Comparative analysis of a new assessment of the seismic risk of residential buildings of two districts of Barcelona

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Abstract

There are personal and institutional decisions that can increase the seismic resilience of the buildings in a city. However, some of these decisions are possible if we have basic knowledge of buildings' seismic risk. The present document describes the main results of a detailed study of seismic vulnerability and seismic risk of residential buildings of Ciutat Vella (the ancient district of Barcelona) and Nou Barris (one of the newest districts of Barcelona). In this study, we assessed seismic risk according to the Vulnerability Index Method-Probabilistic named as VIM_P. Moreover, we analyzed the influence of basic buildings' features in the final vulnerability and seismic risk values. For instance, we assessed the seismic vulnerability and the seismic risk of groups of buildings defined according to the number of stories of the buildings. Findings of this research reveal that the annual frequency of exceedance of the collapse damage state in Ciutat Vella buildings is, on average, 4.7 times higher than for the buildings in Nou Barris. Moreover, according to the *Best* vulnerability curve, 70.31% and 2.81% of Ciutat Vella and Nou Barris buildings, respectively, have an annual frequency of exceedance of the collapse damage state greater than $1x10^{-5}$.

Keywords

Seismic risk, Seismic vulnerability, Seismic vulnerability functions, Barcelona

1. Introduction

The seismic risk knowledge is essential information to take actions that can contribute to increasing the seismic resilience in cities. Therefore, each town has the responsibility of assessing its own seismic risk (UNISDR, 2015). Barcelona is a city where the seismic risk is regularly assessed (Aguilar-Meléndez et al. 2019a, b, 2010; Aguilar-Meléndez 2011; Barbat et al. 1996, 2006, 2008, 2009; Carreño et al. 2007; Irizarry et al. 2011; Lantada 2007; Lantada et al. 2009, 2010, 2018; Pujades et

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al. 2000, 2007). Table 1 shows information on relevant examples of the previous studies about Barcelona's seismic risk.

The present study complements the previous work of Aguilar-Meléndez et al. (2019a,b). In this case, a new assessment of Barcelona's seismic hazard was done, applying new ground-motion prediction equations. The new seismic hazard results were applied to assess the seismic risk of dwelling buildings of two districts of the city of Barcelona: Ciutat Vella and Nou Barris (Figure 1). Additionally, a new and detailed comparison between the residential buildings of both districts was performed. To underline some features of the city of Barcelona, we mention that it has 1664182 inhabitants (idescat, 2021a). However, in Ciutat Vella and Nou Barris live 6.48% and 10.45%, respectively, of Barcelona's mentioned total number of inhabitants (idescat, 2021b).

Table 1. Examples of seismic risk results of Barcelona.

Reference of the study	Method to assess seismic risk	Studied buildings	Seismic hazard considered	Seismic vulnerability results	Seismic risk results
Lantada et al. (2010)	VIM (Risk-UE)	Residential and monumental buildings	Two seismic scenarios: i) a deterministic scenario; ii) a probabilistic scenario for a return period of 475 years.	Census zones classified according to the mean vulnerability index from the residential buildings.	Maps of mean damage grade for each district of Barcelona. Five no null damage grades were considered. Economic losses due to seismic scenarios.
Lantada et al. (2018)	VIM	Residential buildings	Seismic hazard scenarios (V-VI, VI, VI-VII, and VII). The intensity of VI-VII in rock has a 475-year return period.	Average vulnerability index for groups of buildings.	Seismic risk scenarios
Aguilar-Meléndez et al. (2019a,b)	VIM_P	Residential buildings	Probabilistic seismic hazard curve determined by a PSHA.	Vulnerability functions of the buildings.	Annual frequency of exceedance of five damage grades for the city and districts. Seismic risk maps to plot scale for the Eixample district. Economic losses for the city.

To assess seismic risk, we applied the Vulnerability Index Method-Probabilistic (VIM_P) proposed by Aguilar-Meléndez et al. (2019a), which is considered as a complementary method to the Vulnerability Index Method (VIM) (Milutinovic and Trendafilosky 2003; Lantada et al. 2010). Both methods (VIM and VIM_P) are based on the assessment of three essential components: 1) seismic hazard, 2) seismic vulnerability, and 3) seismic risk. However, there are significant differences in the procedures to assess each one of these components (Milutinovic and Trendafilosky 2003; Aguilar-Meléndez et al. 2019a).

In the VIM, the seismic hazard is considered through seismic scenarios in macroseismic intensities. Meanwhile, a vulnerability index (a value between zero and one) characterizes the seismic vulnerability of each examined building. Zero represents low vulnerability and one high vulnerability (Giovinazzi, 2005; Lantada et al. 2009, 2010). Finally, to compute a mean damage grade (seismic risk), an empirical function that relates the macroseismic intensity (seismic hazard) and the vulnerability index (seismic vulnerability) is used. The VIM was recently applied to determine the seismic risk of diverse urban areas (Ademović et al. 2020; Cherif et al. 2016; Lestuzzi et al. 2016; Athmani et al. 2015; Guardiola-Víllora and Basset-Salom 2015, 2020; Ruiz et al. 2015). In Spain, the VIM has been applied in two cities: Barcelona (Lantada et al. 2010, 2018) and Valencia (Guardiola-Víllora and Basset-Salom 2015, 2020). It is convenient to highlight that both towns are divided into districts. Simultaneously, they have coincidences on the names of some districts. For instance, in both cities, there is a district called Ciutat Vella, and in both cases, this district is the oldest district of the city. In the present article, all the forthcoming mentions of the Ciutat Vella district correspond to the district with this name in Barcelona.

It is appropriate to emphasize that the VIM_P is a procedure that allows incorporating significant uncertainties that the VIM does not consider. Essentially, these uncertainties are incorporated into the seismic vulnerability assessment, which affects the seismic risk results. Additionally, the VIM_P allows obtaining seismic risk in terms of an annual rate of exceedance of both physical damage and loss (Aguilar-Meléndez et al. 2019a).

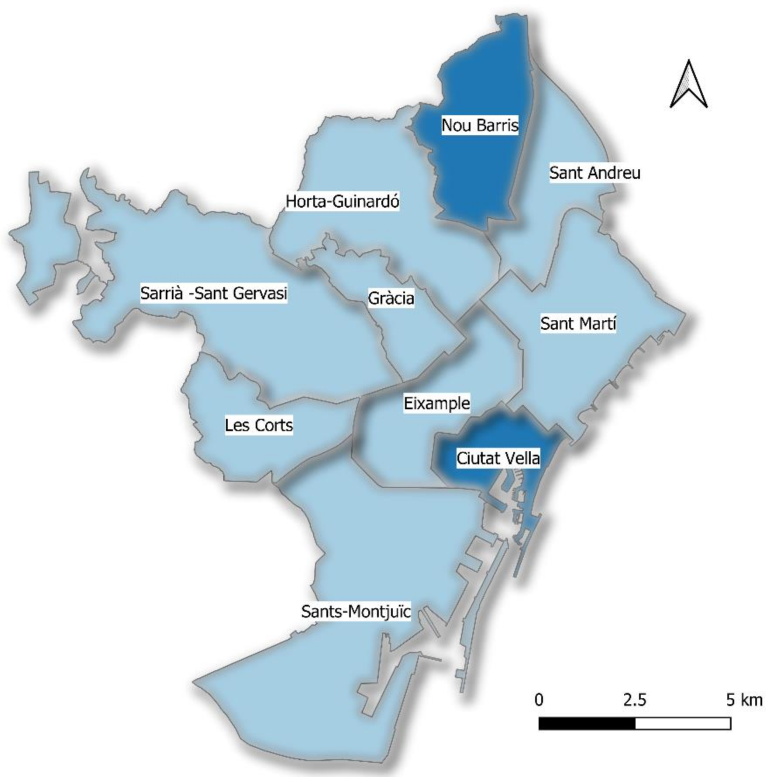


Figure 1. Districts of the city of Barcelona.

At this point, it is useful to mention that the present study has significant differences from the previous works of Aguilar-Melendez et al. (2019a, b). For instance, a relevant difference is the fact that in this study, new seismic hazard curves were determined for Barcelona, and these new curves were used to determine the seismic risk of the residential buildings of Ciutat Vella and Nou Barris. Additionally, in this study, we included a detailed comparison between the results of vulnerability and risk of both districts' buildings.

We divided this article into three sections. The first one is the introduction; the second section describes the use of VIM_P to determine the seismic risk of the residential buildings of Ciutat Vella and Nou Barris. This section includes a summary of the VIM_P methodology, information about the data and procedure applied to compute seismic hazard, and a description of the main steps performed to determine vulnerability and seismic risk. Finally, section 3 is devoted to the discussion and conclusions.

2. Seismic risk assessment of the residential buildings of Ciutat Vella and Nou Barris

2.1. Methodology

According to the VIM_P, the three main steps to compute seismic risk are the following: a) probabilistic seismic hazard assessment (PSHA), b) determination of the seismic vulnerability of buildings and c) computation of the seismic risk of buildings under study. In the following sub-sections, we described the main phases that we performed to apply the VIM_P.

2.1.1.Seismic hazard in the VIM_P

One of the requirements of the VIM_P is that the seismic hazard data to compute seismic risk must be in terms of frequencies of exceedance of macroseismic intensities. Specifically, it is suggested to perform a PSHA to obtain the seismic hazard curve required by the VIM_P (Aguilar-Meléndez et al. 2019a). For this last purpose, it is possible to apply validated software as R-CRISIS (Ordaz et al. 2020) or even a previous version of this software as CRISIS2015 (Ordaz et al. 2015; Aguilar-Meléndez et al. 2017). It is essential to underline that CRISIS2015 and R-CRISIS allow performing PSHA using accelerations or macroseismic intensities (Ordaz et al. 2020).

2.1.2.Seismic vulnerability in the VIM_P

According to the VIM_P, the building's seismic vulnerability is computed based on information about the building's main features. This vulnerability is represented by three Beta-type *pdf* functions named *Lower*, *Best*, and *Upper*. The procedure to determine the vulnerability functions was described by Aguilar-Meléndez et al. (2019a). The *Best* vulnerability function represents the main vulnerability of a building. We called it the main vulnerability to highlight that between the three vulnerability curves used in the VIM_P to describe the vulnerability of a building, the best vulnerability curve describes the mean vulnerability and, therefore, the essential vulnerability of the building. In other words, in the VIM_P, the vulnerability of a building must be represented at least by the *Best* vulnerability function. The *Best* vulnerability function is computed applying the following four steps (Aguilar-Meléndez et al. 2019a):

i. Estimation of the mean vulnerability index $\overline{V_I}$.

$\overline{V_I}$ is computed according to Eq. (*1*)

$$\overline{V_I} = V_I^* + \Delta V_R + \Delta V_m \qquad (1)$$

where V_I^* = vulnerability index of the structural typology; ΔV_R=building regional modifiers; ΔV_m= building-specific modifiers (Milutinovic and Trendafiloski 2003; Lantada 2007). In the case of Barcelona's buildings, the V_I^* values were taken from the building typology matrix (BTM) defined by Milutinovic and Trendafiloski (2003). Additionally, Table 2 shows an example of a V_I^* value. Moreover, the values of ΔV_R and ΔV_m for the buildings of Barcelona were obtained from Lantada (2007).

According to the VIM_P, the value of $\overline{V_I}$ will be the mean of the *Best* vulnerability function. This function will describe the main seismic vulnerability of the studied building.

Table 2. Example of vulnerability indices for the typology M34- Unreinforced masonry bearing walls with a floor system based on slabs of reinforced concrete. These indices were obtained from the Risk-UE building typology matrix (BTM) (Milutinovic and Trendafiloski 2003).

Representative values of the vulnerability[1]				
V_I^{min}	V_I^{-}	V_I^{*}	V_I^{+}	V_I^{max}
0.300	0.490	0.616	0.793	0.860

[1] V_I^{*} = the value of the vulnerability index (V) that is the most probable. V_I^{-} and V_I^{+} = lower and upper values of the range of the probable values of V, respectively. V_I^{min} and V_I^{max} = lower and upper values of the range of less probable values of V, respectively.

ii. Assessment of the confidence interval (V_c and V_d)

V_c and V_d determine the range of the *Best* vulnerability function that contains 90% of the possible values of V. There are two criteria to compute V_c and V_d (see Eq. 3 and the explanation of Eq.3 in step iv. See also a detailed description in Aguilar-Mélendez et al. 2019a). In this work, we applied the simplified criterion that assumes that V_I^{min} and V_I^{max} (Table 2) correspond to V_c and V_d, respectively. Therefore in this study, the values of V_c and V_d are the same for the buildings classified into the same structural typology.

iii. Determination of vulnerability index limits (V_a and V_b)

According to Aguilar-Mélendez et al. (2019a), V_a and V_b, define the minimum and maximum values, respectively, that can take V (see Eq. 3 and the explanation of Eq.3 in step iv. A detailed description is also available in Aguilar-Mélendez et al. 2019a). For instance, in previous studies, Aguilar-Mélendez et al. (2019a,b) adopted -0.04 for V_a and 1.04 for V_b, for studying the Barcelona case. The election of these previous values was also based on previous works (Lantada 2007; Aguilar-Mélendez et al. 2019b). We also used these same values for V_a and V_b in the present study for the reasons mentioned above.

iv. Calculation of Beta *pdf* parameters: α_m and β_m

The parameters previously determined are used to compute α_m and β_m. These last values complete the required information to define the Beta *pdf* function representing the seismic vulnerability of each analyzed building.

In this step, values of β_m between 0.1 and 8 are assumed. This specific range was selected by Aguilar-Meléndez et al. (2019a.) as a result of a sensitivity analysis. The primary purpose of selecting this range was to reduce the calculation time because, according to the sensitivity analysis, values between 0.1 and 8 were enough to consider a wide variety of beta functions used to represent the seismic vulnerability of buildings. However, any user of the methodology could consider a different range of values of β_m. The increment between values of β_m depends on the desired resolution. Then, for each β_m, the corresponding α_m pair is computed using Eq. (2). In this process, we calculated the integral in Eq. (3) for each (α_m, β_m) pair. The final (α_m, β_m) pair correspond to the pair closest to the 0.9 value.

$$\alpha_m = \left(-\beta_m \cdot \frac{\overline{V_I} - V_a}{V_b - V_a} \right) \Bigg/ \left(\frac{\overline{V_I} - V_a}{V_b - V_a} - 1 \right) \tag{2}$$

$$0.9 = \int_{y_1}^{y_2} f(y)\,dy = B_{y2}(\alpha_m, \beta_m) - B_{y1}(\alpha_m, \beta_m) \tag{3}$$

where $y_1 = V_c$; $y_2 = V_d$; $B_{y2}(\alpha_m, \beta_m)$ is the incomplete Beta function (beta cumulative distribution function (CDF)) for y_2 ; $B_{y1}(\alpha_m, \beta_m)$ is the CDF for y_1. Finally, in this step, the computed beta function's mean and standard deviation are determined according to Equations (4) and (5), respectively. A similar procedure described by Aguilar-Mélendez et al. (2019a) is performed to determine the other two seismic vulnerability functions: the lower and the upper.

$$Mean = (V_b - V_a)\left(\frac{\alpha_m}{\alpha_m + \beta_m} \right) + V_a \tag{4}$$

$$\sigma_{\overline{V}} = \sqrt{\frac{\alpha_m \beta_m}{(\alpha_m + \beta_m)^2 (\alpha_m + \beta_m + 1)} \cdot (V_b - V_a)^2} \tag{5}$$

2.1.3. Seismic risk in the VIM_P

According to the VIM_P, the seismic risk is computed with Eq. (6), and the results are annual frequencies of exceedance (ν) for each non-null damage grade (D_k). There are five non-null damage grades. The damage grade 5 means the total collapse of the building.

$$\nu[D > D_k] \approx \sum_I \sum_V P\left[D > D_k \mid V, I\right] P\left[V\right] \gamma'\left[I\right] \tag{6}$$

where $P\left[D > D_k \mid V, I\right]$ = probability that damage (D) is greater than D_k for a building with a vulnerability index (V), that receives the effects of an earthquake with a macroseismic intensity (I) (Aguilar-Mélendez et al. 2019a). This probability of damage is assessed by applying the damage function defined in previous works (Lagomarsino and Giovinazzi 2006; Milutinovic and Trendafiloski 2003; Giovinazzi 2005).

