JOURNAL OF EARTHQUAKE ENGINEERING
2024, VOL. 28, NO. 1, 242–265
https://doi.org/10.1080/13632469.2023.2197078

On the Seismic Vulnerability Assessment of Urban Areas Using Census Data: The Lisbon Metropolitan Area as a Pilot Study Area

Maria Xofi [a,b], Tiago Miguel Ferreira [c], José Carlos Domingues [a], Pedro Pinto Santos [d], Susana Pereira [d], Sérgio C. Oliveira [d], Eusébio Reis [d], José Luís Zêzere [d], Ricardo A. C. Garcia [d], and Paulo B. Lourenço [a]

[a]Institute for Sustainability and Innovation in Structural Engineering (ISISE), Department of Civil Engineering, University of Minho, Guimaraes, Portugal; [b]Department of Construction Management and Engineering (CME), University of Twente, Enschede, Netherlands; [c]School of Engineering, College of Arts, Technology and Environment (CATE), University of the West of England (UWE Bristol), Bristol, UK; [d]Centre for Geographical Studies, Institute of Geography and Spatial Planning (IGOT), Associated Laboratory TERRA, University of Lisbon, Lisbon, Portugal

ABSTRACT
This paper presents a procedure for the application of an index-based vulnerability assessment method to the seismic risk assessment of 292,978 reinforced concrete and 152,916 unreinforced masonry buildings in the Lisbon Metropolitan Area (LMA). A singular innovation of this proposed methodology is that it is tailored to be fed with data from the 2011 national population and housing Census. The vulnerability results are then combined with the seismic hazard component into a GIS tool used to map seismic risk across the LMA. The spatial representation of these results highlights the areas of different levels of vulnerability and risk.

ARTICLE HISTORY
Received 24 May 2022
Accepted 26 March 2023

KEYWORDS
Seismic vulnerability; vulnerability assessment; building typologies; urban scale; seismic risk

1. Introduction

Besides the extreme consequences that single-hazard events may induce, natural hazards have also the ability to take place at the same time or to trigger other natural hazards by means of a cascade effect: for instance, the 2016 Kaikoura (New Zealand) earthquake prompted a tsunami and a series of landslide events that massively damaged the road network system. Multi-hazard events can also have more significant impacts than a single-hazard one, making emergency response mechanisms unable to respond efficiently and effectively. The worldwide increase in urbanization in recent decades (a scenario that is only expected to increase even more in the upcoming future) poses additional difficulties to the effectiveness of disaster risk reduction strategies, as urban agglomerations are increasingly characterized by complex networks of built infrastructures and social dynamics.

Taking into account the significant economic and human impacts on the building stock and infrastructure systems that can result from natural hazards, the research community, policymakers, and risk mitigation planners have, in recent years, devoted considerable attention to the improvement of resilience and the preparedness of vulnerable areas and communities. Nevertheless, although an important amount of research has been done on single-hazard assessments, there is still limited research data for multi-hazard analysis. The work reported in this paper is part of a larger research project aimed at bridging this gap by creating a risk assessment framework for measuring, managing, and mitigating the impacts of multiple natural hazards in urban areas, in the scope of which a common vulnerability assessment methodology applicable to multi-hazard events was developed.

CONTACT Tiago Miguel Ferreira Tiago.Ferreira@uwe.ac.uk School of Engineering, College of Arts, Technology and Environment (CATE), University of the West of England (UWE Bristol), Bristol, UK

As to the specific object of this study, it is generally acknowledged that, of the several natural hazards (e.g. earthquakes, floods, landslides, and fires) capable of affecting peoples' lives across different parts of the globe, earthquakes, in particular, are the most catastrophic events, in what concerns both fatalities and economic losses. Several examples can be used to illustrate this reality, such as the 2021 Haiti earthquake, with about 15,340 casualties and an estimated total loss of 1 billion USD; the 2010 Haiti earthquake, which resulted in an estimated death toll of 100,000–316,000; the 2011 Tohoku earthquake in Japan, which caused 20,475 fatalities and left 1.108 million people homeless; the 2011 Van earthquake, in Turkey, which caused 2.2 billion USD in damage; and the Sikkim earthquake, which struck India in 2011, causing 1.7 billion USD damage (Kassem, Mohamed Nazri, and Noroozinejad Farsangi 2020). Herein, a seismic vulnerability assessment methodology based on an index-based approach is developed and validated for the Lisbon Metropolitan Area, using data from the 2011 national Census survey. This information is used not only to categorize the existing building stock but also to define the parameters to be considered in the vulnerability analysis.

