics, etc. (modified after Brabb, 1984).

Landslide susceptibility assessment (Gefahrenhinweis, Valutazione della scuscettibilità da frana): A quantitative or qualitative assessment of the spatial distribution of landslides that exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding. Although it is expected that landsliding will occur more frequently in the most susceptible areas, in the susceptibility analysis, time frame is explicitly not taken into account. Landslide susceptibility includes landslides which have their source in the area, or may have their source outside the area but may travel onto or regress into the area (after Fell et al., 2008).

Landslide susceptibility map (Gefahrenhinweiskarte, Carta di suscettibilità): A susceptibility map displays the spatial distribution and rating of the terrain units (e.g. pixels, polygons) classified according to their spatial probability / propensity to be affected or reached by a certain landslide type (after Fell 2008).

Comments:

- susceptibility is not a ranking or the degree of slope stability, but a description of the relative (spatial) propensity /probability of a landslide of a given type and magnitude to occur;
- "Susceptibility" is not a synonym of "danger". According to Einstein (1988) a "danger" is a potentially hazardous process characterised by its intensity (e.g. "potentially hazardous process": rockfall; "danger": a 10m3 rockfall). Thus we believe that "danger" here should be discarded by the definition
- Susceptibility can/should be assessed using qualitative and/or quantitative (not only qualitative) criteria, even if it is expressed by susceptibility classes. The difference with respect to hazard is that temporal probability of occurrence is not taken into account.

Magnitude > Landslide magnitude

Main body (Haupt - Rutschkörper, Corpo di frana): The part of the displaced material of the landslide that overlies the surface of rupture between the main scarp and the toe of the surface of rupture. (Cruden, 1993).

Main scarp (Hauptanriss, Scarpata principale): A steep surface on the undisturbed ground at the upper edge of the landslide, caused by movement of the displaced material away (Cruden, 1993).

Mitigation (Gefahrenminderung, mitigazione): ac-

tivities that reduce or eliminate the probability of occurrence of a disaster and/or activities that dissipate or lessen the effects of emergencies or disasters when they actually occur. (Jochim et al, 1988).

Mitigation map (Karte über Verbauungsmaßnahmen, carta delle opere di mitigazione): displays the spatial distribution of measures/activities.

Moved body (Rutschörper, Massa spostata): The displaced material of the landslide that overlies the surface of rupture and the original ground surface between the main scarp and the toe of landslide.

Mudflow (Mure, Colata detritica): When a slope is so heavily saturated with water that it rushes downhill as a muddy river, carrying down debris and spreading out at the base of the slope; the water content may range up to 60%.

Parameter (Parameter, Parametro): Point, linear and areal information that describes the phenomena, parameters have to be specified by values or defined classes, parameters have to be located.

Parameters are measurable values, which mostly require a dimension unit. Here, one should differentiate between geometrical (e.g. width of scar [m], block volume [m³]), physical (e.g. friction angle [°]) and chemical parameters (pH value [-]).

Phenomenon (Phänomen, Indizio/ Evidenza): Phenomena are signs or indicators for historic, recent or future processes (points, linear and areal informations). They can be of geological (e.g. zones of special rock anisotropy), geomorphological (e.g. scarps/scars, bulging), vegetation-related (e.g. tilted trees, disturbed forest), hydrological (saturation zones) or damage-related (e.g. impact marks, damage to buildings) type.

Probability (Wahrscheinlichkeit, Probabilità): A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimation of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event. (Hungr et al, 2005).

Probability of rock failure (Bruchwahrscheinlichkeit einer Instabilität, Probabilità di rottura): Probability of failure of a portion of rock mass, with a specific volume, within a given time unit and within the considered cliff.

Probability of propagation (Ausbreitungswahrscheinlichkeit, Probabilità di propagazione): Probability that a portion of rock mass, with given characteristics, and coming from a given portion of the cliff, transits across a considered area. Characteristics such as height of flight, velocity, mass, and energy can be described by statistical distributions.

Process (Prozess, Evento): A process is a happening initiated at a certain location in dependence of temporally and spatially varying conditions (e.g. state of the subsurface, anthropological influence on slope statics, progressive weathering) and other causative factors (e.g. precipitation, pore water pressure). The further development of the process is affected by movement controlling factors in the process area (e.g. vegetation, composition of the moving mass).

Register (Kataster, Catasto): Registers are independent of scale and, contrary to maps, they can also include information which is not tied to a specific location.

Risk (Risiko, Rischio): Measure of the probability and severity of an adverse effect to life, health, property, or the environment. Quantitatively, Risk = Hazard x Potential Worth of Loss. This can be also expressed as "Probability of an adverse event times the consequences if the event occurs". (Hungr et al, 2005).

Risk is defined in ISO 31000 as the effect of uncertainty on objectives (whether positive or negative).

Risk analysis (Risikoanalyse, Analisi di rischio): The use of available information to estimate the risk to individuals or populations, property or the environment, from hazards. Risk analyses generally contain the following steps: definition of scope, danger (threat) identification, estimation of probability of occurrence to estimate hazard, evaluation of the vulnerability of the element(s) at risk, consequence identification and risk estimation. Consistent with the common dictionary definition of analysis, "A detailed examination of anything complex made in order to understand its nature or to determine its essential feature ", risk analysis involves the disaggregation or decomposition of the system and sources of risk into their fundamental parts. (Hungr et al, 2005).

Risk assessment (Risikobewertung, Valutazione del rischio): It is a step in a risk management process. Risk assessment is the determination of quantitative or qualitative value of risk related to a concrete situation and a recognized threat (also called hazard). Quantitative risk assessment requires calculations of two components of risk: R, the magnitude of the potential loss L, and the probability p, that the loss will occur.

Risk management (Risiko-management, Gestione del rischio): The systematic application of management policies, procedures and practices to the tasks of identifying analysing, assessing, mitigation and monitoring risk. (Hungr et al, 2005).

Risk mitigation (Risikominimierung, Mitigazione del rischio): A selective application of appropriate techniques and management principles to reduce either likelihood of an occurrence or its adverse consequences, or both. (Hungr et al, 2005)

Rockfall (Steinschlag, Crollo in roccia/ Caduta massi): Instability phenomenon that involves the detachment of rock blocks, from a slope and their following movement (by free fall, bouncing, rolling, sliding) along the slope until they reach equilibrium.

Rock avalanche (Bergsturz, Valanga di roccia): Rock

mass falling from a cliff splitting in blocks, for which the movement is like a fluid.

Shallow landslide (Oberflächennahe Rutschung, Frana superficiale): Based on the typological classification of landslides advanced by Hungr et al. (2001), shallow landslides can be defined as reported below. Even though typological, this classification includes also taxonomical elements (material type; movement mechanism).

"Shallow landslides are a gravitational movement of soil down a slope. The movement mechanism can be classified as a slide, not involving significant internal distorsion of the moving mass. The material involved in shallow landslides includes both earth (material smaller than 2 mm) and debris (material larger than 2 mm). The corresponding depth is generally not exceeding 3 m. Precipitation-induced shallow landslides are triggered during rainstorms or periods of rapid snowmelt when shear strength is reduced because of an increase in pore-water pressure." (Hungr et al, 2001)

Susceptibility > Landslide Susceptibility

Vulnerability (Verwundbarkeit, Vulnerabilità): The degree of loss to a given element or set of elements within the area affected by a hazard.

Worth of element at risk (Wert der gefährdeten Elemente, Valore degli elementi a rischio): Economic value, or number of units of each element at risk situated in a given location.



PART C : ANNEX2 - DESCRIPTION OF TYPES OF PROCESSES

1. What is a landslide?



A landslide is a downslope movement of rock or soil, or both, occurring on the surface of rupture—either curved (rotational slide) or planar (translational slide) rupture—in which much of the material often moves as a coherent or semicoherent mass with little internal deformation.

It should be noted that, in some cases, land slides may also involve other types of movement, either at the inception of the failure or later, if properties change as the displaced material moves downslope.

1.1 Classification factors: type of movement and involved material

The most important criteria of classification is the **type of movement**; the table below shows the classification Varnes (1978); Cruden, Varnes (1996) with some integration using the definitions of Hutchinson (1988) and Hungr et al. (2001).

The identification of the movement is not always easy because the mechanism of the landslides are often complex to understand.

		TYPE OF MATERIAL				
TYPE OF MOVEMENT			ENGINEERING SOIL			
		BEDROCK	PREDOMINANTLY COARSE	PREDOMINANTLY FINE		
Falls		Rock fall	Debris fall	Earth fall		
Topples		Rock topple	Debris topple	Earth topple		
Slides	Rotational	Rock slide	Debris slide	Earth slide		
Olides	Translational	TOCK Side				
Later	al spread	Rock spread	Debris spread	Earth spread		
		Rock flow	Debris flow	Earth flow		
Flows		Rock avalanche	Debris avalanche /			
		(deep creep)	(soil creep)			
Complex		Combination of two or more principal types of movement				

Table 16: Classification oflandslides

1.2 Classification factors: activity states and styles

(WP/WLI 1993)



(1) active: currently moving

(2) suspended: has moved within the last 12 months, but is not active at present

(3) re-activated: an active landslide which has been inactive

(4) dormant: an inactive landslide which can be reactivated by its original causes or other causes

(5) abandoned: an inactive landslide which is no longer affected by its original causes

(6) stabilised: an inactive landslide which has been protected from its original causes by remedial measures

(7) relict: an inactive landslide which developed under climatic or geomorphological conditions considerably different from those at present

1.3 Classification factors: velocity

Cruden and Varnes (1996)

Velocity Class	Description	Velocity (mm/sec)	Typical Velocity	Probable Destructive Significance
7	Extremely Rapid	-5×10^{3}	5 m/sec	Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
б	Very Rapid	5 x 10 ¹	3 m/min	Some lives lost; velocity too great to permit all persons to escape
5	Rapid	- 5 x 10 ⁻¹	1.8 m/hr	Escape evacuation possible; structures; possessions, and equipment destroyed
4	Moderate	5 - 10-3	12 m/month	Some temporary and insensitive structures can be temporarily maintained
3	Slow	- 5 x 10		Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not
2	Very Slow	5 x 10 ⁻⁹	1.6 m/year	large during a particular acceleration phase Some permanent structures undamaged by movement
	Extremely SLOW	— 5 x 10 ⁻⁷	15 mm/year	Imperceptible without instruments; construction POSSIBLE WITH PRECAUTIONS

1.4 Description of features

Based on Cruden and Varnes (1996)



1. Crown: The practically undisplaced material still in place and adjacent to the highest parts of the main scarp.

2. Main Scarp: A steep surface on the undisturbed ground at the upper edge of the landslide, caused by movement of the displaced material away from the undisturbed ground. It is the visible part if the surface of rupture.

3. Top: The highest point of contact between the displaced material and the main scarp.

4. Head: The upper parts of the landslide along the contact between the displaced material and the main scarp.

5. Minor Scarp: A steep surface on the displaced material of the landslide produced by differential movements within the displaced material.

6. Main Body: The part of the displaced material of the landslide that overlies the surface of rupture between the main scarp and the toe of the surface of rupture.

7. Foot: The portion of the landslide that has moved beyond the toe of the surface of rupture and overlies the original ground surface.

8. Tip: The point of the toe farthest from the top of the landslide.

9. Toe: The lower, usually curved margin of the displaced material of a landslide, it is the most distant from the main scarp.

10. Surface of Rupture: The surface which forms (or which has formed) the lower boundary of the displaced material below the original ground surface.

11. Toe of the Surface of Rupture: The intersection (usually buried) between the lower part of the surface of rupture of a landslide and the original ground surface.

12. Surface of Separation: The part of the original ground surface overlain by the foot of the landslide.

13. Displaced Material: Material displaced from its original position on the slope by movement in the landslide. It forms both the depleted mass and the accumulation.

14. Zone of Depletion: The area of the landslide within which the displaced material lies below the original ground surface.

15. Zone of Accumulation: The area of the landslide within which the displaced material lies above the original ground surface.

16. Depletion: The volume bounded by the main scarp, the depleted mass and the original ground surface.

17. Depleted Mass: The volume of the displaced material, which overlies the rupture surface but underlies the original ground surface.

18. Accumulation: The volume of the displaced material, which lies above the original ground surface.

19. Flank: The undisplaced material adjacent to the sides of the rupture surface. Compass directions are preferable in describing the flanks but if left and right are used, they refer to the flanks as viewed from the crown.

20. Original Ground Surface: The surface of the slope that existed before the landslide took place.

2. What causes landslides?

There are two primary categories of causes of landslides: natural and human-caused; often, landslides are caused by a combination of both factors.

2.1 Natural Occurrences

This category has three major triggering mechanisms that can occur either singly or in combination:

WATER	SEISMIC ACTIVITY	VOLCANIC ACTIVITY
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Geological causes
Weak materials, such as some volcanic slopes or unconsolidated marine sedi- ments, for example
Susceptible materials
Weathered materials
Sheared materials
Jointed or fissured materials
Adversely oriented mass disconti nuity (bedding, schistosity, and so forth)
Adversely oriented structural discontinuity (fault, unconformity, contact, and so forth)
Contrast in permeability
Contrast in stiffness (stiff, dense material over plastic materials)

Morphological causes Tectonic or volcanic uplift Glacial rebound Glacial meltwater outburst Fluvial erosion of slope toe Wave erosion of slope toe Glacial erosion of slope toe Erosion of lateral margins Subterranean erosion (solution, piping) Deposition loading slope or its crest Vegetation removal (by forest fire, drought) Weight of the trees and/or wind stress on the treetops

Effects of all of these causes vary widely and depend on factors such as steepness of slope, morphology or shape of terrain, soil type, underlying geology, and whether there are people or structures on the affected areas.

Triggers

Intense rainfall

Rapid snowmelt

Prolonged intense precipitation

Rapid drawdown (of floods and tides) or filling

Earthquake

Volcanic eruption

Thawing

Freeze-and-thaw weathering

Shrink-and-swell weathering

Flooding



2.2 Human Activities

Populations expanding onto new land and creating neighborhoods, towns, and cities is the primary means by which humans contribute to the occurrence of land slides. Disturbing or changing drainage patterns, destabilizing slopes, and removing vegetation are common human-induced factors that may initiate landslides.



