




A probabilistic approach for seismic risk assessment based on vulnerability functions. Application to Barcelona

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Abstract

Risk assessment and management is an important step towards resilient and sustainable cities. Among many other perils, both natural and manmade, seismic risk is a major threat for resilience and sustainability. In recent decades, several methods for seismic risk assessment have been proposed, including the well-known Vulnerability Index Method (VIM). In this study, a probabilistic version of the VIM, which we call the Vulnerability Index Method-Probabilistic (VIM_P), is proposed. The VIM_P requires essential information on the seismic hazard and on the vulnerability of the building stock. Seismic hazard is determined using the exceedance rates of macroseismic intensities, as defined in the European Macroseismic Scale (EMS). Seismic vulnerability is defined by means of vulnerability probability density functions (*pdf*) that describe the probability distribution of the corresponding vulnerability index. Beta-like functions are used for these *pdfs*. VIM_P quantifies seismic vulnerability by means of three vulnerability curves, *Lower*, *Best* and *Upper*, according to the quantity and quality of available information, thus allowing three estimates of seismic vulnerability and risk. Then, seismic risk is computed via the convolution of seismic hazard and seismic vulnerability, considering semi-empirical damage functions. Seismic risk is given through the exceedance frequencies of the damage grades. To highlight the capabilities of the VIM_P, the seismic risk of about 70,000 residential buildings in Barcelona was assessed. According to the results, the exceedance frequency of the collapse damage state for more than the 50% of the buildings in the *Eixample* district would be greater than 1×10^{-5} . This confirms the relatively high seismic risk in the city, mainly due to the high vulnerability of the built environment. Specific software, USERISK20015, has been developed for routine applications of VIM_P. It is hoped that VIM_P and this new tool for seismic risk assessment will be useful to stakeholders and civil protection authorities for risk management and prioritizing actions that can help to create more resilient, sustainable cities.

Keywords Seismic hazard · Seismic vulnerability · Seismic risk · Vulnerability index

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1 Introduction

The Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015) is an example of a specific initiative to increase the resilience of cities, and gives continuity to the 2005–2015 Hyogo Framework (ISDR-UN 2005). These two documents highlight the importance of knowledge of different risks in cities to increase their safety and resilience. In recent decades, a range of methods have been proposed to find out more about these risks. Table 10 in the “Appendix” summarizes some relevant procedures to compute seismic risk in urban areas. Among them, Hazus (FEMA 1999) is an outstanding methodology proposed to assess the seismic risk in urban areas of the USA. Subsequently, the Risk-UE project (Vacareanu et al. 2004; Mouroux and Le Brun 2006) was undertaken to provide a similar method for European cities. As part of this project, two standard methodologies were proposed: the Level 1 Method (LM1), which is vulnerability index-based (VIM), and the Level 2 Method (LM2), which is capacity spectrum-based (Milutinovic and Trendafiloski 2003; Barbat et al. 2006). LM1, as proposed by Milutinovic and Trendafiloski (2003), was an early version based on ongoing studies that were subsequently published (Giovinazzi 2005; Lagomarsino and Giovinazzi 2006; Giovinazzi et al. 2006; Barbat et al. 2006). LM1 itself was also based on previous methods using vulnerability indices and macroseismic intensities (Benedetti et al. 1988; Bernardini 2000; ATC-13 1985, among others). The introduction of the new European Macroseismic Scale, EMS-98 (Grünthal 1998), was also crucial for the development of LM1. The versatility and robustness of LM1 has been demonstrated in many applications in European cities, including Barcelona, Bitola, Bucharest, Catania, Nice and Thessaloniki, and in other cities worldwide (BRGM 2004; Milutinovic et al. 2004; Faccioli et al. 2004; ICC/CIMNE 2004; Kostov et al. 2004; Lungu et al. 2004; Spence and Le Brun 2006; Pitilakis et al. 2006; Kappos et al. 2008; Lantada et al. 2010; Castillo et al. 2011; Athmani et al. 2015; Guardiola-Víllora and Basset-Salom 2015; Ruiz et al. 2015; Lestuzzi et al. 2016; Cherif et al. 2016).

LM1 entails the following three steps: assessment of seismic hazard; assessment of the seismic vulnerability of the buildings; and assessment of expected damage. The main purpose of the seismic hazard module is to select a credible earthquake scenario in terms of macroseismic intensity. For each building in the risk analysis, the vulnerability module seeks to determine a vulnerability index, taking values between zero, for well-designed seismic resistant buildings, and one, for buildings with bad seismic performance. Well-established, semi-empirical functions (Giovinazzi 2005; Lantada et al. 2009a, 2010) link vulnerability and macroseismic intensity, so that a mean damage grade can be computed for each studied building. The mean damage grade and simplified assumptions on damage distribution are then used to generate damage probability matrices (DPM), which define a complete distribution of the damage in the building (five non-null damage states are considered). Finally, the expected damage and risk is computed, at whichever level is required (neighborhood, district or city), by means of a weighted mean damage index, which considers the contribution to damage of all the buildings in the studied area. Other losses linked to physical damage, such as economic cost, injured and dead people, and homeless people, can also be computed. Then, the seismic risk results can be used to generate expected damage and risk maps for selected hazard scenarios, for instance. However, up-to-date vulnerability index-based methods do not consider the significant uncertainties in the properties of the buildings, and the vulnerability indices are assessed in a deterministic way. Aguilar-Meléndez et al. (2010) proposed a new procedure, called VIM_P, which allows these uncertainties to be incorporated into the vulnerability analyses. Accordingly, the main

purpose of the present article is to describe the VIM_P in detail. The main challenges of VIM_P are: (a) to develop a complementary version of VIM that can incorporate uncertainties into the VIM, and mainly focuses on the vulnerability; and (b) to generate results, concerning seismic risk, that cannot be obtained with VIM. For instance, VIM_P allows the seismic risk to be quantified in terms of the annual rate of exceedance of loss, which is one of the most common metrics to communicate seismic risk results to stakeholders (Marulanda et al. 2013). In this article, after this introduction (Sect. 1), Sect. 2 describes the most relevant characteristics of the VIM_P (Aguilar-Meléndez et al. 2008, 2010). Section 3 summarizes the main results of the application of VIM_P to the city of Barcelona (Spain) where the seismic risk of 69,982 residential buildings is assessed. Finally, Sect. 4 is devoted to the discussion and conclusions.

2 Probabilistic VIM (VIM_P)

Like VIM, VIM_P uses five non-null damage grades: 1 (slight), 2 (moderate), 3 (severe), 4 (extensive), and 5 (collapse) (Grünthal 1998). The following equation, which was adapted from McGuire (2004), allows the annual frequencies of exceedance, ν , to be computed for each non-null damage grade, D_k .

$$\nu [D > D_k] \approx \sum_I \sum_V P[D > D_k | V, I] P[V] \gamma'[I] \quad (1)$$

$P[D > D_k | V, I]$ is the probability that damage, D , is greater than the damage grade, D_k , for a building with a vulnerability index V , subjected to an earthquake with a macroseismic intensity I ; $P[V]$ is the probability of the vulnerability index, V , and $\gamma'[I]$ is the annual frequency of exceedance of intensity, I . The symbol \approx is preferred because the annual rate, $\gamma'[I]$, is used rather than the probability $P[I]$. According to McGuire (2004), the value of $\gamma'[I]$ can be considered a “very close estimator of the probability” for values of $\gamma[I] < 0.1$. A similar criterion was summarized by Ellingwood (2006), who stated, “The annual probability and annual mean rate of occurrence are numerically interchangeable for randomly occurring events with probabilities less than 0.01/year”. In the present study, the value proposed by McGuire (2004) is taken as a reference value. Thus, in Eq. (1), the total probability theorem is applied, assuming that the intensity I and the vulnerability V are independent random variables (Aguilar-Meléndez et al. 2010).

For the operational implementation of the VIM_P, two codes are recommended: R-CRISIS (Ordaz et al. 2017) and USERISK2015 (Aguilar-Meléndez et al. 2016). R-CRISIS concerns seismic hazard and successive versions of the CRISIS code have been widely validated for Probabilistic Seismic Hazard Analysis (PSHA) (Aguilar-Meléndez et al. 2017). USERISK2015 was developed exclusively to compute seismic risk according to the VIM_P. Therefore, for identification purposes, the R-CRISIS & USERISK2015 procedure was defined to recognize the case when both codes R-CRISIS and USERISK2015 are simultaneously applied to assess seismic risk of buildings in urban areas, according to VIM_P. Figure 1 shows the main modules of this software. The R-CRISIS module is based on the Cornell–Esteva improved method (see Cornell 1964, 1968; Esteva 1968, 1969). The R-CRISIS and USERISK2015 procedure is applied in the present study to compute the seismic risk of residential buildings of Barcelona. To illustrate the method in a simplified way, only the seismic risk of two buildings is assessed in this section. However, it is important to underline that VIM_P can be used for seismic risk assessment of numerous buildings at urban level. The two case study

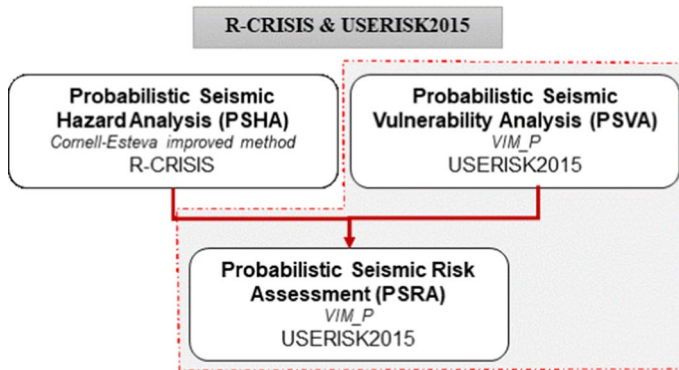


Fig. 1 Diagram of the R-CRISIS and USERISK2015 procedure. Dotted line encloses VIM_P (adapted from Aguilar-Meléndez et al. 2018)

Table 1 Main features and data of two buildings in Barcelona, Spain

Data	Building BCN1	Building BCN2
1. Structural typology	<i>Unreinforced masonry bearing walls with composite steel and masonry slabs (M33)</i>	<i>Irregular concrete frames with unreinforced masonry infill walls (RC32)</i>
2. Reliability parameter	7	7
3. Conservation state	Good	Good
4. Number of levels	2	3
5. Construction date	1970	1975
6. Soil type	Rock	Rock

buildings are named BCN1 and BCN2. Table 2 describes their main features and the data needed to apply VIM_P.

