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AN OVERVIEW OF VULNERABILITY ASSESSMENT OF BUILDINGS IMPACTED BY GRAVITATIONAL NATURAL HAZARDS. POSSIBLE APPLICATIONS IN SWITZERLAND

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ABSTRACT

Vulnerability assessment is becoming more and more a crucial point to be tackled in the framework of risk management of natural hazards. The assessment of the impact of these hazards on built environment is essential to all the public authorities involved in risk management and land use planning.

The purpose of the present study is to collect the most significant methodologies for vulnerability assessment developed so far and propose some criteria to evaluate them in order to suggest the most suitable to a specific territory, e.g. the Swiss, in this study.
This evaluation is carried out for three major gravitational natural hazards, i.e. landslides, debris flows and rock falls.

1. INTRODUCTION

Gravitational natural hazards, such as landslides, debris flows and rock falls can cause a lot of damages in highly urbanized areas situated in mountainous regions all over the world.

Within the framework for risk analysis and management, and according to the definition of risk made by the UNDRO (1984), the assessment of the vulnerability of built environment constitutes a fundamental step in evaluating the impact of natural hazards on human assets and, subsequently, in allocating resources and establishing engineering solutions to mitigate consequences. At the same time, vulnerability is very complex to assess, on the one hand due to limited data available on disasters at the local level and, on the other hand, because it is a relatively new field of study which brings together scientists from different disciplines (Fuchs, 2009), therefore many constraints/conditions of different nature have to be satisfied.

Vulnerability is perceived as ''the degree of loss to a given element, or set of elements, within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss)'' (UNDRO, 1984). Vulnerability to landslides can be expressed using economic (monetary, quantitative) or heuristic (qualitative) scales (Galli & Guzzetti, 2007). In this study we mostly refer to economic scale to evaluate the degree of loss.

For gravitational hazards such as landslides, debris flows and rock falls, due to the high difficulty in defining their intensity and to the scarce availability of data regarding damages caused by past events, methods for vulnerability assessment and so-called "vulnerability curves" are quite limited in literature, at least if compared to the large number of vulnerability curves built for other hazards, like floods, storms or earthquakes – which can be in part explained by the fact that floods, just like earthquakes and storms damage more buildings in a single event than other hazard types (Douglas, 2007).

This is the reason why, over the last ten years, integrated approaches to manage all types of natural hazards, including vulnerability assessment methods, have been developed in many European countries, including Switzerland (Bründl, et al., 2009). These vulnerability assessment methods can be qualitative or quantitative (Fuchs, et al., 2012).

This work aims to evaluate the methodologies for vulnerability assessment, according to some specific criteria which should allow to establish which the most suitable method to a specific territory is. In particular, Switzerland will be taken as a reference and, based on the results of the evaluation, recommendations will be given to improve the vulnerability assessment methods and curves available for this country, in order to make them fit better to the three types of natural hazard considered (landslides, debris flows, rock falls).

2. COLLECTION OF VULNERABILITY ASSESSMENT METHODS FOR GRAVITATIONAL HAZARDS

According to Hollenstein (2005), studies on vulnerability assessment on mass movements-related disasters are limited. In addition, vulnerability assessments are usually carried out for all the gravitational hazards together (identified under the general term "landslides", which therefore includes also rock falls and debris flows).

In the methodologies developed during the last years, vulnerability is assessed in different ways: empirically or analytically, by means of curves, numerical models, indicators and/or matrices. Based on the overviews elaborated by several authors (Hollenstein, 2005; Papathoma-Köhle, et al., 2011; Totschnig & Fuchs, 2013; Fuchs, 2014) and a further research on new developments published after 2014 (Ciurean, et al., 2014; Guillard-Gonçalves, et al., 2016), some of the most recent and interesting methodologies are considered hereafter to evaluate a possible suitable approach for the Swiss territory.

In order to better focusing on each methodology, the collection is realized separately for each gravitational hazard.

