Quantitative vulnerability estimation for individual landslides

Estimation quantitative de la vulnérabilité aux glissements de terrain

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ABSTRACT: Vulnerability has not been systematically considered for landslides until recently, but is a fundamental component in the evaluation of risk. Vulnerability depends on the landslide intensity, the characteristics of the elements at risk, and the impact of landslide. A quantitative model is proposed to estimate the vulnerability of the exposed structures and individuals. The model accounts for landslide intensity, different classes of vulnerable elements and the impact of both slow and rapid moving slides.

RÉSUMÉ : La vulnérabilité est un facteur important du risque associé aux glissements et n'a pas été considérée jusqu'à tout récemment. Elle dépend de l'intensité et de l'impact du glissement et des propriétés des éléments exposés. L'article propose un modèle calculant la vulnérabilité de structures et d'individus. Ses paramètres caractérisent l'intensité du glissement, tiennent compte de différentes classes de vulnérabilité et distingue l'impact de glissements évoluant lentement et rapidement.

KEYWORDS: Landslide, Quantitative vulnerability evaluation, Intensity, Susceptibility

1 INTRODUCTION

The ISSMGE glossary of risk assessment terms defines vulnerability as the degree of loss to an element within the area affected by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). In contrast to flooding and earthquakes, it is not straightforward to define or assess, the vulnerability to landslides, due to the complexity and range of the landslide process (Leroi 1996). However vulnerability can influence the losses to a greater degree than the hazard (Einstein 1988; Alexander 2004). Despite this, it is an economic and political necessity to quantify vulnerability (Varnes 1984; Alexander 1984).

Two different perspectives exist for the vulnerability estimation: that based on the natural sciences and that based on the social sciences (Crozier 2004). Most often, the assessments of landslide risk are based on the natural science approaches. Some apply damage matrices (Leone 1996) based on qualitative (Cardinali 2002) and quantitative approaches (Fell, 1994). Conceptual frameworks for quantitative vulnerability estimation have been presented (Düzgün and Lacasse 2005, Uzielli *et al* 2008).

2 PROPOSED MODEL

Following Uzielli *et al* (2008) and Li (2010), the proposed model defines vulnerability as a function of landslide intensity and susceptibility of element at risk. The parameters are established on the basis of the landslide impact mechanism and categories of vulnerable elements. The proposed vulnerability model is defined by Eq. 1 and represented graphically in Fig. 1:

$$\text{For } I \le 1\text{-}S \qquad V = \tfrac{1}{2}[I/(1\text{-}S)]^2$$
$$\text{For } I > 1\text{-}S \qquad V = 1\text{-}\tfrac{1}{2}[(1\text{-}I)/S]^2 \qquad (1)$$

$V \in [0, 1]$ is the vulnerability of elements exposed to the threat. For structures, 1 means that the structure is completely destroyed, while values less than one represent the degree of damage and 0 describing no damage. For individuals, 1 means loss of life, while a value < 1 is the probability of loss of life. $I \in [0, 1]$ is the intensity of landslide. An intensity of 1 means that the landslide has the potential of destroying all elements in its path.

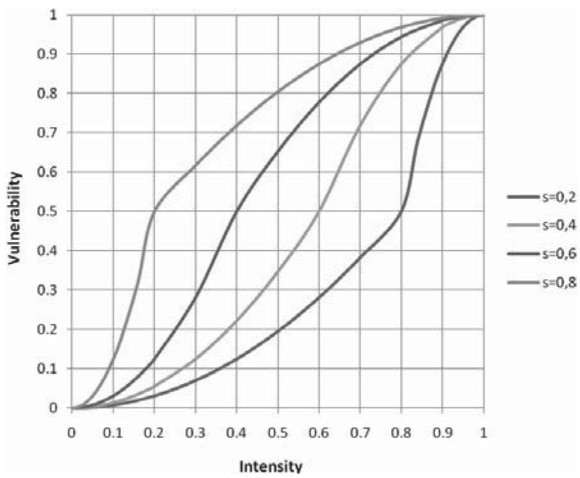

Fig. 1 Vulnerability (*V*) from susceptibility (*S*) and landslide intensity (*I*).