$P[V]$ = probability of V. Value computed from the seismic vulnerability functions from each studied building;

$\gamma'\left[I\right]$= annual frequency of exceedance of I (Aguilar-Mélendez et al. 2019a). Value determined from the seismic hazard curve.

In the following sections, we include the description of the essential data used to apply the VIM_P. We also highlight relevant results of seismic vulnerability of Ciutat Vella and Nou Barris's districts. Additionally, we include the main values of the seismic risk results for the same districts of Barcelona.

2.1.4. The VIM_P versus the Capacity Spectrum-Based method to assess seismic risk

The VIM_P methodology has shown to be robust to assess seismic risk, and its application has been considered helpful in sites like Barcelona, where a great number of buildings should be evaluated and where seismicity data other than macroseismic intensities are scarce and not enough to cover long return periods. For instance, in this region, there are references of historic earthquakes potentially damaging with significant return periods (Ojeda et al., 2002), and at the same time, there are no acceleration records of seismic ground motions in Barcelona of significant earthquakes. Therefore, the more representative catalog of earthquakes for the region of Barcelona is based on macroseismic intensities data. In the VIM_P, the data in terms of macroseismic intensities can be used directly to compute the seismic hazard using CRISIS2015 (Ordaz et al., 2015) or R-CRISIS (Ordaz et al., 2020). Additionally, the VIM_P applies damage function based on macroseismic intensities and a vulnerability index; therefore, the data of the earthquakes and the damage functions are consistent (macroseismic intensities) and robust.

The VIM_P methodology is a derivation of the VIM that allows determining seismic risk scenarios. The VIM methodology is related to valuable and extensive work developed in the last 25 years in different countries with emphasis on some European countries as Italy, Spain, Greece, among many others (see for instance Vacareanu et al., 2004; Faccioli et al., 2004; Giovinazzi, 2005; Lagomarsino and Giovinazzi, 2006; Barbat et al., 2006; Dolce et al., 2006; Bernardini, 2007a, b; Barbat et al., 2009; Vicente et al., 2011; Neves et al., 2012; Ferreira et al., 2013, 2017a,b; Athmani et al. 2015; Guardiola-Víllora and Basset-Salom 2015, 2020; Ruiz et al. 2015; Cherif et al. 2016; Lestuzzi et al. 2016; Maio et al., 2016; Apostol et al., 2019; Giuliani et al., 2019; Ortega et al., 2019; Ademović et al. 2020; Basset-Salom and Guardiola-Víllora, 2020; Kassem et al., 2020; Romis et al., 2020; Taibi et al., 2020). Recently, Aguilar-Meléndez et al. (2019a) highlighted that the seismic risk results obtained according to the VIM_P agree with the results determined through the application of the VIM. Similarly, Lantada et al. (2009) developed a comparison between the VIM method and the capacity spectrum-based method (CSBM). They determined a good correlation between the seismic results determined by the VIM and CSBM methods. However, because of the difficulty of getting detailed structural information about a great number of buildings, the VIM method showed a better resolution and detail of the damage scenarios. For these reasons, it is possible to affirm that VIM and VIM_P allow determining reasonable values of the seismic risk of buildings in urban areas. Moreover, the results obtained are compatible with, but more resolutive than, those obtained applying the CSBM methods. According to this, it is possible to affirm that the VIM_P is a robust methodology that allows obtaining good results about the seismic risk of buildings. In the next section, we describe the application of the VIM_P to assess the seismic risk of the residential buildings of two districts of the city of Barcelona.

2.2. Seismic hazard in Barcelona

We performed a PSHA for Barcelona considering the seismic sources (Figure 2) and seismicity data (Table 3) utilized by Aguilar-Melendez et al. (2019a); however, in this case, we apply new GMPEs (Ground Motion Prediction Equations). This section describes the primary data used to compute the seismic hazard and the main results obtained.

Seismic sources

The geometry of the seismic sources used in the present study is shown in Figure 2. Moreover, the seismicity of these sources was represented according to the truncated Gutenberg-Richter relation (see Eq. (7)). For this last purpose, the seismic parameters of the seismic sources of Figure 2 (Table 3) were determined according to an earthquake catalog based on macroseismic intensities (Secanell et al., 2004). The seismic sources and their respective seismicity parameters have been used in different studies of the seismic hazard of Barcelona and Catalonia (Irizarry et al., 2011; Secanell et al., 2004; Irizarry, 2004).

On the other hand, R-CRISIS allows computing directly seismic hazard in terms of macroseismic intensities. Therefore, and mainly because these are the only representative seismicity data for the studied areas, we choose this option to compute the seismic hazard of Barcelona. In other words, we assigned directly to R-CRISIS the geometry of the seismic sources of Figure 2 and its respective seismicity parameters in terms of macroseismic intensities (Table 3).

$$\lambda(I) = \alpha \frac{e^{-\beta(I - I_{\min})} - e^{-\beta(I_{\max} - I_{\min})}}{1 - e^{-\beta(I_{\max} - I_{\min})}} \tag{7}$$

where $\lambda(I)$ is the annual frequency of exceedance of the macroseismic intensity I, I_{min} is the minimum epicentral intensity considered, I_{max} is the maximum epicentral intensity for each zone, α is the annual frequency of exceedance of intensities greater or equal to I_{min}, and β is the slope related to the Gutenberg-Richter law (Goula et al., 1997; Ordaz et al., 2020).

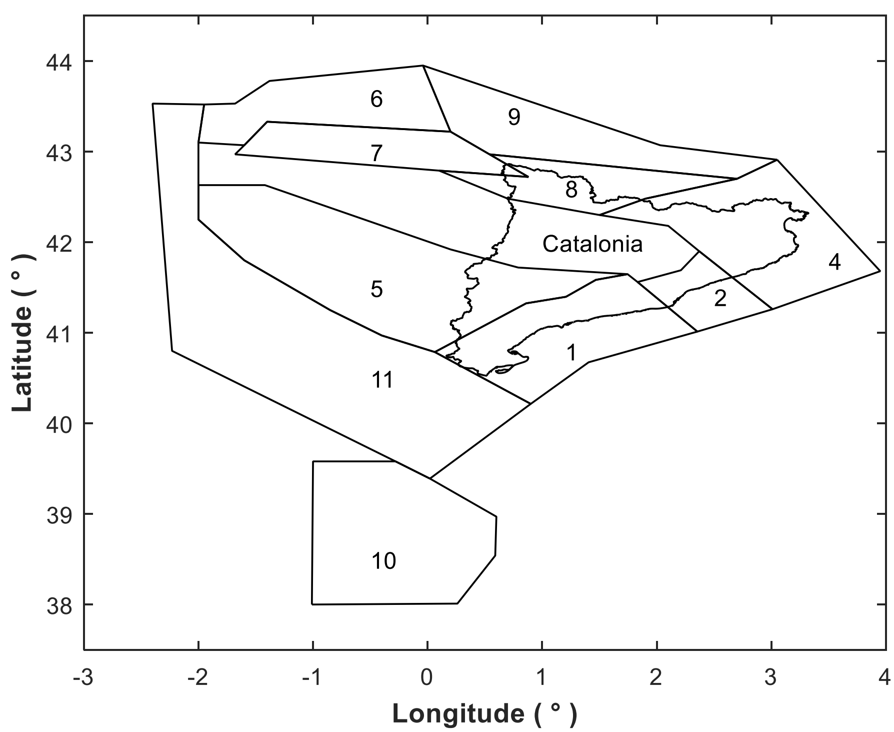


Figure 2. Seismic sources considered to compute the seismic hazard of Barcelona.

Ground Motion Prediction Equation

Mezcua et al. (2020) recently developed new GMPEs for Spain. These GMPEs were developed considering more than 3700 intensities data. The GMPEs developed allows computing values of macroseismic intensities for Spain. In this work, we applied two of the four GMPEs determined by Mezcua et al. (2020), the Pyrenees and the SCR (Stable Continental Region), because these two GMPEs (Mezcua et al., 2020) are enough to cover the regions of the seismic sources that were considered in the present work.

Table 3. Seismicity parameters of the seismic sources of Figure 2. Adapted from Secanell et al. (2004)

Seismic source	α	σ (α)*	β	σ (β)*	h (km)*	$I_{\min}$*	$I_{\max}$*	$I_{\max}$ observed *
1	0.100	0.030	1.864	0.559	7	V	VIII	VII
2	0.128	0.033	1.608	0.324	7	V	IX	VIII
4	0.157	0.030	1.256	0.186	10	V	X	IX
5	0.040	0.014	1.319	0.373	10	V	IX	VIII
6	0.099	0.025	1.977	0.640	10	V	VII	VI
7	0.957	0.090	1.420	0.116	15	V	X	VIII
8	0.218	0.040	1.716	0.246	15	V	IX	VIII
9	0.070	0.020	1.737	0.214	10	V	VIII	VII
10	0.635	0.059	1.201	0.083	10	V	XI	X
11	0.060	0.016	0.886	0.242	10	V	IX	VIII

* $\sigma(\alpha)$ is the estándar deviation of α; $\sigma(\beta)$ is the standard deviation of β; h is the depth in km; I_{min} is the minimum epicentral intensity assigned to the seismic source; I_{max} is the maximum epicentral intensity assigned to the seismic source; I_{max} observed is the maximum epicentral intensity observed in the seismic source.

Table 4. Ground Motion Predictions Equations determined by Mezcua et al. (2020)

Zone	Average intensity	Standard Deviation
Stable Continental Region	$-0.223 + 1.347M - 0.0023R - 1.235logR$	0.59
Pyrenees	$-2.559 + 1.774M - 0.0062R - 0.933logR$	0.60

Local site effects

Figure 3 shows the surface geological features of different areas of the city of Barcelona. These geological features were considered by Cid et al. (1999) to define the five seismic zones shown in Figure 4: Rock, Soil type I, Soil type II, Soil type III, and artificial soil (A). Rock seismic zone corresponds to rocky outcrops. Zone I corresponds to Holocene outcrops. Meanwhile, zone II corresponds to Pleistocene outcrops with a tertiary substrate. Otherwise, zone III corresponds to Pleistocene outcrops without tertiary substrate. Finally, seismic zone A corresponds to artificial soil. With these references and considering the work of Lantada 2007 and Aguilar-Meléndez et al. 2019a,b, we also considered for the present work the criteria of increasing in a half degree the macroseismic intensities in rock to determine the macroseismic intensities in soil sites.

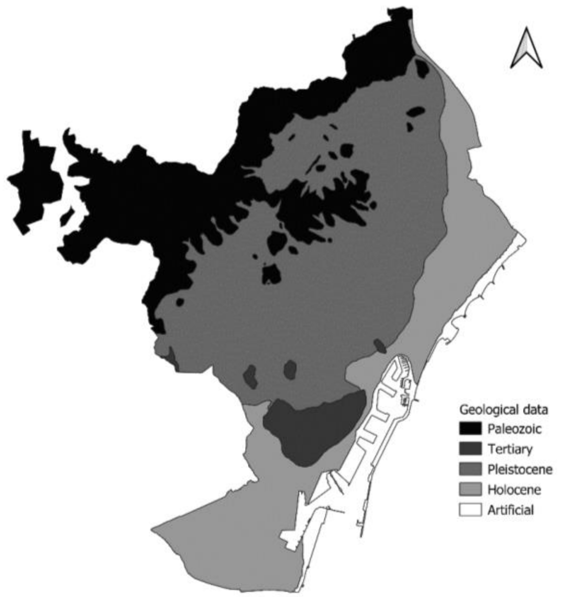


Figure 3. Surface geological features in the city of Barcelona, according to Cid et al. (1999)

Seismic hazard results

Figure 5 includes seismic hazard curves for the city of Barcelona for two cases, curves computed by Aguilar-Melendez et al. 2019a and curves computed in the present work. As was mentioned previously, the main difference in both cases is the GMPEs used. In the first case, GMPEs of López-Casado et al. (2000) were applied, and in the second case (present work), GMPEs of Mezcua et al. (2020) were used.

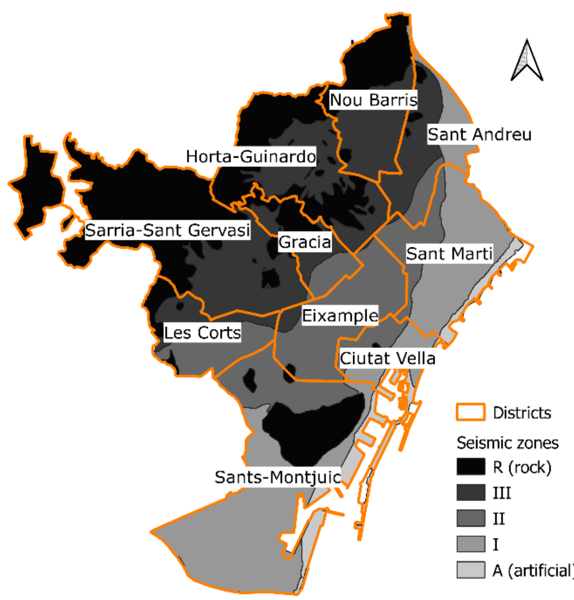


Figure 4. Districts of the city of Barcelona and seismic zones (Cid et al., 1999)

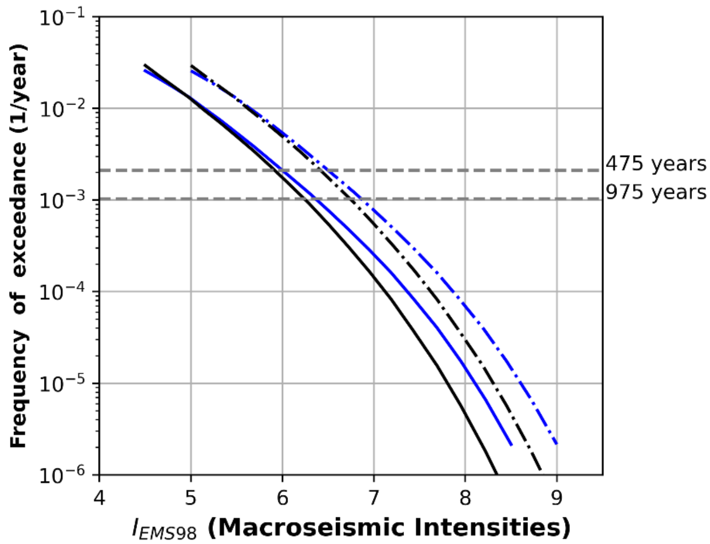


Figure 5. Curves of seismic hazard for Barcelona's rock sites (continuous black line this work and continuous blue line Aguilar-Meléndez et al. 2019a), and Seismic hazard curves for Barcelona's soil sites (dotted black line this work and dotted blue line Aguilar-Meléndez et al. 2019a).

2.3. Data of the residential buildings of Barcelona

We used the same building database of Barcelona that was used by Aguilar-Meléndez et al. (2019a). According to this data, the number of residential buildings in Barcelona's districts ranges approximately from 2500 to 10000 (see Figure 6). The district of Ciutat Vella has 5675 residential buildings, and in the Nou Barris district, there are 6916 residential buildings.