2.1 Approaches for debris flows

In the study of debris flows vulnerability, there is a larger number of studies available compared to other gravitational hazards (Papathoma-Köhle, et al., 2011).

1) In Switzerland, the FOEN (Borter & Bart, 1999) presents some vulnerability curves related to the intensity of the phenomenon and its impact (degree of loss) on the buildings (Papathoma-Köhle, et al., 2011).

2) From the study of a well-documented event which occurred in the Austrian Alps in August 1997, Fuchs et al. (2007) obtained a vulnerability curve for buildings of the dominant type, i.e. brick masonry and concrete, located on the fan of the torrent, based on the damage ratio and the intensity of the phenomenon. The relationship between debris flow intensity and vulnerability is expressed by a second order polynomial function (Fig. 1). The intensity is expressed by the deposit height and the curve concerns intensities lower than 2.5 m deposit height.

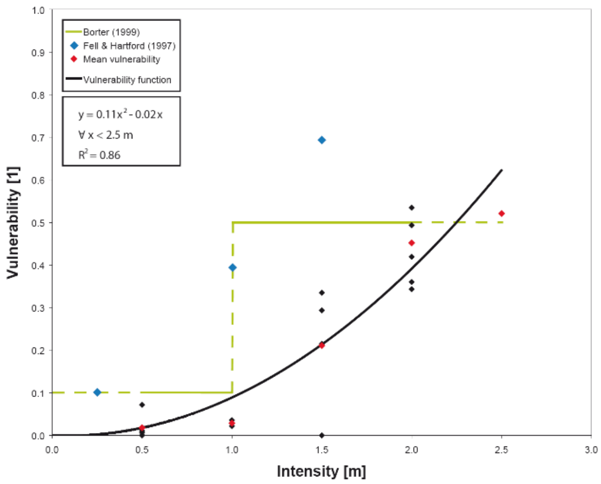


Fig. 1 Comparison between FOEN (Federal Office of the Environment) vulnerability curve (green, Borter & Bart, 1999) and the one proposed by Fuchs (black, 2007) according to data of a past event (black dots).

3) In their landslides risk assessment methodology, Sterlacchini et al. (2007) analysed the vulnerability of built environment affected by a potential risk scenario due to an earth-debris flow, defined based on an existing susceptibility map for a municipality in North-East Italy (Corvara, Badia). A "cause-effect" correlation was applied to analyze the relationship between the natural event and the physical effects on buildings. The physical effects considered are the aesthetic, functional and structural damage suffered by the exposed elements (Cardinali, et al., 2002). The vulnerability scenario of this study is based on data derived from written reports and literature about historical damage and disruption suffered by buildings during past "similar" events.

4) The study of Quan Luna et al. (2011) aims at developing physical vulnerability curves for debris flows through the use of a dynamic run-out model able to calculate physical outputs and to determine the zones where the elements at risk could actually suffer an impact. A specific large debris flow event was reconstructed and modelled, and three empirical vulnerability curves were obtained, as functions of debris flow depth, impact pressure and kinematic viscosity, respectively. All of the buildings involved were single to three storey brick masonry and concrete structures.

5) Ciurean et al. (2014) performed a quantitative vulnerability assessment of buildings using run-out modelling and damage data from a particular event occurred in 2003 in the Fella river region (Italy). They proposed a set of vulnerability curves for buildings which are built according to occupancy classes, building material types and number of floors. They considered two possible parameters to express the intensity of the phenomenon, analysed by means of a run-out model: the impact pressure and the debris flow height.