The formulation developed in this research is based on the GNDT level II approach, which combines a typological approach and a vulnerability index-based estimation and is based on data from post-earthquake damage observations and information concerning the typological characterization of the building stock, subsequently translated into a few empirical parameters (GNDT-SSN 1994). The seismic vulnerability results and the seismic hazard components were then integrated into a Geographic Information System (GIS) tool developed in the open-source software QGIS to obtain the different seismic risk levels for the municipalities of LMA.

Although the present work reports a single-hazard analysis (seismic), establishing a simplified common methodology that can be applied to other natural hazards (such as floods and landslides) will allow for the creation of a framework for multi-hazard analysis at the urban scale, which may help multi-disciplinary teams such as engineers, urban planners, and emergency managers to understand the potential impacts of multiple hazard events and plan suitable and effective strategies (e.g. retrofitting or safety evacuation paths) aimed at reducing the impact to vulnerable buildings and communities.

2. The Lisbon Metropolitan Area

2.1. Overview of the Case Study

Home to nearly 2,813,000 people (approximately 27% of the Portuguese population) and covering an area of 3,001 km^2, the Lisbon Metropolitan Area (LMA), centered in the Portuguese capital city of Lisbon, is the largest urban area in the country. Spanning two districts separated by the Tagus River (the part north of the river belongs to the Lisbon District, whereas the south is part of the Setúbal District), the LMA comprises 18 municipalities (see Fig. 1) and 211 parishes. According to the 2011 Census survey, the LMA has a density of 935 inhabitants per km^2 and, according to the 2011 housing survey, a property concentration of 449,573 buildings. Lisbon records the highest average levels of income per capita in Portugal and, with a gross domestic product (GDP) of €66.5 bn in 2016 (EUROSTAT), it is the most important contributor to the national GDP (35.9%).

Because of its proximity to the Africa-Eurasia plate boundary, the Lisbon Metropolitan Area is one of the most critical seismic zones in Portugal. This location makes the region prone to devastating offshore and onshore earthquakes, which is critical given its economic and demographic relevance. The long list of earthquakes that occurred in the past in this area is topped by the 1755 Lisbon earthquake, which stands among the largest earthquakes ever registered worldwide, with an estimated magnitude between 8.5 and 9. The proximity of the Africa-Eurasia plate boundary also impacts the seismicity of this area by triggering several onshore crustal faults, the most relevant of those, the Lower Tagus Valley (LTV) fault, that passes through Lisbon.

