Landslide Hazard analysis and mapping: recent advances and challenges

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Outline

- Some basic concepts of landslide risk
- Framework of the landslide hazard and risk analyses
- Quantitative vs. qualitative approaches
- Non-spatially explicit hazard analyses
- Spatially explicit hazard analyses
- Uncertainties
Risk Analysis: basic concepts

Hazard: A condition with the potential of causing an undesirable consequence. Quantitatively, the probability of a particular threat occurring in an area within a defined time period.

Landslide hazard assessment is the use of available information to estimate the zones where landslides of a particular type, volume, velocity and runout may occur within a given period of time.

Hazard level: a measure of the intensity and probability of occurrence of a hazardous event.

Hazard zonation: the division of land into homogeneous areas or domains and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk.

Source: Britannica
**Risk Analysis: basic concepts**

<table>
<thead>
<tr>
<th>Type</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact by large rockmass</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Impact by single blocks</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>Impact by landslide mass</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>Loss of support due to undercutting</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>Differential settlement /tilting</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
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</tbody>
</table>

Risk: A measure of the **probability and severity** of an adverse effect to health, property or the environment. Quantitatively, Risk = Hazard x Potential Worth of Loss.

Exposure: people, property, systems, or other elements present in hazard zones that are thereby exposed to potential losses. Quantitatively, the **probability** that the element at risk is in the landslide path at the time of its occurrence.

Vulnerability: **the degree of loss** of a given element or set of elements exposed to the occurrence of a landslide of a given intensity.

Landslide Risk Framework

We will focus on hazard analysis

Landslide Risk Components

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Zonation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location, volume and classification of existing landslides</td>
<td>Landslide inventory map</td>
</tr>
<tr>
<td>Location, volume and classification of potential landslides</td>
<td>Landslide susceptibility map</td>
</tr>
<tr>
<td>Areas with a potential to experience landsliding in the future (travel distance – head retreat)</td>
<td>Landslide hazard map</td>
</tr>
</tbody>
</table>

**Hazard Analysis**
- Frequency (annual probability)
- Intensity – frequency relationships

**Risk Analysis**
- Elements at risk (exposure)
- Vulnerability
- Expected damages
Qualitative versus Quantitative Analysis

**Qualitative**
An analysis which uses word form, descriptive or numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur.

Is the approach most frequently used so far. It is useful in identifying hot spots and prioritize actions.

**Quantitative**
An analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

(a) It yields reproducible and consistent results
(b) Reduces subjectivity. It eliminates misinterpretations and the use of ambiguous terms (i.e. probable, unlikely, or extremely unlikely)
(c) It allows the direct comparison of the risk level between areas
(d) Cost-benefit analyses
(e) Consideration of risk tolerance and acceptability
Risk Analysis: How is risk determined?

\[ R = H \times \sum (E \times V) \]

- **R**: Risk
- **H**: Hazard
- **E**: Elements at risk
- **V**: Vulnerability

Varnes (1984)

The main goal of the landslide hazard analysis is determining the probability of occurrence for the whole range of landslide magnitudes (volume, area)
Hazard level: what is the concept behind it?

Behind the definition of hazard level we find the **damaging capability** of the landslide.

Is therefore the **landslide magnitude** the appropriate indicator of the potential damage?

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**Red: high hazard**
- People are at risk of injury both inside and outside of buildings. A rapid destruction of buildings is possible
- Events occurring with a lower intensity, but with a higher probability of occurrence. People are mainly at risk outside buildings, or buildings can no longer house people

The red zone designates a prohibition domain

**Blue: moderate hazard**
- People are at risk of injury outside of buildings. Risk is considerably lower inside of buildings. Damage to buildings should be expected, but not a rapid destruction, as long as the construction type has been adapted to the present conditions.

The blue zone is mainly a prescription domain

**Yellow: low hazard**
- People are at low risk of injury. Slight damage to buildings is possible.
- Damage might occur inside the building but not at the structure

The yellow zone designates an awareness domain

**Yellow–white hatching: residual hazard**
- Very low probability of a high-intensity event can be designated by yellow-white hatching. The yellow-white hatched zone is mainly an awareness domain, (residual danger)

**White: no danger** or Negligible danger, according to currently available information

Hazard level: what is the concept behind it?