$S \in [0, 1]$ is the element susceptibility: S=0 means that the vulnerable element has high inherent resistance under impact. The terms V, I and S are non-dimensional and the values of 1 and 0 indicate the highest and lowest boundaries for the three parameters. To account for the landslide impact in the vulnerability estimation, two stages of deformation are considered: 1) a slow deformation stage and 2) the failure (rapid movement) stage.

3 LANDSLIDE INTENSITY

The definition of vulnerability requires information on landslide intensity (Guzzetti *et al* 1996), which should include information on the landslide severity degree and spatial dimensions.

3.1 *Slow deformation stage*

Under slow deformation, cracks and tilting may occur in structures located on the landslide, due to displacement and velocity of the ground surface and foundation substrata. The intensity parameters include landslide velocity and local deformation, which describe the severity degree, and landslide depth, which reflects the spatial dimensions. The model is defined as:

$$I_{def} = 1 - (1 - I_{d\text{-}def})(1 - I_{d\text{-}vel})(1 - I_{d\text{-}dep}) \quad (2)$$

where $I_{d\text{-}def}$, $I_{d\text{-}vel}$ and $I_{d\text{-}dep}$ are the parameters for deformation, velocity and landslide depth at the location of the structure. The deformations include settlement, horizontal movement and inclination (Bell 1978; Peng 1992; Zheng 2007). A basic relationship (Eq. 3) seems to provide a good approximation:

$$W_s = aW_g + bW_s \quad (3)$$

where W_s and W_g are the deformations of structure and ground, a is the slope and b is the intercept. Table 1 gives the range of a and b vs movement and structure types (Peng 1992; Zheng 2007). The deformation intensity depends on the ratio of deformation to allowable threshold value as shown in Table 2.

Table 1. *a* and *b* as function of ground deformation and structure type

Structure	Brick masonry, concrete structures		Reinforced (RC) concrete structures	
	a	*b*	*a*	*b*
Settlement (mm)	0.87-0.99	0.50-1.27	0.96-1.03	1.19-3.57
Tension (mm/m)	0.74-0.89	—	0.68-0.71	—
Compression (mm/m)	0.28-0.32	—	0.24-0.27	—
Inclination (mm/m)	0.99-1.06	0.80-0.90	0.69-0.97	0.03-0.2

Table 2. Proposed value of intensity parameters for deformation

Ratio of deformation to allowable threshold	$I_{d\text{-}def}$
<0.2	0.1
0.2-0.4	0.2
0.4-0.6	0.4
0.6-0.8	0.6
0.8-1.0	0.8
1.0-1.2	0.9
≥1.2	1.0

According to the landside movement scale and response of structures (Cruden and Varnes 1996), the intensity of the landslide velocity can be obtained by the model described in Eq. 4 (Li 2010). v is the velocity of landslide (mm/s).

$$\begin{aligned} &\text{For } v \le 5\times10^{-7} && I_{d\text{-}vel} = 0 \\ &\text{For } 5\times10^{-7} < v \le 5\times10^{-1} && I_{d\text{-}vel} = 1/36[\log_{10} v + 6.30]^2 \\ &\text{For } v \ge 5\times10^{-1} && I_{d\text{-}vel} = 1 \end{aligned} \quad (4)$$

For structures on a moving landslide, the degree of damage depends mainly on the relative depth of the structure foundation to the sliding surface. Ragozin (2000) quantified the vulnerability of structures as a function of the foundation depth h (m) depending on the depth of predicted landslide d (m).The model described by Eq. 5 is proposed used.

$$\begin{aligned} &\text{For } d/h < 0.8 && I_{d\text{-}dep} = (1.25 \cdot d/h)^{1/3} \\ &\text{For } 0.8 < d/h \le 1.2 && I_{d\text{-}dep} = 1 \\ &\text{For } d/h > 1.2 && I_{d\text{-}dep} = 1.44 \cdot (d/h)^{-2} \end{aligned} \quad (5)$$