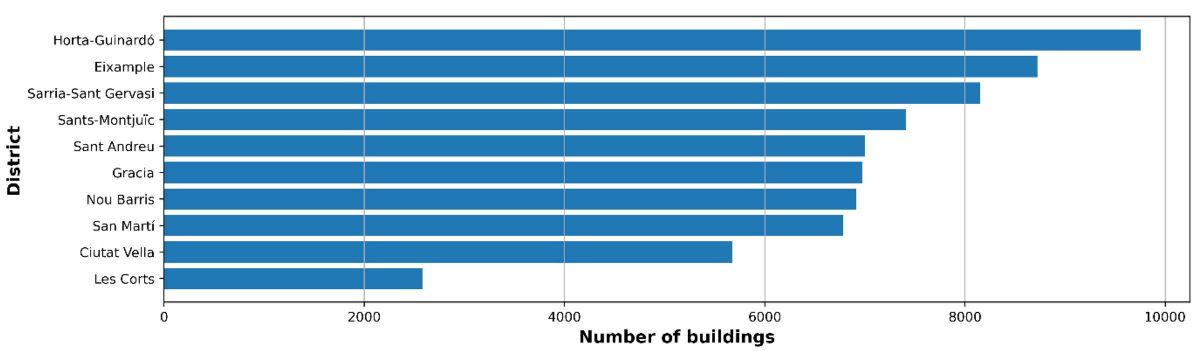


Figure 6. Number of buildings of each district of Barcelona

The database of Barcelona's buildings (Aguilar-Mélendez et al. 2019a,b; Lantada et al. 2010, 2018) that we used to assess seismic vulnerability and seismic risk includes the information listed in Table 5. It is essential to highlight that this database has typologies valid for both the VIM method (Milutinovic and Trendafiloski, 2003) and the VIM_P method (Aguilar-Meléndez et al. 2019a).

The more common structural materials of the residential buildings in Barcelona are masonry and reinforced concrete, with 69.8% and 26.2%, respectively (Figure 7). Similarly, we analyzed Ciutat

Vella and Nou Barris's residential buildings' data, and we observed that the proportion of buildings according to their primary structural material is similar between Barcelona (Figure 7) and its Nou Barris district (Figure 7). Additionally, we identified that the Ciutat Vella district has a significantly higher proportion of masonry buildings (88.5%) than the percentage of masonry buildings in Barcelona's whole city (69.8%).

Table 5. Basic information of the database of the residential buildings in Barcelona

	Datum
1	Id of the building
2	Cadastral plot code
3	Sub-District code
4	District code
5	Stories of the building
6	Structural Typology
7	Construction year
8	Seismic Zone
9	Conservation state
10	Building position in the block

If we analyze the typologies distribution by district, we can observe significant differences in the distribution of the masonry typologies of the buildings in Ciutat Vella and Nou Barris. For instance, in Ciutat Vella, the M31 typology is the most common typology, with 81.1% of the masonry buildings (Figure 8). However, this typology represents only 21.0% of the masonry buildings in Nou Barris (Figure 8). In this last district, the most common typology is the M34 typology, with 44.4% of the masonry buildings (Figure 8).

Figure 7. Distribution (%) of buildings by primary structural material (M-Masonry, S-Steel, RC-Reinforced Concrete, W-Wood) for 69982 buildings in Barcelona, 5675 buildings in Ciutat Vella, and 6916 buildings in Nou Barris.

Other relevant information in the database is the year of construction of each building. Based on this last information, we determined that Ciutat Vella and Nou Barris's buildings have a mean age of 119.58 years and 59.88 years, respectively. Similarly, the mean number of stories of residential buildings equals 5.85 stories in Ciutat Vella and 4.03 in Nou Barris. The detailed distribution of the buildings by the number of stories in Ciutat Vella and Nou Barris is shown in Figure 9. Moreover, it is possible to observe in Figure 9 differences between the buildings' distributions according to their stories in Ciutat Vella and Nou Barris. For instance, the most common buildings in Ciutat Vella have six stories (40.22%), while in Nou Barris, the most frequent buildings have one story (23.68%).

Additionally, it is possible to note in Ciutat Vella that buildings with 5, 6, and 7 stories represent 83.15% of this district's residential buildings.

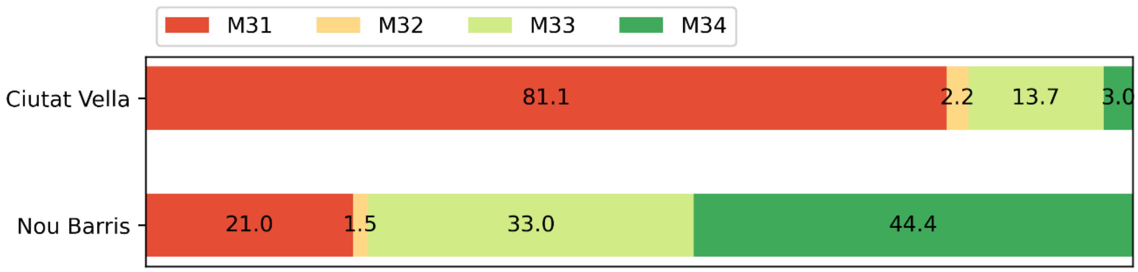


Figure 8. Distribution (%) of masonry buildings by structural typology (according to the Risk-UE building typology matrix) in Ciutat Vella and Nou Barris.

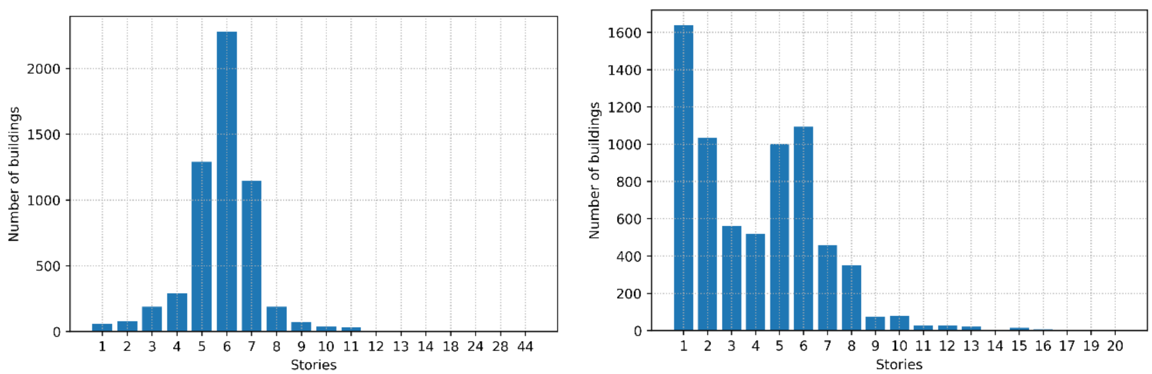


Figure 9. Distribution of buildings by their stories in Ciutat Vella (left) and Nou Barris (right).

2.4. Seismic vulnerability of Ciutat Vella and Nou Barris

It is essential to highlight that, as was mentioned previously (section 2.1.2), a part of the procedure to compute seismic vulnerability functions includes the assessment of the mean vulnerability index (Eq. (*1*)). This mean value depends on three elements: a) the structural typology, b) building regional modifiers, and c) building-specific modifiers.

Eq. *(1*) was assessed to determine the seismic vulnerability of each building that was studied in the present work. For this last purpose, we considered the following conditions: a) the first term of Eq. *(1*) depends on the structural typology of each building according to the typologies of Table 6 (Milutinovic and Trendafiloski, 2003); b) to assess the second term of Eq. *(1*), the regional modifiers that were defined by Lantada (2007) for the buildings of Barcelona were applied (Table 7), and, c) the building-specific modifiers were considered according to the modifiers proposed by Lantada (2007).

In the following part of this section, we included an example of the data and the procedure applied to compute seismic vulnerability of the buildings of the districts of Ciutat Vella and Nou Barris. For this purpose, we selected four buildings from the complete database of the residential buildings of Ciutat Vella and Nou Barris districts in Barcelona city (Table 8). Subsequently, we applied the VIM_P and used the data in Table 8 to compute the seismic vulnerability functions representing the four buildings' seismic vulnerability. Table 9 shows the parameters that define the vulnerability functions computed, and in Figure 10, it is possible to observe the respective seismic vulnerability curves.

The vulnerability curves of Figure 10 are an input to compute the seismic risk of the buildings of Table 8. However, the vulnerability curves by themselves describe the seismic vulnerability of the buildings. For instance, the probability that in the CV1 building, the vulnerability index will be greater than 0.8 is equal to 50%, 65%, and 79%, according to the lower, best, and upper seismic vulnerability, respectively. Similarly, the probability that in the CV2 building, the vulnerability index will be greater than 0.8 is equal to 27%, 46%, and 63% according to the lower, best, and upper seismic vulnerability, respectively. Therefore, it is possible to conclude that building CV1 is seismically more vulnerable than building CV2. Similarly, the probability that in the NB1 and NB2 buildings, the vulnerability will be greater than 0.8 is equal to 40% and 21%, respectively, if only the best vulnerability curve is considered.

Table 6. Structural Typologies (Milutinovic and Trendafiloski, 2003).

Group	Typology	Description	Representative values of vulnerability**				
			V_I^{min}	V_I^-	V_I^*	V_I^+	V_I^{max}
Masonry	M31	*Unreinforced masonry bearing walls with wooden slabs*	0.460	0.650	0.740	0.830	1.020
	M32	*Unreinforced masonry bearing walls with masonry vaults*	0.460	0.650	0.776	0.953	1.020
	M33	*Unreinforced masonry bearing walls with composite steel and masonry slabs*	0.460	0.527	0.704	0.830	1.020
	M34	*Unreinforced masonry bearing walls with reinforced concrete slabs*	0.300	0.490	0.616	0.793	0.860
Concrete	RC32	*Irregular concrete frames with unreinforced masonry infill walls*	0.060	0.127	0.522	0.880	1.020
Steel	S3	*Steel frames with unreinforced masonry infill walls*	0.140	0.330	0.484	0.640	0.860
	S5	*Steel and RC composite systems*	-0.020	0.257	0.402	0.720	1.020
Wood	W	W*ood*	0.140	0.207	0.447	0.640	0.860

** V_I^* is the more probable value of the vulnerability index for the corresponding typology. V_I^- and V_I^+ delimit the range of the probable values of the vulnerability index for the corresponding typology. V_I^{min} and V_I^{max} increase the range of the probable values of the vulnerability index in order to include the less probable values of the vulnerability index for the same typology.

Table 7. Regional modifiers for buildings in Barcelona (Lantada, 2007)

Period	M31	M32	M33	M34	RC32
<=1940	+0.198	+0.162	+0.234	-	-
1941-1962	+0.135	+0.099	+0.171	-	-
1963-1968	+0.073	+0.037	+0.109	+0.134	+0.228
1969-1974	+0.010	-0.026	+0.046	+0.009	+0.103
1975-1994	-0.052	-0.088	-0.016	-0.053	-0.022
1995-2002	-0.052	-0.088	-0.016	-0.053	-0.022
>2002	-0.052	-0.088	-0.016	-0.053	-0.022

Table 8. Example of the primary data of each residential building of Barcelona used to determine their seismic vulnerability.

No.	Data	Building 1 in Ciutat Vella (CV1)	Building 2 in Ciutat Vella (CV2)	Building 1 in Nou Barris (NB1)	Building 2 in Nou Barris (NB2)
1	Structural typology	M31	M33	M31	RC32
2	Reliability parameter	8	8	8	8
3	Conservation state	Normal	Normal	Normal	Normal
4	Stories of the building	6	4	6	7
5	Construction year	1965	1969	1987	2004
6	Seismic Zone (Terrain)	II(Soil)	II(Soil)	III(Soil)	R(Rock)

According to Aguilar-Meléndez et al. (2019a), the seismic vulnerability of groups of buildings can also be represented using vulnerability functions. Therefore, for the previous example, it could be possible, for instance, to obtain vulnerability functions that represent the seismic vulnerability of the two buildings of Ciutat Vella and the two buildings of Nou Barris. Figure 11 shows the case of the vulnerability curves that represent the seismic vulnerability of the two buildings of Ciutat Vella.

Table 9. Parameters that define the vulnerability functions of the residential buildings of Table 8

Building	*α*	*β*	*Mean*	*SD*	*α*	*β*	*Mean*	*SD*	*α*	*β*	*Mean*	*SD*
	Lower				*Best*				*Upper*			
CV1	4.21	1.41	0.77	0.18	4.68	1.11	0.83	0.16	5.31	0.81	0.90	0.14
CV2	4.76	2.41	0.68	0.18	4.11	1.51	0.75	0.19	4.41	1.11	0.82	0.17
NB1	4.20	2.31	0.66	0.19	4.46	1.81	0.73	0.18	4.22	1.21	0.80	0.18
NB2	0.68	1.01	0.39	0.32	1.16	1.11	0.51	0.30	1.32	0.81	0.63	0.30

In the present work, we applied the VIM_P to determine the vulnerability functions of 5675 residential buildings in Ciutat Vella and 6916 in Nou Barris. To do this, first, the three vulnerability functions (lower, best, and upper) for each studied building were obtained. After that, we used these individual vulnerability functions to determine average vulnerability functions for different groups of buildings. The selection of the different groups had the objective of analyzing the influence of different features in the seismic vulnerability of the studied buildings. The total number of groups analyzed with their respective features is summarized in Table 10 and Table 11. These two tables also indicate the data used to analyze each group or subgroup of buildings.

To determine the seismic vulnerability of the groups of buildings in Table 10 and Table 11, according to the VIM_P, the procedure defined by Aguilar-Meléndez (2011) and Aguilar-Meléndez et al. (2019a) was applied. The procedure can be summarized in two steps: Step 1. Determination of three vulnerability functions for each building of the group according to the VIM_P and Step 2. Determination of three representative vulnerability functions for the whole residential buildings in this group, based on the vulnerability functions computed in Step 1.

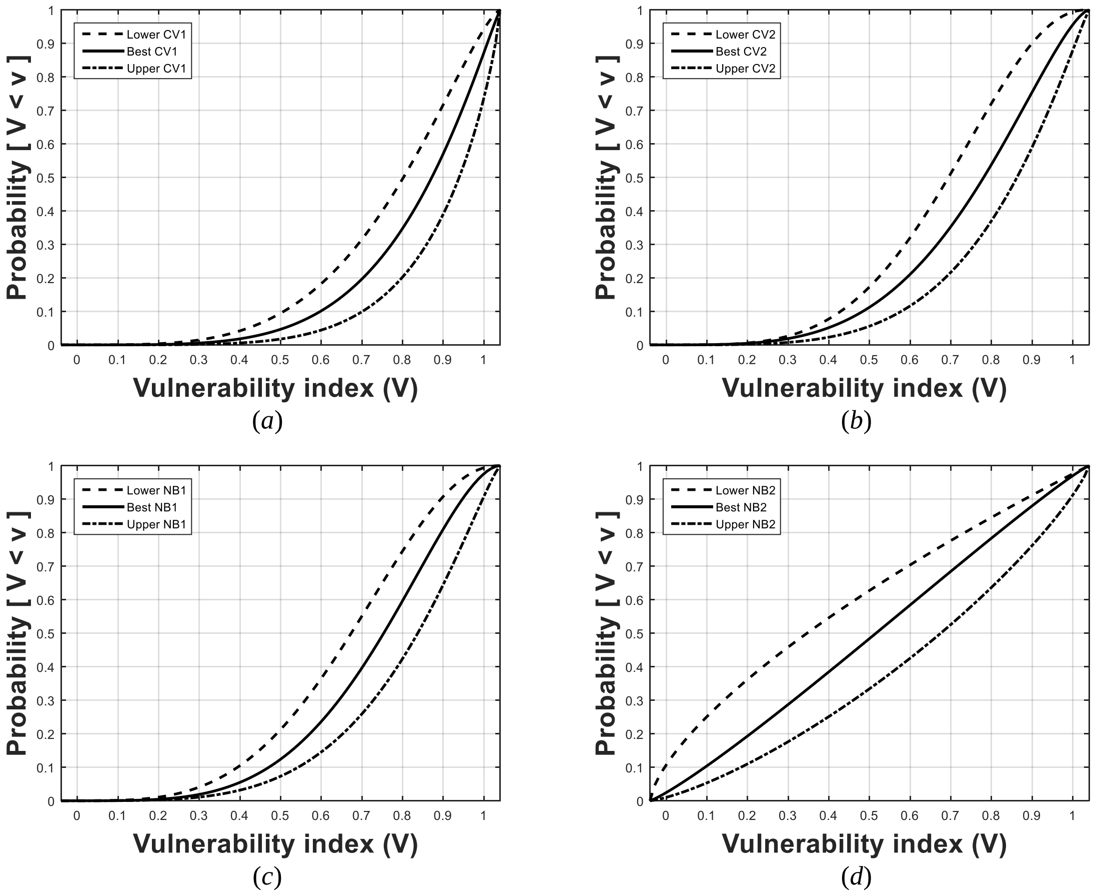


Figure 10. Vulnerability functions of the buildings of Table 8. Building CV1 (a), building CV2 (b), building NB1 (c), and building NB2 (d).

