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Quantification of model uncertainty in debris flow vulnerability assessment

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ABSTRACT

An appropriate treatment of uncertainties constitutes an important part of the risk assessment process. According to ISO 31000:2009, risk is the "effect of uncertainty on objectives". In order to quantify uncertainties in a risk estimate, the ambiguity in hazard, vulnerability and elements at risk need to be quantified. This paper presents a methodology to quantify uncertainty in vulnerability assessment for buildings affected by debris flow, focusing on model uncertainty. Two models for vulnerability assessment expressing the vulnerability of buildings to debris flow and the corresponding model uncertainty are proposed: The first model describes the degree of loss as a function of intensity representing uncertainty by uncertainty bands. Uncertainty bands give a good overview of the uncertainty in the model and are easy to understand by stakeholders. The second model describes the probability of exceeding different damage states as a function of intensity. This model is less intuitive, but more suitable for use in a probabilistic vulnerability assessment, as it provides a probability distribution of damage for all values of intensity. The models were developed using empirical data on debris height and degree of loss of buildings following a debris flow event in the Martell valley in South Tyrol, in August 1987. The proposed models were developed for typical South Tyrolean buildings. Although the results of the study are not transferable to other areas in the world, the model development procedure may be applied for other types of architecture and building types in different locations. The paper demonstrates the value of the proposed models as essential tools for both simple and advanced treatment of uncertainties associated with vulnerability and potential losses.

1. Introduction

Risk and the associated uncertainties are central features of geotechnical and geological engineering. Engineers can deal with uncertainty by ignoring it, being conservative, using the observational method, or quantifying it (Christian, 2004). However, estimations performed by ignoring uncertainties may be unreliable and critical scenarios may be overlooked. When using deterministic approaches, a common strategy is to make conservative estimations, i.e. to include the uncertainties in an unfavourable way to be on the safe side. Nevertheless, conservative estimations may result in exaggerated and thus un-economic mitigation measures. The observational method is most relevant for construction processes, where field measurements are made during construction and operation. In this paper, the proposed strategy is to deal with uncertainties by quantifying them. Quantification of uncertainties provides valuable information to stakeholders to support cost–benefit analyses of mitigation measures. For example, a scenario with low potential losses should not be overlooked if the uncertainties associated with the estimations are large.

Risk has three fundamental components: hazard, elements at risk and their vulnerability. In order to perform a probabilistic risk assessment, the uncertainty in all these three components needs to be assessed.

The objective of the present study is to quantify uncertainty in vulnerability assessment in order to provide decision makers with a tool that will facilitate vulnerability assessment and lead to better risk reduction strategies and actions. In literature, there is a lack of guidelines on how to treat the uncertainty associated with vulnerability models. In an effort to fill this gap this study will focus on quantification of model uncertainty. Two models for vulnerability assessment are proposed, expressing the vulnerability of buildings to debris flow and the corresponding model uncertainty. The models are based on empirical data regarding debris height and degree of loss concerning buildings after a debris flow event in the Martell valley in August 1987 in South Tyrol (Italy).

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2. Background

2.1. Terminology

The terminology used in this paper is based on the recommendations of ISSMGE Glossary of Risk Assessment (2004). Vulnerability is defined 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)".

2.2. Uncertainty within the risk assessment process

Uncertainty can be classified in many different ways. One possibility is to classify uncertainty into aleatory uncertainty, which represents the variability of the physical properties, and epistemic uncertainty, which stems from limited knowledge. The aleatory uncertainty cannot be reduced, while epistemic uncertainty can be reduced by e.g. increasing the number of tests, improving the measurement methods or evaluating calculation procedure with model tests.

Uncertainty may be also classified as input/data, model/procedure or output uncertainty, according to the stage of the vulnerability assessment it is related with (Figure 1). The input to a vulnerability model could be qualitative (described with words), semi-quantitative (ranked on a relative scale, also denoted categorical) or quantitative (described as a dimensionless number between 0 and 1, Consortium MOVE, 2010). In this paper only quantitative models are considered.

2.2.1. Review on model uncertainty characterization in geotechnical engineering

Quantification of model uncertainty is often ignored or the effect of model uncertainty is badly underestimated (Whitman, 2000). Rohmer et al. (2014) treated model uncertainty of earthquake loss models by considering different plausible models and defined the model uncertainty as the weighting of the adequacy of each model. For inclusion of model uncertainty into estimates, Nilsen and Aven (2003) suggested to employ the best model available and compensate for the error associated with the model by introducing an adjustment factor, i.e. a model uncertainty factor, which might be additive or multiplicative. Use of a multiplicative model uncertainty factor is common in geotechnical reliability analysis (Ronold and Bjerager 1992; Phoon and Kulhawy, 2005; Nadim, 2007; Lacasse et al., 2013). The model uncertainty can be characterized by a systematic comparison between respective model predictions and observed performance data (Zhang et al., 2012). The model uncertainty factor could be modelled as a random variable, quantified in terms of a mean, a standard deviation (and/or coefficient of variation) and the probabilistic density distribution that best fits the data. A mean value different from 1.0 expresses a bias in the model, while the standard deviation expresses the variability in the predictions by the model.

For vulnerability functions, however, the model uncertainty could not be represented by a single factor, since the model uncertainty varies with the intensity. Section 2.3 outlines two main types of model uncertainty associated with vulnerability curves; uncertainty bands and use of fragility curves.