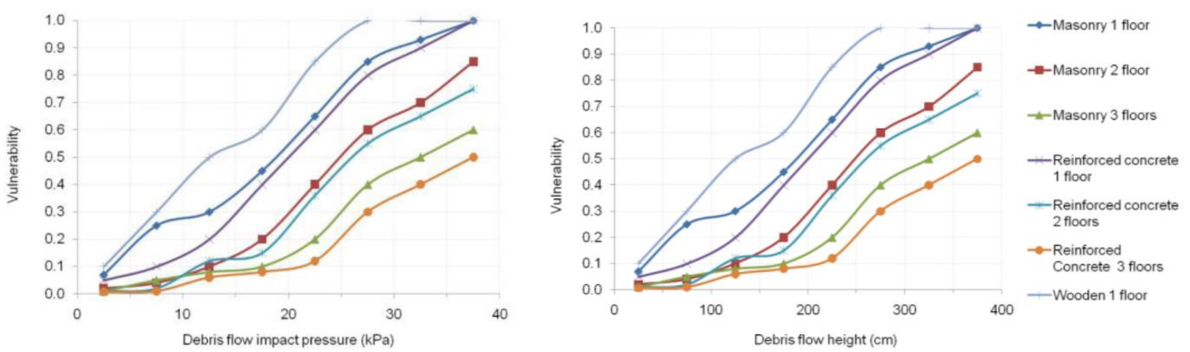
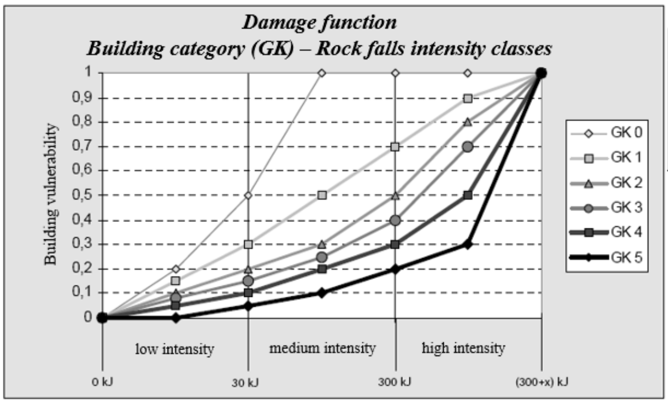


Fig. 2 Vulnerability curves for debris flows accounting impact pressure (left) or debris flow height (right) as intensity parameter (Ciurean, et al., 2014).

2.2 Approaches for rock falls

The vulnerability of built environment affected by a rock fall event has been more and more studied in last decades. However, compared to other natural hazards, rock falls are very complicated phenomena to study under the point of view of vulnerability assessment of the built environment. In addition, the quantification of the vulnerability, when based on empirical or heuristic approaches, requires data from historical rock falls records, which are very often not available. This is the reason why appropriate alternatives are required; the use of analytical and numerical models can be considered as such (as proposed by Mavrouli & Corominas, 2010).

1) For rock falls, the FOEN (Borter & Bart, 1999) estimated vulnerability curves in terms of damage functions of six different categories (type) of buildings, based on the intensity of the event. Vulnerability values are attributed to buildings according to their typology, for use at the regional scale (Mavrouli & Corominas, 2010).



	Building vulnerability for ROCK FALLS						
Building category	0 kJ	low intensity	30 kJ	medium intensity	300 kJ	high intensity	(300+x) kJ
GK 0	0.0	0.2	0.5	1.0	1.0	1.0	1.0
GK 1	0.0	0.15	0.3	0.5	0.7	0.9	1.0
GK 2	0.0	0.1	0.2	0.3	0.5	0.8	1.0
GK 3	0.0	0.08	0.15	0.25	0.4	0.7	1.0
GK 4	0.0	0.05	0.1	0.2	0.3	0.5	1.0
GK 5	0.0	0.0	0.05	0.1	0.2	0.3	1.0

Building category		Resistance
GK0	Lightest, simple structures	None
GK1	Light structures	Very low
GK2	Rock masonry, concrete and timber	Low
GK3	Brick masonry, concrete structures	Medium
GK4	Reinforced concrete structures	High
GK6	Reinforced structures	Very high

Fig. 3 Vulnerability curves with table of values and description of the six building categories considered (modified from Borter & Bart, 1999).

2) More recently, Agliardi et al. (2009) proposed a rock falls vulnerability function starting from a quantitative risk assessment procedure supported by 3D rock falls numerical modelling. The numerical model was calibrated by a back analysis of an event occurred in Fiumelatte (Italy) in 2004; then, the computed impact energy and observed damage for each building impacted were combined, to establish an empirical vulnerability function according to which the expected degree of loss for each element at risk was determined (Agliardi, et al., 2009).