To compute the seismic vulnerability according to the VIM_P, we applied the USERISK2015 software (Aguilar-Meléndez et al. 2016). Figure 12 shows the seismic vulnerability curves for Ciutat Vella and Nou Barris districts that were also determined by Aguilar-Meléndez et al. (2019b). However, in this work, we performed a more extensive assessment of the seismic vulnerability of the buildings of Ciutat Vella and Nou Barris because, in this work, we assessed new seismic vulnerability curves of sub-groups of these dwelling buildings (Table 10 and Table 11). Figure 12 includes the seismic vulnerability curves that describe the seismic vulnerability for 5675 residential buildings in Ciutat Vella (GCV1) and 6916 residential buildings of Nou Barris (GNB1). Using these results, we can affirm that the mean vulnerability index for the *Best* curve for Ciutat Vella buildings is 0.90 (Figure 12). We also can determine that the probability that a building in Ciutat Vella has a vulnerability index greater than 0.8 would be 73.52%, 83.59%, and 88.37%, counting the *Lower*, *Best*, and *Upper* vulnerability curves, respectively. Similarly, we can observe that the mean vulnerability index for the *Best* curve for Nou Barris buildings is 0.69 (Figure 12). Simultaneously, the probability that a residential building in Nou Barris has a vulnerability index greater than 0.8 would be 21.33%, 34.03%, and 52.14 %, if the *Lower*, *Best*, and *Upper* vulnerability curves are considered, respectively.

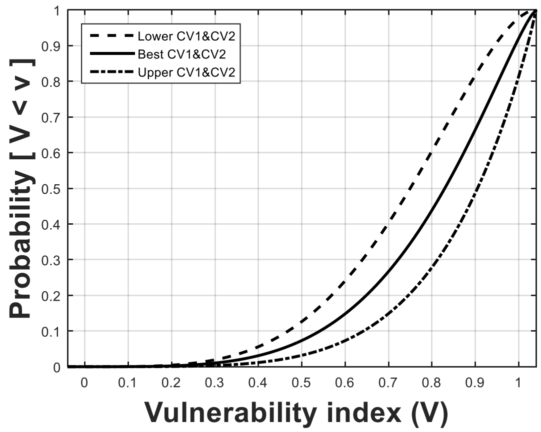


Figure 11. Vulnerability functions of a group of two buildings of Ciutat Vella (CV1 and CV2)

Table 10. Group and subgroups of buildings of the district of Ciutat Vella that were studied in the present work.

ID	Group	Subgroup	Number of residential buildings in the group or subgroup	Steps of the procedure to obtain the vulnerability functions	Data considered to compute the vulnerability functions	Number of vulnerability functions determined
GCV1	Ciutat Vella		5675	Step 1*	***	17025
				Step 2**	****	3 (Figure 12)
GCV2		Ciutat Vella Masonry	5022	Step 1*	***	15066
				Step 2**	****	3 (Figure 14a)
GCV3		Ciutat Vella RC	459	Step 1*	***	1377
				Step 2**	****	3 (Figure 14b)
GCV4		Ciutat Vella M31	4069	Step 1*	***	12207
				Step 2**	****	3 (Figure 15)
GCV5		Ciutat Vella M31<1969	3993	Step 1*	***	11979
				Step 2**	****	3 (Figure 16a)
GCV6		Ciutat Vella M31>=1969	76	Step 1*	***	228
				Step 2**	****	3 (Figure 16b)
GCV7		Ciutat Vella Stories<6	1908	Step 1*	***	5724
				Step 2**	****	3 (Figure 13a)
GCV8		Ciutat Vella Stories >=6	3767	Step 1*	***	11301
				Step 2**	****	3 (Figure 13b)

* Assessment of three vulnerability functions for each building according to the VIM_P
** Assessment of three representative vulnerability functions for the whole residential buildings in this group, based on the vulnerability functions determined in step 1.
*** The six data of each building as the data mentioned in Table 8.
**** The vulnerability functions of each building that were obtained in step 1.

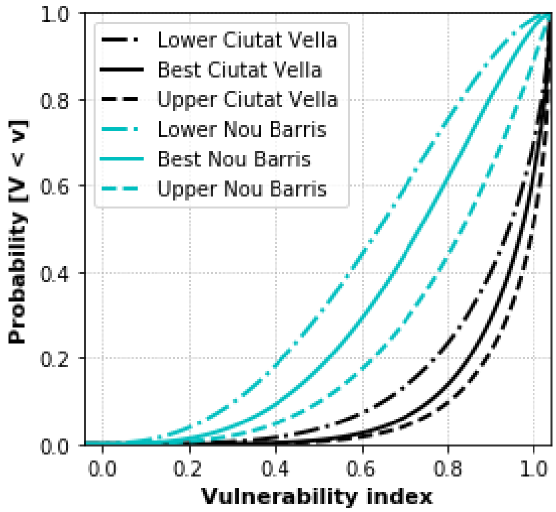
It is essential to highlight that the VIM_P computes the seismic vulnerability of each building considering the structural typology and the additional data mentioned in Table 8. And the seismic vulnerability results are vulnerability functions in terms of probability of non-exceedance of the vulnerability index. Therefore, because all the vulnerability functions are in the same units, it is possible to use these vulnerability functions to compute representative seismic vulnerability curves of groups of buildings with different structural typologies (see also Aguilar-Meléndez et al. 2019a).

Table 11. Group and subgroups of buildings of the district of Nou Barris that were studied in the present work.

ID	Group	Subgroup	Number of residential buildings in the group or subgroup	Steps of the procedure to obtain the vulnerability functions	Data considered to compute the vulnerability functions	Number of vulnerability functions determined
GNB1	Nou Barris		6916	Step 1*	***	20748
				Step 2**	****	3 (Figure 12).
GNB2		Nou Barris Masonry	4885	Step 1*	***	14655
				Step 2**	****	3 (Figure 14c)
GNB3		Nou Barris RC	1761	Step 1*	***	5283
				Step 2**	****	3 (Figure 14d)
GNB4		Nou Barris M31	1026	Step 1*	***	3078
				Step 2**	****	3 (Figure 15)
GNB5		Nou Barris M31<1969	961	Step 1*	***	2883
				Step 2**	****	3 (Figure 16c)
GNB6		Nou Barris M31>=1969	65	Step 1*	***	195
				Step 2**	****	3 (Figure 16d)
GNB7		Nou Barris Stories<6	4757	Step 1*	***	14271
				Step 2**	****	3 (Figure 13c)
GNB8		Nou Barris Stories >=6	2159	Step 1*	***	6477
				Step 2**	****	3 (Figure 13d)

* Assessment of three vulnerability functions for each building according to the VIM_P
** Assessment of three representative vulnerability functions for the whole residential buildings in this group, based on the vulnerability functions determined in step 1.
*** The six data of each building as the data mentioned in Table 8.
**** The vulnerability functions of each building that were obtained in step 1.

In this study, we computed the seismic vulnerability curves of two groups of buildings that were defined, taking into account the number of stories of the buildings (Figure 13): a) buildings with five or fewer stories, and b) buildings with six or more stories. Figure 13 and Table 12 summarize the results for the groups of buildings defined according to their number of stories. These results indicate that the mean vulnerability index of the *Best* curve of seismic vulnerability is equal to 0.87 and 0.91 for Ciutat Vella buildings with less than six stories (GCV7) and more than five stories (GCV8), respectively. Similarly, in Nou Barris, we obtained that the mean vulnerability index of the *Best* curve of seismic vulnerability is equal to 0.7 and 0.67 for buildings with less than six stories (GNB7) and more than five stories (GNB8), respectively.



Seismic Vulnerability Curves for the group of buildings*		***α***	***β***	***Mean***	***SD***
Ciutat Vella (GCV1)	*L*	3.85	0.63	0.86	0.16
	B	5.62	0.64	0.90	0.12
	U	5.65	0.49	0.92	0.11
Nou Barris (GNB1)	*L*	2.81	1.77	0.61	0.22
	B	3.40	1.52	0.69	0.21
	U	3.47	1.04	0.77	0.19

*L=Lower, B=Best, U=Upper

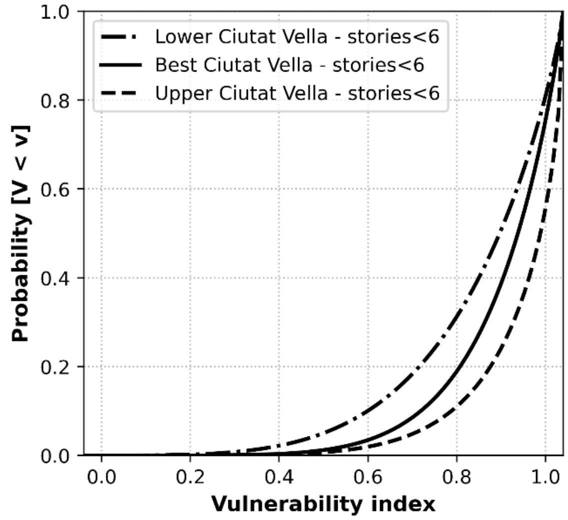
Figure 12. Seismic vulnerability curves for Ciutat Vella (GCV1) (black lines) and Nou Barris (GNB1) (cyan lines) considering V_a*=-0.04 and* V_b*=1.04 (some of the values of the table were published in Aguilar-Meléndez et al. 2019a).*

Based on the seismic vulnerability results included in Table 12, we observed that in Ciutat Vella, the buildings with six or more stories (GCV8) are, on average, more vulnerable than the buildings with fewer than six stories (GCV7). For instance, in Ciutat Vella, the probability that V is greater than 0.8 is equal to 77.40 % and 85.94% (*Best* curve-Table 12) for buildings with fewer than six stories (GCV7) and more than five stories (GCV8), respectively. On the other hand, if we consider the *Best* curve for the Nou Barris buildings (Table 12), then the probability that V is greater than 0.8 is equal to 34.39% and 33.61% for buildings with fewer than six stories (GNB7) and more than five stories (GNB8), respectively.

Table 12. Probabilities that V exceeds the values of 0.7, 0.8, and 0.9 (probabilities computed from the vulnerability curves of Figure 13 corresponding to the buidlings of groups).

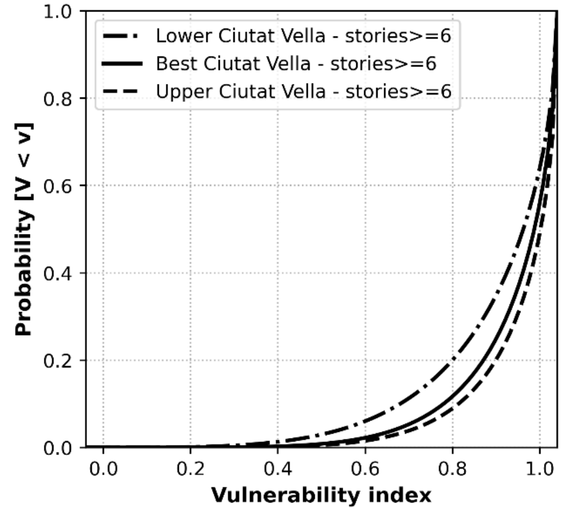
District	**Group of buildings**	**P(V>0.7) [%]**			**P(V>0.8) [%]**			**P(V>0.9) [%]**		
		Lower	***Best***	***Upper***	***Lower***	***Best***	***Upper***	***Lower***	***Best***	***Upper***
Ciutat Vella	Stories<6 (GCV7)	79.95	90.24	94.47	64.76	77.40	86.69	41.01	51.89	68.91
	Stories>=6 (GCV8)	87.61	93.95	95.58	77.12	85.94	89.13	58.19	68.17	73.74
Nou Barris	Stories<6 (GNB7)	40.13	55.28	70.99	22.04	34.39	52.48	6.99	13.15	27.79
	Stories>=6 (GNB8)	34.72	50.41	67.02	20.10	33.61	51.75	7.41	15.66	31.37

Additionally, we determined the seismic vulnerability of masonry and concrete buildings. Figure 14 shows that in Ciutat Vella, there are considerable differences among the vulnerability of masonry (Figure 14a) and reinforced concrete (RC) buildings (Figure 14b). For instance, if we consider the best curve, the probability that V is greater than 0.8 is equal to 89.17% and 22.35% for masonry buildings (GCV2) and RC buildings (GCV3), respectively. This significant difference between the masonry and RC buildings of Ciutat Vella agrees with the seismic vulnerability results assessed by Lantada et al. (2018). Remarkably, they applied the VIM for Ciutat Vella's buildings and obtained a vulnerability index average of 0.59 and 0.93 for reinforced concrete and masonry buildings, respectively.



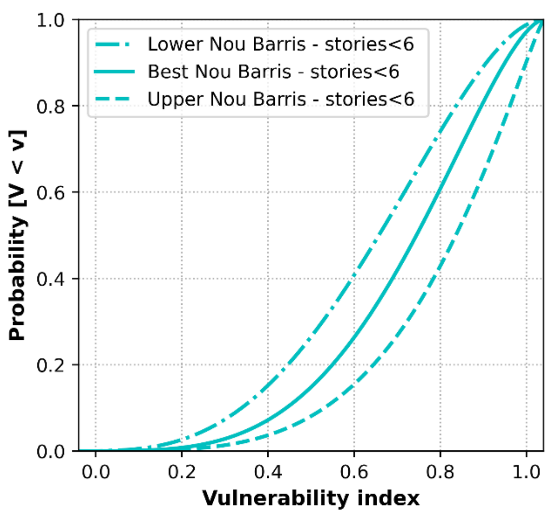
Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	3.98	0.86	0.82	0.17
Best	6.11	0.91	0.87	0.13
Upper	5.66	0.54	0.91	0.11

(a)



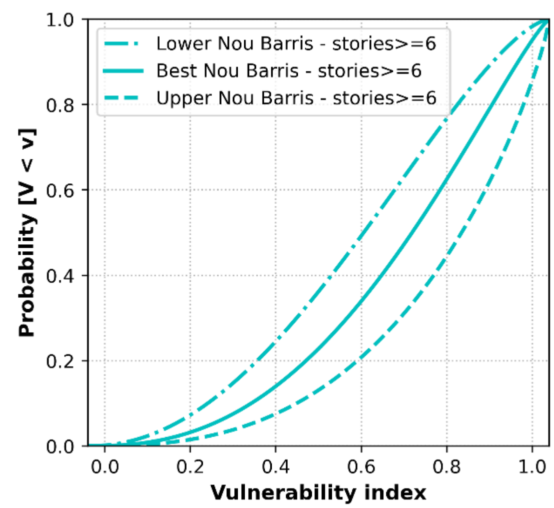
Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	3.78	0.54	0.87	0.16
Best	5.39	0.53	0.91	0.12
Upper	5.64	0.46	0.92	0.11

(b)



Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	3.17	1.88	0.63	0.21
Best	3.91	1.67	0.70	0.19
Upper	3.95	1.15	0.77	0.18

(c)



Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	2.16	1.55	0.58	0.25
Best	2.50	1.23	0.67	0.23
Upper	2.60	0.83	0.76	0.22

(d)

Figure 13. Seismic vulnerability curves of buildings in Ciutat Vella with fewer than six stories (GCV7) (a) and with six or more stories (GCV8) (b) and seismic vulnerability curves of buildings in Nou Barris with fewer than six stories (GNB7) (a) and with six or more stories (GNB8). For these cases, it was considered V_a=-0.04 and V_b=1.04.