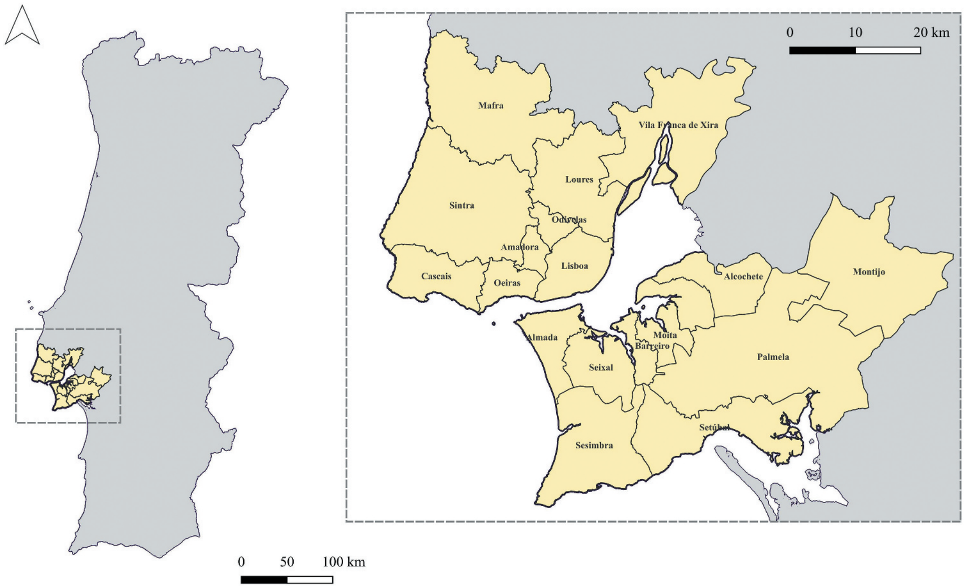

Figure 1. Division of the LMA into 18 municipalities.

2.2. Typological Categorization of the Building Stock

In many European countries, and particularly in their urban areas, ancient unreinforced masonry (URM) structures, with a wide range of building techniques and typologies, coexist with reinforced concrete (RC) buildings, the predominant type of construction in urbanized areas. In the case of the Lisbon Metropolitan Area, and according to the 2011 housing survey, RC and URM buildings account for, respectively, 65% and 34% of the building stock, with the remaining 1% consisting of "Other" (e.g. steel and timber) buildings. The majority of the buildings (91%) are for residential use, with only a small portion for mixed (commercial and residential) and commercial use (8%, and 1%, respectively). Figure 2 illustrates the distribution of the building stock and the two main typologies in the Lisbon Metropolitan Area. The main geometric, material, and structural characteristics of the URM and RC building typologies in the LMA are briefly presented in the following subsections.

2.2.1. Unreinforced Masonry (URM) Buildings

According to Simões et al. (2017) and Bernardo et al. (2021), the URM buildings in the LMA can be categorized into the four main typologies listed and generically described below. More details about specific aspects of these buildings, namely, regarding the characteristics and quality of the vertical and horizontal resisting systems, can be found in Simões et al. (2020), Lamego et al. (2017) or Bernardo et al. (2022), for example.

- **"Pre-Pombalino"** buildings – these buildings date back to the period before the 1755 Lisbon Earthquake and are characterized by irregular geometry, reduced dimensions in plan, and narrow façades. They are up to four stories high with poor-quality masonry walls, and often some buildings have a rebounded ground floor, as the upper floors stand out on the front façade wall, increasing the interior space (Simões et al. 2017). The ground floor is typically made of stone, while the upper levels were made with wood planks supported by timber beams, fixed or simply supported on the facades and interior walls (Bernardo et al. 2021).
- **"Pombalino"** buildings – these buildings were built in the aftermath of the 1755 Earthquake, between 1755 and 1870. The structural regularity of the "Pombalino" buildings, with window openings aligned both vertically and horizontally, provided them with superior structural