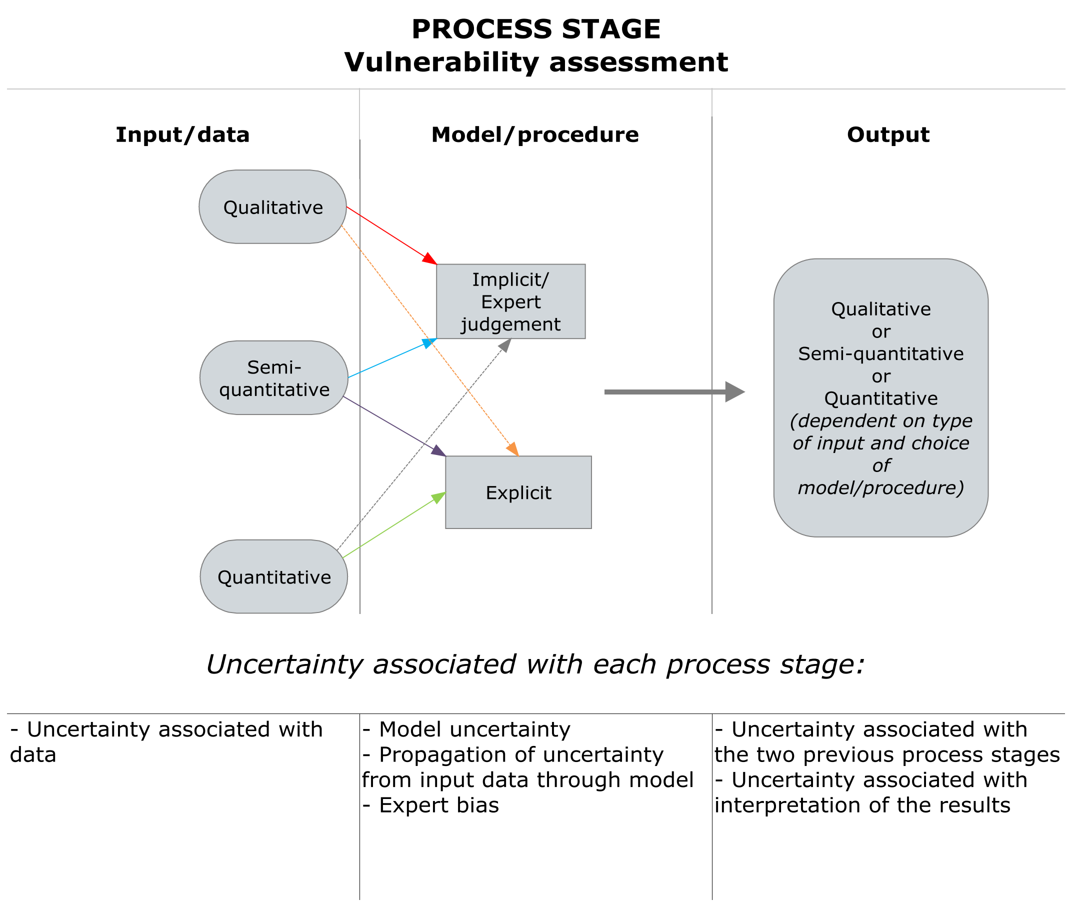

Fig. 1. Framework for classification of uncertainties within the vulnerability assessment process (Consortium MOVE, 2010). Input/data uncertainty is partly related either to real variability or to lack of knowledge. Model/procedure uncertainty is an aggregation of conceptual model uncertainty concerning how the real world is represented and abstracted e.g. through mathematical modelling and its inherent assumptions. The uncertainty in the output (i.e. the vulnerability) is an aggregation of uncertainty associated with input parameters and model uncertainty, in addition to the uncertainty associated with interpretation of the results.

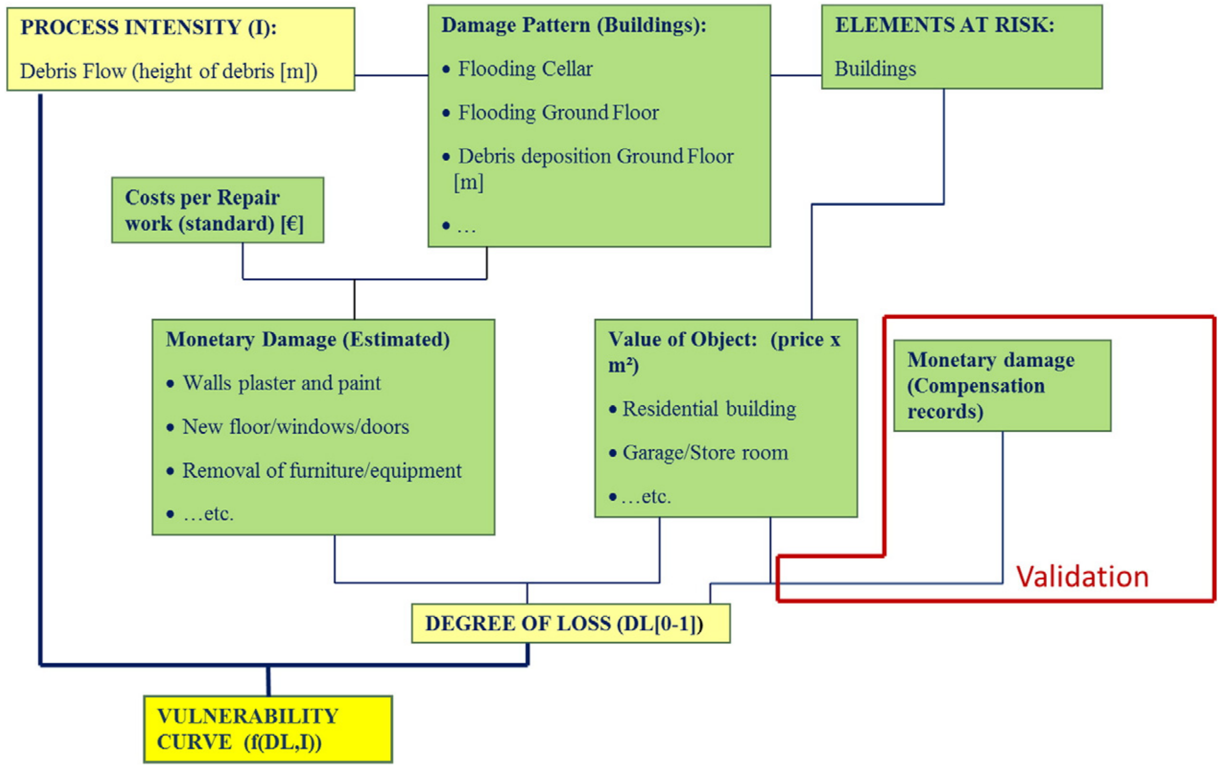

Fig. 2. The methodological steps leading to the development of the vulnerability curve (Papathoma-Köhle et al., 2012a).

Examples of uncertainty analysis related to landslide vulnerability assessment are given by Uzielli and Lacasse (2007), Kaynia et al. (2008), Uzielli et al. (2009) and Totschnig and Fuchs (2013). Totschnig and Fuchs (2013) proposed quantitative vulnerability models for debris flow and illustrated the uncertainty in vulnerability curves by confidence bands for the best-fitting function. Uzielli and Lacasse (2007) and Kaynia et al. (2008) performed simplified probabilistic estimations of vulnerability to landslides applying the first-order second moment (FOSM) approach to assess the uncertainties in the model input parameters. Uzielli et al. (2009) applied Monte Carlo Simulation to estimate the uncertainty associated with rainfall-induced landslide risk for a building.

In these studies the propagation of uncertainty from input through the model to the output has been assessed, but model uncertainty is not included explicitly.

2.3. Vulnerability models

Vulnerability models provide valuable information to local authorities, and emergency and disaster planners concerning the economic loss related to different intensity scenarios that can be used for the cost–benefit analysis of structural protection measures (Fuchs and McAlpin, 2005). As far as quantitative vulnerability assessment is

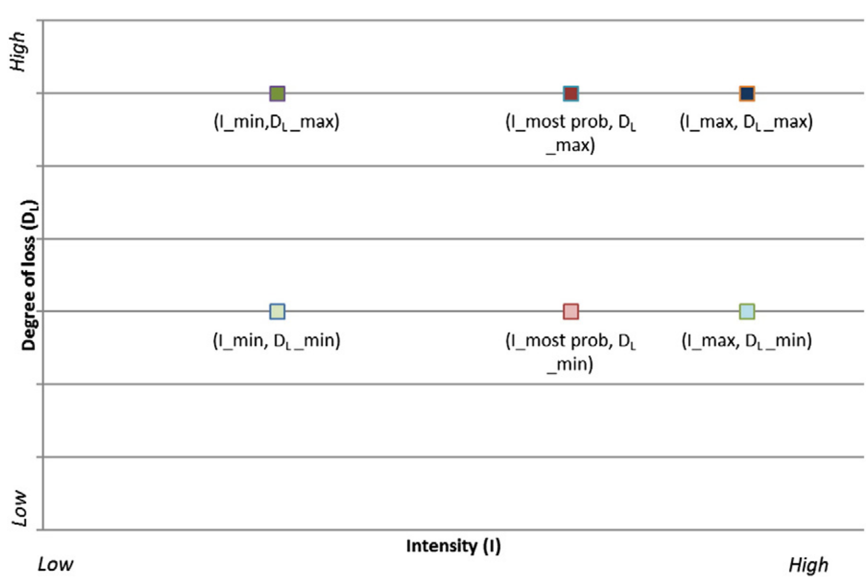

Fig. 3. Representation of one observation/data point (building) according to the 6-point data idea.