3) Mavrouli and Corominas (2010) investigated the response of reinforced concrete buildings to rock falls impacts, considering a single hit on the basement columns, and they proposed an analytical evaluation of the vulnerability. For a range of rock falls paths and intensities, they calculated a damage index (DI), defined as the ratio of structural elements that fail to the total number of structural elements (Quan Luna, et al., 2011). The vulnerability value obtained are expressed in matrix form as the potential damage that a rock block causes to a building, as a function of its velocity and size. From these results, fragility curves are also produced, which express the probability of exceeding a certain limit state of the building (threshold of strain),

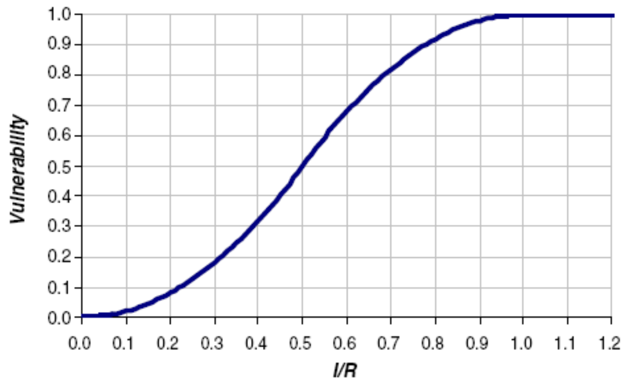
2. 3 Approaches for landslides

Several studies have been conducted on the vulnerability of built environment impacted by landslides, but no unique methodology exists for its assessment.

1) Uzielli et al. (2008) proposed a scenario-based quantitative estimation of vulnerability, in which vulnerability is defined quantitatively as a function of two parameters: landslide intensity and susceptibility of vulnerable elements. Intensity is modelled as a composite parameter, accounting for kinetic (velocity) and kinematic (absolute displacement) characteristics. For susceptibility, a tentative model accounting two factors (structural typology and state of maintenance) is proposed, which needs to be improved, refined and calibrated.

2) Remondo et al. (2008) developed a quantitative procedure for mapping landslides risk, starting from considerations on hazard, vulnerability and exposed elements. Their empirical approach is based on a detailed study and inventory of landslides occurrence and damages in last 50 years in the area of Bajo Deba (northern Spain). Past events revealed a prevalence of shallow and translational slides. Vulnerability was assessed by comparing losses with the actual monetary value for each type of elements affected (buildings, transport infrastructures and land resources) and then mapped for single-magnitude scenarios.

3) Li et al. (2010) proposed a quantitative model to evaluate the vulnerability of structures to slow or rapid landslides, accounting for the intensity of phenomenon and the resistance of the exposed elements. The quantitative definition of vulnerability varies according to the value of the ratio between intensity and resistance. Intensity is defined as a function of 2 non-dimensional factors: (i) a dynamic one, i.e. landslide velocity, and (ii) a geometric one, i.e. debris-depth for rapid landslides or deformation factor for slow landslides. The evaluation of the resistance of buildings takes into account: structural type, height, state of maintenance and depth of foundations elements.



$$V = f(I, R) = \begin{cases} 2\dfrac{I^2}{R^2} & \dfrac{I}{R} \leq 0.5 \\ 1.0 - \dfrac{2(R-I)^2}{R^2} & 0.5 < \dfrac{I}{R} \leq 1.0 \\ 1.0 & \dfrac{I}{R} > 1.0 \end{cases}$$

$$I = f\left(I_{\text{dyn}}, I_{\text{gem}}\right) \qquad R_{\text{str}} = \left(\xi_{\text{sfd}} \cdot \xi_{\text{sty}} \cdot \xi_{\text{smn}} \cdot \xi_{\text{sht}}\right)^{\frac{1}{4}}$$

Fig. 4 Theoretical changing trend of vulnerability function and relative formulas (modified from Li, et al., 2010).