2.1 Seismic hazard

To compute the seismic risk of buildings, a seismic hazard curve is required, in terms of frequency of exceedance versus macroseismic intensities. This curve is the result of a PSHA, which can be executed using R-CRISIS. In VIM_P, at least a segment of the seismic hazard curve must be considered. The values of frequency of exceedance of the macroseismic intensities are considered in the computation of seismic risk.

For the buildings, BCN1 and BCN2 (Table 1), the seismic hazard at a rock site of Barcelona was assessed. Figure 2 shows the seismic hazard curve, which was computed by applying CRISIS2012 (Ordaz et al. 2013; Aguilar-Meléndez et al. 2013). According to this curve, the return period of VI EMS'98 macroseismic intensity is 475 years.

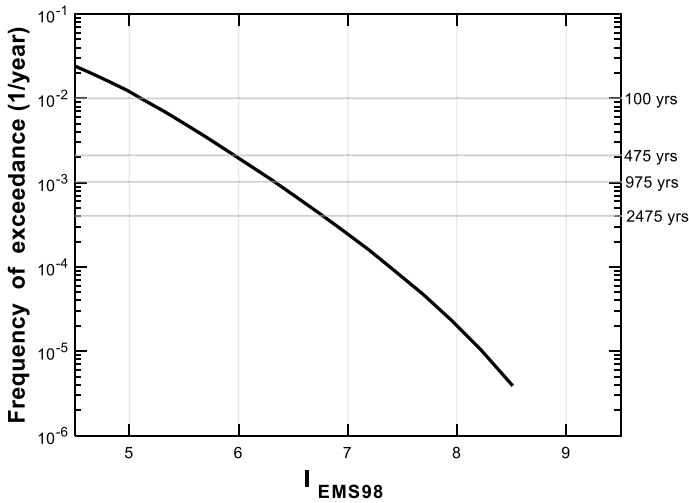


Fig. 2 Seismic hazard curve for a rock site in Barcelona (computed with CRISIS2012). I_{EMS98} are EMS'98 macroseismic intensities (Aguilar-Meléndez et al. 2013)

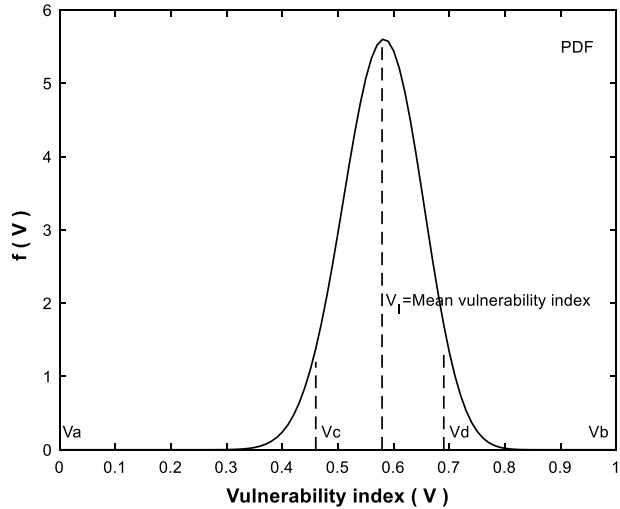
2.2 Seismic vulnerability

Seismic vulnerability is a measure related to the expected damage and structural response of a building during strong seismic ground motions. Thus, the data needed to assess the seismic vulnerability of buildings, both in the former VIM and in the VIM_P, are mainly: structural typology, number of levels, main characteristics of the structural materials, age, and conservation state. In fact, VIM_P focuses on the reliability of this information. This reliability is the basis of the process to assess seismic vulnerability in a probabilistic way.

Seismic vulnerability is described by three Beta-type probability density functions (*pdfs*) that describe the variability of a specific vulnerability index. Vulnerability indices take values in the 0–1 range, although negative values close to 0 and values slightly greater than 1 may also be allowed. One of the three *pdfs* is named the *best vulnerability curve (Best)* and it is the main representation of the seismic vulnerability of a building (Fig. 3). This *Best* curve defines the probability of the vulnerability of the building and it contains uncertainties related to knowledge of the level of its seismic vulnerability. Two additional curves can be used to consider the reliability of information on structural typology. To sum up, in VIM_P, the vulnerability of each building is represented by means of three Beta-type *pdf* functions: *Lower*, *Best*, and *Upper*.

Aguilar-Meléndez et al. (2010) found that Beta-type *pdf* functions were adequate for VIM_P purposes because of their versatility to fit a variety of shapes, even asymmetric shapes, in a restrained domain. Beta-type *pdf* functions have been used, with good results, in seismic risk assessments (McGuire 2004; ATC-13 1985; ATC-25 1991) and they are defined by means of two parameters, α and β . In the following, the main steps to set up the *Best* curve are described.

Fig. 3 Beta-type pdf, used in VIM_P to define the Best curve of seismic vulnerability



2.2.1 Best vulnerability curve

To define vulnerability curves in VIM_P, the parameters, α_m and β_m , of the beta function must be determined. Equation (2) shows the definition of these curves.

$$f(V; \alpha_m, \beta_m) = \frac{\Gamma(\alpha_m + \beta_m)}{\Gamma(\alpha_m)\Gamma(\beta_m)} \frac{(V - V_a)^{\alpha_m - 1} (V_b - V)^{\beta_m - 1}}{(V_b - V_a)^{\alpha_m + \beta_m - 1}} \quad V_a \leq V \leq V_b; \alpha_m, \beta_m > 0 \tag{2}$$

where V is the seismic vulnerability index, α_m and β_m , are shape parameters, V_a and V_b are the lower and upper limits, respectively, of the distribution, and Γ is the gamma function. Equation (2) can be expressed in terms of the following standard Beta probability function.

$$f\left(\frac{V - V_a}{V_b - V_a}; \alpha_m, \beta_m\right) = \frac{\Gamma(\alpha_m + \beta_m)}{\Gamma(\alpha_m)\Gamma(\beta_m)} \left(\frac{V - V_a}{V_b - V_a}\right)^{\alpha_m - 1} \left(1 - \frac{V - V_a}{V_b - V_a}\right)^{\beta_m - 1} \tag{3}$$

$V_a \leq V \leq V_b; \alpha_m, \beta_m > 0$

To obtain α_m and β_m , in practical cases, it is considered first that the mean value is equal to the mean vulnerability index, \bar{V}_I , when $V_a = 0$ and $V_b = 1$ (Fig. 3); and equal to $\frac{\bar{V}_I - V_a}{V_b - V_a}$, when $V_a \neq 0$ and/or $V_b \neq 1$ [Eq. (5)]. The following equation can be used to obtain \bar{V}_I .

$$\bar{V}_I = V_I^* + \Delta V_R + \Delta V_m \tag{4}$$

In this equation V_I^* is the vulnerability index of the structural typology, while ΔV_R , and ΔV_m are regional and building specific modifiers, respectively. Details on these modifiers can be found in Milutinovic and Trendafiloski (2003) and Lantada (2007). The first equation to obtain the Beta-pdf parameters is:

$$\left(\frac{\bar{V}_I - V_a}{V_b - V_a}\right) = \frac{\alpha_m}{\alpha_m + \beta_m} \tag{5}$$

Table 2 Vulnerability indices for the structural typologies of buildings BCN1 and BCN2. Taken from the Risk-UE building typology matrix (BTM) (Milutinovic and Trendafiloski 2003)

Group	Typology	Description	Representative values of vulnerability				
			V_I^{min}	V_I^-	V_I^*	V_I^+	V_I^{max}
Masonry	M33	Unreinforced masonry bearing walls with composite steel and masonry slabs	0.46	0.527	0.704	0.830	1.02
Concrete	RC32	Irregular concrete frames with unreinforced masonry infill walls	0.06	0.127	0.522	0.880	1.02

Table 3 Values of each term of Eq. (4) for buildings BCN1 and BCN2

Building	V_I^*	ΔV_R	ΔV_m	\bar{V}_I
BCN1	0.704	0.046	-0.08	0.67
BCN2	0.522	-0.022	-0.08	0.42

The second condition is that the values V_c and V_d (see Fig. 3) determine the 90% confidence interval between 5 and 95% confidence limits.

$$0.9 = \int_{y_1}^{y_2} f(y)dy = B_{y_2}(\alpha_m, \beta_m) - B_{y_1}(\alpha_m, \beta_m) \tag{6}$$

In this equation, y_1 and y_2 correspond to V_c and V_d , respectively; and $B_{y_2}(\alpha_m, \beta_m)$ and $B_{y_1}(\alpha_m, \beta_m)$ are the incomplete Beta functions (beta cumulative distribution function) for values of y_2 and y_1 , respectively.