Other examples include oversteepening of slopes by undercutting the bottom and loading the top of a slope to exceed the bearing strength of the soil or other component material. However, landslides may also occur in once-stable areas due to other human activities such as irrigation, lawn watering, draining of reservoirs (or creating them), leaking pipes, and improper excavating or grading on slopes. New construction on landslide-prone land can be improved through proper engineering (for example, grading, excavating) by first identifying the site's susceptibility to slope failures and by creating appropriate landslide zoning.

Excavation of slope or its toe

Human Causes

- Use of unstable earth fills, for construction
- Loading of slope or its crest, such as placing earth fill at the top of a slope
- Drawdown and filling (of reservoirs)

Deforestation—cutting down trees/logging and (or) clearing land for crops; unstable logging roads

Irrigation and (or) lawn watering

Mining/mine waste containment

Artificial vibration such as pile driving, explosions, or other strong ground vibrations

Water leakage from utilities, such as water or sewer lines Diversion (planned or unplanned) of a river current or longshore current by construction of piers, dikes, weirs, and so forth

3. What is a rock fall?

Falls are abrupt, downward movements of rock or earth, or both, that detach from steep slopes or cliffs. The falling material usually strikes the lower slope at angles less than the angle of fall, causing bouncing. The falling mass may break on impact, may begin rolling on steeper slopes, and may continue until the terrain flattens.





Occurrence and relative size/range

Common worldwide on steep or vertical slopes—also in coastal areas, and along rocky banks of rivers and streams. The volume of material in a fall can vary substantially, from individual rocks or clumps of soil to massive blocks thousands of cubic meters in size.

Velocity of travel

Very rapid to extremely rapid, free-fall; bouncing and rolling of detached soil, rock, and boulders. The rolling velocity depends on slope steepness.

Triggering mechanism

Undercutting of slope by natural processes such as streams and rivers or differential weathering (such as the freeze/thaw cycle), human activities such as excavation during road building and (or) maintenance, and earth quake shaking or other intense vibration.

4. What is a topple?

A topple is recognised as the forward rotation out of a slope of a mass of soil or rock around a point or axis below the center of gravity of the displaced mass.





Occurrence

Know to occur globally, often prevalent in columnar jointed terrain, as well as long stream and river courses where the banks are steep.

Velocity of travel

Extremely slow to e extremely rapid to extremely rapid.

Triggering mechanism

Sometimes driven by gravity exerted by material located upslope from the displaced mass and sometimes by water or ice occurring in cracks within the mass; also vibration, undercutting, differential weathering, excavation, or stream erosion.

5. What is a translational landslide?

The mass in a translational landslide moves out, or down and outward, along a relatively planar surface with little rotational movement or backward tilting. This type of slide may progress over considerable distances if the surface of rupture is sufficiently inclined, in contrast to rotational slides, which tend to restore the slide equilibrium. The material in the slide may range from loose, unconsolidated soils to extensive slabs of rock, or both. Translational slides commonly fail along geologic discontinuities such as faults, joints, bedding surfaces, or the contact between rock and soil. In northern environments the slide may also move along the permafrost layer.



Occurrence

One of the most common types of landslides, worldwide. They are found globally in all types of environments and conditions.

The surface of rupture has a distance-to-length ratio of less than 0.1 and can range from small (residential lot size) failures to very large, regional landslides that are kilometers wide.

Velocity of travel

Movement may initially be slow (1.5 meters per month) but many are moderate in velocity (1.5 meters per day) to extremely rapid. With increased velocity, the landslide mass of translational failures may disintegrate and develop into a debris flow.

Triggering mechanism

Primarily intense rainfall, rise in ground water within the slide due to rainfall, snowmelt, flooding, or other inundation of water resulting from irrigation, or leakage from pipes or human-related disturbances such as undercutting. These types of landslides can be earthquake-induced.



6. What is a rotational landslide?

In this case surface of ropture is curved upvard (spoon-shaped) and the movement is more or less rotational around an axis parallel to the countour of the slope. The displaced mass may, under certain circumstances, move as a relatively coherent mass along the rupture surface with little internal deformation. The head of the displaced material may move almost vertically downward, and the upper surface of the displaced material may tilt backwards toward the scarp. If the slide is rotational and has several parallel curved planes of movement, it is called a slump.





Occurrence

Because rotational slides occur most frequently in homogeneous materials, they are the most common landslide occurring in "fill" material.

Velocity of travel

Extremely slow (less than 0.3 meter or 1 foot every 5 years) to moder ately fast (1.5 meters or 5 feet per month) to rapid

Triggering mechanism

Intense and (or) sustained rainfall or rapid snowmelt can lead to the saturation of slopes and increased groundwater levels within the mass; rapid drops in river level following floods, ground-water levels rising as a result of filling reservoirs, or the rise in level of streams, lakes, and rivers, which cause erosion at the base of slopes. These types of slides can also be earthquake-induced.



PART C : ANNEX3 - 1 METHODOLOGY REGARDING LANDSLIDE HAZARD MAPPING

Methodology	Advantage	Disadvantage	Onset			Runout		
Methodology			Regional	Local	Specified study	Regional	Local	Specified study
Geomorphological field analysis	Analysis of many parameters; detailed	Very subjective and time consuming	-	х	х	-	х	x
Index Method	Standardisation	Subjective indexing	x	х	х		х	х
Statistics	Objectiv, automation, standardisation	Extensive data collection and processing	x	х	(x)	-	-	-
Process-based	Objectiv, quantitative	Very detailed knowledge of area neccesary	х	х	х	-	х	x

Table 17: Scales and usability of the methods

1.1 Onset

1.1.1 Geomorphological field analysis (L_O, S_O)

Geomorphological field analysis methods are based on the subjective assessment of landslide onset susceptibility based on expert- knowledge. This approach requires experience of prior events and direct knowledge of landslide triggering control factors in the study area, and it is usually suitable for site-specific to local scale analysis.

1.1.2 Index method R_O1, R_O2, (L_O, S_O)

From the literature many different evaluation methods are known. Keeping to the problem - due to the expected present available data - most likely qualitative methods are useful. Within these methods the use of parameter maps or indexed maps seems to be suitable. The advantages are the automation in the processing, the drawbacks are the subjectivity in indexing. Index method combined with engineering geological mapping and statistical analysis are appropriate for regional and local scale landslide susceptibility studies. For weighting the index of the parameter maps statistical analysis of mapped events are useful. For example indexing the slope inclination classes can be done by knowledge from literature or if enough available data of events are present by statistical analysis.

1.1.3 Statistical methods (R_O1, R_ O2, L_O, S_O)

Statistical methods are based on the definition of a statistical relationships between geo-environmental controlling parameters and landslide onset susceptibility. The most well-known approaches (Carrara et al., 1991) are based on the use of available morphological, structural, lithological, and land-use maps and landslide information (Guzzetti et al, 2005). These maps are normally available at regional scale; this approach is well suitable for regional scale analysis. The statistical relationships between geo-environmental controlling parameters (litho logy, structural parameters, slope gradient, slope aspect, slope curvature, etc.) and onset susceptibility can be defined using multivariate statistical approaches. An example has been presented in for a regional scale analysis. This approach bases on the use of discriminant analysis to classify the percentage of landslides based on several geo-environmental parameters (Guzzetti et al. 2005).

1.1.4 Process-based methods

Process-based methods are mostly based on numerical simulation of the hill slope failure processes (Borga et alii, 2002). Limit equilibrium theory is often used to analyse the stability of natural slopes. A number of methods and procedures based on limit equilibrium principles have been developed for this purpose. Regardless of the specific procedures, the following principles are common to all methods of limit equilibrium analysis:

- 1. a failure surface or mechanism is postulated;
- 2. the shearing resistance required to equilibrate the failure mass is calculated by means of statics;
- 3. the calculated shearing resistance required for equilibrium is compared with the available shear strength. This comparison is made in terms of the factor of safety, which is defined as the factor by which the shear strength parameter must be reduced in order to bring the slope into a state of limiting equilibrium along a given slip surface;
- 4. the mechanism or slip surface with the lowest factor of safety is found by iteration.

Use of the method at regional, local or site-specific scales and available data dictates the assumptions used in the modelling of hill slope stability:

1.1.4.1 Planar infinite stability analysis (L_O, S_O)

Planar infinite slope analysis has been applied to the determine landslide susceptibility, particularly where the thickness of the soil cover is small compared with the slope length and where landslides are due to the failure of a soil cover overlying a drainage barrier. The drainage barrier may be bedrock or a denser soil mass. In this case, soil thickness corresponds to the depth of the drainage barrier. A translational failure plane may develop at any hydraulic conductivity contrast where positive pore water pressure can develop. Examples of such conditions include loose near-surface soil in thick glacial deposit, loose volcanics overlying denser soil layers, loose colluvial soil overlying decomposed residual soil common in granitic terrain.

The static determinacy and mathematical simplicity that results from the assumptions embedded into this model make infinite slope analysis uniquely well suited for drawing unambiguous conclusions about the effects of ground water flow on slope stability. The principal disadvantage of infinite-slope analysis is that mechanical one-dimensionality precludes accurate assessments of slopes in which ground water flow or topography produces forces that vary in directions other than the slope-normal direction.

1.1.4.2 2D slope stability modelling (S_O)

If there is a need to analyse slopes and where the potential slip surface cannot be assumed to be parallel to the hill slope, 2D slope stability models are used. Conventional 2D slope stability analyses investigate the equilibrium of a mass of soil margined by an assumed potential slip surface and the surface of the slope, assuming a two-dimensional (2-D) cross section and plane strain conditions for analysis. Forces and moments tending to cause instability of the mass are compared to those tending to resist instability. Successive assumptions are made regarding the potential slip surface until the most critical surface (lowest factor of safety) is found. As for the infinite slope stability case, the stability or instability of the mass depends on its weight, the external forces acting on it (such as surcharges or accelerations caused by dynamic loads), the shear strengths and pore water pressures along the slip surface, and the strength of any internal reinforcement crossing potential slip surfaces. Many of the 2D methods are denominated "limit equilibrium" methods. In these methods, the factor of safety is calculated using one or more of the equations of static equilibrium applied to the soil mass margined by an assumed, potential slip surface and the surface of the slope (as it is done for the Infinite Slope Stability Case). These methods require that a potential slip surface be assumed in order to calculate the factor of safety. Calculations are repeated for a sufficient number of trial slip surfaces to ensure that the minimum factor of safety has been calculated. For computational simplicity the candidate slip surface is often assumed to be circular or composed of a few straight lines. The limit equilibrium methods (Ordinary Method of Slices (OMS), Simplified Bishop, Spencer) address static equilibrium by dividing the soil mass above the assumed slip surface into a finite number of vertical slices.

1.2 Runout

1.2.1 Empirical approaches (L_R, S_R)

The empirical approaches are developed by reference to actual landslide data and include the angle of reach method and the volume change method.

The angle of reach method (Corominas, 1996) establishes a relationship between the angle of reach and other indexes expressing the mobility of landslides and vertical drop, horizontal reach and volume of landslide mass by means of simplified plots and regression equations. Predicted by this approach, whatever the mechanism of motion, all kinds of landslides experience a continuous reduction of the angle of reach with volume increase. The angle of reach is found independent of the vertical drop.

The volume-change method (Cannon, 1993; Fannin and Wise, 2001) estimates the potential travel distance of debris flows by establishing an averaged volumechange formula through dividing the volumes of mobilized materials of landslide by the lengths of the debris trail. The initial mobilized volume is progressively reduced during downslope flows until movement stops where the volume of actively flowing debris becomes negligible. This approach is sensitive to the initial mobilized volume and traveling path geometry.

1.2.2 Dynamic modeling (L_R, S_R)

Generally speaking, regardless of the rheological scheme used, it is possible to obtain a set of differential equations that is valid for debris flows by depth integration of the mass and momentum conservation equations. These mathematical models are nowadays frequently applied to various real cases of debris flows, however, the scientific literature on the limits of the numerical, physical and mathematical assumptions of these models is rather sparse. The mathematical models suitable to describe the propagation and the stopping of the flow differ in the structure of the equations, in the closure relationship linked to the rheology of the flow and to the nature of the bed shear stresses (lverson, 1997; Hungr, 1995; Brufau et al., 2000).

If an appropriate rheological model is selected, the required rheological parameters are determined either through laboratory experiments or via back-analysis of field observations, geological investigations and weather conditions. The flexibility of easy association with versatile rheological formulas makes the continuum models attractive in reproducing the runout process and in predicting some of the key kinematic parameters during motion. The continuum models are hence more sophisticated and they provide more information required for landslide hazard assessment.

Approach	Methods/Models	Merits	Limitations	References	Table 18: Emp ches available runout model
Empirical	Mass Change	Evaluates the influence of slope, vegetation types and channel morphology by multivariate regression analysis	Does not explicitly account for the mechanics of the processes involved	Corominas, 1996 Cannon, 1993 Fannin and Bowman, 2008;	
	Angle of reach	Derives a linear relationship between factors influencing the angle of reach and the volume of materials.	The method affords only a preliminary quantification of the travel distance		

ical approaor landslide

1.3 Hazard

The definition of landslide hazard incorporates the concepts of location, time and size: Hazard assessment requires the quantitative prediction where a landslide will occur, when or how often it will occur, and how large the landslide will be.

The probability function for landslide size may be estimated from the analysis of the frequency–area distribution of known landslides, obtained from landslide inventory maps.

The temporal probability of slope failures may be based on the availability of a

multi-temporal landslide inventory map, which are analyzed to estimate the frequency of landslide occurrence in each mapping unit. To obtain an estimate of the frequency of landslide occurrence the number of landslides in each mapping unit can be used. For each mapping unit landslide recurrence can be obtained by past landslide occurrence.

Finally, the quantitative estimate of the probability of spatial landslide occurrence may be obtained by using the approaches reported above.

PART C : ANNEX3 - 2 METHODOLOGY REGARDING ROCKFALL HAZARD MAPPING

2.1 Rockfall onset susceptibility

In this section it is assumed that rockfall detachment zones (i.e. rockfall sources) have already been identified by suitable approaches (i.e. morphometric, geomorphological, geomechanical parameters). Necessary data acquisition is reported in chapter 4. Once rockfall sources have been identified, they can be ranked according to their onset susceptibility (i.e. propensity to fail) or not (method R_O1).

If required, susceptibility ranking of rockfall sources can be performed according to heuristic, statistical, or rock-slope stability analysis methodologies.

2.1.1 Heuristic or statistical susceptibility ranking (R_O2, L_O1, S_O1)

Heuristic ranking can be performed using many different approaches. Three main families of methods are available:

- direct methods
- indirect heuristic methods
- indirect statistical methods

2.1.1.1 Direct methods

Direct methods consist in subjective assessment of onset susceptibility based on expert- knowledge. This approach requires a direct experience of the study area, and is usually suitable for site-specific to local scale analysis.