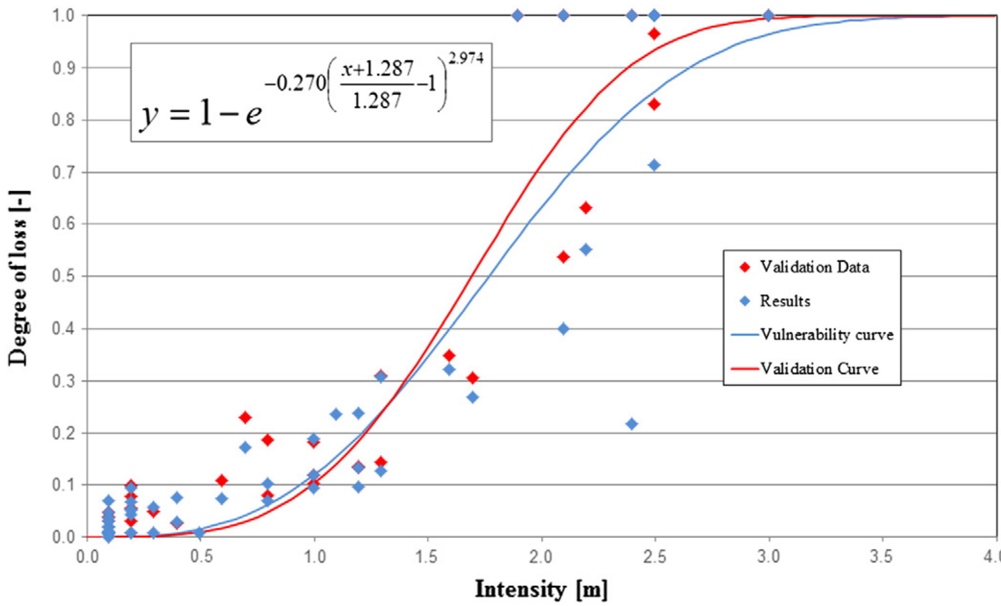

Fig. 4. The vulnerability and the validation curve developed based on data from Martell municipality in South Tyrol (Papathoma-Köhle et al., 2012a). The equation expresses the Weibull distribution where Y is the degree of loss and X is the intensity of the process, here expressed as debris height in m.

concerned, vulnerability models may be divided into two conceptually different groups:

1. Models describing the degree of loss as a function of intensity.
2. Models describing the probability of exceeding different damage states for different intensities. The definition of the damage states is a part of the model. The models are usually denoted fragility curves.

The first group of models is suitable for deterministic vulnerability assessment (i.e. that vulnerability is represented by one value) and may be used for probabilistic vulnerability assessment (i.e. vulnerability is represented by a probability distribution), when uncertainty related to the input data is included. It may also be extended to also include model uncertainty (see Section 4.2).

Papathoma-Köhle et al. (2011) reviewed a range of vulnerability assessment methodologies for alpine hazards. Studies that focus on the development of vulnerability curves for debris flow include BUWAL (1999), Romang (2004), Fuchs et al. (2007), Akbas et al. (2009), Tsao et al. (2010) and Quan Luna et al. (2011) in case studies in Switzerland, Austria, Italy, and Taiwan. In the majority of the studies, debris flow intensity was expressed as debris height. As far as information regarding the degree of loss is concerned, in most of these studies, the development of the curve was based on data provided by local authorities or insurance companies.

Most of the proposed methodologies are usually developed for a specific construction type that is common in the study area. The above mentioned vulnerability models do not consider different

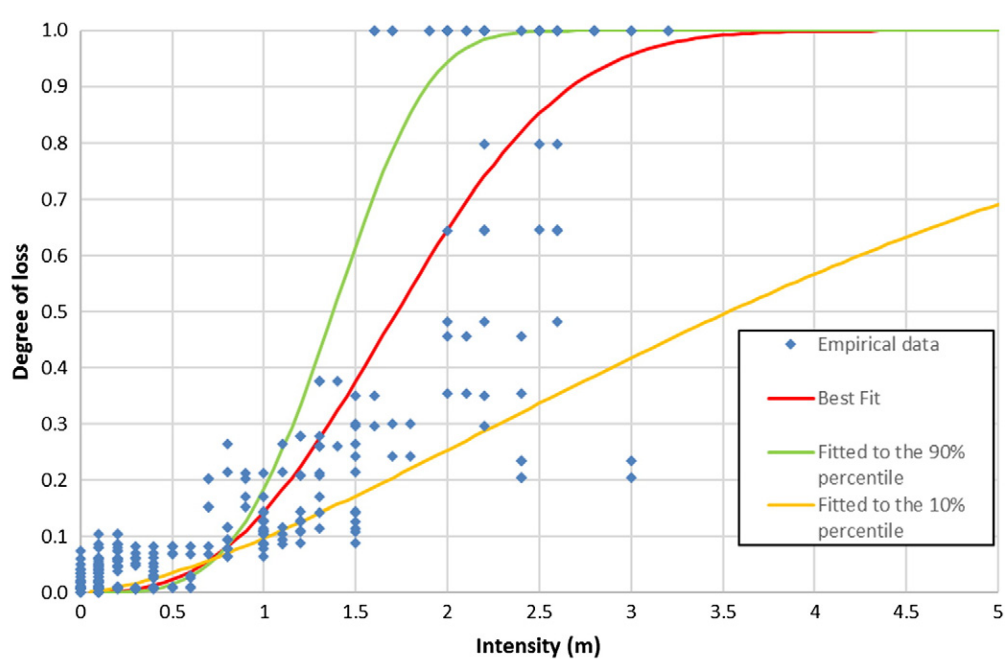

Fig. 5. Degree of loss with uncertainty bands as a function of the process intensity (debris height).

characteristics of the buildings such as number of floors, material, condition, or size. However, there are some studies that consider some characteristics of the buildings such as number of floors (Totschnig et al., 2011), material and state of maintenance (Uzielli et al., 2008) or material, height, age and depth of foundation (Li et al., 2010).

The second group of models (fragility curves) has been widely applied in probabilistic risk and vulnerability assessment, especially for earthquake risk assessment but recently also for landslide risk assessment. The methods used to estimate fragility curves can be classified into four categories – empirical, engineering judgmental, analytical and hybrid – based on the scale of the study area, the availability and quality of input data and the local technology in construction practice (Pitilakis et al., 2011).

Studies on fragility curves for landslides include Mavrouli and Corominas (2010) and Negulescu and Foerster (2010) for buildings hit by rockfalls and landslides (which cause settlement and displacements) respectively. The fragility curves incorporate uncertainty implicit, as for each intensity, the curves describe the probability of exceeding a certain damage (or a probability distribution of damage) rather than a single value of degree of loss.

3. Methodology

In the following, the development of vulnerability curves as well as procedures for uncertainty quantification is described. The assessment of model uncertainty is based on empirical data, where the first step is to represent the degree of loss and intensity including uncertainty. Two approaches for assessing model uncertainty for vulnerability are proposed: Model uncertainty with uncertainty bands and model uncertainty for use in probabilistic modelling.