3.2 *Failure stage*

3.2.1 *Landslide intensity for structures*

The structures located within the release zone of a rapidly moving landslide are completely destroyed and have a vulnerability of 1.0. For the structures within the run-out distance, the impact mechanisms can be divided into two main categories: burial and impact pressure. For structures, the intensity of the landslide is defined as a function of its depth and impact pressure, where I_{pre} and $I_{f\text{-}dep}$ are impact pressure and landslide depth parameters:

$$I_{fai\text{-}s} = 1 - (1 - I_{pre})(1 - I_{f\text{-}dep}) \quad (6)$$

(1) Impact pressure

After the landslide fails, the horizontal impact pressure is the main cause of damage to structures (Glade 2004; Ulusay 2007). Petrazzuoli (2004) analyzed the collapse limit load of regular and irregular RC structures to horizontal pressure with the strong beams and weak columns structural models. The proposed vulnerability model uses the average value of each typology to estimate the horizontal pressure limit P vs the number of stories n, in which the values of coefficient α and β for each structure type are listed in Table 3.

$$P = \alpha \ln(n) + \beta \quad (7)$$

Table 3. Coefficients α and β in Eq. 7 for different structure types.

Structure	Strongly aseismic	Weakly aseismic	Strongly non-aseismic	Weakly non-aseismic
Regular structure				
A	-4.384	-2.717	-2.157	-1.276
B	19.125	13.164	10.568	7.693
Irregular structure				
A	-3.779	-2.467	-1.821	-1.343
B	14.553	10.288	8.068	6.066

The ratio of landslide impact pressure on the building to horizontal pressure limit is defined as the intensity parameter I_{pre} (Table 4). The horizontal pressure limit of RC frame can be obtained according to Eq. 7, while the limit pressure of terracotta panels in Table 5 can be used for masonry structure.

Table 4. Proposed values of impact pressure intensity parameter.

Landslide impact pressure/Structure horizontal pressure limit	I_{pre}
<0.1	0.05
0.1-0.2	0.20
0.2-0.4	0.40
0.4-0.7	0.70
0.7-1.0	0.90
≥1.0	1.00

Table 5. Estimated resistances of buildings and elements (Spence 2004)

Building elements	Failure pressure(kPa)
Terracotta tile infill panel with openings	7.6-8.9
Terracotta tile infill panel without openings	5.5
Tuff infill panel (length 4 m, thickness 40 cm)	6.8-9
Tuff infill panel (length 4 m, thickness 60 cm)	10-13
Weak non-aseismic RC buildings (1 to 3 storeys)	4.5-8
Strong non-aseismic RC buildings (4 to 7 storeys)	5-9
Weak aseismic RC buildings (multi-storeys)	5-10
Strong aseismic RC buildings (multi-storeys)	6-14

(2) Landslide depth

As inferred from the structural damage, the intensity parameter for landslide depth should be defined as the ratio of landslide depth to height of structure. When landslide depth is equal to or greater than the structure, the structure loses completely lose its functionality. The proposed values of $I_{f\text{-}dep}$ are found in Table 6.

Table 6. Proposed values of landslide depth intensity parameter

Ratio of landslide depth to height of structure	$I_{f\text{-}dep}$
<0.2	0.10
0.2-0.4	0.30
0.4-0.6	0.50
0.6-0.8	0.70
0.8-1.0	0.90
≥1.0	1.00

Depending on location, the persons within the affected area can be divided into two categories: indoors and outdoors. Landslide velocity, depth and width become the intensity parameters:

$$I_{fai\text{-}p} = \mathrm{I} - (\mathrm{I} - I_{f\text{-}vel})(\mathrm{I} - I'_{f\text{-}dep})(\mathrm{I} - I_{wid}) \quad (8)$$

where $I_{f\text{-}vel}$, $I'_{f\text{-}dep}$ and I_{wid} are the parameters of landslide velocity, depth and width, respectively. A moving slide depth greater than knee-height makes it difficult to escape. Using 1.6 m and 0.482 (Swami 2006) as average height and leg ratio, a threshold value of 0.8m for critical landslide depth is obtained. The values of $I'_{f\text{-}dep}$ in Table 7 are proposed:

For landslide width, five degrees are identified to allow for change in landslide activity conditions (Table 8). The landslide velocity scale defined by Eq. 9 is identical to that proposed by Li (2010). The value ν is the velocity of the landslide (mm/s).

$$\begin{aligned} &\text{For } v \le 5\times10^{-1} && I_{d\text{-}vel} = 0 \\ &\text{For } 5\times10^{-1} < v \le 5\times10^{3} && I_{d\text{-}vel} = 1/16[\log_{10} v + 0.3]^2 \\ &\text{For } v \ge 5\times10^{3} && I_{d\text{-}vel} = 1 \end{aligned} \quad (9)$$