Therefore, the procedure to estimate the Beta pdf that represents the Best curve of seismic vulnerability of a building can be summarized in four steps. Step 1) assessment of \bar{V}_I ; Step 2) determination of V_c and V_d ; Step 3) determination of V_a and V_b ; Step 4) estimation of values of α_m and β_m . The BCN1 and BCN2 buildings (Table 1) are used below to explain further details of these four steps.

Step 1: Mean vulnerability index, \bar{V}_I

For the BCN1 and BCN2 buildings, \bar{V}_I is computed according to Eq. (4). V_I^* values were taken from Table 2 (Milutinovic and Trendafiloski 2003) and ΔV_R and ΔV_m were taken from Lantada (2007). The \bar{V}_I values for the BCN1 and BCN2 buildings are 0.67 and 0.42 (see also Table 3).

Step 2: Confidence limits

The values of V_c and V_d (see Fig. 3) can be computed according to two criteria. A first simplified criterion assumes that values V_I^{min} and V_I^{max} (Table 2) correspond to values V_c and V_d , respectively. Hence, in 90% of cases, the vulnerability index, V , will take values between V_I^{min} and V_I^{max} . Noticeably, according to this criterion, V_c and V_d would be the same for all the buildings in the same structural typology. Table 2 shows these values for masonry (M33) and reinforced concrete (RC32) building types. V_I^* is the most probable vulnerability index; V_I^- and V_I^+ delimit the range of probable values of the vulnerability index. V_I^{min} and V_I^{max} increase the range of the probable values to include less probable, yet

possible, values of the vulnerability index. Thus, according to this criterion, and considering that BCN1 and BCN2 are M33 and RC32 buildings, respectively, V_c and V_d for BCN1 and BCN2 are 0.46 and 1.02, and 0.06 and 1.02, respectively.

In the second criterion, V_c and V_d are shifted according to the following equation:

$$V_c = V_I^{\min} - \Delta V_R - \Delta V_m \quad \text{and} \quad V_d = V_I^{\max} + \Delta V_R + \Delta V_m \tag{7}$$

According to this equation and Table 2, (V_c, V_d) would be (0.494, 0.986) and (0.162, 0.918) respectively for BCN1 and BCN2 buildings. Note that, in some cases, the interval (0, 1) can be expanded towards negative and positive values, thus allowing inclusion in the analysis of highly resistant and highly vulnerable buildings, respectively. Vulnerability indices greater than 1.02 may occur mainly in ancient monumental buildings (Goded et al. 2012, 2016). In the present study, the first criterion was used to fix V_c and V_d parameters.

Step 3: Vulnerability index limits

V_a and V_b , determine the range of possible vulnerability indices [see Eq. (3)]. For consistency of the VIM_P, V_a and V_b must be the same for all studied buildings, otherwise the interpretation of the results could lead to misleading conclusions. According to VIM, the vulnerability indices for most of the buildings are in the range -0.02 to 1.02 . These values correspond to the minimum V_I^{\min} and the maximum V_I^{\max} for buildings in the Risk-UE BTM (Milutinovic and Trendafiloski 2003). These values also correspond to the minimum V_c and maximum V_d , in the VIM_P. In this way, V_a and V_b must define a range wide enough to contain all the V_c and V_d indices. For the purposes of this study, and considering the results of the application of the VIM in Barcelona city (Lantada 2007), values of -0.04 and 1.04 were adopted for V_a and V_b , respectively. The following factors support this choice: (i) 90% of the vulnerability indices are in the V_c - V_d range (Fig. 3), and (ii) 100% of the vulnerability indices must fall in the V_a - V_b interval. In addition, $|V_a| - |V_c|$ and $V_b - V_d$ are equal to 0.02, which is a value similar to the increments of the most common vulnerability index modifiers (Milutinovic and Trendafiloski 2003).

Step 4: Beta pdf parameters: α_m and β_m

Parameters α_m and β_m for a specific building are computed as follows. Values of β_m between 0.1 and 8, with the desired resolution $\Delta\beta_m$, are assumed. Then, for each β_m , the corresponding α_m pair is computed by means of the following equation:

$$\alpha_m = \left(-\beta_m \cdot \frac{\bar{V}_I - V_a}{V_b - V_a} \right) / \left(\frac{\bar{V}_I - V_a}{V_b - V_a} - 1 \right) \tag{8}$$

Note that \bar{V}_I , V_a and V_b in this equation are known quantities. Then, for each (α_m, β_m) pair, the integral in Eq. (6) is computed. A least squares approach can be used to obtain the (α_m, β_m) pair that is closest to the 0.9 value. Afterwards, standard formulas can be used to compute the statistics of the Beta pdf function. The mean and standard deviation values are:

$$Mean = (V_b - V_a) \left(\frac{\alpha_m}{\alpha_m + \beta_m} \right) + V_a \quad \sigma_{\bar{V}} = \sqrt{\frac{\alpha_m \beta_m}{(\alpha_m + \beta_m)^2 (\alpha_m + \beta_m + 1)}} \cdot (V_b - V_a)^2 \tag{9}$$

This procedure was used to compute the *Best* curve for buildings BCN1 and BCN2. Table 4 shows the corresponding α_m , β_m , V_a and V_b that define these curves, which were computed using USERISK2015 according to the first criterion to determine V_c and V_d . In this table, the mean and the standard deviation are also shown.

Table 4 Best vulnerability functions for BCN1 and BCN2 buildings

Building	$V_a = -0.04; V_b = 1.04$			
	α_m	β_m	Mean	$\sigma_{\bar{V}}$
BCN1	4.43	2.31	0.67	0.18
BCN2	0.75	1.01	0.42	0.32

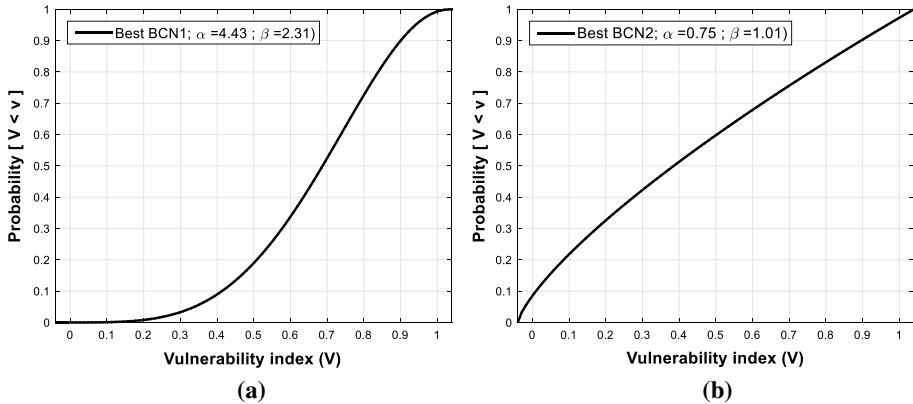


Fig. 4 Best vulnerability curves for BCN1 (a) and BCN2 (b) buildings

From the comparison of the BCN1 and BCN2 (Fig. 4) Best vulnerability curves, it follows that the probability that the vulnerability indices are greater than 0.8 are 0.273 and 0.169 for the BCN1 and BCN2 buildings, respectively. Hence, building BCN1 is more vulnerable than BCN2.

Vulnerability indices for the BCN1 and BCN2 buildings may take values in the ranges between 0.18 and 1.0, and between -0.04 and 1.04 , respectively. Mean values and standard deviations of these Best vulnerability distributions are shown in Table 4. Hence, VIM_P takes into account the considerable uncertainties in seismic vulnerability, so that seismic risk assessments also incorporate these uncertainties.