The landslide mechanism has a significant influence on the damages.

Solà de Santa Coloma, Andorra

Large landslides are not necessarily more harmful than small ones.

Mutriku, N. Spain. Differential displacement

La Frasse, CH
Rock avalanches and large rockslides are always classified as high intensity events (catastrophic events).

To quantify risk, the landslide magnitude has to be replaced by the landslide intensity (*).

(*) a set of parameters describing the destructiveness of the landslide (Hungr, 1997)

Calculation of the Landslide intensity

Intensity is **spatially distributed**

The analysis of the landslide intensity must be spatially explicit

Intensity cannot be obtained directly. It must be computed from the landslide magnitude

Design of remedial and protective measures are based on landslide intensity calculations
Quantitative Risk Analysis (QRA)

\[ R = \sum_{i=1}^{i} \sum_{j=1}^{j} [P(M_i) \times P(X_j : M_i) \times P(T : X_j) \times V_{ij} \times C] \]

R: expected loss due to the occurrence of a landslide (debris avalanche) of magnitude \( M_i \) on an element located at a distance \( X \) of the landslide source, impacted with an intensity \( j \)

\( P(L_i) \): probability of a debris avalanche of magnitude \( i \)

\( P(X_j : M_i) \): probability of the debris avalanche reaching a point located at a distance \( X \) from the source with an intensity \( j \), given that the event has occurred

\( P(T : X_j) \): the temporal-spatial probability of the element at risk (exposure)

\( V_{ij} \): vulnerability of the exposed element for a debris avalanche of magnitude \( i \) and intensity \( j \)

C: value of the exposed element

Determining \( P(M_i) \) usually involves a high degree of uncertainty
Resolution and accuracy of the analysis

It depends among other factors:

• Purpose: inform, advise, oblige

• Object: singular location, linear feature, area

• Scale: site specific, local, regional, national

• Available input data and tools: data bases, DTM, numerical codes,…

• Approach: qualitative or quantitative
Object of the analysis

Examples of types of landslide hazard analyses: (a) and (b) areal; (c) linear; (d) singular location (based on Corominas and Moya, 2008. Engineering Geology, 102: 193–213)
Scale of the analysis

It is crucial the correspondence between the goals, the scale of work and the quality of the available information.


Spatially distributed hazard/risk vs. Non spatially distributed
## Scale of the analysis

<table>
<thead>
<tr>
<th>Scale</th>
<th>Runout</th>
<th>I(M)/F</th>
<th>Hazard descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>National &lt;1:250,000</td>
<td>Not considered</td>
<td>Not considered</td>
<td># landslides/administrative unit/yr</td>
</tr>
<tr>
<td>Regional 1:250,000-1:25,000</td>
<td>Usually not considered</td>
<td>Often, a fixed value (constant)</td>
<td># landslides/km²/yr</td>
</tr>
<tr>
<td>Local 1:25,000-1:5,000</td>
<td>considered</td>
<td>Non spatially distributed magnitude (intensity)</td>
<td>Annual probability of occurrence (or return period) for a given magnitude</td>
</tr>
<tr>
<td>Site specific &gt;1:5,000</td>
<td>considered</td>
<td>Intensity spatially distributed</td>
<td>Annual probability of occurrence (or return period) for a given intensity</td>
</tr>
</tbody>
</table>

Scale of analysis

Medium to small scale analyses
Regional to National scale maps
QRA - Medium to small scale

Two main approaches:

Non-spatially explicit

• The frequency of landslides is that of the trigger (rainfall)
• Magnitude of the trigger often cannot be matched to that of the landslides

Spatially explicit

• Frequency of the trigger is combined with landslide susceptibility maps (spatial probability)
• Coupled hydrological and slope stability models
Preparing non-spatially explicit landslide hazard maps

These approaches calculate the probability of occurrence and the density slope failures.