2.1.1.2 Indirect heuristic methods

Indirect heuristic methods are based on the definition of functional relationships between geo-environmental controlling parameters and onset susceptibility. The most simple approach (e.g. for L_O1) is based on the use of available topographical, geological, land-use and infrastructure maps (e.g., Baillifard et al, 2003). Being these maps normally available also at regional scale, this approach is well suitable for regional scale analysis.





0.5

based on a combination of slope gradient, geomorphological interpretation and historical source areas mapped from Comunità Montana del Gemonese (1977) Figures 1: Example of local scale onset susceptibility ranking (ref: L_O1) with a simple heuristic approach for the Venzone-Carnia study area (Friuli Venezia giulia). More advanced heuristic methods (e.g. for S_O1) make use of geomechanical data for the definition of onset susceptibility. A possible approach is the RHAP method (Mazzoccola and Sciesa, 2000) presented within the Falaise Interreg Project (Figures 1 to 2). For characterization of the onset susceptibility, the first step consists in the identification of homogeneous sectors of the rocky cliff, according to rock mass properties and slope morphology along the runout zone. The identification is performed through field surveys, with the help of appropriate check lists.

The rocky cliff is successively analyzed through a geomechanical survey in order to attribute a different onset susceptibility to each homogeneous area. First, the cliff is divided into a regular squared grid. For each grid element, the number of unstable elements is assessed, and a relative susceptibility index is calculated as the number of unstable elements normalized by the maximum number, assumed to be 5. Then, the onset susceptibility for each homogeneous area is calculated as the mean susceptibility of all the included squared elements.

Figures 2: Example of site-specific scale onset susceptibility ranking (ref: S_O1) with RHAP approach for a sub-area of Timau study area (Friuli Venezia Giulia).



2.1.1.3 Indirect statistical methods

The functional relationships between geo-environmental controlling parameters and onset susceptibility can be defined using bivariate or multivariate statistical approaches. An example has been presented in Frattini et al. (2008) for a regional scale analysis. The approach is based on the use of discriminant analysis to classify the activity of rocky cliffs based on several geo-environmental parameters (lithology, density of lineaments, slope gradient, slope aspect, slope curvature, etc.).

2.1.2 Stability analysis (L_O2, S_O2)

Rock-slope stability analysis allows either to estimate a kinematic feasibility of specified block failure modes (Hoek and Bray, 1981) or to compute the Factor of Safety of blocks subjected to specific sets of driving and resisting forces. For rock-

fall susceptibility assessment purposes, this allows to discriminate sectors of a rocky cliff that are kinematically more suitable to fail, or more close to critical (limit-equilibrium) conditions, and classify their "susceptibility" accordingly. Two main families of stability analysis can be distinguished and considered suitable:

- kinematic analysis;
- limit-equilibrium analysis. •

Figures 3: Example of site-specific scale onset susceptibility ranking

(ref: S_O2) with spatially-distributed kinematic stability analysis of plane, wedge and toppling failure of rock blocks, for a sub-area of Villa Santina study area (Friuli Venezia Giulia).

2.1.2.1 Kinematic analysis

Distributed kinematic analysis of rock block stability (Guenther, 2003; Guenther et al., 2004) includes several methods to check the kinematic feasibility for planar, wedge, and toppling failure of rock blocks bounded by discontinuities of known orientations. Methods combining all measured discontinuity orientations (Matheson, 1983) or the modal orientation values for different sets (to be characterised by preliminary stereographic analysis) exist. The methods assume planar and persistent discontinuities, pure frictional shear strength, and generally provide conservative results. Given a number of feasible failure mechanisms, a rockfall onset susceptibility can be assessed depending on the total number of possible failure modes for each slope unit, or the ratio between the number of feasible failure modes and the total theoretical failure modes.



based on spatially-distributed kinematic analysis (SlopeMap; Guenther, 2003)

Susceptibility represents the ratio of the number of feasible failure mechanisms on all theoretically possible mechanisms







Input Data for modelling (in GIS):

- Slope geometry: slope and aspect maps from DEM (resolution important)
- Parameters: orientation and estimated friction angle of discontinuities

Model Outputs:

• maps of kinematic feasibility for different failure modes

Advantages:

- easy spatially distributed implementation in GIS
- easy zonation of "susceptibility"

Disadvantages:

- possibly too conservative
- no account for forces, no sound evaluation of Factor of Safety

2.1.2.2 Limit-equilibrium analysis

Limit-equilibrium analysis (LEA) can be performed for specific types of instability, geometry and boundary conditions. LEA can be carried out with a deterministic or probabilistic approach to include uncertainties and parameter variability. As a consequence, a probability (susceptibility) of failure can be estimated.

Figures 4: Example of limit equilibrium analysis scheme for the planar failure of a block of pre-defined geometry subjected to a set of driving and resisting forces. Analysis can be performed using a probabilistic approach aimed at estimating a probability of failure.

A temporal prediction could be associated to a specific scenario if the recurrence time for a specific triggering event could be included (e.g. earthquake magnitude, rainfall resulting in a specific groundwater level or saturation condition, etc.)



Input Data for modelling:

- Slope geometry: slope and aspect maps from DEM (resolution important)
- Block size and geometry
- Driving and resisting forces magnitude and orientation

Model Outputs:

Factor of Safety (deterministic), Probability of Failure (probabilistic)

Advantages:

 More sound assessment of slope stability, probabilistic analysis of susceptibility

Disadvantages:

 Difficult spatially-distributed implementation, lumped use in site-specific situation

2.2 Rockfall Runout modelling

Currently, a large variety of models for calculating runout zones of rockfall events exist. All existing rockfall models may be categorized in two main groups: empirical models and process- based models (Dorren 2003).

Empirical models are based on simplified assumptions in rockfall scenarios and generally consist on data acquired in a study area which are analysed by statistical methods. Process-based models describe or simulate the physical processes of motion of falling rocks over slope surfaces.

2.2.1 Empirical methods (R_01)

For the determination of rockfall runout zones on a regional scale, several empirical measures have been suggested (Domaas, 1994, Keylock and Domaas (1999). The most widely adopted method for analysing the travel distance of rockfalls are based on geometrical approaches: the angle of the shortest line between the top of the rockfall source scar and the stopping point of the landslide ("Fahrböschung" Heim, 1932; reach angle, Corominas, 1996; geometrical slope angle, Meissl, 1998) and the minimum of the line between the talus apex and the stopping point of the landslide (Lied, 1977; minimum shadow angle, Evans and Hungr, 1993) (Fig. XX)



Empirical methods can be applied in practice using several approaches:

- analysis along selected profiles for which the maximum runout distance is calculated using *α* or *β* angle, and then manual interpolation of results along ptofiles in order to define a rockfall runout zone.
- application of a GIS-based models to define the shadow area between the source zone (or talus apex) and the *α* (or *β*) angle (CONEFALL, Jaboyedoff and Labiouse, 2003).

Figures 5: Sketch of the characteristic rokfall path profile. Geometrical slope angle- α ; shadow angle - β (modified after Meißl 1998).

2.2.1.1 **a** angle (reach angle, geometrical slope angle)

The angle of the shortest line between the top of the rockfall source scar and the stopping point is based on the "energy line" approach (Heim, 1932).



Figures 6: Geometrical sketch for energy-line approach (Heim, 1932).

From the geometric relationship between a point on the cliff C with coordinates (x0, y0, z0) and a random subjacent (z <z0) point P with coordinates (x, y, z) gives the following mathematical relationship (Jaboyedoff, 2003):

$$0 > (x - x_0)^2 + (y - y_0)^2 - \tan\left(\frac{\pi}{2} - \varphi_p\right)^2 * ([z - z_0)]^2$$

Several values have been reported in the literature: 28.5° (Onofri e Candian, 1979); 32° (Toppe, 1987); 37° (Meißl, 1998); 33° (Heinimann et al. 1998); 36.9° (Copons et al., 2009); 34°-40° (Melzner, 2009).

These values can be very different according to the cliff height, the use of actual versus straigth-line path, the percentage of blocks enveloped within a certain angle. Hence, the applicability of the reach angle approach is limited by these problems, and values need to be calibrated for each single case-study.

Input Data for modelling:

- Slope geometry: DEM (resolution not very important)
- Source areas: points, lines or polygons
- Parameters: angle *a*, (optional) cone aperture with respect to slope direction

Model Outputs:

- maximum runout distance and/or zone,
- (optional) count of source cells potentially contributing to rock fall, velocity calculated with the energy-line approach.

2.2.1.2 $\boldsymbol{\beta}$ angle (minimum shadow angle)

The minimum shadow angle is based on the idea that travel distnace is controlled by the propagation along the talus, because the kinetic energy acquired during fall from the cliff is largely lost at the first impact with the talus (Hungr and Evans, 2003). The advantage of the minimum shadow angle is that it is less sensitive to

Input Data for modelling:

- Slope geometry: DEM (resolution not very important)
- Talus apex: points, lines or polygons
- Parameters: angle $\boldsymbol{\beta}$, (optional) cone aperture with respect to slope direction

Model Outputs:

- maximum runout distance and/or zone,
- (optional) count of source cells potentially contributing to rock fall.

Advantages:

- low sensitivity to DTM resolution,
- easy implementation over large areas,
- easy zonation of "susceptibility"

Disadvantages:

- angles need calibration site by site, especially in relation to the cliff height,
- impossibility to assign an onset susceptibility to each cell

cliff height. However, values reported in the literature are significantly different also for this angle: 28-30° (Lied, 1977); 17° (Domaas, 1994); 31.5° (Meißl, 1998); 22° (Wieczorek et al., 1998); 24°-27.5 (Evans and Hungr, 1993); 25.5° (Copons and Villaplana, 2008), 21° (Holm and Jakob, 2009).

Advantages:

- low sensitivity to DTM resolution,
- easy implementation over large areas,
- easy zonation of "susceptibility"

Disadvantages:

• impossibility to assign an onset susceptibility to each cell

2.2.2 2D modelling

2D models simulate the motion (fall, rebound and rolling) of blocks along a profile (Bozzolo and Pamini, 1986; Pfeiffer and Bowen, 1989; Stevens, 1998; Jones et al, 2000). When analysing large areas, it is necessary to identify a number of "representative" profiles and to perform a simulation for each profile. The results can be

Input Data for modelling:

- Slope geometry: Cross sections along most probable paths
- Slope materials: Restitution coefficients for impact and friction coefficients for rolling. Possibility to introduce a stochastic variation of parameters

Model Outputs:

2D Trajectories, velocity profiles, distribution of arrest points

spatially distributed by expert-knowledge geomorphological interpretation or by interpolation of output data about energy or about the frequency of block arrested along the slope.

Advantages:

- easy implementation with slope profiles,
- easy visualization of trajectory impacts and bounces,

Disadvantages:

- not possible to account for 3D effects,
- difficulty to interpolate among different profiles
- subjectivity in the choice of profile position, spacing and geometry





2.2.3 3D modelling

3D models are able to simulate block motion along a slope by including lateral dispersion of trajectories due to morphological complexity (Descoeudres and Zimmermann, 1987: Guzzetti et al., 2002; Agliardi and Crosta, 2003; Crosta et al., 2004; Dorren et al., 2006; Lan et al., 2007) The results are distributed over the entire study area, without need for interpolation of data.

Input Data for modelling:

- Slope geometry: DEM (resolution very important)
- Source areas: raster theme with location of source cells
- Parameters: restitution coefficients, rolling friction coefficient, block mass, volume and shape, other parameters for complex phenomena

Model Outputs:

 3D trajectories, statistics for each cell (e.g. for number of transits, velocity, height, energy) 3D modelling requires a complete spatial coverage of data are more complex and difficult to handle. The reliability of these models depends on the quality of the algorithms used for the simulation of physical processes, the introduced assumptions, etc.

Advantages:

- simulation of 3D effects,
- possibility to implement a quantitative hazard assessment,
- easy zonation of "hazard",
- possibility to simulate complex phenomena

Disadvantages:

- strong sensitivity to DEM resolution,
- need for calibration of parameters that are frequently unknown,
- need for robust and meaningful algorithms
- assumptions depending on adopted algorithms
- more difficult calibration, data analysis/visualization



Figures 8: Example of local scale 3D modelling (ref: L_R) for the Timau stduy area (Friuli Venezia Giulia).

2.3 Susceptibility zoning

2.3.1 Max runout, classified runout (R_S1, R_S2)

The simplest form of rockfall susceptibility zoning involves mapping the largest area potentially affected by rockfall runout trajectories. In this case, no further zonation is provided with respect to the reach probability in different parts of the runout area, and nothing is said about the spatial distribution of intensity (i.e. velocity, kinetic energy, height). A further step towards a more sound susceptibility assessment would require the runout area according to the probability that a given distance from the source (or, more general, a given point on the slope) is reached by rockfall trajectories. This can be best accomplished by the used of 2D and 3D modelling tools, as better explained in the following two sections.

Nevertheless, a simple evaluation of rockfall runout (without further zoning) could be considered useful only as a "minimum requirement" approach for regional scale studies, where 2D modelling is not feasible and 3D modelling could be too time consuming for the aims of a simple analysis for rockfall reconnaissance / prioritization. In these simple cases, a first estimation of rockfall runout can be made using the shadow angle approach, with or without a simple zoning based on the number of "shadow cones" (each emanating from a source cell) contributing to each location in the runout area (Jaboyedoff and Labiouse, 2003).

2.3.2 Onset susceptibility + reach probability (L_S)

In 2D modeling, a typical approach to susceptibility assessment to classify the runout and to define a reach probability is the analysis of the percentage of blocks passing through a certain distance. This approach allows to trace a line of equal probability of transit and arrest by interpolation or subjective extension of 2D modelling results between adjoining analysis sections. The most important limitation is that a 2D model cannot account for lateral deviation of trajectories, thus overestimating the frequency of blocks which pass through each slope unit. Using 3D models, according to a conceptually similar approach it is possible to define a transit frequency for each slope unit accounting for longitudinal and lateral separation of block trajectories. Normally, the frequency analysis is performed by simulating a large number of blocks starting from each source area, and introducing uncertainty of parameters (block volume, restitution coefficients, rolling friction coefficients, etc.) through a stochastic approach. Runout distance can change as a function of some assumptions (eg. maximum local slope control on the trajectory).