2.2.2 Lower and Upper curves

Often, it is not easy to make a clear decision on the building typology in densely populated areas. The lack of availability of information or reconstruction and upgrades of buildings after information was collected may be some likely reasons. VIM_P considers this additional uncertainty by means of a reliability parameter. Two additional vulnerability curves are considered: Lower and Upper curves. The following equation defines the new mean values of these curves.

$$\overline{V_{L-L}} = \overline{V}_I - \frac{I_f - f}{I_f} \cdot \phi \cdot \sigma_{\bar{V}} \quad \overline{V_{L-U}} = \overline{V}_I + \frac{I_f - f}{I_f} \cdot \phi \cdot \sigma_{\bar{V}} \tag{10}$$

\overline{V}_I and $\sigma_{\bar{V}}$ are the mean value and the standard deviation in Eq. (9). f is the reliability factor, which, in VIM_P, may take values in the range 0–10. These limits mean null and full

Table 5 Parameters of the *Lower* and *Upper* vulnerability curves for BCN1 and BCN2 buildings

Seismic vulnerability curve	$V_a = -0.04; V_b = 1.04$							
	BCN1				BCN2			
	α	β	f	ϕ	α	β	f	ϕ
<i>Lower</i>	2.53	2.01	7	1.96	0.27	0.81	7	1.96
<i>Upper</i>	4.1	1.31	7	1.96	1.22	0.81	7	1.96

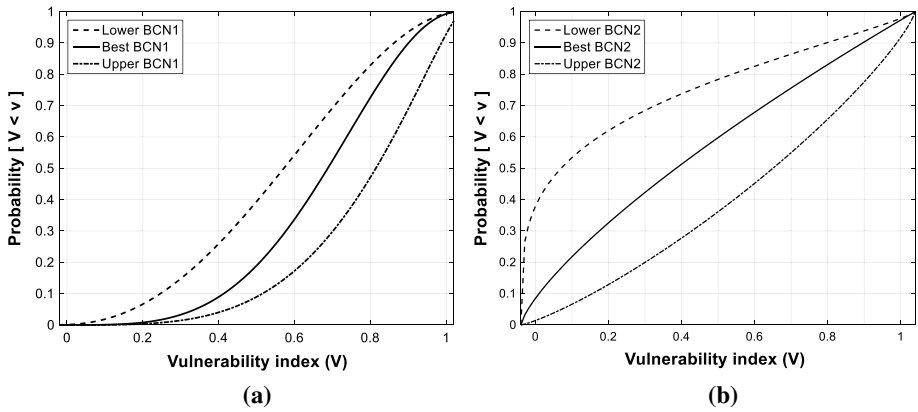


Fig. 5 Vulnerability curves for the BCN1 and BCN2 buildings

reliability, respectively. I_f and ϕ are parameters that can be defined in each case. In our case, values of 10 for I_f and 1.96 for ϕ were taken. Thus, the maximum variation of \bar{V}_I would be determined by the 95% confidence interval. V_c and V_d can be determined according to the first criterion as described above; V_a and V_b are maintained at -0.04 and 1.04 , respectively. Then, the parameters α and β are determined in the same way as for the *Best* curve. Parameters for *Lower* and *Upper* curves for the BCN1 and BCN2 buildings are shown in Table 5. Figure 5 shows the corresponding vulnerability curves. Note that $f=7$ and $\phi=1.96$ have been taken in this example.

The *Lower* curves correspond to buildings that are less vulnerable, while the *Upper* curves correspond to more vulnerable buildings.

BCN1 is more vulnerable than BCN2. The probability that the vulnerability index of BCN1 is greater than 0.6 is 45.7% for the *Lower* curve, 82.7% for the *Upper*, and 66.2% for the *Best* curve. For the BCN2 building, these probabilities are 17.45%, 54.79% and 32.11%. Noticeably, the reliability factor, f , controls the separation between these curves. For $f=10$, *Upper* and *Lower* vulnerability curves are equal to the *Best* curve. For a given reliability factor, the separation between vulnerability curves depends on the standard deviation $\sigma_{\bar{V}}$.

2.2.3 Groups of buildings

VIM_P can be used to address groups of buildings. The total probability theorem may be applied to combine the corresponding vulnerability curves. To this end, it is crucial to know the probabilities, or frequencies, of the building types whose vulnerability curves must be combined.

2.3 Seismic risk

Seismic risk is understood here as the exceedance frequency of each non-null damage grade. These frequencies are assessed by means of Eq. (1). In this equation, $\gamma'[I]$ is the annual exceedance frequency of EMS'98 intensity I , which is a result of PSHA studies in the area; $P[V]$ is the probability of the vulnerability index V and is computed using the vulnerability curves defined above. Obviously, these computations require discretizing both the vulnerability index, in the range V_a-V_b , and the intensities, in the range of likely damaging intensities. For details on how these computations are done see Aguilar-Meléndez (2011). The last quantity in Eq. (1) is $P[D > D_k|V, I]$, that is, the probability of damage D_k , given a vulnerability index V and an EMS'98 macroseismic intensity, I . VIM_P takes the following semi-empirical form linking intensity, vulnerability and damage.

$$\mu_D = 2.5 \left[1 + \tanh \left(\frac{I + 6.25\bar{V}_I - 13.1}{2.3} \right) \right] \quad (11)$$

In this equation,¹ μ_D is the mean damage grade, which takes values between zero and five. Then, probabilities of a specific damage grade, D_k , can be easily obtained assuming that the expected damage follows a binomial or Beta-equivalent distribution (Grünthal 1998). Equation (11) was proposed in the framework of the Risk-UE project (Milutinovic and Trendafiloski 2003; Giovinazzi 2005; Lagomarsino and Giovinazzi 2006; Barbat et al. 2006). The details on how the binomial-equivalent Beta distribution is obtained and how these specific probabilities of the damage grades, D_k , are computed are well-explained in these references (see also Lantada 2007; Lantada et al. 2009a, 2010). The most valuable feature of VIM_P is the representation of vulnerability through probability distributions, thus making it possible to obtain seismic risk in terms of the exceedance rates of the damage states.

2.3.1 Individual buildings

The USERISK2015 software implements the above procedure and was used to compute the seismic risk of BCN1 and BCN2 buildings. The seismic hazard at a rock site of Barcelona (Fig. 2), truncated to 475 years, was used for $\gamma'[I]$. The *Lower*, *Best* and *Upper* vulnerability curves were used for vulnerability indices. The results obtained are shown in Fig. 6. The exceedance frequencies of damage grade 4 for the *Lower*, *Best* and *Upper* vulnerability curves are respectively 6.40×10^{-6} , 9.68×10^{-6} , and 3.19×10^{-5} for BCN1, and 7.44×10^{-6} , 1.08×10^{-5} , and 2.7×10^{-5} for BCN2.

An important discussion in risk analysis is *acceptable risk*, that is, the level of risk that society would accept. McGuire (2004) suggests that a criterion of acceptable risk for a residential building would be that the exceedance rate of the damage grade 4, *Extensive*, is lower than 1×10^{-5} . Then, BCN1 would not fulfill this criterion for the *Upper* risk curve nor BCN2 for the *Best* and *Upper* risk curves. Thus, one strength of VIM_P is that the consideration of uncertainties in the vulnerability indices and the reliability factor allows us to

¹ Note that Eq. (11) is deterministic. The development of a specific probabilistic damage function is an improvement of VIM_P that is pending, to become a fully probabilistic approach.

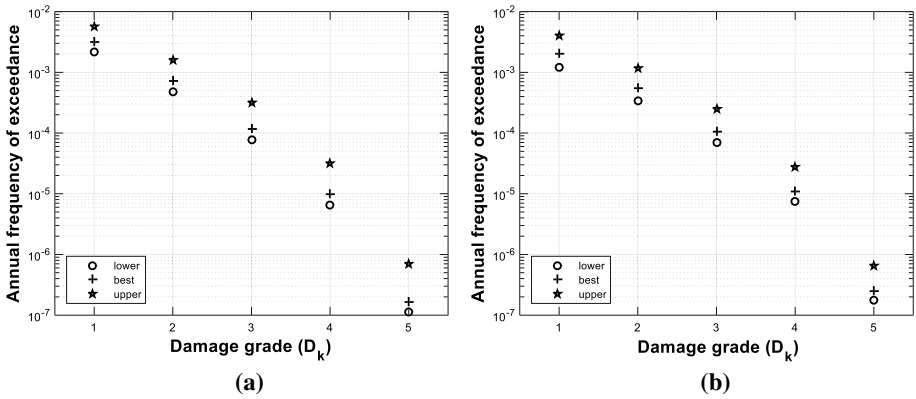
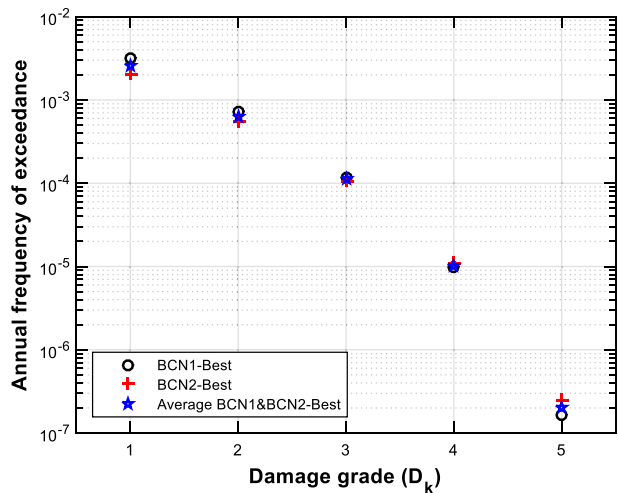


Fig. 6 Seismic risk curves of BCN1 (a) and BCN2 (b) buildings

Fig. 7 Best individual and joint risk curves for the BCN1 and BCN2 buildings. See Table 6 for the values of the joint curve



propose three risk estimates in a probabilistic environment, thus offering stakeholders more and richer information for decision-making.

2.3.2 Group of buildings

The seismic risk of a group of buildings can be assessed based on the total probability theorem. That is, an additional weighted sum should be considered in Eq. (1), to take into account the contributions to risk of the typologies and buildings included in the analysis. In the simple case of two buildings, the joint risk curve would be the mean of the two individual curves. Individual and mean curves for BCN1 and BCN2 *Best* curves are shown in Fig. 7. The values of the mean curve are given in Table 6.