4) Fotopoulou & Pitilakis (2013) developed an analytical method for assessing the vulnerability of low-rise reinforced concrete buildings subjected to seismically induced slow-moving earth

slides. The vulnerability assessment is based on fragility curves, considering as the intensity parameter the Peak Horizontal Ground Acceleration (PHGA) at the bedrock. this is a two-step uncoupled approach: at first, thanks to a dynamic non-linear finite difference slope model, differential permanent displacements are estimated; then, they are statically imposed at the foundation level, using a finite element code, to evaluate the building's response. This method, useful at the site-specific or local scales, considers mechanical characteristics of foundations and soil and the building position within the moving mass.

5) Guillard-Gonçalves et al. (2016) proposed a methodology for semi-quantitative assessment of the physical vulnerability of buildings to landslides in a Portuguese municipality (Loures). The intensity of the phenomenon, expressed in terms of destructive capacity, was evaluated not accounting for velocity, but in terms of slip surface depth and accumulated material height, because landslides affecting the study area are generally slow, very slow or extremely slow. The vulnerability assessment was based on an inquiry of a pool of European experts and a sub-pool of experts familiar with the study area for four structural building types. Vulnerability was not only evaluated building by building; also, average values for basic geographic unit were calculated, to produce vulnerability maps at the regional scale.

	Criterion	Description	Values
C1	Geomorphological proximity and situation at risk	*methodologies for evaluating the vulnerability of built environment developed and applied in regions presenting geomorphological contexts and situations at risk quite different compared to the Swiss are considered in principle less useful for a possible application to Switzerland*	HP = high proximity MP = medium proximity LP = low proximity
C2	Typology of buildings	*evaluation done according to the type of structure, material and construction rules/principles of buildings in Switzerland*	HS (nº) = high similarity MS (nº) = medium similarity LS (nº) = low similarity where (nº) = number of structure type considered
C3	Intensity of the phenomenon	*neither a universal methodology nor a unique parameter exist to identify the intensity of landslides; therefore, methods with the same or very similar choices as Switzerland for characterising landslide intensity can in principle be considered as suitable*	HS = high similarity MS = medium similarity LS = low similarity
C4	Qualitative or quantitative	*methodologies are evaluated taking into account their qualitative rather than quantitative approach*	QLT = qualitative QNT = quantitative
C5	Specific attention to every building	*since many characteristics can change from one type of building to another, methodologies will be evaluated as more or less appropriate according to their tendency to aggregate more than one type of building into the same vulnerability curve.*	ST = 1 structure type/curve MT = 2/+ structure type/curve

Table 1 Criteria description and relative values for the evaluation of vulnerability assessment methods.

3. EVALUATION OF VULNERABILITY ASSESSMENTS FOR SUITABILITY TO A SPECIFIC TERRITORY: SWITZERLAND

The next part of this study aims at formulating some suggestions to improve the vulnerability assessment procedures for the Swiss territory. This goal can be achieved by evaluating the methods and applications reviewed for each of the three gravitational hazards considered (debris flows, rock falls, and landslides) according to some specific qualitative criteria, in order to find the most appropriate vulnerability assessment approach for the Swiss territory.

In this respect, six criteria to perform the evaluation of the methods reviewed were defined as presented in Table 1.

According to the previously mentioned criteria and their possible values, the evaluation of all the methodologies described before is presented here below.