3.1. Development of vulnerability curves

Vulnerability curves express the relationship between the intensity of a debris flow event (here expressed in deposit height in metres) and the degree of loss (expressed as the percentage of the total value of the building). Information regarding these two parameters can be usually acquired from process and damage documentation, modelling or interviews. In lack of such data relevant information can be also acquired from photographic documentation. In a specific study (Papathoma-Köhle et al., 2012a,b), debris flow intensity for each building was assessed by a detailed photographic documentation of a past event. The damage pattern was also assessed from photos and it was then translated into monetary value by calculating the costs of repair works that are required in order to bring the building back to its initial state. The degree of loss is expressed as a percentage of the value of the object that was lost during a debris flow event. For example if a building value is 100 000 Euros and the monetary value of the damage was calculated to be 20 000 Euros, the degree of loss was 20% (expressed as 0.2 in a 0–1 axis). Following the assessment of the degree of loss and intensity for every building that has been affected by the process, the buildings can be represented as points in an XY coordinate system and the vulnerability curve can be created (Figure 2).

The study (Papathoma-Köhle et al., 2012a) focuses on the development of a vulnerability curve without considering uncertainties. The present paper is taking a closer look on the assumption in the study of Papathoma-Köhle et al. (2012a,b), the sources of uncertainty and, finally, the data it used on the specific case study in order to analyse and quantify uncertainties associated with the vulnerability assessment process.

3.2. Representation of intensity and degree of loss including uncertainties

The most important sources of uncertainty for the empirical data points, i.e. in the representation and estimation of intensity and in the estimation of the degree of loss, are:

- Uncertainties related to the estimation of the intensity of the process:
  - The use of deposit height as the single intensity parameter (Note: The effect of velocity, direction and of duration of the water and debris staying inside the building, etc. was not considered. The model uncertainty should account for the uncertainty stemming from use of deposit height as the only intensity parameter.).
  - The assessment of intensity from photographs that were taken after the event (Note: The marks of the water and debris on the building as well as the extent of the damage may give information regarding the deposit height; however, the quality, the aspect and

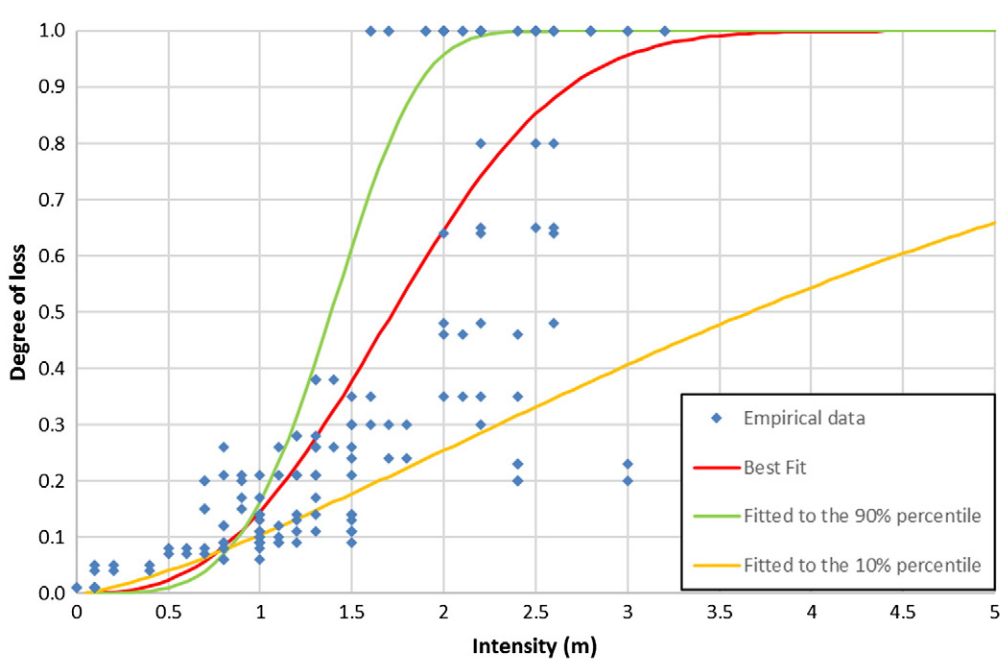

Fig. 6. Degree of loss as a function of debris height for impact related damages.

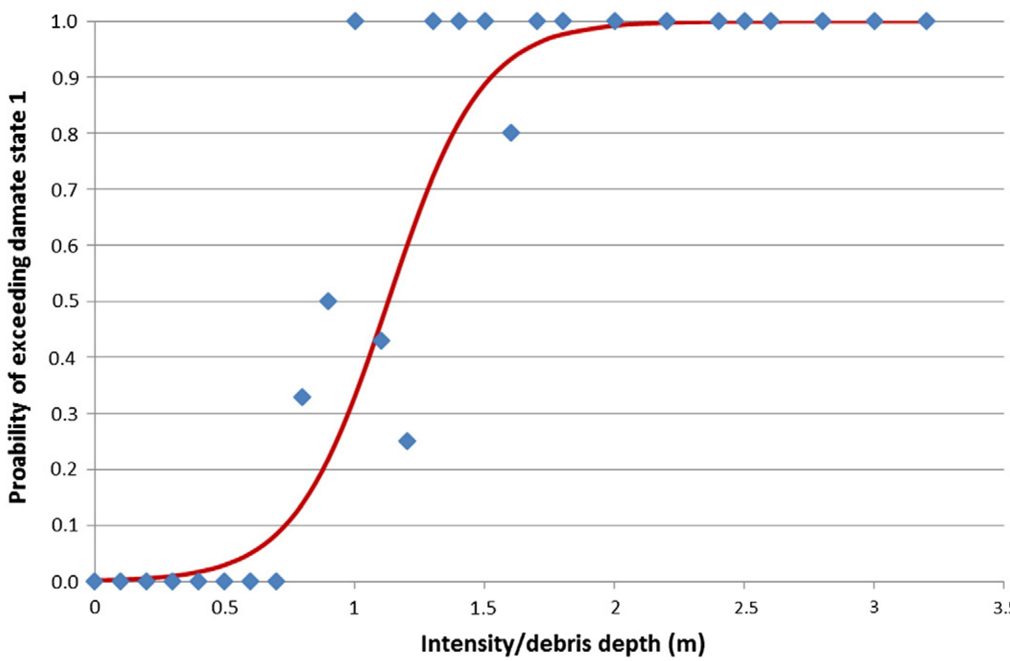

Fig. 7. The fragility curve for damage state 1. The red points are the empirical probabilities listed in Table 3, used for the curve fitting.

the number of photos per building influence the credibility and preciseness of the intensity.).

- Uncertainties related to the estimation of the degree of loss:
  - ○ Assessment of the damage pattern from photos which show mainly the external damage and not the interior damage.
  - ○ Assessment of the cost of reconstruction which was based on and modified from a list of repair costs that were developed for floods rather than debris flows.
- Uncertainties related to the estimation of the value of buildings: often the use and size of basement and attic were unknown.
- Uncertainties related to the credibility of the existing data: For some buildings there is a mismatch between the damage shown on the photo (light damage) and the received compensation (compensated for total rebuilt).

In order to include the uncertainties associated with data from affected buildings into the model uncertainty, the observed intensity for each building is described in three ways:

(1) the most probable value (*I_most prob*);
(2) the assumed minimum value (*I_min*) and
(3) the assumed maximum value (*I_max*).

Ideally, a probability interpretation for the minimum and maximum intensity values should be provided; however, since these values were obtained through expert judgement, it is very difficult to assign probability values.

The degree of loss for each building is also described in two ways

(1) the assumed minimum value (D_L*_min*): it is derived from the assessment of the building assuming that there is no basement, and
(2) the assumed maximum value (D_L*_max*): it is derived from an object value assessment considering the existence of a basement which is as large as the first floor.