Table 6 Joint *Best* risk curve for BCN1 and BCN2

<i>Best</i> curve of seismic risk	$\nu [D \geq D1]$ [1/year]	$\nu [D \geq D2]$ [1/year]	$\nu [D \geq D3]$ [1/year]	$\nu [D \geq D4]$ [1/year]	$\nu [D = D5]$ [1/year]
BCN1 and BCN2	2.58E-3	6.30E-4	1.11E-4	1.02E-5	2.05E-7

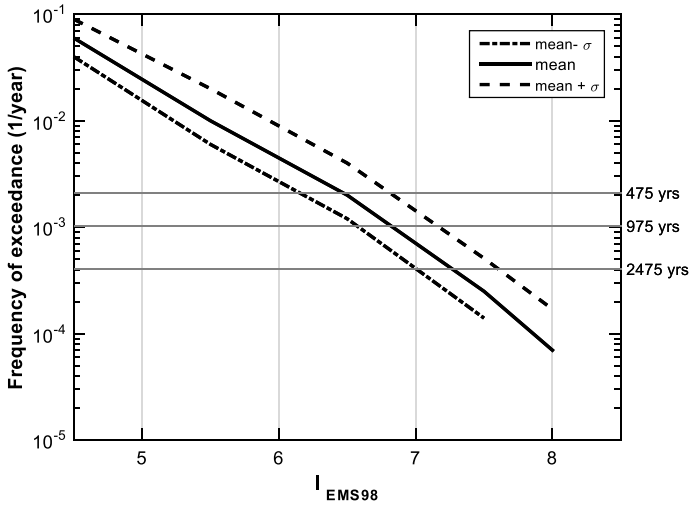


Fig. 8 Seismic hazard curves of Barcelona city (rock site) (adapted from Secanell et al. 2004)

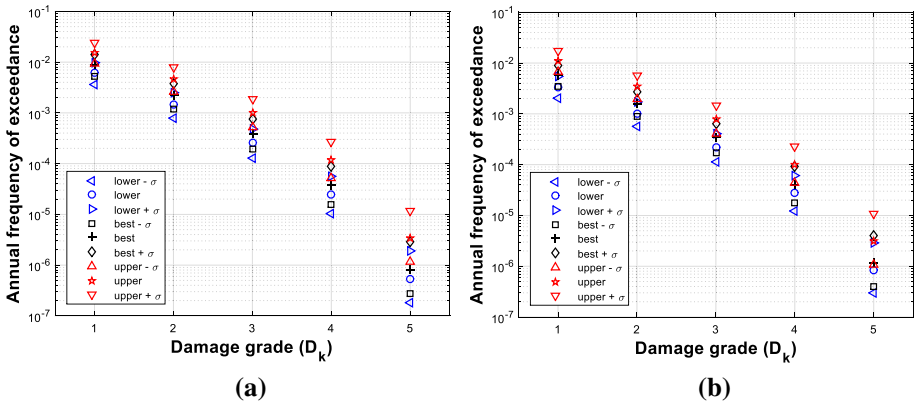


Fig. 9 Seismic risk curves of building BCN1 (a) and BCN2 (b). See explanation in the text

2.3.3 Seismic hazard uncertainties

Uncertainties in hazard curves from PSHA is another important subject of discussion. In fact, many ground motion predictive equations include dispersion parameters to deal with uncertainties (Douglas 2018). Thus, an important issue is the pertinence of representing the

seismic hazard by means of a single curve, or by means of several hazard curves (Marzocchi et al. 2015). In any case, VIM_P allows the use of single and multiple hazard curves. By way of example, let us consider the hazard curves of Fig. 8.

These curves were adapted from the hazard curves for Barcelona at rock sites, developed by Secanell et al. (2004). VIM_P allows an output of three risk curves for every hazard curve. Figure 9 shows these nine seismic risk curves for the BCN1 and BCN2 buildings. Hence, VIM_P and its companion software, USERISK2015, are powerful and versatile tools that can be used to consider the reliability of the assignment of structural typology and uncertainties in the vulnerability and hazard assessment. When adequately fed with proper data and information, USERISK2015 should generate rich and valuable documentation on seismic risk in urban areas that is useful for stakeholders and in particular for civil protection services and earthquake emergency planning.

3 Application to Barcelona

To highlight the applicability and potential of VIM_P, the main results of a probabilistic seismic risk study in Barcelona, using USERISK2015, are shown and discussed in this section. Special attention is devoted to the quantity and quality of data used.

3.1 Probabilistic seismic hazard

A specific new study of the seismic hazard of the city was performed. For this purpose, the R-CRISIS program (Ordaz et al. 2017) was used. The PSHA was made based on macroseismic intensities, according to updated catalogues. The seismic sources were defined taking into account previous seismic hazard studies in Spain and in Catalonia, northeastern Spain, where Barcelona is located. Doubly truncated seismic intensity occurrence laws (Goula et al. 1997; Ordaz et al. 2015) were used in each seismic source. The ground motion predictive equations (attenuation relationships) of López-Casado et al. (2000) were used for both high attenuation and low attenuation zones. Among other attenuation laws, these were preferred because they were obtained using macroseismic intensities. The results show good agreement with previous PSHA studies performed by Goula et al. (1997) and Secanell et al. (2004). The 475 years return period intensity is VI–VII (6.5), which means that we are dealing with a relatively low seismic hazard area. Moreover, the soil effects were included in the analyses according to the guidelines proposed by Lantada (2007). Two extreme hazard curves are shown in Fig. 10, corresponding to the rock site and the soft soil sites (dotted curve) in Barcelona. For comparison purposes, these soil classes are similar to Class A and Class C–D, respectively, as defined in euro code EC08. Further details on this PSHA can be found in Aguilar-Meléndez (2011) and in Aguilar-Meléndez et al. (2013).

3.2 Building database

Barcelona City Council provided a comprehensive database with detailed information about all the buildings in the city. Among many other aspects, the information included all the cadastral plots, built plots, the typology and age of the built plots, and built plots occupied by people counted in the census (dwellings). This information was structured according to the main administrative divisions of the city. Thus, it was available for what are known as small query zones (ZRP from Zones de Recerca Petites, in Catalan), which are

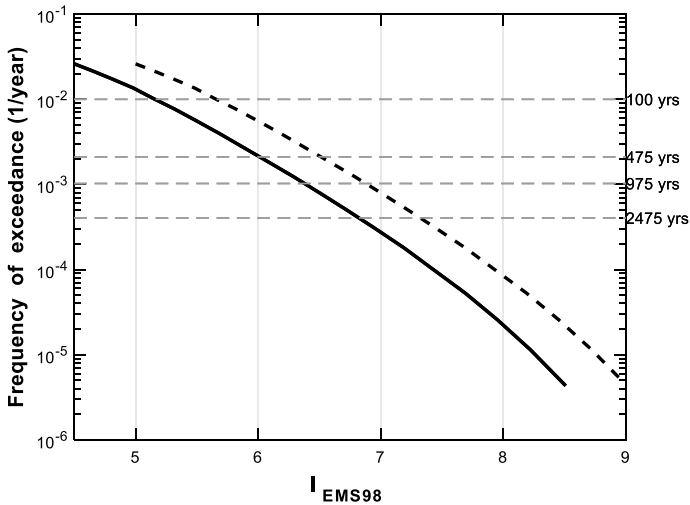


Fig. 10 Seismic hazard curves for Barcelona at the bedrock site (continuous line) and at soil sites (dotted line). Selected return periods are indicated

similar to census areas, for the 28 neighborhoods and 10 districts. Therefore, a detailed vulnerability study could be performed at the required level: individual building, city block, ZRP, neighborhood, district, or whole city.

Other information that is sensitive to vulnerability, such as the conservation state and date of the last renovation, was also available. Hence, Barcelona is an excellent benchmark for vulnerability and risk assessments. Concerning the buildings considered in the analyses, Barcelona has 78,668 cadastral plots, 71,256 (90.6%) of which are built. Information about typology is available for 70,137 (98.4%) of these buildings. Buildings of a known age and typology number 69,982, that is, over 98% of the buildings in the city. The risk analysis was performed for this group of buildings, because it allows good quantification of vulnerability. Noticeably, 83.6% (58,481) of the last set of buildings were dwellings occupied by people in the city census.

3.3 Seismic vulnerability

USERISK2015 (Aguilar-Meléndez et al. 2016) was used to compute three seismic vulnerability curves for each one of the 69,982 buildings under study. These curves were then used to compute seismic risk. Mean vulnerability functions were obtained for all Barcelona. In spite of the high quality of the available data, to illustrate the potentiality of VIM_P, a reliability factor of 7 was used. Figure 11 shows the *Low*, *Best* and *Upper* vulnerability curves. Table 7 contains their corresponding parameters. The mean vulnerability index for the *Best* curve is 0.79. In addition, the probability that a building in Barcelona has a vulnerability index greater than 0.8 would be 42.71%, 70.78% and 56.86% if the *Lower*, *Upper* and *Best* vulnerability functions are adopted, respectively. These values confirm the high vulnerability of the buildings of Barcelona, as also found in previous deterministic studies (Lantada 2007).