An example of this approach is given by the RHAP methodology (Mazzoccola and Sciesa, 2000).

Conceived for use with 2D modelling, applies to rockfalls ranging from single blocks to rock masses up to 1000 m3 in volume, and it is suitable for local scale studies. The method allows to rank the susceptibility level with respect to a specific site. For this reason, susceptibility ranking from different sites are not comparable in absolute value. The methodology allows to combine an heuristic susceptibility zonation with a 2D runout analysis. From each source zone characterized by a different susceptibility value, one or more representative trajectories are used to perform 2D rockfall stochastic simulation in order to perform a preliminary longitudinal zonation of rockfall arrests along the slope. The simulations are performed considering modal block volumes and shape, and calibrating restitution coefficients using historical data and extent of scree slope deposits. From the percentage of block passing through a certain distance, the slope is zoned in 4 zones with different preliminary susceptibility levels: 4 (75% of the blocks), 3 (90%), 2 (100%), 1 (extent of exceptional blocks). The preliminary (transit) susceptibility classification is modified based on the onset susceptibility in a simple manner. Onset susceptibility is reclassified into three classes of activity: low, medium, high. This classification is then used to modify the preliminary susceptibility map by incrementing (high onset activity) or decrementing (low onset activity) the hazard level of one class.

2.3.3 Onset susceptibility+reach probability+runout intensity (L_S)

Using 2D or 3D models allows to calculate a reach or transit frequency for each slope unit (usually a pixel) accounting for longitudinal and lateral separation of block trajectories, as well as a set of intensity descriptors of rockfall phenomena (e.g. velocity, kinetic energy, height). Normally, the analysis is performed by simulating a large number of blocks starting from each source area, and introducing uncertainty of parameters (block volume, restitution coefficients, rolling friction coefficients, etc.) through a stochastic approach. A conceptually similar approach (i.e, combining reach probability and intensity) has been implemented with 2D modelling by Jaboyedoff et al. (2005) in order to allow susceptibility assessment according to the Swiss Guidelines.

In the RHV approach (Crosta and Agliardi, 2003), rockfall susceptibility/hazard at a given location on a rockfall-prone slope is assumed to be a function of rockfall reach probability (transit frequency), block kinetic energy and trajectory height. The

approach thus assesses susceptibility/hazard by taking into account both rockfall frequency and intensity. The required parameters can be computed for each slope unit by performing 3D numerical modelling at suitable level of detail (depending on the analysis scale). The methodology follows these steps:

- identification of potential rockfall sources and characterisation of their onset susceptibility;
- rockfall runout modelling by using a 3D numerical modelling tool;
- for each model cell (i.e. slope unit), extraction and reclassification of the simulated: a) frequency of reach (c), b) height (h), and kinetic energy (k) of blocks/trajectories;
- calculation of the modulus of the "rockfall hazard vector" (RHV) defined as:

 $|RHV| = \sqrt{c^2 + e_c^2 + h^2}$

Figures 9: Main assumptions and parameter definitions of the RHV rockfall susceptibility assessment methodology (after Crosta and Agliardi, 2003).



cla	ss c (nor	malised)	k	h
-	regional scal	le local scale	(kJ)	(m)
1	< 0.2	< 0.01	≤ 700	≤ 4
2	0.2 - 1	0.01 - 0.1	700 - 2500	4 - 10
3	> 1	> 0.1	≥ 2500	≥ 10

Figures 10: Parameter reclassification scheme used in the RHV rockfall susceptibility assessment methodology (after Crosta and Agliardi, 2003).



Figures 11: Example of Local scale rockfall susceptibility with RHV approach (ref: L_S) for Villa Santina study area (Friuli Venezia Giulia).
2.4 Susceptibility zoning

2.4.1 Expected frequency associated to a reference scenario

The most simple and simplistic approach for the assessment of temporal probability is to assign an expected frequency to a scenario which is considered the most "representative" for the study area. This is a strong simplification, since it is well known that frequency depends on the volume of rockfall.

The expected frequency can be defined using both heuristic and statistical approaches.

2.4.1.1 Heuristic approach (L-H1, L-H2, S_H1)

The heuristic assessment of probability is performed through a subjective estimation of event frequency based on:

- expert knowledge regarding the geological setting;
- frequency of past events;
- similarity with other areas where data are available.

An example of heuristic temporal probability is the approach used in BUWAL (Bundesamt für Umwelt, Wald und Landschaft, 1998) methodology. This methodology accounts for frequency and intensity, thus allowing to perform, although in a simplified manner, a real hazard assessment. BUWAL methodology firstly requires the identification of areas potentially impacted by an expected rockfall scenario. Normally, only a single scenario is considered, this being the most "representative" scenario. For this scenario, the intensity is estimated in terms of both expected volume and velocity, using tables that allows to assign classes of intensity based on ranges of values for these two parameters. Regarding the velocity, rockfall always belongs to class 3 according to the BUWAL classification.

For the same scenario, the frequency of the "representative" events is estimated using four classes or recurrence time, Tr: high (Tr < 30 years), medium (30 < Tr < 100 yr), low (100 < Tr < 300 yr), very low (Tr > 300 yr). Table xxx provides a link between the activity of landslides and the expected recurrence time. The width of the frequency intervals allows to incorporate the uncertainty in the estimation.

Frequency class	Recurrence time: T _r (yr)	Landslide activity
1	< 30	active landslides and dormant landslides with high frequency reactivations
2	30 - 100	dormant landslides with medium frequency reactivations
3	100 - 300	dormant landslides with low frequency reactivations
4	> 300	relict landslides

Table 19: definition of frequency classes in BUWAL methodology.

Advantages:

- the method is simple
- the method allows to assign different frequencies to different sectors of the study area

Disadvantages:

- the method is subjective
- given the uncertainty, frequency is roughly estimated for classes of recurrence times defined using large range of values.

Applicability:

the method requires a direct experience of the expert with regard to a rockfall problems at a specific location. Hence, the approach is suitable for local scale analysis. When applied to regional scale studies the estimation becomes very uncertain and arbitrary.

2.4.1.2 Statistics of historical data (L_H2)

A statistical approach is based on the analysis of historical events aimed at identifying an average recurrence time of events, independently from the volume of possible rockfalls. Since the number of events usually available is limited, the statistics need to be calculated using data for large regions, assuming that the frequency is equal for the entire area.

Advantages:

- the method is data driven and objective
- the method is simple

Disadvantages:

- rockfall events are rarely collected for small volumes and for events occurring in rural areas without damages to infrastructures; hence, the average frequency is normally underestimated.
- Frequency is assumed constant over large areas

Applicability:

the method is suitable for large areas, where the number of events is sufficient to estimate a reliable (although underestimated) recurrence time.

2.4.2 Magnitude-frequency relationships (S-H2)

In order to obtain a fully quantitative evaluation of the hazard related to rockfall occurrence, the annual frequency of rockfall events should be estimated with reference to specific event magnitudes (i.e. volumes) classes, as for flood or earthquake events. This requires knowing or assuming the relationship which describes the magnitude-frequency distribution of rockfall events in a given area characterised by specific geological and geomorphological features. For rockfalls, several authors (Hungr et al., 1999; Dussauge et al., 2003; Malamud et al., 2004) demonstrated that the magnitude-cumulative frequency (MCF) distribution of events in given volume classes j can be described by a power law in the form:

 $\log N(V) = NO + b \log V$

where N(V) is the cumulative annual frequency of rockfall events exceeding a given volume, No is the total annual number of rockfall events, and b is the power law exponent.

The annual frequency of rockfall events in a given volume class can be derived from MCF curves by subtracting the cumulative frequencies for each considered volume class (Hungr et al., 1999). The parameters of MCF curves themselves have no universal significance, although the exponent b has been found to vary in a quite narrow range, i.e. -0.7 < b < -0.4 (Hungr et al., 1999; Dussauge et al., 2003), and should be based on complete local rockfall inventories.

Unfortunately, historical databases and inventories of landslide events (i.e. the preferred source of M-F information) are rarely available, and site-specific data collection may be unfeasible for large areas or when budget constraints exits. Mo-reover, landslide size values reported in historical databases may be incomplete or estimated at the order-of-magnitude level of accuracy (Hungr et al., 1999). Data may be incomplete both in space (i.e. data sampling only in specific sub-areas) and

in time (i.e. data recorded only for specific time windows), due to undersampling and censoring effects.

When available, magnitude-frequency relationships would provide a means to estimate the return period of landslide events exceeding a given magnitude, T(V)=1 / N(V), and then the probability of a specified number of events to occur in a given reference time, thus allowing a full probabilistic evaluation of landslide onset hazard.



Figures 12: Example of MCF (magnitude-cumulative frequency) curve for rockfalls (Hungr et al., 1999).

2.4.3 Combining frequency with susceptibility

When attempting to assess rockfall "hazard" (including the expected frequency of events) at different levels (see previous sub-sections), the frequency of event onset must be integrated with the onset and runout susceptibility in order to obtain hazard maps accounting for all these components.

Possible approaches (at different levels of complexity) to do this could include:

- producing "scenario-based susceptibility maps" by modelling rockfalls involving block volumes corresponding to specified return periods (either single "design volume" if only a heuristic or statistical hazard assessment is possible, different maps for different volumes if a M-F curve is available);
- 2. adapting RHAP-type and RHV-type approaches by scaling the probability of reach at any point of the slope with the onset probability corresponding to specified return periods (by multiplication);
- 3. modifying the "modified BUWAL approach" often used by administrations and basin authorities in Italy in order to incorporate (as matrix input data) the event frequency (estimated by heuristic, statistical and M-F approaches) and the intensity (kinetic energy) obtained by numerical modelling with volumes consistent with onset frequency. In this case, the separate use of "modified BUWAL" Tables 1 (velocity) and 2 (size) would be not necessary, and kinetic energy could be directly used. This approach could also allow using the method for each slope unit, accounting for the variability of rockfall intensity along the slope.

ROCKFALL STRUCTURAL COUNTERMEASURE SURVEY FORM

A) GENERAL DAT	A										
Province	Municipality			ID	Existing in	ventory (Y / N)		Survevor		Date	
				I I	Ū		L		I		
Survey map scale			Т	opographic map] [Photo ID		
2	I							J I	I		
	Location on the slope (1)		NOTE					1			
	Type of countermeasure (2)		NOTE					KEYS	TO ATTRIBUTES		
	Minimum elevation (m. a.s.l.)	1									
	Maximum elevation (m. a.s.l.)										
	Map topology	Point		Line	Polygon			(1)	1: Rocky cliff (NOTE: specify approxi	mate haight	from base)
	I						1		2: Chute / channel (NOTE: specify wi	dth / cross-s	section area / slope estimates)
B) SOURCE AREA	A] [3: Talus (NOTE: specify grain size / sl	lope / veget	ation estimates)
								-	4: Talus base (NOTE: specify approxi	imate local s	slope and distance from base)
	Type of source (3)		NOTE] [5: Valley floor		
	Maximum extent (m, m2)		NOTE					1 '			
	Evidence of activity (Y / N)	DES	SCRIPTION					(2)	1: Rigid barrier (wooden beams or ste	el girders)	
									2: Flexible barrier - low capacity (<50	0 kJ; no up	slope ropes / brakes)
									3: Flexible barrier - medium capacity	(500-3000 k	kJ; upslope ropes / brakes)
								-	4: Flexible barrier - high capacity (>30	000 kJ; add	itional ropes / brakes)
C) COUNTERMEA	SURE DATA SHEET							1	5: Gabion wall (NOTE: specify size a	and number	of modules)
								-	6: Reinforced concrete wall (NOTE: s	specify spe	ssore indicativo e particolari)
	Materials (4)		NOTE] [7: Ditch (excavated)		
	State of efficiency (5)		NOTE		Efficacy (5)			1	8: Embankment (fill)		
	Description of damages			1					9: Draped steel wire mesh (double-twis	sted hezago	nal mesh)
								1	10: Reinforced draped steel wire mesh	n (armed by	/ steel cables)
DIMENSIONS	Length (m)		Г	ELEMENTS AT RISK (6)		QUANTITY			11: Draped wire panels / plates (reinfo	rces square	e mesh)
	Average base width (m)		L					1	12: Rock bolts / anchors (NOTE: spec	cify type)	
F	Average top width (m)							"			
F	Minimum heigth/depth (m)							(3)	1: Very fractured/disrupted rocky cliff	F	
F	Average heigth/depth (m)								2: Rocky cliff		
F	Maximum heigth/depth (m)							1	3: Discontinuous outcrops		
F	Area (m2)								4: Unstable scree (secondary rockfall	s)	
	÷			E			L	1	5: Rockslide scarp/accumulation		
								-	6: Other (specify)		
D) ADDITIONAL N	IOTES AND SKETCHES] .			
								(4)	1: Wooden	(5) 1:	: Poor/bad
									2: Steel	2:	: Fair
									3: Earth fill	3:	: Very good
									4: Reinforced earth fill		
									5: Reinforced concrete		
								(6)	1: Housing buildings (NOTE: specify	number, siz	ze, #stories)
									2: Industrial buildings (NOTE: specify	/ number, si	ze)
									3: Public interest buildings (e.g. school	ol, hospital)	
									4: Road (NOTE: specify type, span len	gth, width)	
									5: Railway (NOTE: specify type, span I	length, num	ber of tracks)
									6: Lifelines (NOTE: specify type)		
									7: Other (specify)		



PART C : ANNEX4 - DATA COLLECTION

1.1 Data collection for landslides

REGIONAL EXTENT analysis scale 1:10.000 - 1:50.000

GRID ≤ 30m

Data	Direct information	Data collection and analysis	Required accuracy	Output
DTM-AL		slope angle		slope angle map
	topography	slope aspect	grid ≤30m	slope aspect map
		slope profile		
Cooloriool mon		lithologies		geological map
Geological map				lithological map
Landslida data		historical landslides		data sheet or map of historical landslide
				landslide inventory map
Topographic map, orthophotos		land use - vegetation - massmove events - verification		
Land use		land use		landuse map

Data	Direct information	Data collection and analysis	Required accuracy	Output
		slope angle		slope angle map
DTM-AL	topography	slope aspect	grid≤ 5m	slope aspect map
		slope profile		
				geological map
Geological map		lithologies	survey scale = analysis scale	lithological map (define geotechnical lithotype units)
Tectonic map		structural elements		tectonic map (in geological map)
Landslide data		historical landslide	data availability	landslide inventory map
	land use	land use – soil type – vegetation	from laserscan and digital camera accuracy	orthophoto map
Orthophoto	soil type vegetation			.landuse map
Observation points		landslide source area (scarp)	for homeogenious	parameters from engineering geological mapping
		landslide deposition area	area	
Land use		land use	survey scale = analysis scale	landuse map

Data	Direct information	Data collection and analysis	Required accuracy	Output
		slope angle		slope angle map (>50°, >60°, >70°)
DTM-AL	topography	slope aspect	grid ≤ 2m	slope aspect map
		slope profile		
				geological map
Geological map		litologies	survey scale =	lithological map (breakdown in geotechnical litho type)
Tectonic map		structural elements	analysis scale	tectonic map (in geological map)
Geomorphologic		active processes and form		geomorphologic map
map				
Landslide data		historical landslide	data availability	landslide inventory map
	land use		from laserscan accuracy	orthophoto map
Orthophotos	soil type vegetation	land use – soil type – vegetation		
Observation points		landslide source area (scarp)	as many as	parameters from engineering geological mapping
		landslide deposition area	hossing	
Land use		land use	survey scale = analysis scale	landuse map

It should be noted that the landslide inventory is often the basis for all the landslide susceptibility zoning, and it is important that this activity is done thoroughly. For precipitation-induced shallow landslides the data will usually need to cover 10, 20 or more years so a number of significant rainfall events can be sampled in the inventory (this is particularly important if the inventory is to be used as the basis for frequency assessment) (Frattini et al., 2010). In many cases it will not be possible to create a good inventory from past records, so the inventory has limitations. These can be overcome with time if responsible authorities establish a system for gathering data which can then be incorporated in later zoning studies.