Simplifications:
- Spatial distribution not calculated
- Runout not considered
- Landslide intensity not calculated
- Exposure not considered


<table>
<thead>
<tr>
<th>Table 12 Regional hazard assessment (non-spatially explicit)</th>
</tr>
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<tbody>
<tr>
<td><strong>Methodology</strong></td>
</tr>
<tr>
<td>Recurrence of landslides is obtained from sets of aerial photographs and/or satellite images taken at known time intervals. Landslide frequency is then obtained</td>
</tr>
<tr>
<td>Landslide-triggering events of different magnitudes are related to landslide density. Return periods or the exceedance probability of the trigger are then calculated</td>
</tr>
<tr>
<td>Seismic shaking probability for given time intervals combined with the probability of landsliding based on Newmark models</td>
</tr>
</tbody>
</table>
Medium to small scale analysis: non-spatially explicit

MORLEs – Multiple occurrence of regional Landslide events

Landslide susceptibility map might not be necessary

Homogeneous area
The exact location of the failure is not known. Neither landslide size nor runout are taken into account

Magnitude: Landslide density
Hazard: Events per terrain unit and year
The relation between the magnitude of the trigger and that of the landsliding event has to be first established.

Frequency of storms as function of the storm magnitude

Medium to small scale analysis: non-spatially explicit

Some restrictions:

The relation between the magnitude of the trigger and that of the landsliding event cannot be always found.

Density of landslides (events/km²) vs the Normalised Storm Rainfall (NSR) (Govi & Sorzana, 1980)
Scale of analysis

Large to medium scale analyses

Local to site specific scale maps
Preparing spatially explicit landslide hazard maps

<table>
<thead>
<tr>
<th>Table 13</th>
<th>Spatially explicit landslide hazard analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Methodology</strong></td>
<td><strong>Magnitude/intensity</strong></td>
</tr>
<tr>
<td><strong>Landslide intensity not considered</strong></td>
<td></td>
</tr>
<tr>
<td>Areal analysis</td>
<td>Combining spatial probability (susceptibility) with the probability of a landslide of a given magnitude and probability of occurrence</td>
</tr>
<tr>
<td></td>
<td>Stability models combined with spatially distributed hydrological models and the probability of the critical trigger</td>
</tr>
<tr>
<td>Object-oriented analysis (linear or point-like)</td>
<td>Hazard assessment performed at a reference section (e.g. road segment)</td>
</tr>
<tr>
<td></td>
<td>Hazard assessment performed at a reference location (i.e. where the exposed element is located)</td>
</tr>
<tr>
<td><strong>Landslide intensity calculated</strong></td>
<td></td>
</tr>
<tr>
<td>Areal analysis</td>
<td>Combining the probability of occurrence at identified sources with empirical runout models</td>
</tr>
<tr>
<td>Object-oriented analysis (linear intensity or point-like)</td>
<td>Combining the probability of occurrence with empirical-statistical runout models</td>
</tr>
<tr>
<td></td>
<td>Combining the probability of occurrence with physically based runout models</td>
</tr>
</tbody>
</table>

Large to medium scale analysis: spatially explicit

**Landslide intensity not considered**

The probability of failure is calculated at each pixel or cell.

Hazard is calculated by combining spatial probability with the probability or frequency of the trigger.

Neither landslide size (magnitude) nor the runout of the slide mass are taken into account.

**Drawbacks:** Which probability of the trigger has to be considered? That of the critical rainfall?

What will be the probability of landslide occurrence in case of a rainfall much higher than the critical rainfall?

What about triggers having different areal extent?

*Fig. 3* Probability map of landslide hazard in Kamuell Bend area using a logistic regression model (Model 2). Darker color represents higher probability.


These maps are implicitly prepared for a specific trigger with a given $R_T$. 
Large to medium scale analysis: spatially explicit

\[ P(L_i) \text{ calculated from the soil strength parameters and frequency of the trigger} \]

Coupling hydrological and slope stability models

TRIGRS

\[ \psi_{\text{crit}} = \frac{c'}{\gamma_w \tan \phi'} + \frac{\gamma_s d_b \cos^2 \alpha}{\gamma_w} \left[ 1 - \frac{\tan \alpha}{\tan \phi'} \right] \]

These maps could be considered hazard maps if we assume a fixed volume and lack of runout

Neither landslide size (magnitude) nor the runout of the slide mass are taken into account

Large to medium scale hazard analysis: spatially explicit

Analysis is usually spatially explicit and the intensity computed.