Fig. 11 Lower, Best and Upper mean vulnerability curves for Barcelona (adapted from Aguilar-Meléndez et al. 2018)

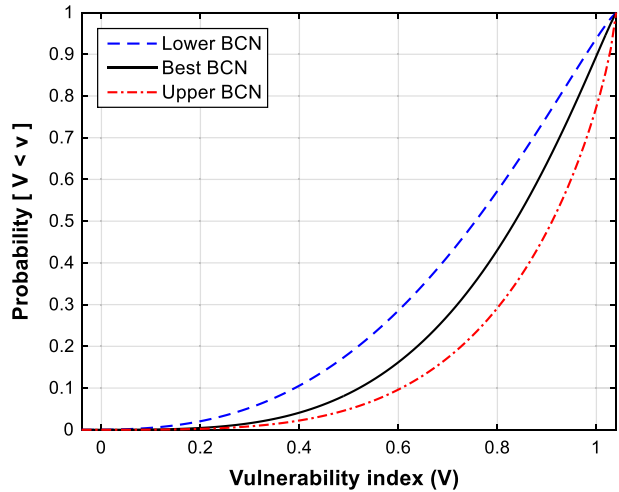
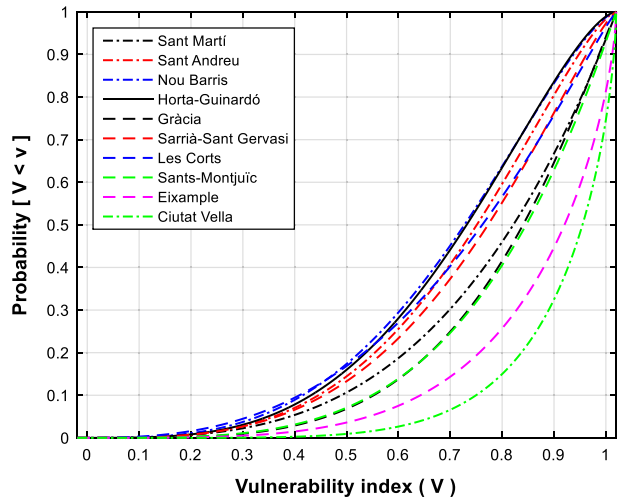


Table 7 Parameters of the mean vulnerability curves of Fig. 11 (Aguilar-Meléndez et al. 2018)

Seismic vulnerability curve	α	β	Mean	SD
$V_a = -0.04; V_b = 1.04$				
Lower	2.76	1.18	0.72	0.22
Best	3.73	1.10	0.79	0.19
Upper	3.75	0.76	0.86	0.17

Fig. 12 Representative curves of the Best seismic vulnerability of residential buildings in the 10 districts of Barcelona



In a similar way, vulnerability curves were determined for the ten districts of Barcelona. Figure 12 depicts the Best vulnerability curves and Table 8 contains the corresponding parameters.

Table 8 Parameters of the *Lower*, *Best* and *Upper* vulnerability curves for the ten districts of Barcelona. The vulnerability limits are maintained at $V_a = -0.04$ and $V_b = 1.04$ (adapted from Aguilar-Meléndez et al. 2018)

N	District	<i>Lower</i>		<i>Best</i>		<i>Upper</i>	
		α_L	β_L	α_B	β_B	α_U	β_U
1	Ciutat Vella	3.85	0.63	5.62	0.64	5.65	0.49
2	Eixample	2.69	0.69	3.92	0.67	4.10	0.53
3	Sants-Montjuïc	2.70	1.04	3.84	1.01	3.83	0.68
4	Les Corts	2.12	1.26	2.78	1.12	2.89	0.75
5	Sarrià-S. G.	2.55	1.37	3.43	1.28	3.42	0.86
6	Gràcia	2.91	1.13	4.07	1.09	3.99	0.72
7	Horta-G.	2.94	1.79	3.67	1.60	3.65	1.08
8	Nou Barris	2.81	1.77	3.40	1.52	3.47	1.04
9	Sant Andreu	2.79	1.60	3.61	1.46	3.61	0.98
10	Sant Martí	2.30	1.04	3.19	0.98	3.15	0.63



curves are considered.

Fig. 13 Maps of probability that the vulnerability index, V , is greater than 0.8 for dwellings in the *Eixample* district. The cases of *Lower*, *Best* and *Upper* vulnerability curves are shown

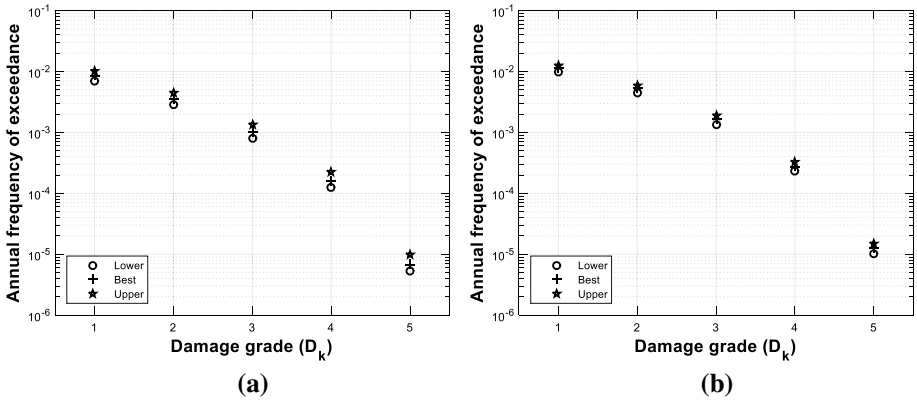
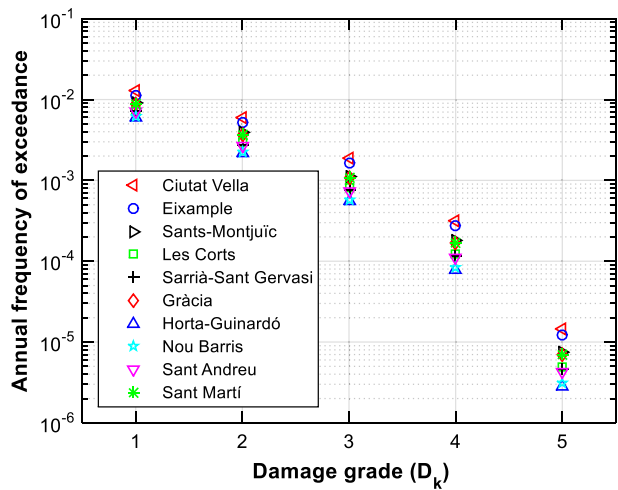


Fig. 14 Seismic risk curves for Barcelona (a) and for the Eixample district (b)

Fig. 15 Average seismic risk curves (*Best*) for residential buildings in the ten districts



The highest vulnerability was obtained for the *Ciutat Vella* (old city) district, which is the location of the oldest buildings in the city. The vulnerability patterns for the ten districts are also in agreement with previous vulnerability studies in the city (Lantada 2007; Lantada et al. 2009a, b, 2010; Marulanda et al. 2013).

USERISK2015 outputs, together with Geographical Information Systems (GIS), can be used to generate vulnerability and other thematic maps. As an example, Fig. 13 shows the probability that the vulnerability index is greater than 0.8 for the *Eixample* district. The cases of the *Low*, *Best* and *Upper* vulnerability curves are shown. These results confirm the high vulnerability of buildings in this important district of the city.

3.4 Seismic risk

The USERISK2015 code has also been used to assess seismic risk. The seismic hazard curves of Fig. 10 for rock and soil sites were used to this end. Three seismic risk curves, corresponding to the *Lower*, *Best* and *Upper* cases, were computed for each building under

Table 9 Exceedance frequencies of damage states for the entire city and for four districts

Urban section	Vulnerability curve	$\nu(D \geq D1)$	$\nu(D \geq D2)$	$\nu(D \geq D3)$	$\nu(D \geq D4)$	$\nu(D = D5)$
		[1/years]				
Overall Barcelona city	<i>Lower</i>	7.05E-03	2.83E-03	8.01E-04	1.26E-04	5.24E-06*
	<i>Best</i>	8.47E-03	3.50E-03	1.01E-03	1.61E-04	6.72E-06*
	<i>Upper</i>	1.02E-02	4.48E-03	1.35E-03	2.25E-04	9.87E-06*
Ciutat Vella district	<i>Lower</i>	1.18E-02	5.37E-03	1.65E-03	2.78E-04	1.23E-05
	<i>Best</i>	1.30E-02	6.06E-03	1.89E-03	3.20E-04	1.43E-05
	<i>Upper</i>	1.41E-02	6.77E-03	2.17E-03	3.76E-04	1.72E-05
Eixample district	<i>Lower</i>	9.92E-03	4.45E-03	1.36E-03	2.29E-04	1.02E-05
	<i>Best</i>	1.14E-02	5.22E-03	1.62E-03	2.75E-04	1.23E-05
	<i>Upper</i>	1.26E-02	5.93E-03	1.87E-03	3.22E-04	1.46E-05
Horta-Guinardó district	<i>Lower</i>	4.70E-03	1.58E-03	3.86E-04	5.31E-05	1.91E-06*
	<i>Best</i>	6.06E-03	2.15E-03	5.45E-04	7.73E-05	2.84E-06*
	<i>Upper</i>	7.90E-03	3.10E-03	8.59E-04	1.32E-04	5.40E-06*
Nou Barris district	<i>Lower</i>	4.76E-03	1.59E-03	3.89E-04	5.35E-05	1.92E-06*
	<i>Best</i>	6.28E-03	2.25E-03	5.78E-04	8.29E-05	3.09E-06*
	<i>Upper</i>	8.29E-03	3.31E-03	9.34E-04	1.47E-04	6.08E-06*

*Cases where the annual frequency of exceedance of the damage state 5 are lower than 1×10^{-5}

study and were used to compute representative risk curves at city and district levels. Figure 14 shows the *Lower*, *Best* and *Upper* risk curves for Barcelona and for the *Eixample* district and Fig. 15 shows the *Best* risk curves for the ten districts of the city. Table 9 shows the frequency of exceedance of damage states for the entire city and for four districts of Barcelona. The districts shown are the two with the highest risk, *Ciutat Vella* and *Eixample*, and the two with the lowest risk, *Horta-Guinardó* and *Nou Barris*.