Historical data or record of temporal distribution of landslides and triggering rainfall should also be added to the inventory. Landslide inventories should include information on where and when the landslides occurred, the type, size and the regional extent of the landslides as well as information on triggering conditions usable to test results from deterministic models. Triggering conditions are not easily determined from aerial photographs and their definition requires nearby measurement of rainfall and observations of soil moisture conditions. For testing deterministic shallow landslide initiation model landslide sources, tracks and deposits should be mapped separately.

Techniques that are applicable for developing landslide inventories include: i) field observations; ii) aerial photo interpretation; iii) analysis of high resolution optical and infrared imagery (Ikonos, Quickbird, IRS CartoSat-1), satellite-based interferometric SAR (InSAR, and DInSAR of Radarsat, ERS, Envisat, TerraSAR-X, CO-Smo/SkyMed, ALOS); iv) use of airborneLIDAR. These techniques are examined in the following sections.

1.1.1 Field mapping

Field mapping involves conventional surveying methods or by using mobile GIS and GPS for the collection of landslide attributes. Field mapping has been applied also together with photo-interpretation to determine landslide distribution and classification relatively to age, degree of activity and typology (Carrara et al. 1999). Field-based approach is extraordinarily time intensive, required more labour. Inventory map updating is connected with difficulties, especially in forested area. It is very precise to pointing out smaller landslide features and recent active slides.

1.1.2 Aerial photograph interpretation

Aerial photograph interpretation (API) still remains the most applicable technique for landslide mapping (Metternicht et al., 2005). Interpretation of single - and multicolored aerial photos is used intensively for the mapping and monitoring of landslide characteristics (e.g. distribution and classification) and factors (e.g. slope, lithology, geostructure, landuse/land cover, rock anomalies). In some cases landslide features are often hidden or obscured by tree cover on aerial photographs. This means a limited usability of this technique. A combined approach of visual interpretation using aerial photos together with field based observation is recognized as labour-intensive and time-consuming. Nichol et al., (2006) reported that for a complete stereo cover of an area of 1000 km2 approximately 400 photo prints at a scale of 1:10,000 were needed. Furthermore previous research regarding the usability of aerial photos in complex environment did not show reliable results for landslide identification. Brardinoni et al. (2003) reported that 85% of the Vancouver landslides which were mapped in the field and were located in densely forested regions could not be recognized on aerial photographs.

1.1.3 Satellite and radar-based imagery

Satellite imagery has been used intensively for the landslide inventory mapping. Using optical imagery system recognition of a landslide can be carried out by considering the size of the features, the contrast between landslides and surrounding areas and the morphological expression. Optical imagery has also demonstrated the difficulty for mapping landslides in heavily forested terrain. Issues of detecting landslides in multi-temporal satellite imagery have still not been overcome due to persistent cloud and forest cover.

Radar technique can be performed either by airborne or satellite-based. Platforms in space are particularly diverse because of the large areas that can be captured within a short span of time. Recently Interferometric Synthetic Aperture Radar (InSAR) has become a preferable technique for landslide mapping and many studies have been conducted in order to produce a suitable method which can delineate landslide features. However there are some difficulties of InSAR, especially related to geometric noise due to the difference in satellite look angles, the vegetation affect on the signal and the atmospheric factors (Catani et al., 2005). InSAR shows to be unsuitable for landslide mapping in forested terrain due to the dense vegetation effect which causes decorrelation (Rott, 2004) and the movement velocities are too high.

1.1.4 LIDAR techniques

Laser-based technology is capable of delivering very dense and accurate point clouds of a landscape in a relatively short time. Thus all the data are inherently in three-dimensional and completely digital models (Kerle et al., 2008). Semi-au-thomatic methodologies are available to detect and interpret individual objects in landscapes including landslides (Tarolli et al., 2010). Many tasks of LIDAR pre-processing are required to achieve of the required data quality for landslide iden-tification. Bare earth extraction (i.e. the process of identifying landscape surface without the objects such as buildings, trees and others) is one of them. This process is important, because the extracted data has a direct impact on the quality of the inventories. Currently available filtering algorithms which are embedded in a number of commercial software produce reliable terrain models and preserve important landslide features (e.g. main scarps that occur on steep slopes) (Tarolli et al., 2010).

1.2 Topography

A range of methods for estimation of shallow landslide susceptibility and hazard requires availability of a medium to high resolution digital elevation model (DEM). Other digital data structures exist to represent topography (e.g. Triangular Irregular Networks — TINs), however we restrict our discussion here to DEMs because of their wide availability and use. The accuracy of the DEM is a function of the accuracy and spacing of the original source data and the accuracy of the interpolation of those data to a regularly-spaced grid.

DEMs are generated from a variety of original topographic data sources including photogrammetrically generated contour maps, ground-based surveys and remote sensing data. At this time, DEMs interpolated from topographic contour data are probably most commonly used for landslide hazard mapping mainly because large scale topographic maps are widely available for many localities. However elevation data from airborne and spaceborne sensors are increasingly available and have been used in a variety of landslide applications. Of the remote-sensing technologies Light Detection and Ranging (LiDAR) has had arguably on the greatest influence over landslide hazard mapping and modeling (e.g. McKean and Roering, 2004; Schulz, 2007). LiDAR-derived DEMs have a very high spatial resolution (1 to 5 m) with low elevation (Z) errors (typically <20 cm in low-slope landscapes without vegetation). In vegetated steeplands LiDAR errors are usually much greater (e.g. Haneberg, 2008). Because tens or hundreds of thousands of laser pulses per second are made during a LiDAR survey, data processing algorithms have been designed to discriminate between returns from vegetation and those from the ground surface (e.g. Haugerud et al., 2003). Thus LiDAR can provide DEMs with a much more accurate depiction of the topographic surface than DEMs derived from photogrammetrically mapped contours even in heavily vegetated areas.

Deterministic shallow landslide susceptibility modeling requires DEMs of adequate resolution to capture landslide features in a given study area. Since most of these study areas are likely to be in highly dissected terrain with high relief, highresolution data (5–10 m) are typically required (Zhang and Montgomery, 1994). Slope angle calculations and other elevation derivatives such as curvature and contributing area are dependent on the scale of the source elevation data and the grid-cell spacing of the DEM (Garbrecht and Martz, 1994; Zhang and Montgomery, 1994; Thieken et al., 1999; Claessens et al., 2005). Finer grid spacing typically produces steeper slope angles and at very fine spacing (e.g. 5 m) large local variability of curvature.

1.3 Soil thickness

Maps of the soil depth on steep hillsides are required for deterministic shallow landslide models that include the effects of infiltration or soil cohesion (Dietrich et al., 1995; Baum et al., 2002). Three methodologies are available to estimate soil depths for landslide assessment: i) manual field methods, such as augering or excavation; ii) use of either soil development models or relationships with topography; iii) geophysical methods. These are summarized below.

1.3.1 Field methods

Augering operations are described in standard handbook for soil properties sampling (Dent and Young, 1981). However, common augering methods to estimate soil depth are time-consuming and expensive (i.e., high sample size) for accurate determination of soil depth (Collins and Doolittle 1987). These methods also result in high levels of soil disturbance. Furthermore, information on soil depth using these methods is often collected only at discrete locations across the landscape.

1.3.2 Topographic relationships and soil mantle evolution models

Since collecting sufficient measurements to map soil thickness compatible with the scale of high-resolution DEMs is very difficult at a regional scale, deterministic modeling efforts have relied on empirical or theoretical models to create soil depth maps (e.g. Casadei et al., 2003; Godt et al., 2008). Field observations of soil depth in

landslide-prone areas indicate that colluvium tends to collect in areas of topographic convergence (hollows) and is periodically removed by shallow landsliding during heavy rainfall (Reneau et al., 1990; DeRose, 1991). Attempts to correlate field measurements of soil depth with topographic attributes such as total topographic curvature and topographic slope have met with varying success and provide somewhat contradictory results. Topographic curvature was shown to be positively correlated with the thickness of colluvial soils in areas of topographic divergence (noses) on low gradient (0–25°) slopes in both Marin County, California (Heimsath et al., 1999) and the eastern Australian escarpment (Heimsath et al., 2000); however little or no correlation with curvature or other topographic attributes was identified on divergent topography in steeper terrain. In convergent steep (generally greater than about 20°) landslide source areas, the colluvial depth is generally poorly correlated with topographic slope. However DeRose et al. (1991) showed that at the scale of shallow landslides, soil thickness in hollows steeper than 20° decreases exponentially with slope angle.

Heimsath et al. (1999) proposed a model for vertical soil depth in temperate, soilmantled landscapes with well-developed dendritic drainage patterns assuming that 1) biogenic activity and moisture content variation is responsible for the production of colluvial soils on hillsides, 2) any mass loss due to solution processes is negligible, and 3) that the net downslope transport of colluvium is proportional to the local slope of the ground. For low-slope environments the net downslope flux of soil is often assumed to be a linear function of slope and analogous to a diffusion process. Numerical solutions to produce maps of soil thickness (Dietrich et al., 1995; Heimsath et al., 1999) require estimates of soil production rates from cosmogenic nuclide or other dating techniques (e.g. Heimsath et al., 1999).

1.3.3 Geophysical methods

In the last decade, the application of geophysics to the investigation of slopes and landslides has widely increased, with specific attention to the characterization of the soil thickness. In such a context, great attention has been dedicated to seismic, electrical and electromagnetic methods (Jongmans et al., 2000). Electrical and electromagnetic methods are based on the observation of the spatial change of the electromagnetic constitutive parameters (electrical resistivity or electrical permittivity) of the subsoil; AC low frequency methods or DC measurements are mainly affected by changes in the electrical conductivity. The conductivity takes place through the moisture-filled pore of the subsoil; therefore, the conductivity value of the subsoil depends on the porosity in terms of the shape size of the pores and the characteristic of the interconnecting pathways, the total amount of pores filled with fluids, the concentration and the mobility of the electrolytes in the moisture and the temperature.

Based on these principles, several methods have been developed. As an example, 2D - 3D Electrical Resistivity Tomography is a high-resolution electrical image which reports the spatial distribution of the subsoil resistivity and allows: 1) to reconstruct the geometry of landslide body (lateral extension and thickness); 2) to identify possible sliding surfaces; 3) to locate areas with high water content (Godio and Bottino, 2001).

Ground-penetrating radar (GPR) is a geophysical tool that is easy to use in the field and can provide an accurate estimate of soil depth as a well-defined threedimensional representation of soil volume. The applicability of GPR is heavily dependent on the electrical conductivity of soil. Soil properties such as clay mineralology, soil moisture, and soluble salt content are the primary factors affecting soil conductivity (Doolittle et al. 2006). Clay particles have high surface areas, waterholding capacity, and cation exchange capacity (CEC) compared with sandy textured soil. As CEC increases, the electrical conductivity also increases, resulting in an overall increase in signal attenuation. The chemical and physical properties of high activity 2:1 clays (i.e., high CEC and shrink-swell potential), such as smectitic and montmorillic clays, greatly attenuate the GPR signal, making it difficult to observe features at great depths. On the other hand, 1:1 low activity clays (i.e., low CEC and shrink-swell potential), such as highly weathered kaolinitic clays, do not attenuate the GPR signal as strongly, allowing for more accurate interpretations.

1.4 Hydraulic and soil-mechanical properties of the hillside materials

The soil-mechanical and hydraulic properties of hillside materials and an estimate of their spatial distribution are typically required for deterministic models of shallow landsliding. Coulomb shearing resistence parameters (angle of internal friction and cohesion) can be obtained from standard geotechnical tests (e.g. Das, 2000; Savage and Baum, 2005). Plant roots are thought to impart shearing resistence to hillside soils significantly (e.g. Schmidt et al., 2001; Borga et al., 2002; Sidle and Ochiai, 2006); however the resisting forces imparted by plant roots are dependent typically on failure depth and are not necessarily effective . It is possible to show that lumping this contribution with cohesion in infinite-slope stability analysis is physically incorrect. Three-dimensional solutions are needed (Dietrich et al., 2006) to represent accurately lateral resisting forces typically associated with vegetation roots.

Hydraulic properties of hillside materials that are required for analyses include the saturated hydraulic conductivity and saturated hydraulic diffusivity. Unlike material strength properties the saturated hydraulic conductivity of soils with similar textures derived from the same parent material can vary over several orders of magnitude. Laboratory tests using either constant or falling head instruments are used for measuring saturated conductivity. Because diffusion solutions to groundwater infiltration are sensitive to the diffusivity term some understanding of the unsaturated hydraulic characteristics of hillside materials is needed to estimate accurately this parameter and to define the range of soil-moisture conditions for which the approximate solution can be applied. Loose, coarse-grained colluvial soils typically involved in shallow landslides exhibit pronounced hysteresis among the relations between moisture content, pressure head and hydraulic conductivity.