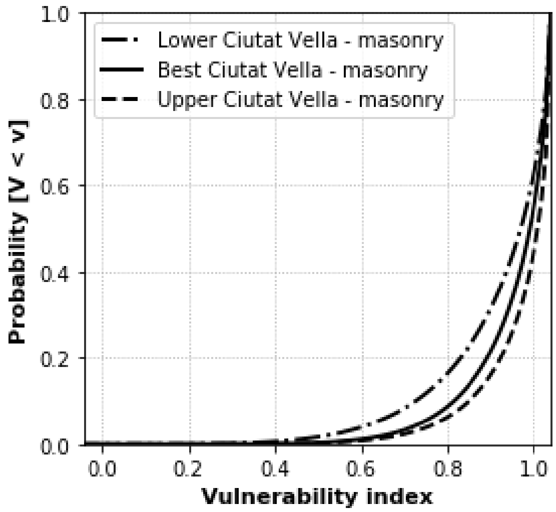
The vulnerability curves of Figure 14 also show that the masonry buildings of Ciutat Vella (GCV2) (Figure 14a) have, on average, higher levels of seismic vulnerability than the masonry buildings of Nou Barris (GNB2) (Figure 14c). For instance, the *Best* curve indicates that the probability that V is greater than 0.9 is equal to 71.39% and 14.20% for masonry buildings in Ciutat Vella (GCV2) and Nou Barris (GNB2), respectively. The difference between the levels of seismic vulnerability of the average masonry buildings in Ciutat Vella and Nou Barris is because, in the VIM_P, the seismic vulnerability assessment depends on the structural typology and the additional features of the buildings. Therefore, the differences in the percentage of masonry buildings of each structural typology in the districts of Ciutat Vella and Nou Barris are relevant factors that contribute to explain the differences in the average vulnerability of the masonry buildings of both districts. For instance, if only it is considered the structural typology, it is possible to identify (Figure 8) that in Ciutat Vella, the greater percentage of masonry buildings are M31 (81.1%), and in Nou Barris, a similar percentage (77.40%) correspond to the typologies M33 and M34, and these last two typologies have a best vulnerability function that has a V_I^* lower than the M31 structural typology (Table 6).

At the same time, the additional data to the typology contribute to explain the differences between the levels of seismic vulnerability of the masonry buildings in Ciutat Vella and Nou Barris. Notably, in the case of the studied buildings of Barcelona, the regional modifiers have a significant influence on the final values of seismic vulnerability (Lantada, 2007). These regional modifiers take into account the constructive considerations available in the construction date of the building, and this information is used to infer the probable seismic performance of the buildings (Lantada, 2007).

Another factor that explains the average higher levels of seismic vulnerability in the masonry buildings of Ciutat Vella is the fact that in this district, the major part of the masonry buildings (81.1%) corresponds to the M31 structural typology, and in Nou Barris, the major part of the masonry buildings (44.4%) are buildings with M34 structural typology. Therefore, in this case if only the structural typology is considered, the M31 structural typology is more vulnerable than the M34 structural typology (Table 6).

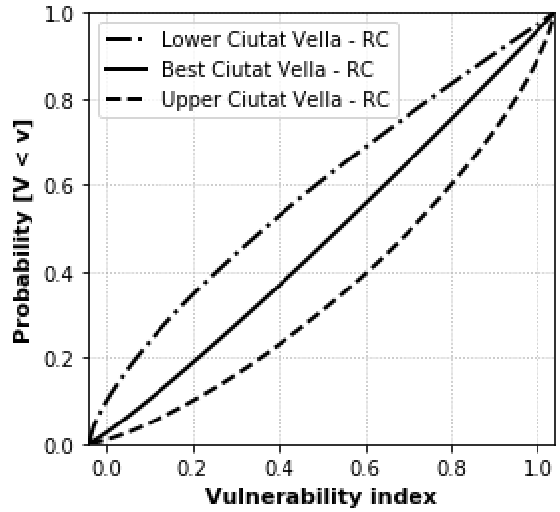
On the other hand, seismic vulnerability values between the RC buildings in Ciutat Vella (Figure 14b) and Nou Barris (Figure 14d) have a similar magnitude order. For example, according to the *Best* curve, the probability that V is greater than 0.9 is equal to 11.35% and 16.61% for RC buildings in Ciutat Vella and Nou Barris, respectively. In this case, the similitude in the average seismic vulnerability curves of the RC buildings in Ciutat Vella and Nou Barris is mainly due to two conditions: a) the whole RC buildings of both districts are classified into the same structural typology, and b) close of 32% and 34% of the RC buildings in Ciutat Vella and Nou Barris, respectively, were built before 1969. And the structural typology and the construction date are two features that significantly influence the final value of the seismic vulnerability of the buildings.

We also assessed the vulnerability for subgroups of masonry buildings. For instance, we studied the M31 buildings. We did this analysis because 81.1% of the masonry buildings of Ciutat Vella correspond to this typology (Figure 8). The vulnerability curves computed (Figure 15) show that the M31 buildings in Ciutat Vella (GCV4) have, on average, higher seismic vulnerability than the M31 buildings in Nou Barris (GNB4). Notably, the *Best* curve (Figure 15) indicates that the probability that V is greater than 0.9 is equal to 73.80% and 38.69% for M31 buildings in Ciutat Vella (GCV4) and Nou Barris (GNB4), respectively.



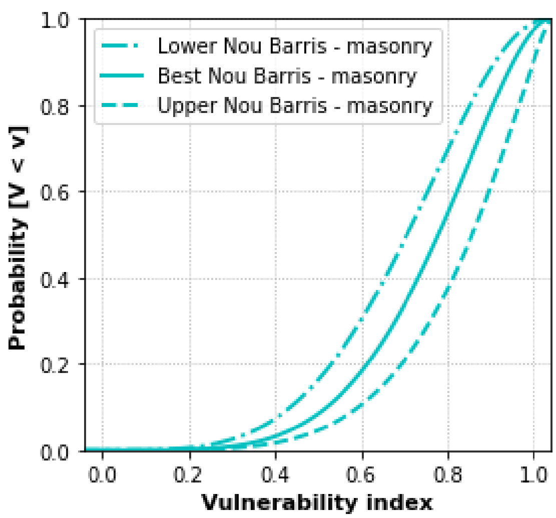
Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	4.64	0.58	0.89	0.14
Best	6.78	0.59	0.92	0.10
Upper	6.66	0.45	0.94	0.09

(a)



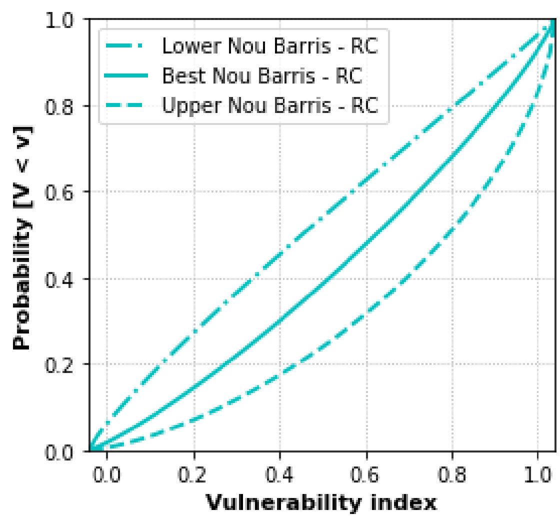
Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	0.70	0.98	0.42	0.32
Best	1.11	0.99	0.53	0.31
Upper	1.32	0.74	0.64	0.30

(b)



Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	4.67	2.26	0.67	0.18
Best	5.32	1.91	0.74	0.17
Upper	5.07	1.27	0.80	0.16

(c)



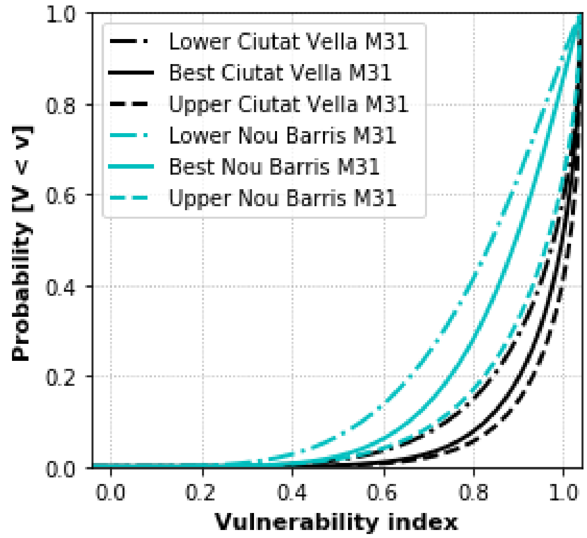
Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	0.84	0.95	0.47	0.32
Best	1.18	0.84	0.58	0.31
Upper	1.41	0.61	0.70	0.29

(d)

Figure 14. Seismic vulnerability curves of buildings of masonry (GCV2)(a) and RC (GCV3)(b) in Ciutat Vella and seismic vulnerability curves of buildings of masonry (GNB2)(c) and RC (GNB3)(d) in Nou Barris. For these cases, it was considered Va=-0.04 and Vb=1.04.

As was mentioned previously, in addition to the structural typology, other features of the buildings are considered to determine their seismic vulnerability. For this last reason, it is possible to have cases where buildings of the same structural typology have different levels of seismic vulnerability.

Notably, in this case, a significant reason that explains the difference between the average M31 buildings in Ciutat Vella versus the M31 buildings in Nou Barris are the regional vulnerability modifiers defined by Lantada (2007). According to these modifiers (Table 7), M31 buildings built in 1940 or before have greater vulnerability modifiers than those built after 1940. Moreover, according to the data, 94.94% and 76.02 % of the M31 buildings in Ciutat Vella and Nou Barris, respectively, were built in 1940 or before. Therefore, the percentage of M31 buildings in Ciutat Vella that have a regional modifier for the buildings of 1940 or before is greater than the percentage of the Nou Barris district that has this feature.



Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	4.67	0.54	0.90	0.13
Best	6.83	0.55	0.93	0.10
Upper	6.74	0.42	0.94	0.09

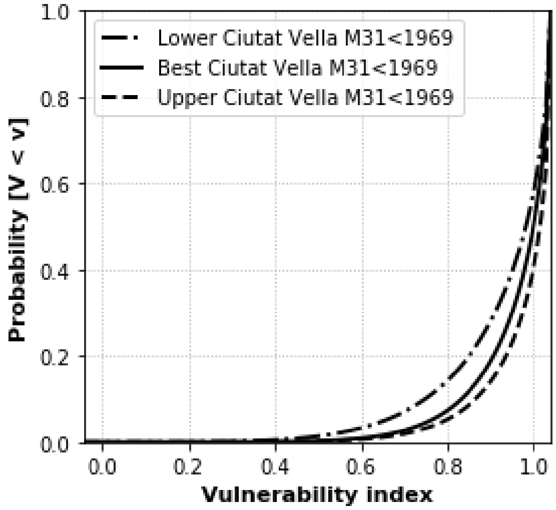
Ciutat Vella

Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	4.42	1.23	0.78	0.17
Best	5.89	1.17	0.83	0.14
Upper	4.72	0.61	0.89	0.14

Nou Barris

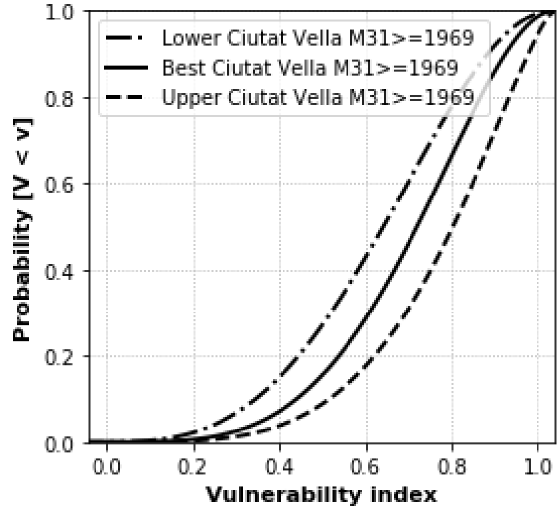
Figure 15. Seismic vulnerability curves for the masonry M31 buildings in Ciutat Vella (GCV4) and Nou Barris (GNB4) considering V_a*=-0.04 and* V_b*=1.04.*

Additionally, we analyzed two subgroups of the M31 buildings of each district, considering the variable of the year of construction. For this analysis, we choose the 1969 year as the reference point because Barcelona’s first seismic code was used in that year (Lantada 2007). The results (Figure 16) indicate that the M31 buildings built during or after 1969 in Ciutat Vella (GCV6) and Nou Barris (GNB6) have, on average, a significantly lower seismic vulnerability than the M31 buildings built before that year. Moreover, if we analyze the Best vulnerability curves (Figure 16), we can verify additional conclusions. For instance, in this last case, we can observe that the probability that V is greater than 0.8 is equal to 90.79% and 28.8% for the M31 buildings in Ciutat Vella built before 1969 (GCV5) (Figure 16a) and during or after 1969 (GCV6) (Figure 16b), respectively. We also observed that, on average, the M31 buildings that were built during or after 1969 in Ciutat Vella (GCV6) (Figure 16b) have higher levels of seismic vulnerability than the buildings that were also built during or after 1969 in Nou Barris (GNB6) (Figure 16d). For instance, the *Best* vulnerability curve shows that the probability that V is greater than 0.8 is equal to 28.8% and 20.9% for the M31 buildings built during or after 1969 in Ciutat Vella (GCV6) (Figure 16b) and Nou Barris (GNB6) (Figure 16d), respectively.