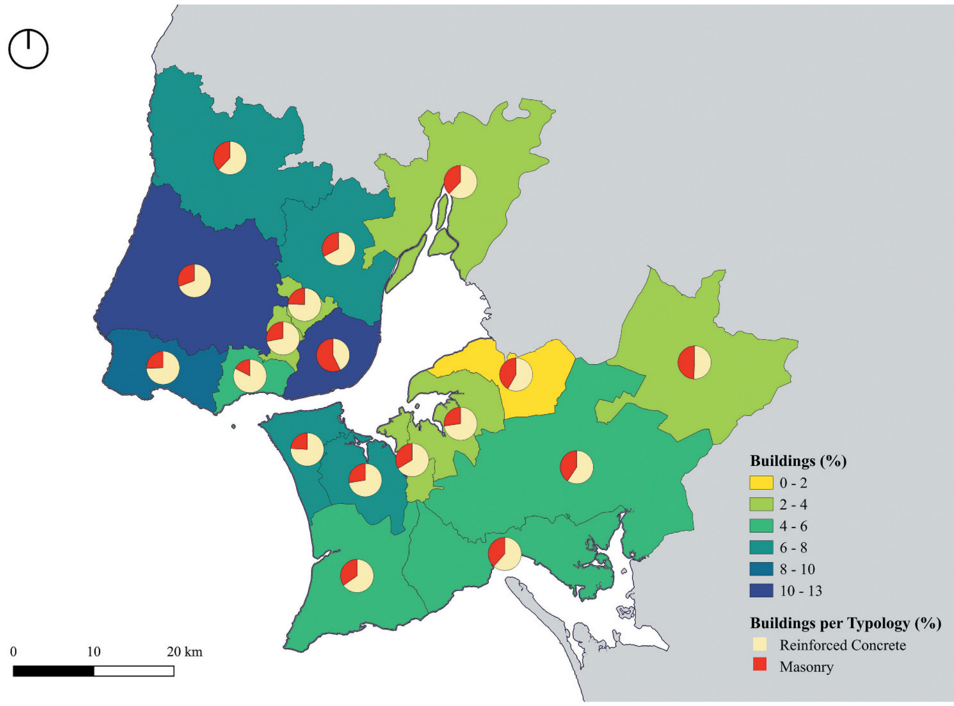

Figure 2. Distribution of building stock and the two main building typologies per municipality.

stability and helped to maintain a consistent and direct gravity load path in the structure. The main innovative feature of this typology is the "Gaiola Pombalina," or "Gaiola" (Portuguese for *cage*), a stand-alone timber-framed wall truss that can absorb horizontal seismic forces. These buildings are typically up to five stories with mixed usage, having the ground floor for commercial use and the remaining ones for residential purposes.

- **"Gaioleiro"** buildings – built between 1870 and 1930, these buildings can be seen as a downgrade compared to the previous "Pombalino" typology: in general, they present lower construction quality and lack any seismic connection detailing. Most of these buildings are up to six stories, with a rectangular shape in plan and decorative elements on the front façades. At the end of their construction period, composite floors (steel beams with infilled ceramic bricks) on balconies, kitchens, and bathrooms were also used. A common characteristic of these buildings was the presence of light shafts in the center of the building to provide natural light and ventilation.
- **"Placa"** buildings – are typically built between 1930 and 1960. This building typology was constructed with a regular geometry of up to five stories and corresponds to a combination of masonry walls and RC elements, such as concrete floor slabs replacing timber floor systems ("Placa" is a Portuguese non-technical word that means *slab*). The concrete floor slabs were typically made with low-strength concrete and a single layer of reinforcement at the bottom. This type of construction detailing results in poor diaphragms, which negatively affects the structural vulnerability of these buildings.

2.2.2. Reinforced Concrete (RC) Buildings

The first design code for RC structures in Portugal was introduced in 1918. However, it was only with the publication of the first seismic code in 1958 and then with the 1983 seismic code that proper consideration was given to the effect of seismic actions. In view of this, the evolution of the Portuguese building codes (and particularly the development of the seismic codes) has governed the level of appropriate seismic design and detailing, thus impacting the building's vulnerability. In terms of their characteristics, RC buildings have been categorized based on their period of construction, which is directly related to the seismic design level and the number of stories. Regarding the first aspect, the RC building stock in the LMA has been categorized into three age bands, according to Silva et al. (2015):

- Pre-code buildings – RC buildings built during the pre-code period, i.e., before 1958. As mentioned before, these buildings were built with no seismic design detailing and are typically known as non-ductile RC frame buildings.
- Mid-code buildings – RC buildings built during the 1958–1983 period. These buildings were designed with minor seismic detailing presenting, therefore, low earthquake resistance.
- Post-code buildings – this category includes the RC buildings built after 1983, which were already designed and detailed seismically according to the modern seismic codes.

With regard to the number of stories, the RC buildings have been typically subdivided into three groups: low-rise buildings, up to 1–3 stories; mid-rise buildings, up to 4–7 stories; and high-rise buildings, which aggregates all the buildings with more than seven stories.

2.3. Population Distribution

Continental Portugal evidences a trend of higher population density in coastal districts, which leads to higher urbanization processes in these areas. According to Morgado (2017), the analysis of the population density cartography at the borough level in the years of the census exercises (1991, 2001, and 2011) shows some stability in population densities, as well as some heterogeneity within the urban centers, namely in the Lisbon and Porto Metropolitan Regions. Table 1 illustrates the percentage of the total population in each of the 18 municipalities in the LMA, as well as the distribution of the population per building typology in each municipality. As can be observed, Lisbon and Sintra are the two municipalities with the highest population density, which accounts for 19% and 13%, respectively, of the total population of LMA. As to the distribution of population per building typology, around 80% of the LMA's residents live in RC buildings, while 20% of the population lives in URM buildings.