Authors (year)	**General Info**	**C1**	**C2**	**C3**	**C4**	**C5**
(Borter & Bart, 1999)	Scale & Location: Local, Switzerland Hazard dependant: YES Intensity proxy: debris height and velocity Vulnerability assessment: curves	HP	HS (6)	HS	QNT	ST
(Fuchs, et al., 2007)	Scale & Location: Local, Austrian Alps Hazard dependant: YES Intensity proxy: deposition height Vulnerability assessment: curves	HP	HS (2)	HS	QNT	MT
(Sterlacchini, et al., 2007)	Scale & Location: Local, Italy Hazard dependant: NO Intensity proxy: debris height and velocity Vulnerability assessment: punctual values	HP	-	HS	QLT	-
(Quan Luna, et al., 2011)	Scale & Location: Local, Italian Alps Hazard dependant: YES Intensity proxy: debris flow depth, impact pressure and kinematic viscosity Vulnerability assessment: curves	HP	HS (2)	MS	QNT	MT
(Ciurean, et al., 2014)	Scale & Location: Local, Italian Alps Hazard dependant: YES Intensity proxy: debris flow depth and impact pressure Vulnerability assessment: curves	HP	HS (7)	MS	QNT	ST

Authors (year)	General Info	C1	C2	C3	C4	C5
(Borter & Bart, 1999)	Scale & Location: Local, Switzerland Hazard dependant: YES Intensity proxy: impact energy Vulnerability assessment: curves	HP	HS (6)	HS	QNT	ST
(Agliardi, et al., 2009)	Scale & Location: Local, Italy Hazard dependant: YES Intensity proxy: impact energy Vulnerability assessment: curves	HP	-	HS	QNT	MT
(Mavrouli & Corominas, 2010)	Scale & Location: Local, Andorra Hazard dependant: YES Intensity proxy: Impact Energy Vulnerability assessment: matrices, damage index and fragility curves	MP	HS (1)	HS	QNT	-
(Uzielli, et al., 2008)	Scale & Location: Local, - Hazard dependant: YES Intensity proxy: slide velocity and absolute displacement Vulnerability assessment: curves	-	HS (6)	MS	QNT	ST
(Remondo, et al., 2008)	Scale & Location: Local, northern Spain Hazard dependant: NO Intensity proxy: runout distance, mass of material and velocity Vulnerability assessment: punctual values	MP	-	LS	QNT	-
(Li, et al., 2010)	Scale & Location: Local, - Hazard dependant: YES Intensity proxy: slide velocity, deformation or debris-height Vulnerability assessment: curves	-	HS (6)	MS?	QNT	ST
(Fotopoulou & Pitilakis, 2013)	Scale: Local, - Hazard dependant: YES Intensity proxy: peak horizontal ground acceleration (PHGA) Vulnerability assessment: fragility curves	MP	HS (1)	LS	QNT	-
(Guillard-Gonçalves, et al., 2016)	Scale & Location: Local, Portugal Hazard dependant: YES Intensity proxy: Slip surface depth or accumulated material height Vulnerability assessment: matrices, curves and maps	MP	MS (4)	MS	QNT	ST

Table 2 Results of the evaluation of all the methodologies for vulnerability assessment according to defined criteria ("-" = no information to evaluate according to our criteria).

4. DISCUSSION

In order to provide useful and accurate information to urban planners and local authorities involved in all the risk management process, a quantitative methodology developed for a general context (risk and geomorphology) very similar to Switzerland, and which considers different structure types can be defined as the best approach for a vulnerability assessment of built environment. Therefore, the evaluation of all the methods was in general conducted based on a simple principle: methods presenting (i) "high" (HP, HS) values for the first 3 criteria, (ii) "quantitative" for the forth and (iii) ST (one curve for each structural type) for the fifth are considered as the most suitable to Switzerland.

According to this principle, the suggestions for Swiss territory are the following:

- Debris flows → apply and validate the methodology proposed by Ciurean et al. (2014)
- Rock falls → apply the methodology currently proposed by the FOEN (Borter & Bart, 1999)
- Landslides → apply and validate the methodology proposed by Li et al. (2010)

As it can be seen in Table 2, not all the methods provide enough information to perform a complete evaluation according to the criteria defined. In some cases, no value could be attributed to a specific criterion.