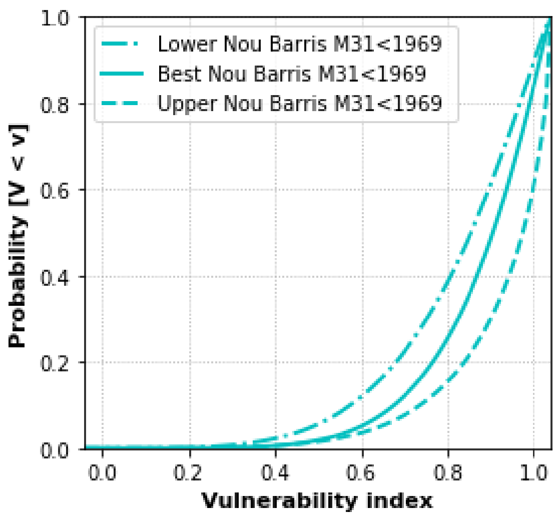
Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	4.69	0.52	0.90	0.13
Best	6.89	0.53	0.93	0.10
Upper	6.79	0.41	0.94	0.09

(a)



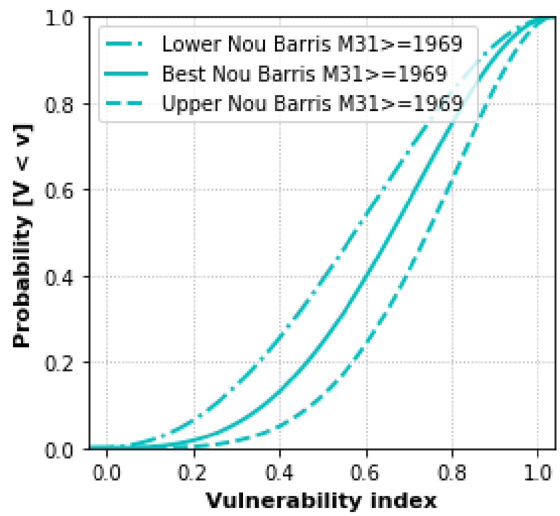
Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	3.56	2.20	0.62	0.20
Best	4.42	2.04	0.68	0.18
Upper	4.41	1.46	0.75	0.18

(b)



Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	4.58	1.19	0.79	0.17
Best	6.08	1.13	0.84	0.14
Upper	4.71	0.56	0.89	0.13

(c)



Seismic vulnerability curve	*α*	*β*	*Mean*	*SD*
Lower	2.55	2.00	0.56	0.23
Best	3.67	2.12	0.63	0.20
Upper	4.84	2.01	0.71	0.18

(d)

Figure 16. Seismic vulnerability curves for the masonry M31 buildings built before 1969 (GCV5) (a) and during or after 1969 (GCV6) (b) in Ciutat Vella (top) and the seismic vulnerability curves for the masonry M31 buildings built before 1969 (GNB5) (c) and during or after 1969 (GNB6) (d) in Nou Barris considering V_a=-0.04 and V_b=1.04.

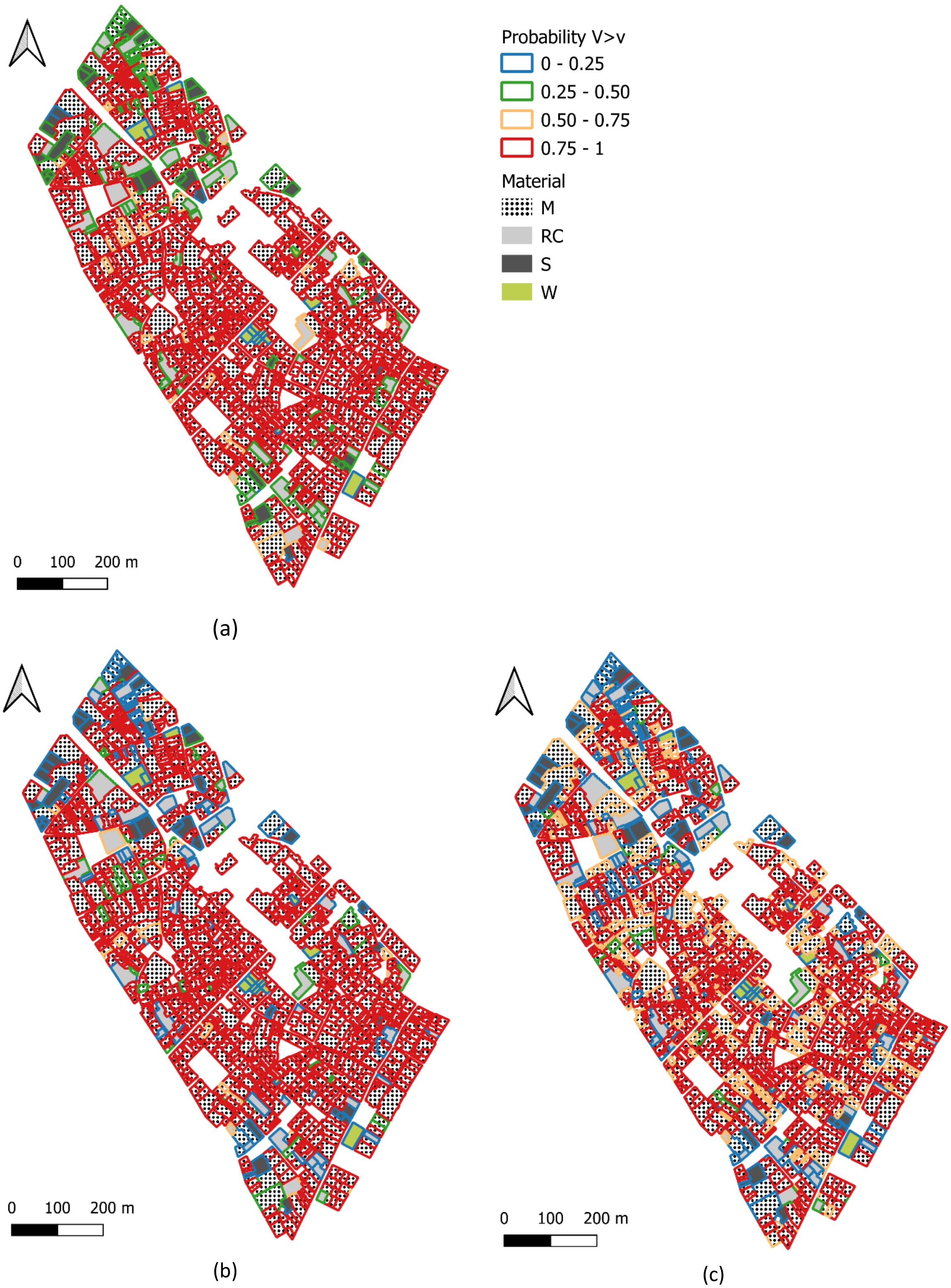


Figure 17. Maps of seismic vulnerability of residential buildings in the Gothic neighborhood of the Ciutat Vella district, in terms of the probability that V is greater than 0.7(a), 0.8(b), and 0.9(c) considering the Best vulnerability functions.

The computed seismic vulnerability curves can also be used to generate seismic vulnerability maps like the ones included in Figure 17. The data of the map of Figure 17a allows identifying that 85.36% of residential buildings in the Gothic neighborhood of Ciutat Vella have a probability superior to 0.75 that V is greater than 0.7 (if the *Best* vulnerability curves are considered). The Ciutat Vella district is divided into four neighborhoods: i) Raval; ii) Gothic; iii) Barceloneta, and iv) Santa Pere, Santa Caterina I la Ribera (Ajuntament de Barcelona, 2020). Similarly, the results represented in the maps of Figure 17b and Figure 17c indicate that 84.44% and 66.36% of residential buildings in the Gothic neighborhood of Ciutat Vella have a probability superior to 0.75 that V is greater than 0.8 and 0.9, respectively (if the *Best* vulnerability curves are considered). In contrast, the results in the Nou Barris district's case show that 24.29% of dwelling buildings of this district have a probability superior to 0.75 that V is greater than 0.7. Similarly, 17.31% and 0.51% of residential buildings in Nou Barris have a probability superior to 0.75 that V is greater than 0.8 and 0.9, respectively (considering the *Best* vulnerability curves).

2.5. Seismic Risk of Ciutat Vella and Nou Barris

According to the VIM_P, Eq. (6) was applied to compute the seismic risk of the studied buildings. Particularly, the seismic risk of each building was computed considering their respective seismic hazard curves and the seismic vulnerability functions of the studied building. For instance, applying USERISK2015, the seismic risk results of the buildings included in Table 8 were computed. For this case, the seismic hazard curves used are the curves of black lines in Figure 5. These curves were truncated to 475 years and the vulnerability functions considered are included in Figure 10. Table 13 and Figure 18 shows the computed seismic risk results. These last results correspond to the seismic risk for each one of the four studied buildings. However, it is also possible to use these seismic risk results to obtain the risk for a group of buildings as it was described by Aguilar-Meléndez et al. (2019a). Figure 19 shows the case of the seismic risk results determined for a group of the two buildings: CV1 and CV2.

Table 13. Results of Seismic risk of buildings CV1, CV2, NB1, and NB2 in Barcelona in terms of the average of the annual frequency of exceedance of the damage grades (1-5) computed considering a seismic hazard truncated to 475 years

Building	VC	ν (D) [1/years]				
		D1	D2	D3	D4	D5
CV1	L	9.5E-3	3.28E-3	7.9E-4	1.03E-4	3.29E-6
	B	1.21E-2	4.61E-3	1.2E-3	1.69E-4	5.91E-6
	U	1.51E-2	6.35E-3	1.8E-3	2.73E-4	1.04E-5
CV2	L	5.99E-3	1.66E-3	3.3E-4	3.51E-5	8.73E-7
	B	8.79E-3	2.94E-3	6.91E-4	8.78E-5	2.73E-6
	U	1.17E-2	4.43E-3	1.15E-3	1.61E-4	5.61E-6
NB1	L	5.59E-3	1.54E-3	3.06E-4	3.26E-5	8.18E-7
	B	7.83E-3	2.46E-3	5.46E-4	6.54E-5	1.89E-6
	U	1.07E-2	3.92E-3	9.91E-4	1.35E-4	4.56E-6
NB2	L	2.24E-3	5.85E-4	1.09E-4	1.07E-5	2.23E-7
	B	3.06E-3	7.94E-4	1.47E-4	1.41E-5	2.89E-7
	U	5.05E-3	1.47E-3	2.98E-4	3.12E-5	7.05E-7

If we consider the individual seismic risk, it is possible to observe that in the CV1 building, the annual frequency of exceedance of the collapse damage state ranges between 3.29x10^{-6} and 1.04x10^{-5}, with a mean value of 5.91x10^{-6}. Similarly, in the CV2 building, the annual frequency of exceedance of the collapse damage state ranges between 8.73x10^{-7} and 5.61x10^{-6}, with a mean value of 2.73x10^{-6}. On the other hand, if we consider the mean values, we can affirm that the CV1 building has twice the seismic risk of the CV2 building. At the same time, it is possible to highlight that if the upper value is considered, we can observe that the seismic risk of the CV1 building exceeds the value of 1x10^{-5}. Therefore, if a decision criterion states that the building with a higher level of seismic risk greater than 1x10^{-5} (Stirrat and Jury, 2017; Hardy et al., 2017) must require an additional detailed revision, then the building CV1 would require this kind of revision.

In this study, we applied USERISK2015 (Aguilar-Meléndez et al. 2016) to compute the seismic risk of Ciutat Vella and Nou Barris's residential buildings. First, we computed seismic risk applying the seismic hazard curves determined in the present work (Figure 5) truncated to 475 years (10% probability of exceedance in 50 years). Additionally, we computed seismic risk considering the same hazard curves but truncated to 975 years (5% probability of exceedance in 50 years). We computed the seismic risk for seismic hazard for these two return periods (475 and 975 years) because, as a part of the seismic risk management, it is convenient to have results of seismic risk for different return periods of seismic hazard to facilitate the stakeholders the decision procedures. Even though the return periods selected are common values to compute seismic hazard (Solomos et al., 2008), they are not unique options. For this reason, the VIM_P allows computing the seismic risk for the diverse return periods that could be necessary.

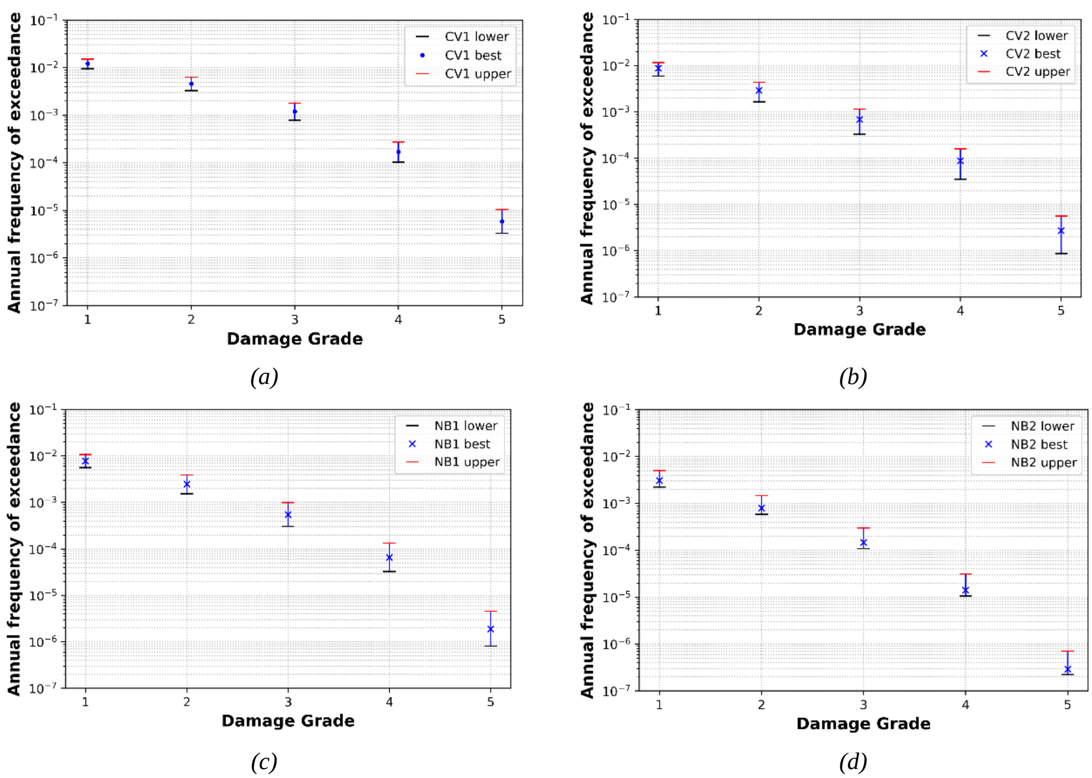


Figure 18. Seismic risk of buildings CV1(a), CV2(b), NB1(c), and NB2(d) in Barcelona in terms of the average of the annual frequency of exceedance of the damage grades (1-5) computed considering a seismic hazard truncated to 475 years

For the first case (475 years), the seismic risk computed of Ciutat Vella and Nou Barris's residential buildings is shown in Figure 20. Specifically, according to Figure 20, on average, the seismic risk of the residential buildings of Ciutat Vella is higher than the seismic risk of the residential buildings of Nou Barris. For instance, if we observe the results obtained using the *Best* vulnerability curves (Figure 20), we can identify that the damage grade 5 (total collapse) has an annual frequency of exceedance equal to 1.46×10^{-5} and 3.14×10^{-6} for the residential buildings of Ciutat Vella and Nou Barris, respectively. These results agree with Lantada et al. (2010) study because they also concluded that the seismic risk in Ciutat Vella is significantly higher than in Nou Barris.

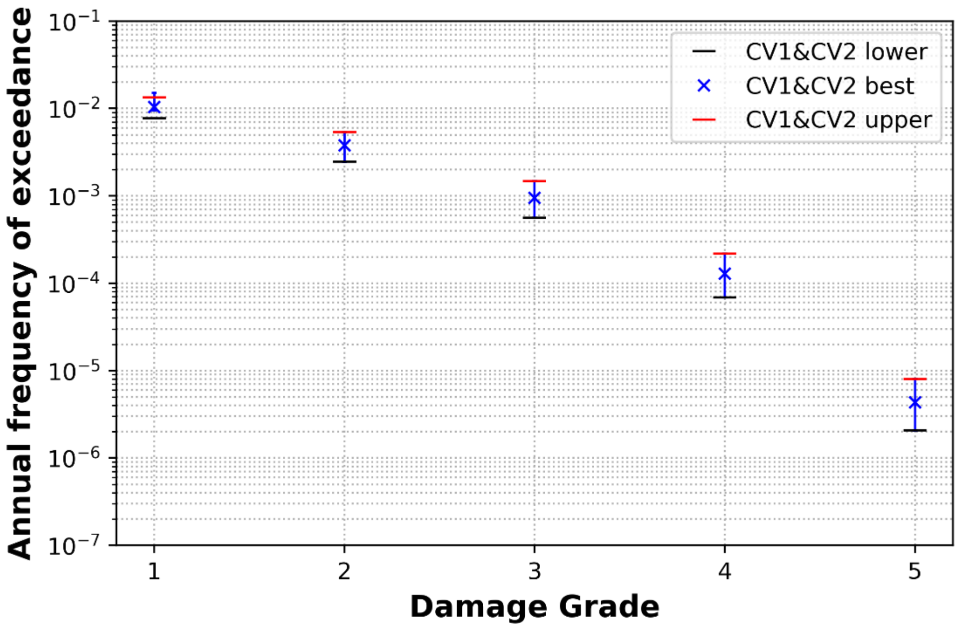


Figure 19. Average risk of buildings CV1 and CV2 in Barcelona in terms of the average of the annual frequency of exceedance of the damage grades (1-5) computed considering a seismic hazard truncated to 475 years

Additionally, the results show that 70.04%, 70.31%, and 82.26% of the Buildings in Ciutat Vella (GCV1) have an exceedance frequency of the collapse damage state greater than 1×10^{-5}, if the *Lower*, *Best*, and *Upper* vulnerability curves are considered, respectively. Similarly, 1.06%, 2.81%, and 28.11% of the Buildings in Nou Barris (GNB1) have an exceedance frequency of the collapse damage state greater than 1×10^{-5}, if the *Lower*, *Best*, and *Upper* vulnerability curves are considered, respectively.