Table 1. Population per municipality and building typology in the municipalities of LMA.

Municipalities			Population per Typology (%)	
No.	Name	Total Population (%)	RC	URM
1.	Alcochete	0.6	0.4	0.2
2.	Almada	6.1	5.2	0.9
3.	Amadora	6.2	5.2	1.0
4.	Barreiro	2.8	2.4	0.4
5.	Cascais	7.3	6.1	1.2
6.	Lisboa	19.4	13.3	6.1
7.	Odivelas	5.1	4.4	0.7
8.	Loures	7.2	6.0	1.2
9.	Mafra	2.7	1.9	0.8
10.	Moita	2.3	2.0	0.3
11.	Montijo	1.8	1.3	0.5
12.	Oeiras	6.1	5.5	0.6
13.	Palmela	2.2	1.5	0.7
14.	Seixal	5.6	4.8	0.8
15.	Sesimbra	1.7	1.3	0.4
16.	Setubal	4.3	3.5	0.8
17.	Sintra	13.4	11.7	1.7
18.	Vila Franca de Xira	4.8	3.9	0.9
TOTAL		**100%**	**81%**	**19%**

3. Methodological Framework

The risk assessment approach applied in this study is composed of two main modules, the hazard, and the vulnerability module, as illustrated in Fig. 3. The main aspects of these two modules are detailed in Sections 3.2 and 3.3.

Results from hazard levels are defined in Section 3.2, and the application of the seismic vulnerability assessment methodology is described in Section 3.2. These are then combined through a vulnerability-hazard matrix, as per Table 2, which relates the building's vulnerability and its exposed hazard class. The resulting data was further implemented in an open-source Geographic Information System software QGIS. Geo-referenced graphical data (i.e. vectorized information and orthophoto maps) with specific information related to the hazard and the characteristics of the buildings were combined within the software to obtain first- and second-order outputs.

3.1. The Hazard Module

The seismic hazard was assessed by combining three components: earthquake intensity, Peak Ground Acceleration (both for a return period of 475 years), and the soil effects capable of producing an amplification of the seismic actions (namely, the distribution of non-consolidated sedimentary geological formations and the proximity of active faults) in the Lisbon Metropolitan Area.

Considering the seismic intensity map in Fig. 4a, it is estimated that about 40% of the LMA territory integrates the class corresponding to the maximum intensity level VIII (Modified Mercalli Scale of 1956), which represents a scenario of ruin, while the remaining 60% of the territory belong to classes corresponding to intensity degrees IX (disaster) and X (collapse). Regarding the distribution of

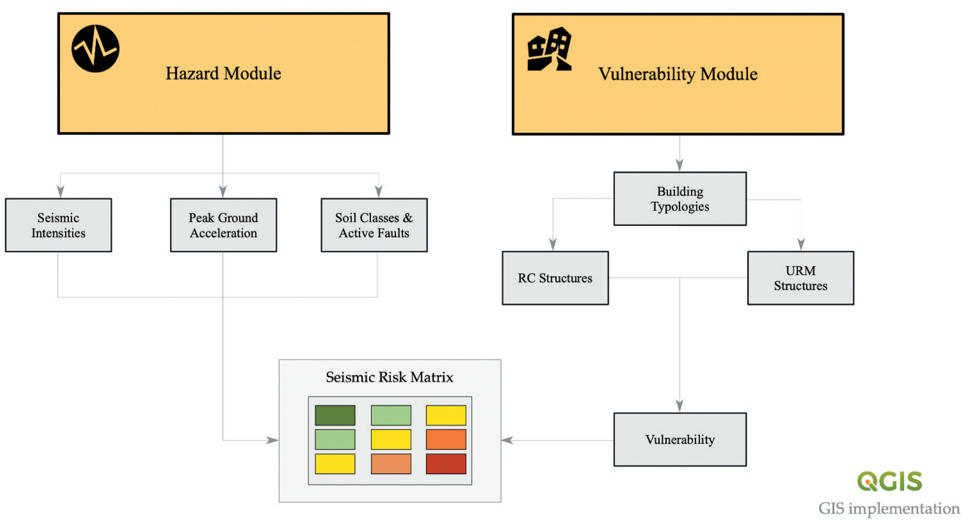

Figure 3. The conceptual framework of the integrated seismic risk assessment approach.