Regarding debris flows, the method proposed by Sterlacchini et al. (2007) seemed the less appropriate, since the assessment is qualitative (no curves) and it does not have any reference to the structural characteristics of each building. The empirical method and the relative vulnerability curve proposed by Fuchs et al. (2007) can be interesting but it aggregates in one curve two structural types (brick masonry and reinforced concrete) which can respond differently to a debris event. Same issue for the curves proposed by Quan Luna et al. (2011), even though the idea of using three different parameters to express the intensity is innovative and interesting. Finally, between the already existing methodology of the FOEN (Borter & Bart, 1999) and the one proposed by Ciurean et al. (2014), the choice fell on the second one, which could improve the FOEN methodology, as it takes into account not only the construction material, but also the height of buildings; in addition it innovatively suggests to consider also the impact pressure as an intensity parameter.

The research of methodologies for vulnerability assessment for rock falls provided few results and the two methodologies found in addition to the Swiss one (Borter & Bart, 1999) are very interesting but not fully appropriate. Agliardi et al. (2009) proposed a very detailed numerical model of the phenomenon but, as vulnerability assessment, only one empirical curve was developed for all the buildings involved in a past event, without any distinction in terms of structural and constructive features. Mavrouli and Corominas (2010) developed an even more refined model for describing the phenomenon and the response of a building to an impact, but they focused on only one structural type. This method seemed very specific for individual buildings and not easy to reproduce and apply to different structure types. In this case, the Swiss methodology was preferred as the best option.

Regarding landslides, the methodology proposed by Remondo et al. (2008) seemed the less interesting because of its punctual vulnerability assessment (neither curves nor matrices) and the fact that it refers to a single average scenario established based on an inventory of past events. Furthermore, the focus is on shallow translational slides, which are only one part of the landslides occurring typically on the Swiss territory. A similar issue affects methodology proposed by Fotopoulou and Pitilakis (2013), which is very specific and focused on seismically induced slow-moving earth slides, a kind of phenomenon not very common in Switzerland. The most recent methodology of Guillard-Gonçalves et al. (2016) seemed at first very interesting, since it produced not only vulnerability matrices and curves, but also vulnerability maps. On the other hand, it must be remarked that the vulnerability assessment is mainly based on expert's judgement, and therefore quite subjective. Furthermore, it considered four structure types which are not well matching (medium similarity) the Swiss ones. Also the last two methods (Uzielli, et al., 2008; Li, et al., 2010) based the vulnerability assessment on several subjective coefficients, which still need to be calibrated and validated. However, they considered six structural types, corresponding to the typical Swiss ones, and they modelled vulnerability as a function of the phenomenon intensity and resistance capacity of buildings. The final choice fell on Li et al. (2010), who proposed an improvement of the methodology of Uzielli et al. (2008) and considered more parameters in the evaluation of both intensity and resistance.

Even if the evaluation was carried out based on five criteria, it was however necessary to add some subjective judgements to formulate the final suggestions. The methodologies chosen are not meant to be taken into account uncritically, but they all need to be calibrated, tested and validated on the Swiss territory, possibly using historical data from past events. A limit of this study is the lack of uniformity among the three approaches suggested, e.g. the type of structures accounted for: it is evident that, according to the hazardous phenomenon considered, vulnerability assessment cannot be the same, but it would be desirable to at least focus on the same structure types for all the three gravitational hazards. This study has to be considered a preliminary tool to propose suggestions for the vulnerability assessment method suitable to a given territory; future developments in terms of uniformity and completeness of the whole approach are planned.

5. CONCLUSIONS

This work aimed to propose some evaluation criteria of methodologies for vulnerability assessment of built environment for three types of gravitational hazards, i.e. debris flows, rock falls and landslides, in order to suggest the most suitable to a specific territory (in this case, Switzerland).

First, a collection of all the methodologies considered was presented. Then five evaluation criteria were described and applied to analyse each methodology.

The results of this evaluation show that the most suitable approaches for the Swiss territory are those of Ciurean et al. (2014) for debris flows, the FOEN (Borter & Bart, 1999) for rock falls and Li et al. (2010) for landslides. These suggestions constitute a preliminary solution to improve vulnerability assessment, in view of further developments in terms of uniformity and completeness of the whole approach.

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