On the other hand, Figure 21 shows seismic risk results computed using seismic hazard truncated to 975 years. These risk results indicate that the damage grade 5 (total collapse) has an annual frequency of exceedance equal to 2.35×10^{-5} and 5.17×10^{-6} for Ciutat Vella (GCV1) and Nou Barris (GNB1) buildings, respectively. Therefore, analyzing these previous results, we can affirm that the seismic risk related to the damage grade 5 in both districts increases by about 70% when we modify the truncation limit of the seismic hazard from 475 years to 975 years. The same seismic risk results indicate that 81.07% and 23.02% of the buildings in Ciutat Vella and Nou Barris, respectively, have an exceedance frequency of the collapse damage state greater than 1×10^{-5}, if the *Best* vulnerability curve and the seismic hazard of 975 years are considered.

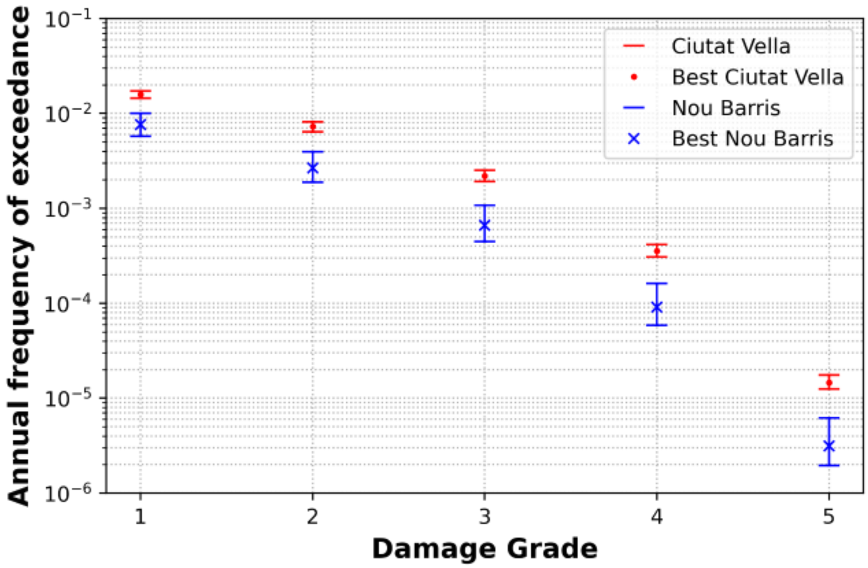


Figure 20. Seismic risk of Ciutat Vella (GCV1) and Nou Barris (GNB1) in Barcelona in terms of the average of the annual frequency of exceedance of the damage grades (1-5) computed considering a seismic hazard truncated to 475 years.

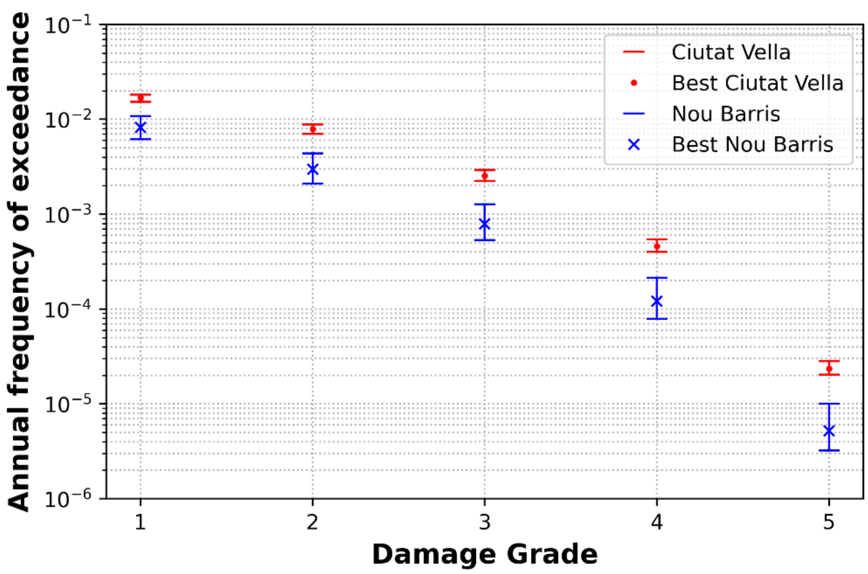


Figure 21. Seismic risk of Ciutat Vella (GCV1) and Nou Barris (GNB1) in Barcelona in terms of the average of the annual frequency of exceedance of the damage grades (1-5) computed considering a seismic hazard truncated to 975 years.

Additionally, Figure 22 shows another way to communicate the seismic risk computed according to the VIM_P. Particularly, in this figure, we can observe maps that display the location and shape of each plot where a residential building exists in the Gothic neighborhood of the Ciutat Vella District. However, at the same time, these maps show the seismic risk of the building located in each plot in terms of the annual frequency of exceedance of the damage grade 5. Moreover, these maps display the main structural material of each studied building.

According to the seismic results of Figure 22, the percentage of dwelling buildings in the Gothic neighborhood that has a frequency of occurrence of damage five greater than $1x10^{-5}$ is 70.42%, 70.57%, and 77.93%, respectively, when the *Lower*, *Best,* and *Upper* vulnerability curves are considered.

Figure 22. Seismic risk maps of the Gothic neighborhood of Ciutat Vella to cadastral plot scale. These maps show the seismic risk and the main structural material of each residential building of the Gothic neighborhood of Ciutat Vella. The seismic risk is in terms of annual frequency of damage D5, and this risk was obtained considering a seismic hazard curve truncated to 475 years and the Lower (a), Best (b), and Upper (c) seismic vulnerabilities curves.

As stated in Figure 23, the average seismic risk of the masonry buildings in Ciutat Vella is higher than the average seismic risk of the masonry buildings in Nou Barris. For instance, according to the *Best* vulnerability curve (Figure 23), the annual frequency of exceedance of damage 5 in the masonry buildings is equal to 1.62x10^{-5} and 3.08x10^{-6} in Ciutat Vella (GCV2) and Nou Barris (GNB2), respectively. These values also mean that the seismic risk of the masonry buildings in Ciutat Vella is 5.3 times higher than the seismic risk of the masonry buildings in Nou Barris. Similarly, we can observe that considering the *Best* vulnerability curves (Figure 24a and Figure 24b), the annual frequency of exceedance of the damage 5 in the reinforced concrete buildings is equal to 2.35x10^{-6} and 3.53x10^{-6} in Ciutat Vella (GCV3) and Nou Barris (GNB3), respectively. Therefore, in this case, the average seismic risk of the reinforced concrete buildings is 1.5 times higher in Nou Barris than in Ciutat Vella.

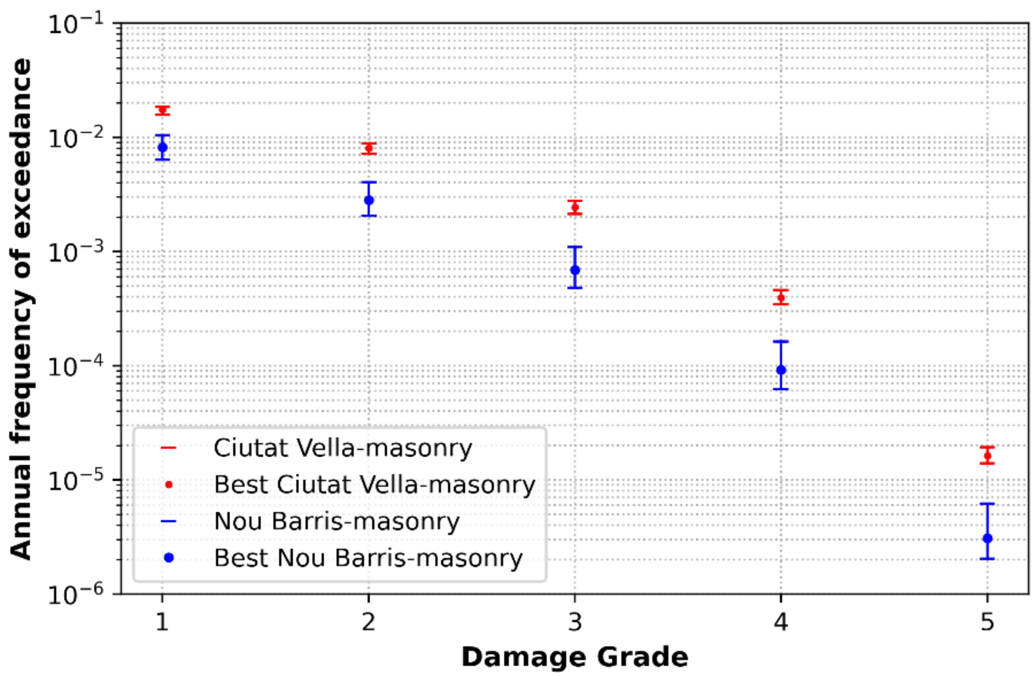
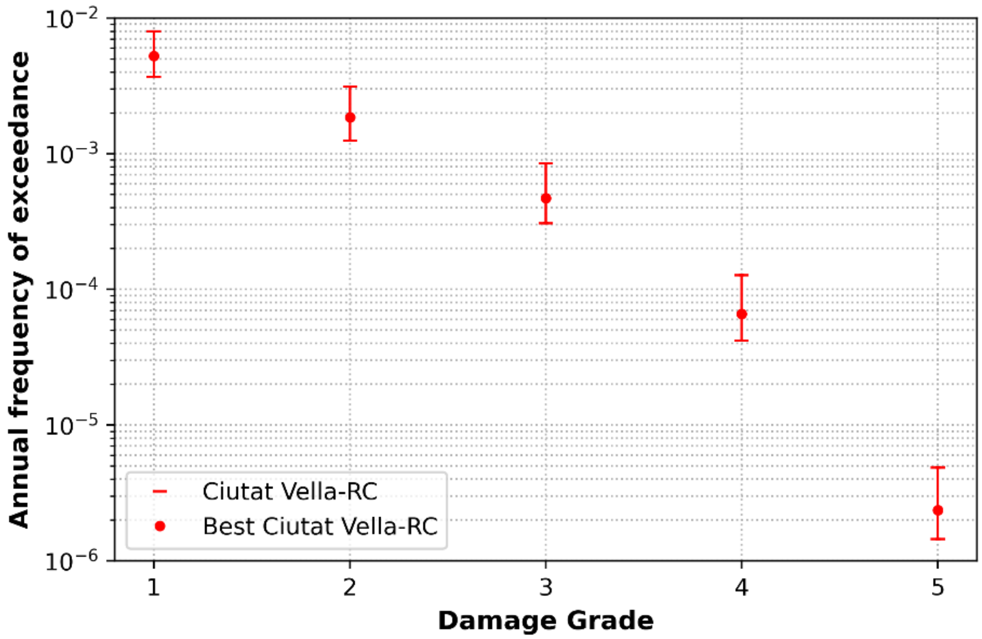


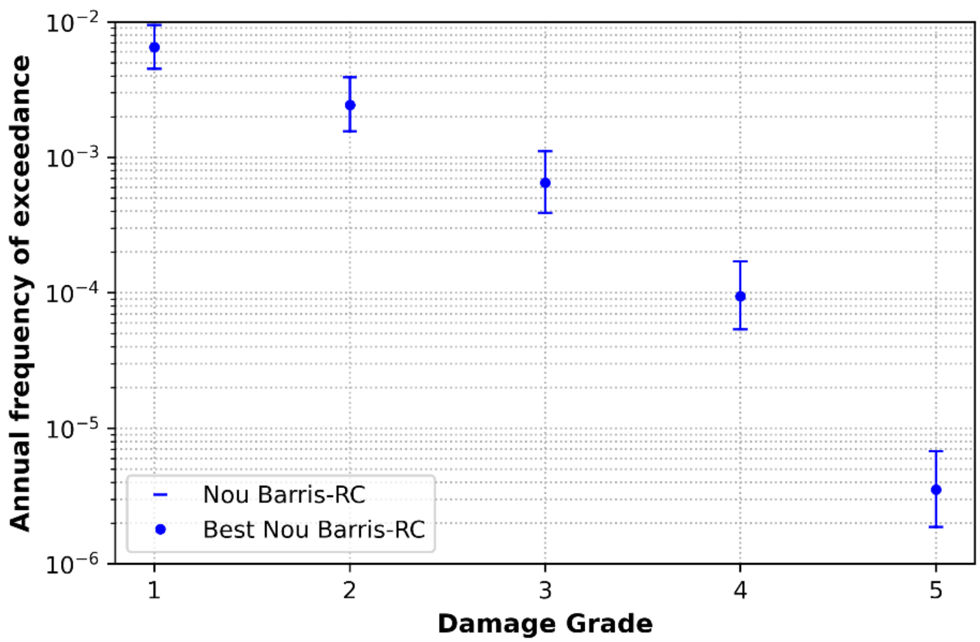
Figure 23. Seismic risk of masonry buildings of Ciutat Vella (GCV2) and Nou Barris (GNB2) in terms of the average of the annual frequency of exceedance of the damage grades (1-5), computed considering a seismic hazard truncated to 475 years.

It can be observed that buildings in Ciutat Vella with six or more stories (GCV8) have, on average, higher seismic risk than buildings with five or fewer stories (GCV7) (Table 14). For instance, for the best vulnerability curve, the average seismic risk for the damage grade 5 is equal to 1.1x10^{-5} and 1.64x10^{-5} for buildings with five or fewer stories and six or more stories, respectively.

Similarly, Table 14 shows that buildings in Nou Barris with six or more stories (GNB8) have, on average, higher seismic risk than buildings with five or fewer stories (GNB7). For example, the best vulnerability curve indicates that the average seismic risk for the damage grade 5 is equal to 2.96x10^{-6} and 3.55x10^{-6} for buildings in Nou Barris with five or fewer stories and six or more stories, respectively.



(a)



(b)

Figure 24. Seismic risk of reinforced concrete buildings of Ciutat Vella (GCV3) (a) and seismic risk of reinforced concrete buildings of Nou Barris (GNB3) (b). The seismic risk is in terms of the average of the annual frequency of exceedance of the damage grades (1-5), computed considering a seismic hazard truncated to 475 years.

Table 14. Seismic risk for the buildings in Ciutat Vella (left) and Nou Barris (right) considering two groups of buildings: I) buildings with five or fewer stories and II) buildings with six or more stories. These results were computed considering a seismic hazard truncated to 475 years and the Best vulnerability curve of the buildings (Figure 9).