The intensity and degree of loss are specified using multiple values; therefore, for each building each observation is represented by 6 data points as shown in Fig. 3. Ideally, a probability based weighting should be given to each of these points. However, the 6 point data set for each observation is the best practically achievable information from the data collection effort and the current presentation is a way to use both the probable ranges of each data point and the most probable value of intensity.

In the following paragraphs, two different models for vulnerability assessment including uncertainty are presented, which correspond to the two conceptually different groups of vulnerability models described in Section 2.3: i) a model describing the degree of loss as a function of intensity in terms of debris height. In this model the uncertainty is represented by uncertainty bands, and ii) a model describing the probability of exceeding different damage states, referred to as fragility curve.

3.3. Modelling uncertainty with uncertainty bands

Based on the empirical points with uncertainty (according to the description in Section 3.2), the procedure for establishing a model with model uncertainty can be described in the following steps:

(1) Assume a shape of the curve:The degree of loss D_L as function of the intensity, I (here debris height) was assumed to be monotonously increasing with values between 0 and 1. The following shape was assumed, i.e. the Weibull cumulative PDF (Papathoma-Köhle et al., 2012a, 2012b):

$$D_L = 1 - e^{\left({}^{-I}/{}_{a}\right)^{b}} \qquad 1$$

a and b are constants to be found by curve fitting analysis. However, other types of functions are also possible.

(2) Determine the constants a and b, i.e. find the best fit of the curve to the data. In this paper, a curve fitting routine in MatLab was applied.
(3) Plot the curve: Plot the degree of loss, D_L as function of intensity, I (debris height) with the value of the constants a and b as found in step 2. The empirical data is plot together with the curve.
(4) Find the uncertainty bands by first selecting the levels of the uncertainty bands. In this approach, the 10% and 90% percentiles

Table 1
Definition of 6 damage states.

Damage state	1	2	3	4	5	6
Degree of loss	≤0.1	0.1–0.2	0.2–0.3	0.3–0.5	0.5–0.8	>0.8

of the degree of loss were chosen as low and high estimates of the model in order to show the most probable span (A larger span could also have been used, e.g. curves fitted to the max and min of the data in each intensity interval. However, when using percentiles rather than extremes, more data points are included in the estimation, e.g. according to the 3-sigma rule for normally distributed data, which makes the procedure more robust to single, deviating observations.).
The next step is to process the data and estimate the 10% and 90% percentiles of the degree of loss for intensity intervals covering the range 0–3 m. Curves may be fitted to the 10% and 90% percentile datasets by applying the same procedure as described in steps 1–3 above.

The application of this procedure is shown in Section 4.2.

3.4. Model uncertainty for use in probabilistic modelling

In the area exposed to debris flow, the buildings suffered damages in a range of different severities. The distribution of the structural damage can be estimated from empirical data points on degree of loss and intensity (preferably formulated with uncertainty as described in Section 3.2). In order to be able to use a vulnerability model in probabilistic analyses, the model uncertainty needs to be formulated in such a way that the damage of the building may be specified as a probability distribution for each intensity. To achieve this, it is convenient to formulate the vulnerability in terms of exceedance probability functions for damage,

Table 2
Damage probability matrix of buildings for 6 damage states, based on data in Annex A.

Intensity/debris height (m)	1 (0–0.1)	2 (0.1–0.2)	3 (0.2–0.3)	4 (0.3–0.5)	5 (0.5–0.8)	6 (0.8–1.0)
0	100	0	0	0	0	0
0.1	100	0	0	0	0	0
0.2	100	0	0	0	0	0
0.3	100	0	0	0	0	0
0.4	100	0	0	0	0	0
0.5	100	0	0	0	0	0
0.6	100	0	0	0	0	0
0.7	67	33	0	0	0	0
0.8	50	33	17	0	0	0
0.9	0	100	0	0	0	0
1.0	57	43	0	0	0	0
1.1	75	25	0	0	0	0
1.2	0	66	34	0	0	0
1.3	0	40	50	10	0	0
1.4	0	0	50	50	0	0
1.5	20	40	35	5	0	0
1.6	0	0	0	0	0	100
1.7	0	0	0	0	0	100
1.8	0	0	100	0	0	0
2.0	0	0	0	21.5	7.5	71
2.2	0	0	14	14	15	57
2.4	0	0	33	67	0	0
2.5	0	0	0	0	0	100
2.6	0	0	0	12.5	37.5	50
2.8	0	0	0	0	0	100
3.0	0	0	0	0	0	100
3.2	0	0	0	0	0	100

Table 3
Amount of affected buildings where damage state 1 is exceeded for different intensities.

Intensity (m)	≤0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	≥1.5
Amount of affected buildings where damage state 1 is exceeded	0	0.33	0.5	1	0.43	0.25	1	1	1	0.8	1

i.e. fragility curves. In this section, a procedure for establishment of such curves from the empirical data is outlined.

Procedure (The reader is also referred to Section 4.3, to see the application of each of the steps below.):

1) Define damage states relevant for the observed damage in the study area.
2) Re-arrange data on debris height and degree of loss into a damage distribution matrix, showing the amount of the observed damages within each damage state for each of the observed intensities
3) For each damage state:
   a. calculate the probability of exceedance for each intensity for the current damage state
   b. Fit a fragility curve to the exceedance probability data calculated in a) as a function of intensity. The fragility function was assumed to be a monotonously increasing function between 0 and 1, expressed by the following equation:

$$P = \frac{1}{1 + e^{aI+b}}, \quad 2$$

   where P is the probability of exceeding the current damage state, I is the intensity/debris height and a and b are constants to be found in a curve fitting analysis (either by applying curve fitting routines in e.g. MatLab or by performing linear regression applying transformed, linearly related variables).

The application of this procedure is shown in Section 4.3.

4. Results: application of the methodology for Martell, South Tyrol (Italy)

4.1. Vulnerability curve for Mortell, South Tyrol (Italy)

The methodology described in Section 3.1 was applied in Martell valley, in South Tyrol (Italy). The valley of Martell, a 24 km long tributary valley to the Vinschgau valley, is one of the numerous alpine valleys of South Tyrol. The inhabitants of the valley have often suffered due to the occurrence of debris flow events in the past. One of the most severe debris flow events that the municipality of Martell has experienced with catastrophic consequences took place in August 1987.

In Fig. 4 the vulnerability curve developed using the methodology described in Section 3.1 is shown (in blue). The uncertainty in the empirical data points is not considered. The blue dots in Fig. 4 represent the buildings that were used for the development of the curve. A second curve (validation curve) has also been developed using real compensation data and is shown in the same figure (red curve). The compensation data was provided by the municipality of Martell and it is the exact amount that each building owner received in order to restore the damages caused by the debris flow following the event. These data were available only for some buildings that are represented in Fig. 4 with red dots. The visual comparison of the two curves is satisfactory (Papathoma-Köhle et al., 2012a).