Frequency is a spatially distributed parameter.

The observed number of landslide events depends on the study or target area:

Whole slope (i.e. regional mapping)

Road (road maintenance)

Village (urban planning)
The frequency (F) for the whole road indicates 16 rockfalls in a period of 20 years for a road length of 2.0 km. The:

\[
F = \frac{16 \text{ events}}{20 \text{ yr} \cdot 2 \text{ km}} = 0.8 \text{ events} \cdot \text{yr}^{-1} \cdot \text{km}^{-1}
\]

The frequency at each cut slope is:

\[
F_A = \frac{1 \text{ event}}{20 \text{ yr} \cdot 0.3 \text{ km}} = 0.17 \cdot \text{yr}^{-1} \cdot \text{km}^{-1}
\]

\[
F_B = \frac{4 \text{ events}}{20 \text{ yr} \cdot 0.4 \text{ km}} = 0.5 \cdot \text{yr}^{-1} \cdot \text{km}^{-1}
\]

\[
F_C = \frac{8 \text{ events}}{20 \text{ yr} \cdot 0.3 \text{ km}} = 1.33 \cdot \text{yr}^{-1} \cdot \text{km}^{-1}
\]

\[
F_D = \frac{3 \text{ events}}{20 \text{ yr} \cdot 0.1 \text{ km}} = 1.5 \cdot \text{yr}^{-1} \cdot \text{km}^{-1}
\]
Two approaches can be followed (Roberds, 2005):

(a) Assess the frequency of failure of each slope, assess propagation separately and then mathematically combine them. A magnitude-frequency relation is required at each slope or land unit and, afterwards, the estimation of the run-out distance for each landslide magnitude (i.e. Corominas et al., 2005; Agliardi et al., 2009)

(b) Assess the frequency of each combination of the slope instability mode and propagation mode directly as, for instance, the frequency of a rockfall in a roadway based on statistics of past rockfall impacts (i.e. Bunce et al. 1997; Hungr et al. 1999; Dussauge-Peissser et al. 2002)

In case (b) landslide susceptibility maps might not be necessary although runout analysis is required to calculate intensity and define the potentially affected areas (scenarios)
There is no unique risk map. Different scenarios have to be considered.
Large to medium scale hazard analysis: M-F

Obtaining M-F relations

Records of landslide incidences

Hungr et al. 1999
The statistical distribution of the rockfall scars is an indicator of the rock fall frequency, and magnitude (size) during the last thousands of years.
New tools: Terrestrial Laser Scanner - TLS

Point clouds

Discontinuities

Deformation

Rock falls

range = 1/2 * time * light speed
The failure mechanisms at the Solà d’Andorra is plane failure (prismatic blocks).

Each rock fall scar is the result of either a single or successive events that share the same basal failure surface.

Borrassica, Forat Negre
- 15 scans
- 5 stations
- Area: 2.11 Ha
**Metodology: steps**

Rockfall scar volumes (calculation on a TLS point cloud)

- Fitting of planes on scar edges (1 failure each plane)
- Calculation of dimensions (area $A$, height $H$)
  - (max step 20 cm)
- Stochastic calculation of volume distribution ($V = A \times H$)
- Scar volume distribution

Maximum credible volume

Power law: $F(V) = \alpha V^b$

where:
$F(V)$ cumulative frequency of rock fall volumes $> V$

$\alpha$ y $b$ are constants

In case of incomplete record, is the extrapolation acceptable?

Dussage-Peisser et al. 2002. NHESS, 2: 15-26

The extrapolation has been suggested for estimating the frequency of large landslides (Malamud et al. 2004; Picarelli et al. 2005)
Eastern, Central Pyrenees

- Average elevation of Andorra: 1830 m
- Intensely fractured granodiorites
- On average, 1 rockfall every 2 years poses a high risk to the populated area.

Max historically recorded volume: 1000 m³
Potential volume: defining credible scenarios


Since year 2000, non-developable area Buildings were there before the code (uses are restricted)
Potential volume: defining credible scenarios


GEO, 1998
Potential volume: defining credible scenarios

Identifying kinematically detachable rock masses

Cells where the discontinuity sets F3 and F5 outcrop are unfavourable.