For a building that has the mean vulnerability index of those in the entire city, the exceedance frequencies of damage five (total collapse) were lower than 1×10^{-5} . Values of 5.24×10^{-6} , 6.72×10^{-6} , and 9.87×10^{-6} were obtained respectively for the *Lower*, *Best* and *Upper* vulnerability curves (see Table 9). These frequencies were higher than 1.0×10^{-5} for the representative building for the *Ciutat Vella* and *Eixample* districts (Table 9). However, for the representative building for the *Horta-Guinardó* and *Nou Barris* districts, the frequency of occurrence of damage state five is lower than 1.0×10^{-5} (Table 9).

USERISK2015 outputs can also be used to generate seismic risk maps. Figure 16 shows the geographical distribution of the seismic risk of the *Eixample* district at plot/building scale, for the *Lower*, *Best* and *Upper* cases. The frequencies of exceedance of damage 5 in the residential buildings of the *Eixample* district are in the range $0-2.3 \times 10^{-5}$.

Strictly speaking, Fig. 14b corresponds to a building equivalent to one with the mean vulnerability curve of the buildings in the *Eixample* district; meanwhile Fig. 16 provides detailed information about the seismic risk of individual buildings in the same District. Moreover, according to the risk analysis results, the percentage of residential buildings in the *Eixample* district that have a frequency of occurrence of damage 5 greater than 1×10^{-5} are 52.68%, 56.55% and 70.07% respectively when the *Lower*, *Best* and *Upper* vulnerability curves are considered.

The results of this risk analyses reveal that the seismic risk of residential buildings in Barcelona should not be ignored. The significant risk is mainly due to the high seismic vulnerability of buildings in Barcelona.

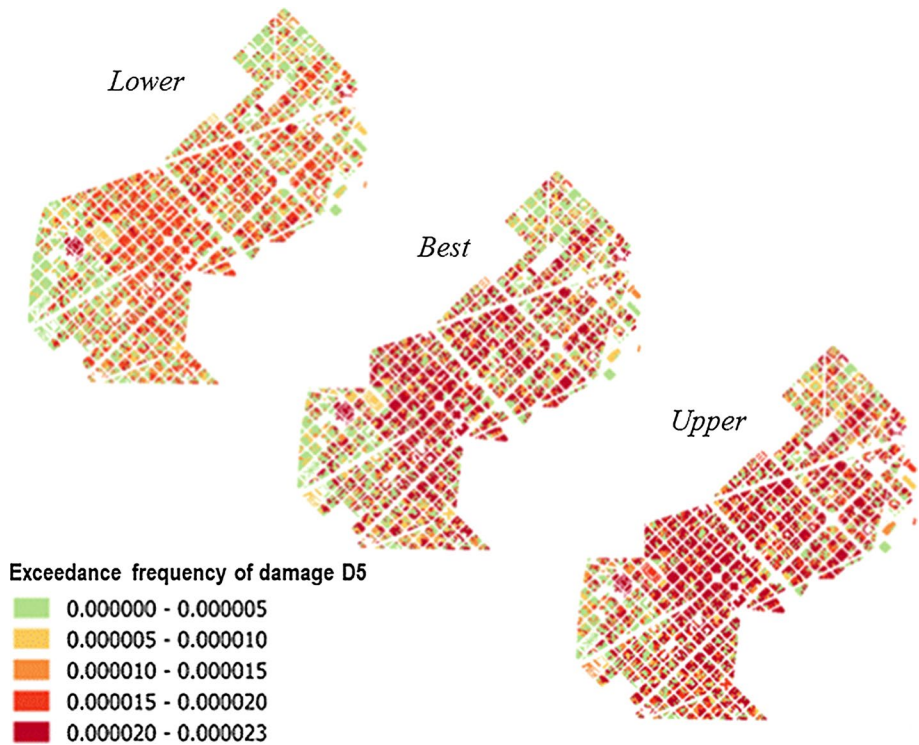


Fig. 16 Seismic risk maps of the *Eixample* district. The exceedance frequencies of the damage state 5 are mapped at building level

3.4.1 Economic cost

The main parameter to quantify the risk due to natural disasters is economic cost. Then, seismic risk results are used to appraise economic losses. According to Marulanda et al. (2013), the overall value of the total residential buildings of Barcelona is estimated to be €31,523 million.

To appraise the seismic risk of the city in economic terms, the computed exceedance frequencies of each damage grade are used. Dolce et al. (2006) proposed the following economic cost factors: 0.035, 0.145, 0.305, 0.800 and 1.000 for the occurrence of damage states 1, 2, 3, 4 and 5, respectively. Thus, these damage factors may be applied to the exceedance rates of each damage state to obtain the economic cost as a function of its exceedance rate (return period).

The cost analysis was performed at city and district levels. In addition, to see the influence of regional modifiers of vulnerability, the economic cost for the entire city was assessed with and without these modifiers. Figure 17 shows the result obtained with and without regional modifiers. The *Low*, *Best* and *Upper* curves are shown for both cases. The economic risk curve of Marulanda et al. (2013) is also shown.

For low return periods, for example less than 500 years, the risk curve of Marulanda et al. (2013) shows good agreement with the *Best* curve of our analysis when regional modifiers are not considered. Moreover, Lantada et al. (2010) estimated an overall economic cost due to earthquakes in Barcelona of €10 billion for a 475 return

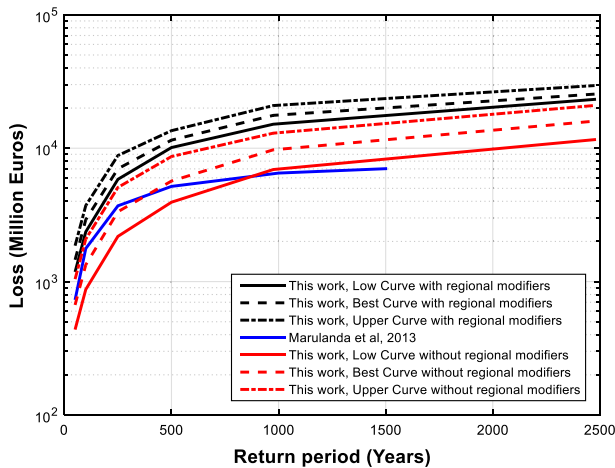


Fig. 17 Seismic economic losses for residential buildings of Barcelona

period. This cost would roughly correspond to our value for the *Best* curve, allowing for regional modifiers. The economic appraisals performed with VIM_P are richer, as they show a range between €4 and 9 billion when regional modifiers are not considered and between €9.9 and 10.3 billion when regional modifiers are taken into account.

3.4.2 Prioritizing actions

Then, the risk results were analyzed in mind that a criterion has been established to prioritize prospective actions for upgrading the seismic strength of buildings. Let this criterion be the condition that the exceedance frequency of damage state 5 is greater than 1×10^{-5} . For the building that is representative of the mean vulnerability of Barcelona, this critical value is not exceeded (Table 9), neither it is exceeded for the buildings that are representative of the districts of *Les Corts*, *Sarrià-Sant Gervasi*, *Horta-Guinardó*, *Nou Barris* and *Sant Andreu*. However, this limit is exceeded in the case of the *Eixample* and *Ciutat Vella* districts (Table 9) and in three other districts, namely, *Sants-Montjuïc*, *Gràcia* and *Sant Martí*. Moreover, concerning individual residential buildings in the *Eixample* district (Fig. 16), 52.7% have an annual frequency of occurrence of damage grade 5 above 1×10^{-5} for the *Lower* curve.

These risk results, at city, district, neighborhood and single building scales, should be used to prioritize and take decisions on vulnerability reduction, to help reduce seismic risk in Barcelona.

4 Discussion and conclusions

4.1 VIM and VIM_P

As stated above, VIM_P is an extension of VIM as proposed in the framework of the Risk-UE project in the early 2000s. The main idea of the development of VIM_P (Aguilar-Meléndez 2011) was not to substitute VIM, but rather to take advantage of the potentialities of VIM to include it in a probabilistic environment, in a relatively easy and straightforward

way. This way, an important advantage of including the seismic vulnerability of each building as a random variable into the main risk integral is that it allows to compute the seismic risk taking into account the important uncertainties involved in the seismic vulnerability of residential buildings. Thus, both methods are supplementary as many of the computations required in VIM_P are performed using VIM. In some way, VIM_P involves the repeated application of VIM. As stated in many previous studies, results obtained with VIM should be understood as averages or means. VIM_P helps to understand how disperse these results are because it incorporates uncertainties in the seismic hazard and in the vulnerability, including one related to the reliability of the assessment of building typology. Accordingly, seismic risk results are given for three possible choices, *Lower*, *Best* and *Upper*. For each of these choices, the results contain uncertainties in the seismic risk assessments. In this respect, VIM_P results are particularly useful for decision-making. In the Appendix, Table 11 highlights the main features of VIM and VIM_P methods.