Although there were no human casualties due to early evacuation, the debris flow event resulted in significant material loss. The villages

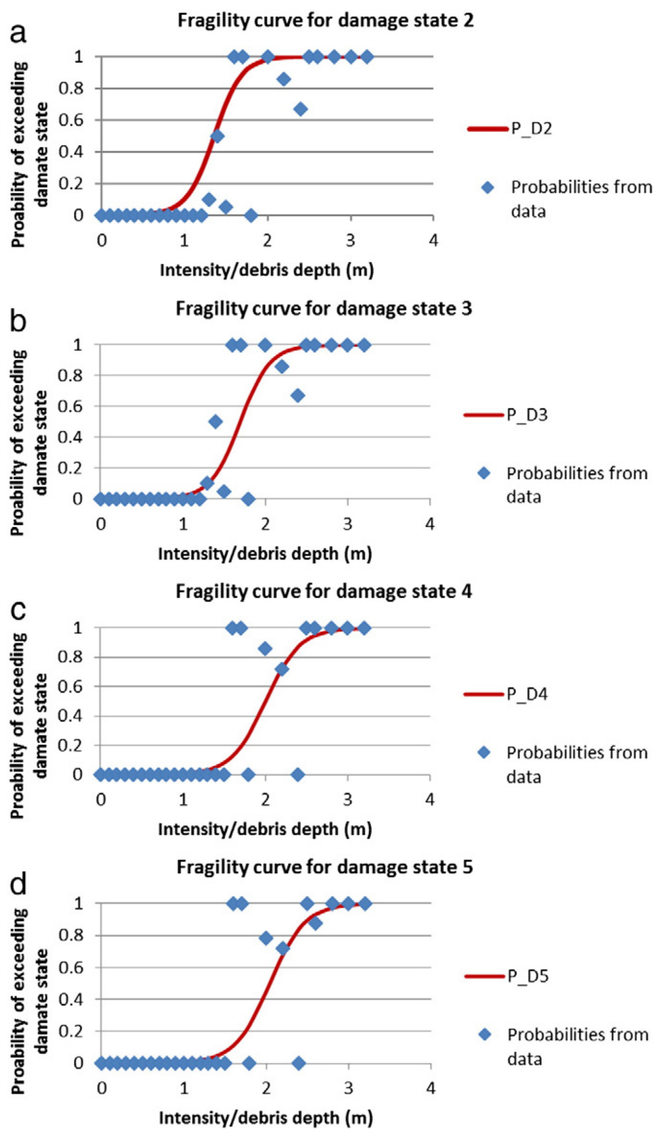

Fig. 8. Establishing fragility curves from empirical data for damage states a) 2, b) 3, c) 4 and d) 5.

of Gand, Ennewasser and Latsch suffered most of the damages as far as the built environment and infrastructure are concerned. The required data for testing the methodology were allocated by the municipality of Martell. Detailed photos of more than 50 buildings that have suffered serious damages following a debris flow event in Martell valley in August 1987 were provided. The resulting curve (Figure 4) showed clearly that the costs of reconstructing the buildings and, consequently, the degree of loss rise as the intensity of the process increases. The sudden increase of the degree of loss after the deposit height of 1 m indicates the importance of building characteristics (physical vulnerability indicators) such as the existence of windows or other openings and their height, condition and possibly size, to name a few characteristics. This kind of information derived by the specific vulnerability curve is important for the development of risk reduction and management strategies. It should be used in order to enable recommendations for building reinforcement in hazardous areas. Possible recommendations for specific objects to reduce their vulnerability could include the scrapping of windows on the slope side or the reconsideration of their design (Papathoma-Köhle et al., 2012b). However, in order to develop the curve and due to the limited data available, many assumptions had to be made which raised the uncertainties of the study significantly. Analyses of the uncertainty related to the specific study are presented in the following section.

4.2. Quantification of model uncertainty from empirical data from Martell using uncertainty bands

The outcome of the procedure described in Section 3.3 using the empirical data from the Martell debris flow event is shown in Fig. 5. This figure shows:

- The degree of loss curve obtained from best fit to the data
- A high estimate of the degree of loss, fitted to the data corresponding to the 90% percentile of the degree of loss
- A low estimate of the degree of loss, fitted to the data corresponding to the 10% percentile of the degree of loss
- The blue dots show the empirical data with 6 data points for each observation (see Annex A for data set).

Fig. 5 shows a relatively high number of data points above the curve for low intensities. This is in conflict with the assumption that low intensities result in a low degree of loss, and that the curve relating

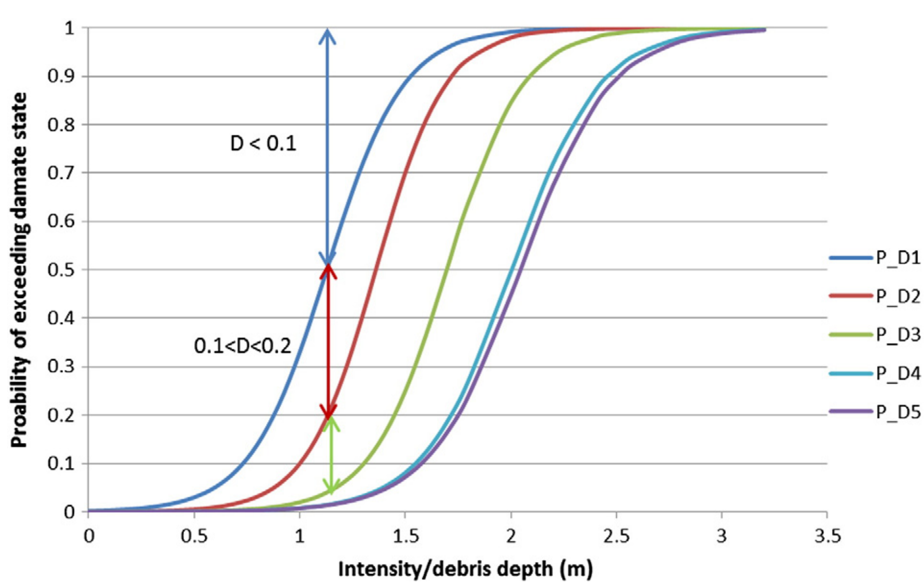

Fig. 9. Fragility curves for damage states 1–5 as a function of intensity. The arrows indicate the procedure to estimate the probability distribution for damage for one intensity.

Table 4
Calculation of probability distribution of damage for debris height I.

Damage state (degree of loss)	D1 <0.1	D2 0.1–0.2	D3 0.2–0.3	D4 0.3–0.5	D5 0.5–0.8	D6 >0.8
Probability of damage state for intensity I	$1 - P_{D1}(I)$	$P_{D1}(I) - P_{D2}(I)$	$P_{D2}(I) - P_{D3}(I)$	$P_{D3}(I) - P_{D4}(I)$	$P_{D4}(I) - P_{D5}(I)$	$P_{D5}(I)$

the degree of loss with intensity is S-shaped. This discrepancy (i.e. data points above the curve) can be explained as follows: for the data points where a relatively high degree of loss is observed for a low debris height, the damage is mainly caused by water into the cellar. An improved curve for impact-related damage could be obtained by distinguishing between damage caused by the impact and damage caused by water into the cellar. The improvement is performed in two steps:

1. A new data set is defined by removing the purely water-related damage data from the original data set (see Annex A; data points checked for the "impact-related" column).
2. A curve for impact-related damage is fitted to this new data set, using the same procedure, steps 1–4, as described in Section 3.3.

The curve for purely impact related damage is shown in Fig. 6. Fig. 6 shows:

- The degree of loss curve obtained from best fit to the data
- A high estimate of the degree of loss, developed from the data corresponding to the 90% percentile of the degree of loss
- A low estimate of the degree of loss developed from the data corresponding to the 10% percentile of the degree of loss
- The blue dots show the empirical data with 6 data points for each observation.

It is evident that the fit between this curve and the data is better than the one in Fig. 5, especially for the data with low intensity, and that the assumption of an S-shaped curve is reasonable. Properties and application of the model are discussed in Section 5.