Table 7. Proposed values of landslide depth intensity parameter

Landslide depth (m)	$I'_{f\text{-}dep}$
<0.1	0.10
0.1-0.3	0.30
0.3-0.6	0.70
0.6-0.8	0.90
≥0.8	1.00

Table 8. Proposed values of landslide width intensity parameter

Landslide width (m)	I_{wid}
< 50	0.10
50-200	0.30
200-400	0.50
400-700	0.80
≥ 700	1.00

4 SUSCEPTIBILITY

4.1 *Susceptibility of structures*

The capacity of a structure to withstand the landslide hazard depends on the morphological characteristics and utilization conditions (Amatruda 2004; Coburn 2002). Four parameters were considered, including structure type s_{str}, maintenance state s_{mai}, ratio of service years to design service life s_{ser} and the difference in the directionality of landslide movement and the principal longitudinal direction of the structure s_{dir}, with the model given in Eq. 10. Together, these parameters describe the susceptibility of the structures to be damaged by a landslide (Table 9 for s_{str}, Table 10 for s_{mai}, Table 11 for s_{ser}, Table 12 for s_{dir}).

$$S_s = 1-(1-s_{str})(1-s_{mai})(1-s_{ser})(1-s_{dir}) \tag{10}$$

Table 9 Structure susceptibility parameter (Heinimann 1999)

Structural typology	Resistance	s_{str}
Lightest, simple structures	Very high	1.00
Light structures	High	0.90
Rock masonry and concrete	Medium	0.70
Brick masonry, concrete structures	Low	0.50
Reinforced concrete structures	Very low	0.30
Reinforced structures	Extremely low	0.10

Table 10 Proposed values of maintenance state susceptibility parameter

State of maintenance	s_{mai}
Extremely good	0.00
Good	0.05
Slight deformation	0.25
Medium deformation	0.50
Serious deformation	0.75
Extremely Serious deformation	1.00

The damage would be most serious when the angle between the two directions is 0°and be lightest when the angle gets close to 45° (Table 12).

Table 11 Proposed values of service year susceptibility parameter

Ratio of service year to design service life	s_{ser}
≤ 0.1	0.05
0.1 - 0.4	0.10
0.4 - 0.6	0.30
0.6 - 0.8	0.50
0.8 - 1.0	0.70
1.0 - 1.2	0.80
> 1.2	1.00

Table 12. Values of directionality difference susceptibility parameter.

Directionality of landslide movement (°)	s_{dir}
0-5	1.0-0.6
5-15	0.6-0.4
15-30	0.4-0.2
30-45	0.2-0.0

4.2 *Human susceptibility*

The susceptibility of persons to be hurt or killed by the landslide depends strongly on the cognitive and reaction capacity upon the occurrence of a landslide and the protection measures at the site, e.g. escape routes or early warning system. The following model was proposed to describe the landslide susceptibility for persons:

$$S_p = 1-(1-s_{hel})(1-s_{age})(1-s_{war}) \tag{11}$$

where s_{hel}, s_{age} and s_{war} are the susceptibility parameters, health condition, age and existence of a warning system, respectively.

A person's health condition, i.e. evacuation capacity, can be divided into three classes: 1) healthy, 2) weak physical condition, e.g. chronic disease slowing down movement, and 3) complete incapacitation with inability to evacuate. The susceptibility parameter values listed in Table 13 are proposed.

On the basis of fatality rate-age distribution data from earthquakes, Li (2010) proposed a quadratic polynomial function (Eq. 12) in terms of age a, which was adopted in this paper:

$$s_{age} = 0.95 - 0.00486\,[\text{INT}(a/5)\ \text{-}5]^2 \tag{12}$$

where INT() is the downward rounded integer function.

Table 13. Proposed values of health condition susceptibility parameter.

Health condition	s_{hel}
Healthy	0-0.1
Weak physical condition	0.1-0.8
Complete incapacitation	0.8-1.0

"Early warning" refers to all the measures that can be taken before the occurrence of a catastrophic event reducing the risk or contributing to avoid it (Table 14). Completeness level in the table refers to the efficiency of early warning or other mitigation measures in place to reduce or avoid risk.