Equivalent cubic volumes
\[ V \sim A^{3/2} \]

Equivalent prismatic volumes
\[ V \sim 0.5 A^{3/2} \]

Potential volume: defining credible scenarios

Kinematically detachable rock masses vs. rock fall scars

Kinematically detachable volumes: up to 50000 m³
Max estimated sliding plane area: 1361 m²

Scar Volumes: up to 3000 m³
Max observed sliding plane area: 213 m²

Large potential volumes 1 order of magnitude bigger than the scar volumes!

Is it a possible upper bound?

\[ y = 817.74x^{-0.572} \]
\[ R^2 = 0.9529 \]

\[ y = 1919.2x^{-0.9224} \]
\[ R^2 = 0.9869 \]
Potential volume: defining credible scenarios

What does the landscape tell us?

Cumulative number vs area

Deviation from the trend


Yosemite rockfalls. Guzzetti et al. 2003
NHESS, 3: 491–503
Potential volume: defining credible scenarios

Two granodiorite rock mass outcrops in the Pyrenees, showing different pattern of instability. Yellow dashed lines define large sliding surfaces. (Left) Pala de Morrano, Aigüestortes-Sant Maurici National Park, Central Pyrenees. Exposed basal sliding planes (030°/52°) either single or step-path have generated surfaces over 4000 m²; (Right) Forat Negre-Borrassica in the Solà de Santa Coloma, Principality of Andorra, Eastern Pyrenees. The largest basal sliding plane (155°/57°) measured has an area of 213 m² (Corominas et al. 2017 In press . 4° WLF)

Is the occurrence of a failure of $10^6$ m³ a credible scenario for Andorra?

Is the surveillance of the rock slope (long term deformation) a valid landslide risk management option for the urban area of Andorra?
Landslide risk prediction: uncertainties

Frequency and return periods are valid concepts for repetitive events like floods and earthquakes. Landslides do not repeat themselves. Each landslide event modifies the original slope conditions.

Canillo landslide
Andorra, Central Pyrenees

Coll de Pal, translational slides
Eastern Pyrenees, Spain
(Lack of) Stationarity

Two consecutive rainfall events (very close to each other) may not be able to de-stabilize the same slopes.

Movable material (colluvium, till) on the slopes is progressively swept down by debris flows and shallow landslides. Because the slopes have been emptied, the chances of a new storm could trigger further slope failures might have been drastically reduced.
Landslide risk prediction: uncertainties

(Lack of) Stationarity

The occurrence is constrained by the availability of pyroclastic soils on the slopes and washing operated by high intensity short duration rainfall.

Documentary sources: the occurrence of the events may be correlated with the explosive eruptions of the Vesuvius volcano; in particular, between the 1811 and 1848.

Fron view of the Monte Albino debris avalanche in Nocera Inferiore occurred on March 2005 (Cascini et al. 2010).

Cumulative distributions of: i) Vesuvius explosive eruptions occurred from 1631 up to now; ii) hyperconcentrated flow incident data (events occurred after the Vesuvius eruptions are circled in red).
Landslide risk prediction: uncertainties

Loss of strength of ice-bonded joints
(Harris et al. 2009, Earth Science Reviews, 92: 117-171)

Climate change: Permafrost degradation

Ice-covered detachment surface exposed by release of the 2003 rockfall on the Matterhorn Lion ridge
Photo: L. Trucco

An increase of the rock avalanche and debris flow activity has been detected in alpine regions

Aiguille du Midi
Photo J.P. Robert

Rockfall events in the Montblanc massif in 2007 (red) and 2008 (yellow)
Ravanel et al. 2010, Landslides, 7: 493-501
Landslide risk mitigation measures: critical issues

Mitigation measures are designed for a reference event (i.e. 100 y return period).

The frequency of the design event is usually determined based on the observation of past events.

Increase of landslide frequency might be amenable for many of the existing mitigation structures.

Engineering designs can be undersized if climate change causes not only affects landslide frequency but landslide magnitude.

Debris flow diversion channels
Sarno, Campania, Italy
Thank you very much for your attention