4.3. Model uncertainty for use in probabilistic modelling for Martell

The procedure described in Section 3.4 was applied to the empirical data from the Martell debris flow event. From the data, the distribution of the structural damage for the whole affected area can be estimated. The first step is to define the damage states. Originally, 10 damage states with equal interval sizes were defined: 0–0.1; 0.1–0.2 … and 0.9–1. However, due to few empirical data for degree of loss higher than 0.5, the corresponding damage states were merged, i.e. a larger interval size was used. The interval size 0.1 was kept for damage states for degree of loss of up to 0.3 in order to not make the span of the interval too large compared to the degree of loss it represents. Smaller interval size for lower degree of loss is also applied by Quan Luna et al. (2011) who applied the following subdivision of degree of loss: Light damage 0–0.1, medium damage: 0.1–0.5, heavy damage 0.5–1 and destruction 1. The resulting 6 damage states applied in this study are shown in Table 1.

The data on debris height and degree of loss for all buildings (se Annex A) is re-arranged into a damage distribution matrix, which can be seen in Table 2. The distributions of damage (divided into the 6 damage states) are shown for each of the observed intensities. For example, for an intensity (debris height) of 0.8 m, 50% of the damages are within damage state 1; 33% of the damages are within damage state 2; and 17% of the damages are within damage state 3. For intensities less than 0.7 m, all the damages are within damage state 1, i.e. the degree of loss is less than 0.1. For intensities higher than 2.8, all the damages are within damage state 6.

The matrix shows how the amount/fraction of damages in a damage state changes with intensity.

The probability of exceeding a certain damage state increases with intensity. The fragility curves are monotonously increasing, S-shaped and with values between 0 and 1. From Table 2, the empirical exceedance probability (i.e. the percentage of affected buildings where the damage is more severe than the analysed damage state) for each damage state and intensity may be estimated. Table 3 shows the percentage of affected buildings exceeding damage state 1 for different intensities as calculated from Table 2. The data may be used to formulate fragility functions.

Fig. 7 shows the data points from Table 3 and the fragility curve fitted to these data.

The procedure illustrated for damage state 1 was repeated for damage states 2–5. Fig. 8a)–d) shows the resulting fragility curves together with the empirical probabilities used for curve fitting. The fragility curve for a certain damage state describes the probability, as a function of intensity, that the damage exceeds that damage state.

The fragility curves for damage states 1–5 (P_{D1}, P_{D2}, P_{D3}, P_{D4} and P_{D5}) are collected in Fig. 9. There is no curve for damage state 6, as it includes the total loss, i.e. degree of loss = 1 and thus cannot be exceeded. Fig. 9 also shows the calculation of damage probability distribution for any intensity from the fragility curves.

It is remarkable that the curve for damage state 5 almost coincides with the curve for damage state 4 (Figure 9). This is due to the low number of observations in damage state 5 (i.e. a degree of loss between 0.5 and 0.8); see Table 2. The curve is still included to show this trend in the data. The reason for the low number of observations in damage state 5 may be artificial, i.e. caused by the limited number of available empirical data or stemmed from a practical assessment of degree of loss (if the degree of loss is more than 0.5 a total rebuild of the building may be more practical than reconstruction of damaged parts).

The calculation of damage probability distribution for any intensity, as illustrated with arrows in Fig. 9, is shown in Table 4.

The calculation of probability distribution of damage illustrated in Fig. 9 and described in Table 4 may be used for each realization of intensity. Table 5 shows an example for intensity 1.5 m.

Table 5
Calculation of probability distribution of damage for debris height 1.5 m.

Damage state	D1	D2	D3	D4	D5	D6
Probability of damage state for intensity 1.5 m	$1 - P_{D1}(1.5)$ =0.11	$P_{D1}(1.5) - P_{D2}(1.5)$ =0.19	$P_{D2}(1.5) - P_{D3}(1.5)$ =0.45	$P_{D3}(1.5) - P_{D4}(1.5)$ =0.17	$P_{D4}(1.5) - P_{D5}(1.5)$ =0.01	$P_{D5}(1.5)$ =0.07

Table 6
Distribution of damage for 100 buildings hit by debris flow with a height of 1.5 m.

Damage state	D1	D2	D3	D4	D5	D6
Number of buildings	11	19	45	17	1	7

Even if the same information is expressed in Table 2, the procedure described in Tables 4 and 5 is to be preferred for vulnerability assessment of future possible events, because:

- It is based on the best fit to all of the empirical probabilities and is thus less sensitive to single, deviating observations,
- The procedure may be used for all intensities, also for those intensities for which no observations have been made.

5. Application of the results of the uncertainty analysis

The assessment of uncertainty is beneficial, not only because the uncertainties associated with the results can be quantified but also because possible ways to reduce these uncertainties may be highlighted. For example, in this paper, during the uncertainty assessment, the revelations of large uncertainties for low intensities in Fig. 5 resulted in an effort to reduce uncertainty by proposing a better model, for impact related damage only, as shown in Fig. 6. The focus on uncertainty is an important reminder of the limited knowledge of the processes and the need of collecting more, better and relevant data to reduce uncertainty, even if the aleatory part of the uncertainty cannot be reduced.

The results of a risk assessment may be used for various purposes such as cost–benefit analysis (e.g. the comparison of the estimated risk with costs of mitigation measures) or funding prioritisation by comparing risk estimates associated with different hazard types or for different locations. When comparing risk estimates, not only the expected values, but also the uncertainties associated with each estimate should be compared. For instance, decision makers and stakeholders may need to know whether a low estimated risk associated with large uncertainties is likely to cause higher losses than an estimated medium risk associated with minor uncertainties.

Decision makers may use a range of methods for analysing uncertainties. Each of the methods presented in this paper has its own advantages and application possibilities as shown in the following paragraphs.

5.1. Uncertainty assessment using uncertainty bands

The model described in Figs. 5 and 6 provides a best fit curve and uncertainty bands for each intensity level. The best fit curve represent the average degree of loss of the observed buildings, while the uncertainty bands show the spread and uncertainty in the data represented by observation of single buildings. The model is a tool to estimate the most probable degree of loss as well as the range of values that the degree of loss is expected to fall within, either for a single intensity value (i.e. without uncertainty) or a range of intensity values (i.e. intensity specified with uncertainty). The degree of loss may vary within the uncertainty bands when it is assessed for one building. However, when the loss estimation concerns areas consisting of many buildings, the uncertainties will be smoothed out and the uncertainty in the loss for the whole area will be smaller than the aggregated model uncertainty.

The advantage of uncertainty representation with uncertainty bands is that it provides a quick illustration of the uncertainty and it is easy to understand for stakeholders. However, the curve could be mainly applied for illustrative/orientational purposes as it specifies the ranges of the possible degree of loss, without providing the exact probability distribution for each intensity level.

5.2. Fragility curves

The curves describe the distribution of damage either for one building or for a group of buildings experiencing the same intensity. Used for a single building the curve describes the probability of loss within different damage states, while for a group of buildings the curve could be used to describe the most probable distribution of losses. Table 6 shows the most probable distribution of damage if 100 buildings were affected by a debris flow with a debris height of 1.5 m.

To include uncertainty in intensity, when applying the model, the intensity should be defined over a range of plausible values with a given probability distribution. The probability of exceeding a certain damage state could then be estimated by modelling the intensity as a random variable using Monte Carlo Simulation. The analysis consists of repeated estimations of the probability from the current fragility curve sampling from the probability distribution of the intensity. A set of simulations needs to be performed for each damage state to find the probability of all damage states. The principle of the described procedure is similar to the procedure proposed by Mavrouli and Corominas (2010).