5 VULNERABILITY OF PERSONS IN STRUCTURES

When a landslide occurs, the vulnerability of persons in the structures is directly correlated with the structure damage.

To estimate the casualty level in a building, one needs to assess the proportion of people trapped in the debris of a collapsed building and the casualty level for different degrees of damage.

When buildings collapse, not all the occupants are trapped inside. The number of people trapped in a collapsed building depends on the size and type of building, the collapse itself, the time of collapse and the escape options during and after the col-

Table 14. Proposed values of "generic" early warning system susceptibility parameter

Completeness level	S_{war}	Description of risk reduction or risk avoidance measure
None	1.0	Investigate the geological background and deformation of the landslide, without any monitoring measures.
Simple	0.6-1.0	Simple manual monitoring measurements with low precision and measurements at long interval (one month), e.g. manual measurement of extension velocity of crack and subsidence velocity of head of landslide.
Moderate	0.2-0.6	Accurate monitoring equipment with moderate precision, long interval readings (one month) and low distribution density of monitoring points; monitoring involves only geological parameters); investigation of population exposed to landslide risk; simple emergency plan includes warning transmission and evacuation paths.
Comprehensive	0.0-0.2	Accurate monitoring equipment with high precision and close interval readings (one day/one week); density of monitoring points high enough to sense deformation of entire landslide; monitoring involves geophysical, atmospheric, hydrodynamic and soil quantities; decision procedures in place based on experience with time prediction, triggering threshold and evacuation successes/failures with landslide; overview of population and public facilities exposed; overall emergency plan includes warning transmission, evacuation paths, logistics, medical assistance and so on.

lapse. Masonry and reinforced concrete, have different collapse mechanisms and rubble characteristics. The total collapse of masonry buildings provides smaller cavities than the collapse of frame structures. Li (2010) proposed an exponential description of the vulnerability of persons inside structures. Coburn (2002) estimated the average percentage of occupants trapped in a collapsed building to range between 30% and 70%, and estimated the injured proportion of occupants at collapse (Table 15).

The four levels of casualty, i.e. fatalities, seriously injured, moderately injured and lightly injured or uninjured, were denoted by vulnerability values of 1, 0.8, 0.5 and 0.2. The vulnerability of persons (V_p) in different structures is listed in Table 16 (V_s = 1 or collapse). Equation 13 quantifies the vulnerability of persons V_p (index α for different structures is listed in Table 16).

$$V_p = 0.001 \exp(\alpha V_s) \quad (13)$$

Table 15. Casualty distribution, collapsed buildings (Coburn 2002)

Class	Fatalities	Seriously injured	Moderately injured	Lightly injured or uninjured
Masonry	17.5	10	17.5	55
RC frame	21	0.8	9.2	70
RC shear wall	10	0.7	9.3	80
Steel	16	0.6	9.4	75
Timber	0.6	0.2	10.2	89

Table 16. Vulnerability of persons and value of index α

Structure type	Masonry	RC frame	Steel	RC shear wall	Timber
V_p (when V_s = 1)	0.45	0.40	0.36	0.31	0.24
α	6.1	6	5.9	5.75	5.5

6 CONCLUSIONS

A model for the quantitative estimate of landslide vulnerability is proposed with two parameters: landslide intensity and susceptibility of the elements at risk. A reliable estimate of landslide intensity should consider the relationship between landslide severity and spatial dimensions. For the slow-moving landslides, the quantitative relationships for three categories of ground deformation and structure response are considered in the assessment of the landslide intensity. Based on empirical data, a function describing the ratio of landslide depth to foundation depth can be used to estimate the effect of geometric intensity.

In the landslide failing stage, intensity models were established for stationary and non-stationary vulnerable elements. Impact pressure and landslide depth were included in the vulnerability assessment of structures. For persons in open space, the parameters include landslide velocity, depth and width.

Functions of horizontal limit pressure versus the number of storeys of different structures were proposed to quantify the landslide impact intensity parameter of the moving mass. For the human susceptibility, generic mitigation measures were proposed to include a component of risk prevention and emergency awareness. Further, collapse mechanisms and construction characteristics of different construction types, the vulnerability functions for persons in different structure categories were proposed.

The model has limitations and needs further research. Some of the subjective and empirical parameters in the model should be calibrated and gradually documented with the addition of objective data, experience, observations and expert judgment.

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