In-situ tests on hillside materials in field areas probably provide the most representative estimates of material properties at the scale of shallow landslides. Data from well and ring permeameter tests of unsaturated materials can be used to estimate the saturated field hydraulic conductivity (Reynolds et al., 2002). The term field saturated is often used for these types of tests because air is usually entrapped in the soil by infiltrating water, which is typically the case during natural rainfall. Permeameter data can also be reduced to estimate unsaturated- zone parameters as well. Disc permeameters provide measurements of hydraulic conductivity at small negative pressures and data can be reduced to estimate soil–water characteristic curves and diffusivity (Clothier and Scotter, 2002).

2.1 Data collection for rockfall

REGIONAL EXTENT analysis scale 1:10.000 - 1:50.000

GRID ≤ 30m

Data	Direct information	Data collection and analysis	Required accuracy	Output
DTM-AL	topography	slope angle slope aspect slope profile	grid ≤30m	slope angle map slope aspect map
DSM-AL	vegetation land use soil type	land use (tree heights) block volume on talus		verify on land use map texture on lithological map
Geological map		lithologies		geological map lithological map
Tectonic map		structural elements		tectonic map
Geomorphologic map		active processes and form – talus characteristic		geomorphologic map
Rockfall data		main historical rockfall events		data sheet or map of main historical rockfall events
Orthophoto		land use – soil type – vegetation – active talus		orthophoto map
Out crop - soil type Land use		soil type land use rolling / bouncing / sliding coefficients		outcrop and soil type map

Data	Direct information	Data collection and analysis	Required accuracy	Output
DTM-AL	topography	slope angle slope aspect slope profile	grid ≤ 5 m	slope angle map (>50°, >60°, >70°) slope aspect map
DSM-AL	vegetation land use soil type	land use (tree heights) block volume on talus	grid ≤ 5 m	verify on land use map texture on lithological map
Geological map		lithologies		geological map lithological map (define geotechnical lithotype units)
Tectonic map		structural elements	survey scale =	tectonic map (in geological map)
Geomorphologic map		active processes and form – talus characteristic		geomorphologic map talus / scree characteristics (in geomorphological map)
Rockfall data		historical rockfall events	data availability	data sheet or map of historical rockfall in gis
Orthophoto	land use soil type vegetation active talus	land use – soil type – vegetation – active talus	from laser scan and digital camera accuracy	orthophoto map compare talus / scree at various years
Observation points		rockfall source area (scarp) potentially critical volumes estimate of jv, vb from gsi index and compare with data 9 and data 10	as many as possible	rockfall source area (scarp) data sheet potentially critical volumes data sheet map of jv / v_b and gsi in agreement with data 9 and 10

Geomechanical survey		characterization of discontinuities - joint set and block shape identification brmr; q gsi, jv, vb and compare with data 8 and data 10	≥ 3 per homogeneous rock mass type	data sheet for geomechanical rock mass characterization: survey stations rock mass classification: block size measurements – compare with rock fall sources - map of jv / vb in agreement with data 8 and 10 quantification of gsi – map of gsi in agreement with data 8 and 10
Als nadiral Als oblique		estimate of jv, vb from gsi and compare with data 8 and data 9 critical volume cubage	0,1 ÷ 0,2 M	map of jv / vb and gsi in agreement with data 8 and 9 3d model and/or section every 2 ÷ 5 meter of potential critical volumes
Joint set (dip dir / dip aspect)		joint set (dip dir / dip aspect) through lidar analysis directly from the dem	grid ≤ 5 m	complete joint set of data 9
Potential sliding zone		potential sliding zone for each joint set (planar and intersection)	grid ≤ 5 m	map of potential sliding zone and compare with slope angle map (>50°, >60°, >70°) and rockfall source area
Out crop - soil type Land use		soil type land use rolling / bouncing / sliding coefficients	grid ≤ 5 m	outcrop and soil type map
Existing rock fall mitigation / protection methods	DSM – DEM	draped mesh (effectiveness) rock net (effectiveness) wall (effectiveness) ditch (effectiveness) rock shed (effectiveness)	in specific field check list	effectiveness of existing rock fall mitigation / protection methods in specific map

DATA	DIRECT INFORMATION	DATA COLLECTION AND ANALYSIS	REQUIRED ACCURACY	OUTPUT
DTM-AL	topography	slope angle slope aspect slope profile	grid ≤ 2m	slope angle map (>50°, >60°, >70°) slope aspect map
DSM-AL	vegetation land use soil type	land use (tree heights) block volume on talus	grid ≤ 2m	verify on land use map texture on lithological map
Geological map		litologies		geological map lithological map (breakdown in geotechnical litho type)
Tectonic map		structural elements	survey scale = analysis scale	tectonic map (in geological map)
Geomorphologic map		active processes and form – talus characteristic		geomorphologic map talus / scree characteristics (in geomorphological map)
Rockfall data		historical rockfall events	data availability	map of historical rockfall events with gis database

Orthophotos	land use soil type vegetation active talus	land use – soil type – vegetation – active talus	from laser scan accuracy	orthophoto map compare talus / scree at various years
Observation points		rockfall source area (scarp) potentially critical volumes estimate of j_v , v_b using gsi and compare with data 9 and data 10	as many as possible	rockfall source area (scarp) data shett potentially critical volumes data sheet map of j_v / v_b and gsi in agreement with data 9 and 10
Geomechanical survey		characterization of discontinuities - joint set identification and block shape brmr gsi, jv, vb and compare with data 8 and data 10	≥ 3 per homogeneous rock mass type	data sheet for geomechanical rock mass characterization: survey stations rock mass classification: block size measurements – compare with rock fall sources - map of j_v / v_b in agreement with data 8 and 10 quantification of gsi – map of gsi in agreement with data 8 and 10
Als nadiral and oblique Terrestrial laser tls		estimate of jv, vb from gsi and compare with data 8 and data 9 critical volume cubage	0,10 ÷ 0,20 m (als) 0,02 ÷ 0,10 m (tls)	map of j _v / v _b and gsi in agreement with data 8 and 9 3d model and/or section every 2-5m of potential critical volumes
Joint set (dip dir / dip aspect)		joint set (dip dir / dip aspect) through lidar analysis directly from the dem – tls	grid ≤ 2 m	complete joint set of data 9
Potential sliding zone		potential sliding zone for each joint set (planar and intersection)	grid ≤ 2 m	map of potential sliding zone and compare with slope angle map (>50°, >60°, >70°) and rockfall source area

Joint set domain Dip dir/dip combination Slope height Wedge scale Water pressure Seismic force		altitude difference or height slope from subjective analysis slope>50°+slope aspect combination map (dip dir/dip combination) homogeneous zone (joint set domain + height slope + scale wedge + water pressure + seismic force) wedge analysis – ed/rd for homogeneous zone and dip dir/dip slope combination toppling analysis for homogeneous zone and dip dir/dip slope combination		slope>50°+slope aspect combination map (dip dir/dip combination) homogeneous zone map?? wedge analysis – ed/rd map plot wedge volume vs ed/rd – determination for homogeneous zone and dip dir/dip slope combination toppling analysis – ed/rd map for all simulation - frequency distribution ed/rd for dip dir / dip slope combination and wedge / block volume - for ed/rd < 1 to failure map probability of failure map volume of detachable blocks map (compare v _b from wedge analysis and survey)
Out crop - soil type Land use		soil type land use rolling / bouncing / sliding coefficients	grid ≤ 2 m	outcrop and soil type map
Existing rock fall mitigation / protection methods	DSM – DEM – field survey	draped mesh (efficiency and effectiveness) rock net (efficiency and effectiveness) wall (efficiency and effectiveness) ditch (efficiency and effectiveness) rock shed (efficiency and effectiveness)	in specific field check list	effectiveness and effectiveness of exiting rock fall mitigation / protection methods in specific map / chart

3.1 Methodology regarding rock slope mapping for rock fall

The stability of rock slope is mainly dependent upon geological characteristics, such as discontinuities in rock mass and morphological characteristics, such slope gradient, height and orientation and therefore assessing rockfall onset suscepti-

3.1.1 Topography (contour maps, existing DEM-DSM, TLS/LIDAR data)

Physically based rockfall models require a medium to high resolution digital elevation model (DEM) where input data are provided in a spatially distributed form and rock fall sources are defined as points, lines and polygons. The quality of a DTM is a measure of how accurate elevation is at each pixel (absolute accuracy) and how accurately is the morphology presented (relative accuracy). Several factors play an important role for quality of DEM-derived products: terrain roughness; sampling density (elevation data collection method); grid resolution or pixel size; interpolation algorithm; vertical resolution and terrain analysis algorithm. The presence of 3D variations in slope morphology (ridges, convex talus cones, micro-topography) exerts a considerable influence on rockfall trajectories and the increase of resolution of the DEM (HRDEM - ALS DEM) leads to dispersion in the propagation and to modify the kinetic energy profile.

3.1.1.1 Basic, low-resolution, topographic map

The basic, low-resolution, topographic map is built from digital photogrammetric techniques available in electronic format as a 3D CAD file; using the 3D contour

bility requires a detailed characterization of topography, rock mass characteristics (lithology, structure, rock mass features) and rock mass failure (past rockfall evidence)

lines is possible to obtain the Digital Terrain Models (DTM), the maximum scale is: 1: $5.000 \div 25.000$. The quality of DTM grid (horizontal and vertical resolution) allow for a mesh size of: 20 x 20 meters if derived from the 1:25.000 scale and 5 x 5 m from the 1:5.000 scale.

3.1.1.2 Main, medium to high resolution topographic map

In recent years considerable advances have been made in the analysis of rockfall susceptibility, in the modelling of rock trajectories on a 3D slope, as well as in the risk management of rockfalls. These advances need topographical maps and Digital Elevation Models (DEMs) derived from aerial sensors, i.e. aerial photography and airborne LiDAR (Light detection and Ranging). These sensors achieve maximum density of information when the incident ray is perpendicular to topography, typically sub horizontal surfaces. By contrast, the instabilities due to rockfall usually occur on vertical slopes with the result that a greater density of information using terrestrial sensors is obtained. The main, medium to high resolution, topographic map is generated from LiDAR¹, Airborne (ALS)² survey, the scale is 1: 100 \div 1.000. The use of this method allows modeling the topographic surface in a very accurate way, obtaining a Digital Elevation Models (DEMs) and their derivatives in 2.5D³ or even 3D.

²Range resolution is typically 1 cm.

³Elevation models (and especially surface models) may have 2.5D (every XY point have only one Z value stored, usually the topmost surface), or 3D (every XY point may have several Z values) data structure.

¹LiDAR (Light Detection and Ranging), also often referred to as "3D laser scanning", laser scanning was developed in two ways, depending on the position of the sensor: airborne-based for ALS and ground-based for TLS. Ground-based or terrestrial LiDAR (T.L.S.) refers to tripod-based measurements, as opposed to airborne LiDAR measurements made from airplanes or helicopters.

Range & elevation accuracy is related to flying height: $5 \div 10$ cm $\bigcirc 500$ m; $10 \div 15$ cm $\bigcirc 1$ km; $15 \div 20$ cm $\bigcirc 2$ km; > 20 cm $\bigcirc 3$ km.

- Maximum flying height: 500 m (helicopter) with an horizontal vertical accuracy of data acquisition ± 100 mm; 1.000 m (airplane) with an horizontal

 vertical accuracy of data acquisition of ± 150 mm.
- Density of sampling points: 1 ÷ 5 pts/m2 (points per square meter).
- Parallel strips with 20% overlap.
- The half scan angle of the main strips is $5\% \div 10\%$ in the mountain regions.

Steep and vertical cliffs and slope could be captured from an optimal scan angle using a helicopter-based system that can be mounted obliquely. The oblique configuration offer the optimum data collection solution, where a standard airborne laser scan would leave the vertical areas poorly covered, as well as degrading the accuracy of data points at the edges of the peak. With an oblique LiDAR and camera system, data can be captured normal to the outcrop, giving good processing results. In addition, because of the rapid data acquisition it is possible to cover wide

> areas and high cliffs in much shorter time than when using a ground-based scanner. Digital Terrain Model (DTM) and Digital Surface Model (DSM) generated after processing of LiDAR point clouds, having a mesh size for the grid 0,5 ÷ 2,0 meters depending on the

flying height.



Figures 13: Monte Zucco – Point cloud image from ALS oblique with 3D color scheme (Coltop3D) (Jaboyedoff M. et al., 2007).

3.1.1.3 Local / specific slope face topographic map

The local / specific slope face topographic map is generated from Terrestrial Li-DAR (TLS)⁴, survey, the scale is 1: 50 \div 100 (Figure xx). The use of this method allows modeling the topographic surface in a very accurate way, obtaining a DEM (Digital Elevation Model) in 2.5D or even 3D. Digital Terrain Model (DTM) and Digital Surface Model (DSM) are generated, after processing of LiDAR point clouds having a mesh size for the grid 0,1 \div 1,0 meters depending on the target distance.



Figures 14: Principles of laser scanner data acquisition, showing the example of TLS (Jaboyedoff M. et al., 2010).



Figures 15: Caprile (Bus del Diaol) – fullwave form analysis on rockfall fence.



Figures 16: Caprile (Bus del Diaol) – fullwave form analysis on tree.

⁴Resolution is in the order of 5 mm to 1 cm.

Accuracy and precision: can be in the order of 25 to 10 mm for a single shot or 15 to 5 mm for averaged multiple shot measurements. Range precision is independent of the distance to the object



Figures 17: Caprile (Bus del Diaol) – Point cloud data displayed using assigned colour values from a high resolution digital camera (TLS).



Figures 19: Valstagna (Contrada Pieretti) – TLS data mesh and cross section traces.



Figures 18: Valstagna (Contrada Pieretti) – Point cloud data displayed using assigned colour values from a high resolution digital camera (TLS).



Figures 20: Valstagna (Contrada Pieretti) – Fusion of TLS data mesh with ALS oblique point cloud.



Figures 21: Valstagna (Contrada Pieretti) – TLS data mesh of a roof with cross section traces.

3.1.2 Guidance on specific and appropriate procedures involved to conduct TLS LiDAR surveys

Before undertaking a field campaign using TLS techniques the following essential planning components should be considered:

- specifying the resolution (ground point spacing ground pixel size) necessary for the purpose of a project and the required accuracy and precision for mapping,
- defining the area to be mapped, taking into account physical/topographic constraints and the potential for occlusion and /or orientation bias.