6. Perspectives and potential improvements of the models

The observation of the drawbacks of the study is leading to a number of improvements that may enhance the reliability and results of uncertainty analysis in the future. It is for example noteworthy that within the empirical data, only a few of the observed buildings seem to have experienced a degree of loss between 0.5 and 0.8. In order to verify or to improve the fragility curves, this range of degree of loss should be analysed further, by e.g. collecting more data. The analysis of more data would explain whether the lack of data within damage state 5 is artificial or real.

In order to acquire more and detailed data that will provide us with information regarding the vulnerability of the buildings the damage assessment methods used have to be drastically improved. Papathoma-Köhle et al. (2012a) propose methods for data collection following debris flow events that can improve the quality and amount of data regarding damages of buildings affected by debris flow that can improve fragility and vulnerability curves in the future. A more detailed study of the characteristics of the single buildings could reveal which characteristics contribute most to the uncertainty. Indicators that play a major role in the interaction between the debris flow and the building are the design and shape of the building, its foundation, its surrounding, the existence of vegetation or protection measures, the static characteristics of the building, the opening of the buildings and the use of the ground floor (Papathoma-Köhle et al., 2012a,b). According to Papathoma-Köhle et al. (2012a), the presence and the location of openings that allow materials to enter the building cause a significant increase in the degree of loss. This is shown as a steepening of the vulnerability after 1 m, which is the typical height of the lowest openings on the buildings in the study. Further analysis could investigate if variation in the heights and sizes of openings facing the slope could explain some of the spread of the data. Similar analyses could be also performed for other building characteristics, where there is a variation observed among the studied buildings. The buildings used in the study are in general of the same type having several characteristics in common, such as material and shape. However, there are significant differences as far as important details are concerned, for example, the presence of surrounding walls, fence or vegetation, the presence of openings or basement and the age of the building.

The models could be refined to formulate the vulnerability as a function of the characteristics of the building, rather than only building type. Such refinements would require more data of higher detail in the damage assessment, because a variety of building indicators, as well as a variety of intensities should be represented. Eventually, the empirical data could be supplemented with data from numerical analyses, analysing systematically the effect of different building properties in a similar way as Pitilakis et al. (2011). The building indicators could finally be weighted and aggregated to serve as a resistance factor similar to the resistance factor proposed by Li et al. (2010).

Models that formulate the vulnerability as function of the characteristics of the buildings would potentially be associated with less model uncertainty because the variability in the building characteristics is one source of variability in the degree of loss. Another advantage of models that use vulnerability indicators (building characteristics) is their direct transferability. These models could be used for all types of buildings worldwide, also in cases where the dominant building types are different.

7. Conclusions

The uncertainties associated with vulnerability and risk are an aggregation of uncertainties from several sources. When comparing risk estimates, not only the expected values should be compared, but also the uncertainties associated with each estimate. The models proposed in this paper can serve as valuable tools for the quantification of uncertainty in vulnerability and potential loss estimation.

This paper clearly demonstrates how model uncertainty can be estimated from the uncertainty in the empirical data, both from the uncertainty within each data point and from the spread of the data. Two models are proposed: i) a model describing the degree of loss as a function of intensity in terms of debris height. In this model the uncertainty is represented by uncertainty bands, and ii) a model describing the probability of exceeding different damage states. For both models, the curves are assumed to be S-shaped. The plot of the curves together with the empirical data shows that this is a reasonable assumption and there is a good fit between the models and the data.

Expressing model uncertainty by using uncertainty bands is an illustrative way to express the possible range of damages for buildings affected by debris flow of different intensities. This information may be useful for stakeholders and insurance companies to predict possible losses caused by future events. However, the model does not provide a probability distribution for each intensity level.

In a fully probabilistic analysis, fragility curves are useful tools. The fragility functions developed in this paper provide a probability distribution of damage for each intensity level, which is essential information to quantify the uncertainty in potential losses. The probability distribution of damage should be combined with uncertainties associated with the hazard (probability and intensity) by using the Monte Carlo Simulation or other probabilistic methods appropriate for assessing uncertainties.

The proposed models are specific to the building type they are developed for, i.e. for typical South Tyrolean residential buildings. In this respect the vulnerability curves are not directly transferable to other parts of the world; however the methodological steps for the development of the models are transferable and could be applied anywhere in the world for different building types in another environmental context. As indicated in the previous section, the models could potentially be refined to multivariable functions of building properties and, in that way, they may be valid for all building types.

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Annex A. The dataset used for the development of the vulnerability curve in Martell valley (S. Tyrol)

House ID	Intensity (m)			Degree of loss		Impact related
	I_min	*I_max*	*I_most prob*	D_L_min	D_L_max	
1	1.7	2.2	2.1	1.00	1.00	x
2	1	1.5	1.2	0.09	0.11	x
3	2	2.8	2.4	1.00	1.00	x
4	0.8	1.1	0.8	0.09	0.12	x
5	2.2	2.6	2.5	0.65	0.80	x
6	2.2	2.6	2.5	1.00	1.00	x
7	2.2	2.6	2.5	1.00	1.00	x
8	1.6	2	1.9	1.00	1.00	x
9	0	0.2	0.2	0.06	0.07	
10	0.5	0.7	0.6	0.07	0.08	x
11	0	0.1	0.1	0.00	0.00	
12	1.5	2.2	1.6	0.30	0.35	x
13	0	0.1	0.1	0.01	0.01	x
14	0	0.1	0.1	0.01	0.01	
15	0	0.1	0.1	0.01	0.01	
16	0.8	1.5	1.1	0.21	0.26	x
17	0.1	0.4	0.2	0.04	0.05	x
18	0	0.1	0.1	0.01	0.01	
19	0.9	1.3	1	0.17	0.21	x
20	1.5	1.8	1.7	0.24	0.30	x
21	2.8	3.2	3	1.00	1.00	x
22	1.2	1.3	1.2	0.21	0.28	x
23	2	2.5	2.5	1.00	1.00	x
24	2	2.5	2.5	1.00	1.00	x
25	2	2.4	2.1	0.35	0.46	x
26	1	1.5	1.3	0.11	0.14	x
27	2	2.6	2.2	0.48	0.64	x
28	1	1.5	1.2	0.13	0.14	x
29	2.4	3	2.4	0.20	0.23	x
30	0	0.1	0.1	0.03	0.04	
31	0	0.1	0.1	0.02	0.02	
32	0	0.1	0.1	0.02	0.02	
33	0.1	0.3	0.2	0.05	0.06	
34	0.1	0.4	0.3	0.05	0.06	
35	0.1	0.3	0.2	0.01	0.01	
36	0	0.1	0.1	0.03	0.03	
37	0	0.1	0.1	0.04	0.05	
38	0	0.1	0.1	0.01	0.01	
39	0.5	0.6		0.01	0.01	
40	0	0.1	0.1	0.01	0.01	
41	1.3	1.4	1.3	0.26	0.38	x
42	0.1	0.2	0.1	0.01	0.01	
43	0.1	0.4	0.2	0.01	0.01	
44	0.3	0.4	0.3	0.01	0.01	
45	1	1.2	1	0.11	0.13	
46	0.3	0.5	0.4	0.07	0.08	
47	0.1	0.2	0.2	0.09	0.10	
48	0.1	0.2	0.2	0.05	0.06	
49	0.8	1	0.8	0.06	0.08	x
50	0.7	0.9	0.7	0.15	0.20	x
51	1	1.1	1	0.09	0.10	x
52	0.4	0.6	0.4	0.03	0.03	
53	0.1	0.2	0.1	0.06	0.08	

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