District	Buildings	VC	ν (D) [1/years]				
			D1	D2	D3	D4	D5
Ciutat Vella	Residential buildings with five or fewer stories (GCV7)	L	1.72E-02	7.97E-03	2.43E-03	3.96E-04	1.64E-05
		B	1.47E-02	6.36E-03	1.83E-03	2.83E-04	1.10E-05
		U	1.68E-02	7.84E-03	2.41E-03	3.95E-04	1.65E-05
	Residential buildings with six or more stories (GCV8)	L	1.51E-02	6.94E-03	2.11E-03	3.44E-04	1.43E-05
		B	1.66E-02	7.73E-03	2.38E-03	3.91E-04	1.64E-05
		U	1.74E-02	8.27E-03	2.58E-03	4.28E-04	1.81E-05
Nou Barris	Residential buildings with five or fewer stories (GNB7)	L	5.88E-03	1.93E-03	4.58E-04	6.01E-05	1.99E-06
		B	7.59E-03	2.63E-03	6.48E-04	8.74E-05	2.96E-06
		U	9.88E-03	3.82E-03	1.04E-03	1.54E-04	5.88E-06
	Residential buildings with six or more stories (GNB8)	L	5.46E-03	1.78E-03	4.22E-04	5.57E-05	1.86E-06
		B	7.65E-03	2.75E-03	7.04E-04	9.92E-05	3.55E-06
		U	1.05E-02	4.21E-03	1.17E-03	1.78E-04	6.90E-06

VC=vulnerability curve; L=Lower; B=Best; U=Upper

Additionally, we compared the seismic risk of buildings of Nou Barris founded on soil and rock. Figure 25 displays that buildings of Nou Barris founded on soil have, on average, a seismic risk higher than the seismic risk of buildings of Nou Barris founded on rock. For instance, for damage grade 5, the annual frequency of exceedance is equal to 5.11×10^{-7} and 3.68×10^{-6} for buildings on rock and soil, respectively. According to these results, the seismic risk of the Nou Barris buildings founded on soil is, on average, 7.2 times greater than the seismic risk of the buildings of the same district founded on rock.

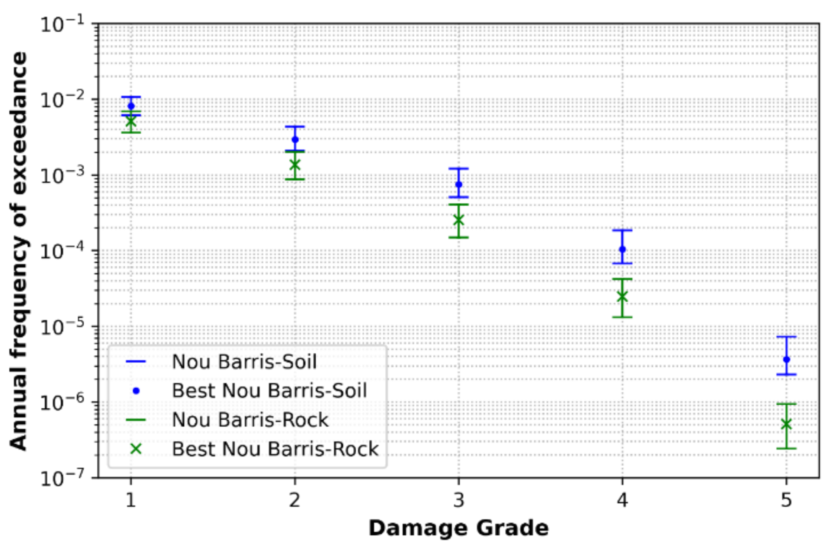


Figure 25. Seismic risk of the buildings in Nou Barris on soil and rock computed considering a seismic hazard truncated to 475 years

2.6. Seismic risk in economic terms

We used the seismic risk results in terms of physical damage (Figure 21a) to assess economic losses. For this purpose, we considered that according to Marulanda et al. (2013), €31523 million is the overall value of Barcelona's total residential buildings. Additionally, we applied the proposal that states that the economic cost factors are equal to 0.035, 0.145, 0.305, 0.800, and 1.00 for the occurrence of damage states 1,2,3,4, and 5, respectively (Dolce et al. 2006).

The economic cost obtained by Lantada et al. (2018) for Ciutat Vella shows good agreement with the losses computed in the present study. Particularly, Lantada et al. (2018) computed €591 and €1105 million of economical cost in Ciutat Vella due to a seismic event of intensity VI and VI-VII, respectively. The losses of €1105 million also correspond to a probabilistic seismic scenario with a return period of 475 years. In this study, the economic losses related to a return period of 475 years are equal to €875.65, €948.55, and €1037.06 million for the *Low*, *Best*, and *Upper* cases, respectively (Figure 26a). Similarly, the economic losses that we computed for Nou Barris are equal to €473.13, €630.12, and €795.97 million for the *Low*, *Best*, and *Upper* case, respectively (Figure 26b). Moreover, the economic losses for the *Best* case are equal to €1349.39 and €965.43 for Ciutat Vella and Nou Barris, respectively (Figure 26b) if a return period of 975 years is considered.

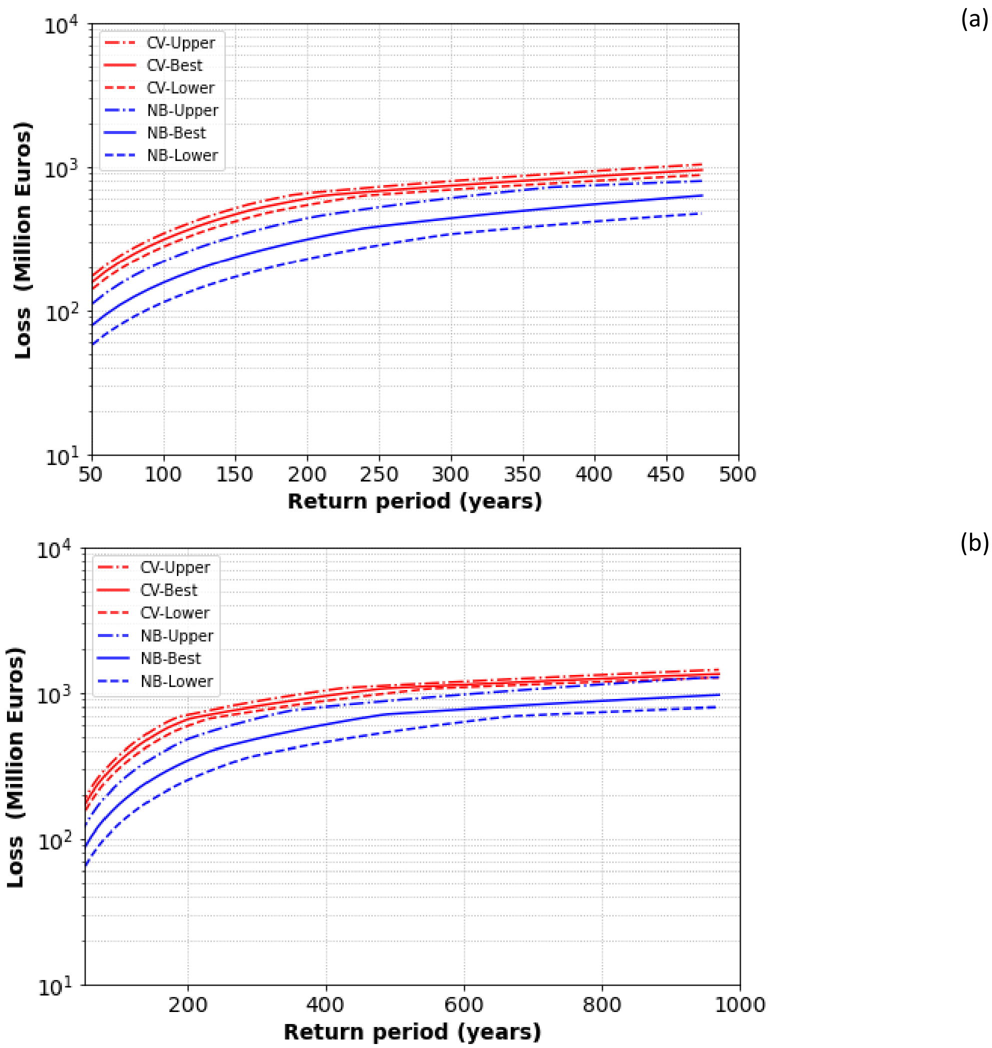


Figure 26. Seismic risk curves of the residential buildings of Ciutat Vella and Nou Barris in terms of economic losses versus return periods. These curves were obtained considering the seismic hazard curves computed in the present work (Figure 5) truncated to 475 years (a) and 975 years (b).

3. Discussion and conclusions

The VIM_P is a versatile methodology to assess seismic vulnerability and the seismic risk of residential buildings. Specifically, in this study, we analyzed the residential buildings of Ciutat Vella and Nou Barris districts in Barcelona. Both seismic vulnerability and seismic risk results obtained with this methodology are valuable information that could be used to make essential decisions oriented to increase seismic resilience in cities.

Seismic hazard

The seismic hazard curve computed for Barcelona agrees with previous seismic hazard assessments. For instance, based on the results (Figure 5), the intensity with a return period of 475 years for a rock site is slightly less than the macroseismic grade VI. This last result agrees with the intensity of VI determined by the IGN (2017) for Barcelona for a return period of 475 years. We highlighted that the Lorca earthquake in 2011 generated substantial damage (Aguilar-Meléndez et al. 2019c), and this disaster contributed to increasing the interest in performing new assessments of the seismic hazard of Spain.

Vulnerability

The results show that the buildings in Ciutat Vella have, on average, significantly higher seismic vulnerability than the buildings in Nou Barris. For instance, if we consider the *Best* vulnerability curve, then the probability that a building has a vulnerability index greater than 0.8 could be 83.59% and 34.03% in Ciutat Vella and Nou Barris, respectively. The results also indicate that in Ciutat Vella, the buildings with six or more stories are, on average, more vulnerable than buildings with five or fewer stories. For example, in this district, the probability that V is greater than 0.9 is equal to 51.89% and 68.17% (*Best*-curve-Table 12) for buildings with fewer than six stories and more than five stories, respectively. However, in Nou Barris's case, the seismic vulnerability between buildings with six or more stories and buildings with five or fewer stories have fewer differences than in the case of Ciutat Vella's buildings. Specifically, when we analyzed a level of seismic vulnerability represented by V>0.7, then the buildings in Nou Barris with fewer than six stories have more probability (55.28%-Table 12) of exceeding that level of vulnerability than the buildings with more than five stories (50.41%-Table 12). However, if we analyze a level of vulnerability represented by V>0.9, then the buildings in Nou Barris with more than five stories have more probability (15.66%-Table 12) of exceeding that level of vulnerability than the buildings with fewer than six stories (13.15%-Table 12).

It is essential to highlight that even though, on average, the masonry buildings in Ciutat Vella have higher levels of seismic vulnerability than the masonry buildings in Nou Barris, in the case of the RC buildings, this behavior is not the same. Conversely, the RC buildings in Nou Barris are slightly more vulnerable than the RC buildings in Ciutat Vella. These differences are mainly related to the age of the buildings because this age is used to determine the design procedures that were considered to design each building. And this feature is considered in the regional modifiers for the Barcelona' buildings (Table 7) that were defined by Lantada (2007). Notably, on average, the masonry buildings in Ciutat Vella are older than the masonry buildings in Nou Barris. On the other hand, on average, the RC buildings in Nou Barris are slightly older than the RC buildings in Ciutat Vella. For instance, if we consider the *Best* curve, the probability that V is greater than 0.9 is equal to 16.61 % and 11.35% for the RC buildings in Nou Barris and Ciutat Vella, respectively.

We also analyzed the case of the masonry buildings M31, and the results show that the M31 buildings in Ciutat Vella are, on average, more vulnerable than the same type of buildings in Nou Barris. This last condition is because not only the structural typology is considered to determine the seismic vulnerability of the buildings, and, in this case, the regional modifiers have a significant influence on the final values of seismic vulnerability of each studied building (Table 7).

On the other hand, a year that has been associated with a relevant reduction in the seismic vulnerability of buildings in Barcelona is 1969. This last condition is because, during this year, the first seismic code in the city was applied. For this last reason, even the M31 buildings in Ciutat Vella have significant differences in their seismic vulnerability depending on the year of construction. For instance, if we consider the best vulnerability curve, then the probability that V is greater than 0.8 is equal to 90.79% for M31-buildings in Ciutat Vella built before 1969 and equal to 28.8% for the M31-buildings built in the same district during or after 1969.

The seismic vulnerability can also be communicated through vulnerability maps like the ones shown in Figure 17 to help a broader range of stakeholders. These maps show the different levels of seismic vulnerability of the buildings in the Gothic neighborhood of Ciutat Vella.

Risk

The results show that if the *Best* vulnerability curve and a seismic hazard curve truncated to 475 years are considered, then 70.31% and 2.81% of the buildings in Ciutat Vella and Nou Barris, respectively, have an exceedance frequency of the collapse damage state greater than $1x10^{-5}$. Therefore, if we consider this last value as the limit of acceptable seismic risk, then it can be observed that the major part (70.31%) of Ciutat Vella's buildings could have a not acceptable level of seismic risk. Consequently, this district could be considered a Barcelona region where the buildings require a special program to verify their structural safety, including their appropriate behavior during earthquakes. On the other hand, in Nou Barris, the percentage of buildings that exceed the reference seismic risk level is 2.81%. Therefore, in this case, it could be convenient to verify the buildings' structural safety with the emphasis on the buildings that exceed the reference level of seismic risk previously mentioned.

It should be noted that the results show that not all the buildings in Ciutat Vella have more seismic risk than the buildings in Nou Barris. Specifically, the RC buildings of Nou Barris have, on average, a seismic risk level 1.5 times greater than the RC buildings of Ciutat Vella if the *Best* curve is considered. Simultaneously, it is convenient to notice that according to the results (Figure 25), the buildings of Nou Barris in soil have, on average, a seismic risk level 7 times greater than the buildings of the same district located in rock.

The seismic risk maps of Figure 22 are an option to communicate the residential buildings' seismic risk to the stakeholders. This information could be used to make decisions that increase the seismic resilience of the cities. It is essential to highlight that the VIM_P allows assessing the seismic risk in terms of annual frequency of exceedance of damage states, which does not occur with the VIM antecedent method. At the same time, the VIM_P allows computing the seismic risk in terms of losses with different return periods. This last type of information is, for instance, relevant for the insurance industry. Therefore, the appropriate application of the VIM_P can contribute to generating valuable information for the different stakeholders related to the management of the seismic risk of buildings in urban areas.

Comparison with previous results

The losses assessed in the present study for Ciutat Vella agree with the losses obtained by Lantada et al., 2018. They assessed losses of €1105 million for a seismic scenario associated with a return period of 475 years, and we estimated losses of €948.55 million for a return period of 475 years. In this aspect, it is convenient to underline that the comparison focuses on the order of magnitude of the economic losses because the methodology used to compute the losses by Lantada et al. (2018) was the VIM, and in the present study, we applied the VIM_P. As was mentioned by Aguilar-Meléndez et al. (2019a), the type of seismic results that can be obtained by each one of these two methods are not the same. On the other hand, the seismic vulnerability results obtained in the present study for the masonry and RC buildings in Ciutat Vella agree with the results determined by Lantada et al. 2018, because they also computed significant differences between the seismic vulnerability of both groups of buildings of the Ciutat Vella district.

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Declarations

Funding

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Conflicts of interest/Competing interests

The authors declare that there is no conflict of interest.

Availability of data and material

The database generated during and analyzed during the current study is not publicly available due to the sensitivity of the data of the buildings.

Code availability

R-CRISIS code can be downloaded at the site http://www.r-crisis.com/ and USERISK2015 can be requested at the site https://sites.google.com/site/userisk2015/

Ethics approval

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Consent to participate

Not applicable

Consent for publication

Not applicable

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