Occlusion (shadow)⁵ of the scanned rock face occurs when parts of a rock face cannot be sampled because it is obscured by protruding features and the laser beam is obstructed and not able to hit the target surface. It may create holes (shadow zones) with missing spatial points in a 3D model. This issue becomes more important in scans of highly irregular rock faces, particularly where the surveyed rock faces are high and steep or very wide.

Orientation bias occurs when the scanner line of sight is sub-parallel to a discontinuity, resulting in a linear trace if viewed from the camera/scanner position. Orientation bias is reduced when the trace appears with significant relief on a 3D model.

 $^{^5 \}rm The$ portion of the surface that is not in the scanner's line of site is referred to as the scanner "shadow zone".

If an entire joint set is in the scanner shadow zone several scans need to be taken at different angles to the face in order to adequately represent the structural conditions at the site.



Figures 22: Monte Zucco – Fusion of ALS data mesh (grey) with TLS data mesh (magenta).



Figures 23: Illustration of the horizontal sampling bias due to the effects of shadowing and the presence of (semi-) parallel surfaces (a) and of the vertical sampling bias due to occlusion (b) (Slob S., 2008)



3.1.2.1 Data quality

The most important data quality parameters of 3D laser scanning devices are:

- <u>Resolution</u>: the minimum distance between measured points (mostly in the order of 5 mm to 1 cm), depending on the range to the object and size of the object; it determines what level of detail can be recognized from the scanned scene or object.
- <u>Accuracy and precision</u>: the range precision is independent of the distance to the object and determines how well the data represents the actual geometry of the scanned scene of object.
- <u>Scanning speed</u>: Depending on the scanner type, resolution, size of the object or scene, scanning speeds can range between a few minutes to half an hour.
- Laser beam divergence: A laser beam is never perfectly parallel, but always has a certain amount of divergence⁶ and results in an averaging of the measurement over a larger area. It also decreases the amount of reflected energy and thus limits the range at which objects or scenes can be scanned.

3.1.2.2 Field work planning

In the field, appropriate procedures concern:

- a. the suitability of a site for LiDAR surveying (i.e. a safe distance from steep cliffs);
- b. the procedures for scanning (i.e. scanner field of view , number of scans⁷ , point spacing, resolution, etc., using the TLS manufacturer's software;
- c. establishing surveying control points (i.e. scanner registration)
- scanning is conducted and point clouds are produced, this generally requires
 5÷25 minutes per scan to produce a point cloud with one to three million points;
- e. taking high-resolution digital images, most scanners automatically capture the images using a built in camera; by knowing the position of the camera relative to the laser and the camera characteristics, a color point cloud can be produced, and also the digital images can be draped onto the point cloud using texture-mapping techniques;
- f. collecting non-digital types of information.

 $^{^{6}}$ A laser beam that is the size of a small dot (15 mm) at around 20 meters, may be the size of a large dish (30 cm) at 100 meters distance (3 mrad = 3 m per 100 m).

 $^{^{7}}$ In general, 5 ÷ 10 scans can be conducted in a day, depending on terrain, scan area, and the travel time to each site. A typical scan is taken from 20 to 100 meters from the rock outcrop, and a typical scan area can vary from 15 x 15 m2 to over 300x300 m2.

3.1.2.3 Scanner Placement, Field of View, Point Spacing and number of Scans

The point cloud must have a uniform point spacing with an average point spacing optimized depending for a particular application:

- <u>geotechnical applications</u> (rock mass characterization, rockfall chute characterization): the point spacings must be of 2 cm or less and point cloud spacings greater than 5 cm are not recommended for any geotechnical applications;
- <u>non-geotechnical</u> applications involving the generation of a 3D digital terrain model, point cloud spacings up to 10 cm could be acceptable.

Depending on the size of the area to be mapped, several scans will need to be taken and individual scans should be merged together, using the overlap between adjacent ones. The distance from the scanner to the slope should be at least as great as the height of the slope of interest. The distance between scans: the scanner horizontal field of view should be 50 degrees or less and at least a 20% overlap between scans should be maintained. Multiple scans of a face taken at different angles should be



plex and/or high risk, then taking multiple scans to eliminate potential scanner shadow zones is recommended; if the orientation of discontinuities relative to the scanning direction could give rise to obscure (in the scanner shadow zone) one or more joint sets. Also, a joint set that is subject to scanner shadow zone is likely to show traces, from which the orientation can be picked up with tracing on a draped photo.

Figures 24: Plan view with recommended distances between scanning locations (Kemeny and Turner, 2008).

3.1.2.4 Establishing surveying control points

In the registered point cloud area there must be at least three targets of known position, placed in different planes and distributed across all the study areas.

<u>The scanner orientation</u> by measuring the orientation of the scanner together with an accurate GPS of the scanner origin (i.e. sighting over a known benchmark) must be registered.

The process of bringing 3D models into a local or global reference / coordinate system is called "registration". It could be the most time-consuming part of a

- Compass clinometer can provide an angular measurement up to 1 ÷ 2°, used for some rapid and practical approaches where rock slope characterization is requested and to orientate the 3D model relative to north in a local reference system is adequate;
- Total station (TS) can provide millimetre accuracy; if used in reflectorless mode on natural features in a rock slope located a few hundreds metres away, the expected precision of the TS is in the order of a few centimetres

terrestrial remote sensing field survey and is the most important factors affecting TLS 3D model accuracy and precision. TLS 3D models can be registered in a variety of coordinate systems: Universal Transverse Mercator (UTM) Geographic Coordinate System; Relative (local) systems oriented with respect to North.

Depending on the accuracy/precision required for a specific project, various amounts of time, cost and effort are necessary and several approaches can be adopted:

ion	". It could be the most time-consumi	ng part of a	and its maximum range under
ng t ng t s t t s t t s t t s t t s t t s t t t s t t t s t t t s	line of sight	Approach A Compass measurement of the trend and plunge of the camera/scanner line-of- sight. Using TDP, the scale is provided by measurement of the distance between the two camera positions. The tilt must be zeroed. No access to the rock slope is required. The point precision and accuracy of this approach has not been tested over a distance larger than 300 m. Approach B Three or more scans are taken from three different positions and merged together; these positions are surveyed with the TS. No access to the rock slope is required. The point accuracy of this approach is lower than approach C-1 and C-2 as, since there is no control point in the neighborhood of the rock slope, a small inaccuracy in the survey of the camera/scanner positions will propagate with the distance.	 and its maximum range under optimal conditions is 1200 metres. Differential Global Positioning System (DGPS) can provide an absolute or relative positional accuracy in the order of a few centimetres.
- r s d e		Approach C C1 Survey of about 6 targets on the rock slope, using a DGPS or TS. The position(s) of the scanner can be incorporated, if available. This approach is the most accurate and precise. C2 Survey using the reflectorless TS of about 6 natural recognizable and scattered features on the rock face. The position(s) of the scanner can be incorporated, if available. No access to the rock slope is required.	Table 20: Registration approach set-up on high mountain rock slopes: the squares represent camera/scanner positions and the stars control points. The filled symbols or lines indicate measu- rement locations (Sturzenegger M.and Stead D. 2009).



3.1.2.5 High-resolution digital images

The high-resolution digital images can be used stand-alone, for rock mass characterization and rockfall applications, or registered with the point cloud using photo draping techniques, and must always accompany each point cloud in order to document the scanning and the overall site conditions. Additional digital images, obtained with telephotos, can also be used to take close-up images of rock features of interest. When there is a potential for occlusion and/or orientation bias, separated pairs of photographs should be taken from different angles.

3.1.2.6 Data processing

The output from ground-based LiDAR is a point cloud consisting of millions of laser distance measurements representing the three-dimensional scanned scene. The most generic point cloud RGB (red, green blue) 3D coordinate file format is a 3D coordinate file (an xyzrgb file). The point clouds by themselves are not useful without software to process the data and make measurements and other calculations⁸. Also, in order to be useful, the point cloud data needs to interface easily with Computer Aided Design/Drafting (CADD) and slope stability programs. The point clouds are therefore processed to extract geotechnical information, which includes discontinuity orientation, length, spacing and block size. High-resolution digital images are also taken of the scanned scene, and these images can be "draped" onto the point cloud using texture-mapping techniques to provide a 3D color DTM of the scanned scene.

If a number of scans along a rock slope are stitched together, then the size of the file goes up accordingly. It is therefore important to store more than just the "finished" DTM files (data files that have been triangulated, stitched, photo draped, edited, etc.) or just the extracted geotechnical data. At a minimum, the original files from the scanner should be stored, as well as the point clouds once they have been registered (preferably in the xyz format so that the data can be easily opened in any point cloud processing program).

<u>For extracting geotechnical data</u>, it is not recommended to stitch the point clouds together because the combined point cloud may have million points and will be very difficult to visualize and rotate in point cloud software. Point cloud software does allow the individual unstitched point clouds to be in the same file, and to combine the fracture orientation data on a single stereonet without having to stitch the point clouds together.

<u>For viewing and making 3D measurements</u>, it may be advantageous to have a single stitched DTM and therefore a triangulated surface is made and only the merged triangulated surface is used for combined 3D measurements.

⁸Point cloud processing software manufacturers are for example: Polyworks: .pif file format and Split FX: .fx file format.

3.1.3 Rock fall source characterization and identification

The characterization of the rock mass is an important criteria for the recognition and evaluation of the detachment area / line / point. Site characterization is required: initially to determine the potential for slope instability; periodically because changes in the stability of rock slopes can occur as slopes weather and deteriorate.

3.1.3.1 Rock mass characterization

Rock masses can be viewed as being composed of blocks of intact rocks and joints or discontinuities; rockfall is produced by the joints in the bedrock, it is therefore important to characterize these joints to be able to determine block volume and rockfall susceptibility in different areas of the rock slope.

Figures 26: Diagram illustrating rock mass properties and paremeters describing rock mass characteristics (Willye et. Al, 2004).





Figure 26 illustrates the parameters that characterize the rock mass, and shows how they can be divided into six classes related to the rock materia! and its strength, the discontinuity characteristics, infilling properties, the dimensions and shape of the blocks of rock, and ground water conditions. Each of the parameters is discussed in the procedures drawn up by the International Society of Rock Mechanics (1981).

The mapping sheets included with the appendix provide a means of recording the qualitative geological data.

Rockfall can be influenced by other, external, factors like: climate, tree roots action, external stress relief and vibration from earthquake.

Several climatic conditions contribute to the instability of a rock or rock slope. Temperature variations, rain, snow, freeze-thaw and erosion conditions can act independently or in conjunction to cause stability problems. Ice on the slope face can induce a wide range of hydrostatic pressures in the slope, potentially enough to cause small failures along pre-existing cracks. Frost action also can contribute to rockfalls, since the frizzed water volume expansion can create large pressures in a confined space.

Where trees exist on the slope or at the crest and the roots have developed into the discontinuities, tree-root leverage is a common cause of rockfall. High winds acting on isolated trees can lever movement of large rocks.

Rocks are not only subjected to vertical forces due to their weight, but also can be subjected to horizontal stresses caused by tectonic forces, deep surface erosion, or glacioisostatic rebound; high horizontal stresses can cause differential rebound in adjacent rock of different.

Long-period vibrations with prolonged durations during an earthquake can cause excessive vibrations of a rock slope and may cause excessive pore water pressures and local rock ravelling. Rock mass site characterization involves the collection of geotechnical data, including information about rock structure, geology, intact rock strength, hydrology, climate, and earthquakes. In the current practice, much of this data is collected by hand directly at exposed slopes and rock outcrops, including measurements of discontinuity orientation, roughness, fill, length, and spacing. There are many issues with the collection of data in the field, including:

- safety hazards associated with the collection of this data;
- difficulties in accessing rock outcrops on large slopes or cliffs;
- human bias and accuracy issues associated with selecting areas for measurement and the accuracy of the hand-collected measurements themselves;
- relatively slow data collection and manpower intensive;
- because of the issue above, slope stability calculations with relatively small data sets;
- the lack of three dimensional information about the slope (other than surveyed points) that could be used for comparison as slopes weather and deteriorate.

3.1.3.2 LiDAR applications to rock mass characterization

In the case of steep rock slopes in alpine terrain, limited accessibility for field investigations presents a major problem, since outcrops yielding most information are often too steep or dangerous to investigate in situ. Remote sensing techniques, such as TLS and ALS techniques have proven to be appropriate tools for characterizing the structure of rock masses, slope and morphology. LiDAR can be used to assist with rock slope stability analyses allowing for: rock mass characterization, rockfall characterization, and detailed 3D measurements.

TLS can produce high resolution DEMs, which can be employed for inventory of rockfalls, monitoring of mass movement time evolution and more accurate numerical simulation of rockfall trajectories and velocities. Furthermore, data obtained from TLS allows the reconstruction of joint geometry and an estimation of the volume of blocks that can fall from steep inaccessible rock slopes.

Geological and geotechnical information can be extracted from the DTM that would be difficult to observe in the point cloud using the only dedicated point cloud software, Split FX software⁹, developed specifically for extracting geotechnical information from point clouds of exposed rock surfaces and has the ability:

- to automatically delineate fracture surfaces in a point cloud and determine the orientation, area, and roughness of each fracture;
- to plot fracture orientations on a stereonet (pole and contour plots);
- to pick joint sets, and determine statistical properties of each set;

- to delineate joint traces (automatic and manual) and determine joint spacing, length and orientation (true spacing and orientation if digital image is draped);
- to trace fractures on draped photos to determine fracture orientations;
- to subtract two point clouds to determine rockfall volume and rate;
- to estimate a rockfall hazard rating from a point cloud.

Many of the above items can still be analyzed using the "generic" point cloud software. For instance, to determine the orientation of a fracture in a point cloud, the points making up the fracture can be selected by hand, and the software will determine the orientation of the best-fit plane through the points. This can be done many times throughout the point cloud, and the orientations can be plotted using a separate stereonet program. In a similar fashion, the generic software can be used to estimate fracture length and spacing, roughness, etc.

At the present time, rock mass information that is being obtained from LiDAR includes discontinuity orientation, length, spacing and block size. In addition, research is presently being conducted to obtain additional information, including roughness, geology, weathering and discontinuity fill. Discontinuity characterization can be achieved, from high resolution¹⁰ and quality of data set, by manually fitting planes on individual recognizable surface or traces in 3D models. The typical workflow for discontinuity characterization is presented in Figure xy.

Discontinuity Orientation Collection. The principal steps are:

1. With standard hand-editing features in point cloud processing software:

⁹Split FX (Split Engineering, <u>www.spliteng.com</u>).