4.2 Computing time

VIM and VIM_P are simplified methods that can be used to compute the seismic risk of thousands of buildings in a relatively short time (Aguilar-Meléndez 2011). For any specific building, VIM_P requires more computational time because it requires computing probability density functions that represent the seismic vulnerability and because the seismic hazard is defined by means of hazard curves giving the exceedance rates for the macroseismic intensities involved in the risk study. In fact, VIM_P requires two software packages: R-CRISIS and USERISK2015. In a standard PC² running under windows OS, USERISK2015 required about 5 h to compute the vulnerability and risk curves for each one of the 69,982 residential buildings of Barcelona. VIM required less than 1 h for a given earthquake scenario defined by means of an EMS'98 macroseismic intensity. Nevertheless, the time is considered worthwhile, considering the quantity and quality of the results that VIM_P produces in comparison to VIM.

4.3 Comparison with previous results

The results obtained with VIM_P in this study show reasonably good agreement with those obtained in previous studies (Lantada 2007; Lantada et al. 2010) using VIM. In fact, VIM is designed to compute earthquake scenarios related to a unique event defined by means of macroseismic intensity at the basement of the site. For an intensity of VI–VII in a rock site and VII in soil sites, the mean damage grade obtained by Lantada et al. (2010) for the buildings in the Eixample District is 2.03. In the VIM_P, values of 2.6, 2.75 and 2.9 are obtained for the *Lower*, *Best* and *Upper* vulnerability curves, respectively. These higher values are attributed to the contribution to damage of higher vulnerability indices involved in the *pdf* vulnerability functions, which consider the uncertainties in the vulnerability indices of the buildings. The way in which the seismic hazard is considered in VIM_P could contribute to these differences too. The seismic risk of Barcelona has been assessed by means of a Capacity Spectrum-Based Method (CSBM) also called Level Method 2 (LM2) in the Risk-UE project. Specific capacity spectra and 5% damped response spectra were developed for buildings and seismic actions respectively. A mean damage grade of 1.90 was obtained, which is close to that obtained with VIM. In addition to the reasons given to explain the differences between the results obtained with VIM and VIM_P, in the CSBM

² Processor Intel® Core™ i7-4600U CPU @ 2.10 GHz 2.70 GHz, and installed RAM of 8.00 GB.

it could also be significant that capacity spectra were developed only for selected buildings representative of masonry and RC building typologies, thus strongly smoothing the vulnerability of buildings in the *Eixample* district.

Concerning the economic cost for the 475 return period scenario, €10,000 and 9078 million were estimated with the VIM (Lantada et al. 2010) and the CSBM (Lantada et al. 2009a), respectively. Moreover, Marulanda et al. (2013) applied to Barcelona the CAPRA (Cardona et al. 2012) method and obtained an overall cost of €5172 million. VIM_P provides values of €10,116, 11,500 and 13,536 million for the *Lower*, *Best* and *Upper* cases, respectively. However, if regional modifiers are not considered, these costs are €3937, 5673 and 8663 million, respectively. As stated above, VIM_P provides slightly higher costs than VIM and CSBM, probably due to a more comprehensive evaluation of the buildings' vulnerability. The costs without considering regional modifiers, although also a little higher, are close to the results of Marulanda et al. (2013).

4.4 Conclusions

VIM has been shown to be a robust and reliable tool for seismic damage and risk assessments based on earthquake scenarios. However, strong assumptions are made on the vulnerability of existing buildings, which, after all, are considered in a deterministic way. Results in VIM are given in terms of damage scenarios so that other indirect losses can also be computed, such as economic cost, homeless and injured people, and victims. The philosophy of VIM_P aims to compute exceedance rates, which is the standard way to define risk. This way, VIM_P incorporates uncertainties in seismic hazard and vulnerability leading to probabilistic results. Somehow, VIM_P contains VIM, as VIM_P requires the application of VIM to many vulnerability indices (buildings), subjected to many earthquake scenarios. Each vulnerability index and each earthquake scenario has its probability of occurrence/exceedance. Thus, VIM_P achieves exceedance rates. In addition, VIM_P allows consideration of the reliability of the building typology, thus leading to *Upper* and *Lower* risk estimates, in addition to the *Best* estimate. With a proper combination of the vulnerability indices (VIM) and vulnerability functions (VIM_P), both methods may be applied to single buildings and to a group of buildings, thus allowing the risk analysis to be performed at whichever level is required.

Despite the low-to-moderate seismic hazard of Barcelona, the application of VIM_P confirms the significant seismic risk of the city as revealed by previous studies. This relevant seismic risk is mainly due to the high vulnerability of the buildings. The *Ciutat Vella* and the *Eixample* districts contain the most vulnerable buildings, and are the most vulnerable districts in the city. The versatility of VIM_P together with the wealth of results VIM_P can provide makes this method an excellent tool for risk management and for prioritizing actions that contribute to seismic risk reduction, particularly in highly populated urban areas.

Acknowledgements This study was made possible by the support of the Barcelona Supercomputing Center (BSC), CONACyT, and the Universidad Veracruzana. The research was partially funded by the Ministry of Economy and Competitiveness (MINECO) of the Spanish Government and by the European Regional Development Fund (ERDF) of the European Union (EU) through projects with references CGL2011-23621 and CGL2015-65913 -P (MINECO/ERDF, EU).

Appendix

See Tables 10 and 11.

Table 10 Relevant methodologies for seismic risk assessment in urban areas (adapted from Aguilar-Meléndez 2011)

Methodology	Hazard	Vulnerability	Risk	Computer codes
ATC-13 (1985)	In terms of MMI	Implicit in the damage probability matrix (expert opinion)	Damage probability matrices (DPM) (expert opinion)	None*
GNDT II (Benedetti et al. 1988)	In terms of PGA	Vulnerability index (with scores and weights, according to characteristics of buildings)	Damage index (0–1)	GNDT II (Benedetti et al. 1988)*
HAZUS (FEMA 2015)	(a) Deterministic scenarios (b) USGS probabilistic ground motion maps (c) Other seismic hazard maps	Capacity and fragility curves for specific structural typologies	DPM (based on fragility curves)	Hazus (ArcGIS is needed)*
Risk-UE LMI (or VIM) (Milutinovic and Trendafloski 2003).	In terms of MMI (a) Deterministic scenario (b) Probabilistic scenario	A total vulnerability index (for each building classified into a structural typology)	DPM (5 non-null damage states), for each building, based on a damage function depending on a vulnerability index and macroseismic intensity	*
Risk-UE LM2 method (Milutinovic and Trendafloski 2003).	Response and demand spectra	Capacity curves for structural typologies	DPM based on fragility curves (4 non-null damage states)	*
CAPRA (Cardona et al. 2012)	Earthquake scenarios (based on probabilistic assessments)	Vulnerability functions for structural typologies	Probabilities of occurrence of damage states based on fragility curves, for each structural typology	CRISIS2007 (probabilistic hazard) ERN Vulnerability (Vulnerability assessment) CAPRA-GIS V2.0 (Seismic risk)

*Different versions of CRISIS software may be used for the hazard assessments

Table 11 Summary of the main features of the VIM and VIM_P methodologies

	VIM	VIM_P
<i>Seismic hazard</i>		
A deterministic seismic scenario can be considered as the seismic hazard of the site	✓	–
A probabilistic seismic scenario can be considered as the seismic hazard of the site	✓	–
The seismic hazard of the site requires a Probabilistic Seismic Hazard Analysis	Optional	✓
The seismic action is represented by a seismic hazard curve (exceedance rate vs. EMS intensities)	–	✓
<i>Seismic vulnerability</i>		
The seismic vulnerability is assessed considering uncertainties in the structural data	–	✓
The seismic vulnerability of each building is represented by a scalar called a vulnerability index	✓	–
The seismic vulnerability of each building is represented by a <i>pdf</i> /Beta type that describe the variation of a vulnerability index	–	✓
The seismic vulnerability of each building can be used to represent the uncertainty related to this seismic vulnerability	–	✓
The seismic vulnerability is defined by a vulnerability index (scalar) and can be plotted by means of deterministic maps	✓	–
The seismic vulnerability can be expressed through probabilistic maps (see Fig. 13)	–	✓
<i>Seismic risk assessment</i>		
The seismic hazard curve (exceedance rate vs. EMS intensities) is used	–	✓
Vulnerability functions (<i>pdf</i> /functions vs. vulnerability index) are used	–	✓
The uncertainty in the seismic vulnerability is explicitly considered	–	✓
The seismic risk can be represented in maps of damage grade for an earthquake of a determined macroseismic intensity	✓	–
It is possible to represent in a map the probabilities of a specific damage state for a specific macroseismic intensity	✓	✓
The method measures the risk by means of loss-exceedance rate	–	✓


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