⁹TLS point density from 500 to 10.000 pts/m2.

- to scan a field site of interest, produce a point cloud, and register the scan into a terrestrial coordinate system;
- to create a surface mesh from the point cloud data;
- 2. With either significant hand-editing or the development of special vegetation or other types of filters in the process of creating a surface mesh, erroneous data points in the point cloud can be filtered by removing of non-rock objects on the rock slope.
- By using the basic property that fractures are flat¹¹, delineation of fracture "patches"¹² from the triangulated surface mesh.



5. Once the sets are identified, the statistical properties of each set can be determined.



Figures 27: Workflow of discontinuity analysis based on LiDAR data (Hu H. et al., 2010).

A particularly useful feature of point cloud processing software is the interaction it allows between the stereonet and the point cloud. Delineating joint sets from stereonet data is difficult and necessitates professional expertise. Normally the data is taken in the field

and the compilation and definition of joint sets is accomplished at a later time. Therefore, any difficulties with interpretation of the data cannot be resolved without additional field work. With access to the point cloud, however, additional analysis can easily be conducted off site. For instance, a group of patches can be selected on the stereonet and then viewed on the point cloud. This allows the user to go back and forth between the stereonet and the point cloud to determine with a great deal of precision the delineation of important fractures and fracture sets. The orientation of a single critical structure such as a fault can be more clearly identified on the digital image rather than the point cloud; because a fault is weak, it may not show any three dimensional surfaces where the orientation could be extracted from the point cloud alone and therefore the fault can be traced on the digital image and the orientation determined from both the trace and the point cloud.

¹¹Flat surfaces are automatically found in the triangulated mesh by first calculating the normal to each triangle, and then finding groups of adjacent triangles that satisfy a flatness criterion.

¹²The term "patch" is used rather than fracture, because a single large fracture may be delineated into several smaller patches, depending on the flatness and roughness of the fracture.



Figures 28: Caprile (Bus del Diaol) – Geomechanical feature identification from a high resolution digital camera (TLS) (Split-FX, 2011)



Figures 29: Caprile (Bus del Diaol) – Detail of geomechanical feature identification (the patch color correspond with pole color in stereonet) (Split-FX, 2011)



Set	Calculated	Orientation	Fisher K	Angular StDe	Avg. R2	Avg. Area [mxm]
10	Yes	88.8, 72.6	104	7.96	0.98	0.1
09	Yes	88.1, 269.5	1000000	0.08	1.00	0.2
08	Yes	66.2, 170.9	90	8.55	0.99	0.1
07	Yes	89.3, 333.4	73	9.51	0.99	0.2
06	Yes	78.5, 218.1	54	11.02	1.00	0.3
05	Yes	89.2, 189.6	73	9.45	1.00	0.3
04	Yes	55.4, 137.4	60	10.42	0.99	0.2
03	Yes	82.7, 127.8	49	11.54	1.00	0.2
02	Yes	79.6, 153.6	62	10.28	0.99	0.2
01	Yes	22.5, 167.4	48	11.73	0.89	0.1

Figures 30: Caprile (Bus del Diaol) – Stereonet illustrating the geomechanical feature extracted from a high resolution digital camera (TLS) (the pole color in stereonet correspond with patch color in point cloud) (Split-FX, 2011)

Determination of fracture length and discontinuity spacing distributions. Another very important aspect in rock mass characterization is the determination of discontinuity set spacing and spacing distribution. Together with the orientation of the discontinuity sets, this determines the variation in size and shape of the blocks that make up the fabric of the rock mass. For most engineering applications dealing with rock masses, this is crucial information. By separating the individual discontinuity sets and surfaces from the entire data set, it becomes possible to analyze these surfaces in 3D space and subsequently derive the distances (spacings) between them. Fracture length and spacing can be measured from either digital images or point clouds. In two dimensions, the measured fracture spacing is referred to as the "apparent" spacing, and can be corrected if the true average orientation of the set is known. In three dimensions (measured from a point cloud or a draped photo), the true spacing can be measured directly if the measurement is made perpendicular to the average strike of the set. Even though automatic trace delineation algorithms are available in many image-processing programs (including Split FX), they are not recommended.

Fracture length and spacing are interrelated, if the fractures are: persistent (fractures long in relation to the spacing), then the measurement of fracture spacing for a given set is well defined and measured perpendicular to the average orientation of the set by a single scanline; non-persistent (fractures short in relation to spacing), then the measurement of fracture spacing need several scanlines perpendicular the average orientation. In either case, a histogram of fracture spacing is produced for each set.

<u>Block Size</u>. Block size is a parameter that depends on the interaction of all the joint sets together, into a fracture network and it can be manually measured from either a digital image or a point cloud.

<u>Discontinuity Roughness, Weathering and Fill</u>: LiDAR and digital image processing have the potential for providing information on discontinuity roughness, weathering and fill but, at present, this area is only at a research phase





Figures 32: Caprile (Bus del Diaol) – Detail of a manual delineated trace with Split-FX and relative dimensions (Split-FX, 2011).


3.1.3.3 Adequacy of TLS for extracting Rock Mass Characterization Information

For extracting fracture information from point clouds, a key measure of accuracy is the error in the estimation of a fracture's strike and dip (or dip and dip direction). Errors in the LiDAR results are due to three primary sources:

- 1. <u>Instrument accuracy and field settings</u>. Errors in the strike and dip less than one degree could be attained even with small fracture surfaces intersected by less laser points (i.e. 50) than large fracture surfaces. Some others sources of possible error are due to atmospheric and temperature errors.
- 2. <u>Procedures and accuracy of point cloud registration</u>. This error affects the calculated fracture orientations for all fractures regardless of their size. The error in the estimation of fracture orientation will depend on the method of scanner registration that is used.
- 3. Software and procedures used for processing point clouds. Differences in how the point cloud is analyzed to determine fracture orientation results in large differences in the estimation of the strike and dip of a fracture surface. One method is to pick three points on a fracture and determine the orientation of the plane made by these three points. Because actual rock fracture surfaces are not flat planes, this technique will show large variations depending on the roughness of the surface and which three points are selected. A better method is to select all the points that make up the fracture and calculate the best-fit plane through those points. This method will also show variations because "selecting all the points that make up a fracture" is not a straightforward task, particularly near the edge of the fracture. If an automated routine is used to select the points that make up the fractures, then changing the parameters in the routine¹³ will result in differences in the calculated best-fit orientations.

3.1.3.4 LiDAR techniques advantages

The LiDAR techniques are ideal for: characterizing rockfall source areas, i.e. to define the size and initial location of rock blocks, that are often difficult to access. i.e. because located in steep remote areas, and characterize using traditional methods involving rappelling down the slope, which is costly and poses safety hazards; determining the number and sizes of the boulders into the slope that pose a rockfall hazard; determining the characteristics and topographic profile of rockfall chutes that often determine the location, velocity and other aspects of a rockfall event; rockfall monitoring conducted by taking LiDAR scans of the same scene at some interval of time (i.e. once every six months or more often in areas with high rockfall risk) the point clouds of these periodic scans must be aligned as accurately as possible and then are processed to evaluate rockfall using "change algorithms"¹⁴; field test sites determined that the movement of boulders as small as 15 cm can be detected when the scans at the site were taken from a distance of about 60 m. Such approaches allow for the quantification of the magnitude and activity of rockfalls in a cliff, eventually quantified the increase in rockfall activity some months previous to the occurrence of larger events or can be used to detect the most active areas.

¹³i.e. the automated routine in Split FX.

¹⁴The change algorithms subtract two point clouds and produce a "difference cloud"; from the change, the movement of a rock block can be tracked, or the size of a block that has move can be monitored.



Figures 33: The methodology used for the application of TLS in our rockfall study (Abellan et alii., 2006).

LiDAR has the following advantages: no physical access is needed to or near the rock surface to

measure discontinuity orientations, which has obvious advantages in terms of safety; inaccessible rock faces can be analyzed, particularly for slope stability and block size analysis this has obvious advantages; the human bias in determining rock mass discontinuities is mostly removed; more discontinuity data can be gathered than using traditional (manual) techniques, which allows proper application of statistical tools; higher accuracy of the orientation measurements can be achieved due to much better statistical sampling and the measuring the average orientation of a fracture rather than the specific location where the geological stratum compass is placed.

3.2 Flow chart for rockfall data collection and analysis



3.3 Flow chart for rockfall data collection and analysis

3.3.1 Sheet 1: description sheet for rock mass survey

The characterization of the rock mass is an important criteria for the recognition and evaluation of the detachment area / line / point. Site characterization is required: initially to determine the potential for slope instability; periodically because changes in the stability of rock slopes can occur as slopes weather and deteriorate.



3.3.2 Sheet 2: discontinuity survey data sheet

It describes the characteristics of each discontinuity in terms of its type, orientation, persistence, aperture/width, filling, surface roughness and water flow. This sheet can be used for recording outcrop mapping data (GCO, 1991)

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3.3.3 Geomechanical rock mass characterization

3.3.3.1 Sheet 3.1: survey stations - data base

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Vb	Angoli a S	90°	Angoli a 60°	Angoli a 45°
(m ³)	123	0,018	0,027	0,0504
	124	0,03	0,045	0,084
	125	0,03	0,045	0,084
	134	0,03	0,045	0,084
	135	0,03	0,045	0,084
	145	0,05	0,075	0,14
	MIN (m ³)	0,018	0,027	0,0504
	MEDIA (m ³)	0,0313333	0,047	0,087733333
	MEDIANA (m ³)	0,03	0,05	0,08
	MEDIANA (cm ³)	30.000	45.000	84.000
		_		
JW	2,00			
JS	1,50			
JA	1,00			
JC	3,00		GSI (Cai 2004)	56,00
SCR	13,10			
SR	31,65		GSI (Sonmez 1999- 2004)	52,00
]				

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DEGREE OF JOINTING / BLOCK SIZE / SOIL PARTICLE SIZE											
VOLUMETRIC	JOINT COUNT	(ROCK) BLO	OCK VOLUME	SOIL PARTICLES							
CLASS	Jv	CLASS	Vb	SIZE	VOLUME						
Extremely low	< 0.3	Extremely large	>1000 m3								
Very low	0.3 - 1	Very large	30 - 1000 m3								
Low	1 - 3	Large	1 - 30 m3								
Moderately high	3 - 10	Moderate	0.03 - 1 m3	Blocks	> 0.1 m3						
High	10 - 30	Small	1 - 30 dm3	Boulder	5 - 100 dm3						
Very high	30 - 100	Very small	0,03 - 1 dm3	Cobbles	0.1 - 5 dm3						
Extremely high	> 100	Extremely small	< 30 cm3	Coarse gravel	5 - 100 cm3						

3.3.3.6 Quantification of gsi chart (sonmez et al. , 2004)



3.3.3.7 Quantification of gsi chart (cai et al.., 2004)

	Joint	or Blo	ck Wa	I Cond	lition		
GS/ Block Size	Very good Very rough, fresh unweathered surfaces	Good Rough, slightly weathered, iron stained surfaces	Fair Smooth, moderately weathered or altered surfaces	Poor Slickensided, highly weathered surfaces with compact coating or fillings angular fragments	Very poor Slickensided, highly weathered surfaces with soft clay coatings or fillings		
Massive- very well interlocked undisturbed rock mass blocs formed by three or less discontinuity sets with very wide joint spacing loint spacing > 100 cm		80				- 10 ⁷	
Blocky-very well interlocked undisturbed rock mass consisting of cubical blocks formed by three orthogonal discontinuity sets Joint spacing 30 - 100 cm 40 – 30 cm		10				(1 m ³)	
Very Blocky-interlocked partially disturbed rock mass with multifaced 20 – angular blocks formed by four or nore discontinuity sets Joint spacing 10 - 30 cm 10 cm		60 50				- 10 ⁴	ne Vb (cm³)
Blocky/disturbed-folded and/or iaulted with angular blocks formed by many intersecting discontinuity sets 5 – Joint spacing 3 -10 cm 3 cm			40	30		(1 dm ³)	Block Volun
Disintegrated-poorly interlocked heavily broken rock mass with a mixture or angular rounded rock pieces Joint spacing < 3 cm 1 cm					20	- 10	
Foliated/laminated/shared-thinly laminated or foliated, tectonically shared weak rock; closely spaced schistosity prevails over any other discontinuity set, resulting in complate lack of blockiness Joint spacing < 1 cm	N/A 12 4.	N/A 5 1.	, , , , , , , , , , , , , , , , , , , ,	67 0.	/ / / / / ⁵ / 25 0	- 0.1	
	Jo	pint Co	ndition	Factor	Jc		

ROCKFALL	sou	RCI		EA	(SCA	RP)		N°		AREA		
	РНО	го							SKETCH			
						+-						
	1											
LOCATION	ļ							ALTIT	JDE (m s.l.m.)			
GEOLOGICAL												
PLACEMENT									eteder			
									SIEREC			
GEOMECHANICAL												
PLACEMENT	ACEMENT											
GEOMETRICAL		T ()						-				
DATA	HEIGH	I (m)				v	VIDHT (n	n)				
SLOPE SHAPE	VER		_		OVERHAN	IGING		C	ONVEX	CONCAV		
TENSI		NCK	YES NO						CONTACT			
			YES NO									
			EOUID			DDIGM	ATIC					
	<0.2	3	0.3_	1	1_3		3_10	10-30	30-100	>100		
Jv	Extremel	vlow	Verv lo	w	Low	Mode	ratelv hight	High	Verv high	Extremely high		
	>1000	m3	30-1000	m3	1-30 m3	0.0	3-1 m3	1-30 dm3	0.03-1 dm3	<30 cm3		
VD	Extremely	large	Very lar	ge	Large	M	oderate	Small	Very small	Extremely small		
POTENTIAL			,	RO)R						
FAILURE	PLAN	WE	DGE OR	M	IULTIBLOCK		SLAB	COLUMN	BLOCK	OVERHANG		
CONFIGURATION	SLIDE		NSLIDE		SLIDE		AILUKE	COLLAPSE	TOPPLING	FAILUKE		
CRITICAL VOLUME		•							-			
ASSESSMENT (m ³)												
ACTIVITY		0	PEN JO	INT [YES NO			TILT	ED BLOCK	6 NO		
EVIDENCE	HEAVI	LY B	ROKEN	ROO	CK MASS	YES NO	NO FRESHLY FRACTURE YESNO					
HAZARD ELEMENT												
NOTE												



PART C : ANNEX5 - REFERENCES

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