Table 2. Seismic risk matrix.

	Hazard			
Vulnerability	Low	Moderate	High	Very High
Low	Low	Low	Moderate	High
Moderate	Low	Moderate	High	Very High
High	Moderate	High	Very High	Extreme
Very High	High	Very High	Extreme	Extreme

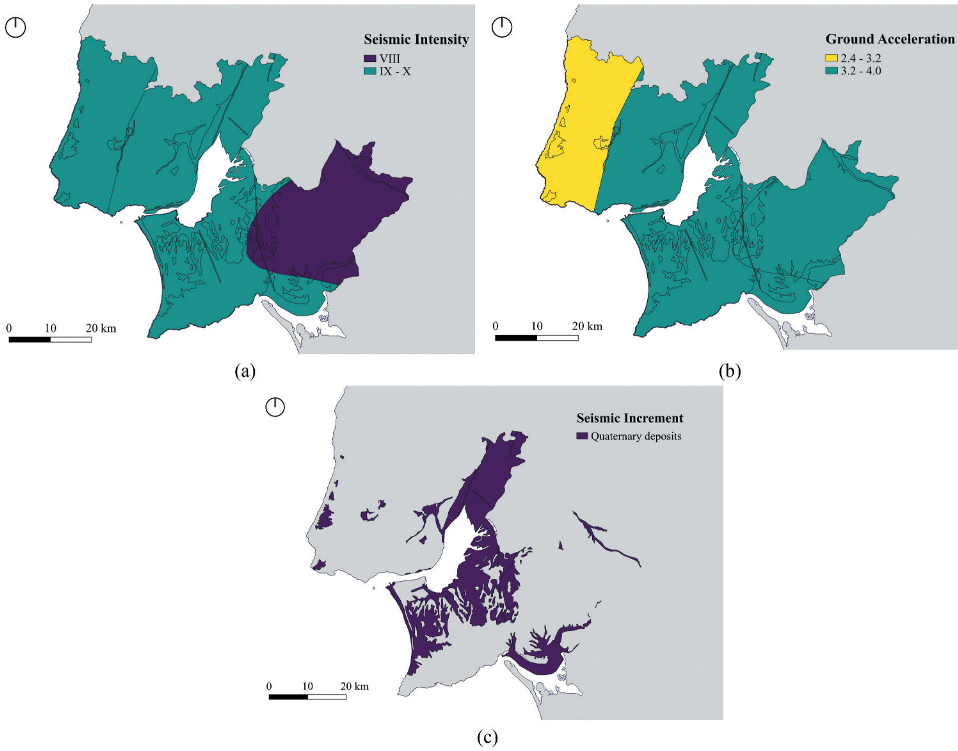

Figure 4. Maps for the LMA, considering a return period of 475 years with (a) maximum seismic intensity, (b) maximum peak ground acceleration, and (c) quaternary deposits.

Table 3. Seismic hazard classes (presence of poorly consolidated sedimentary deposits or active faults).

		Peak Ground Acceleration (m/s^2)					
		Seismic amplification			No seismic amplification		
Seismic Hazard		1.6–2.4	2.4–3.2	3.2–4.0	1.6–2.4	2.4–3.2	3.2–4.0
Intensity zones	VIII	Moderate	Moderate	High	Low	Low	Moderate
	IX	—	High	Very High	—	Moderate	High
	X	—	High	Very High	—	Moderate	High

maximum ground accelerations, presented in Fig. 4b, two ranges of PGA values were considered as per Montilla and Casado (2002): 2.4 to 3.2 m/s^2 and 3.2 to 4.0 m/s^2. Finally, Fig. 4c shows a map with the distribution of the unconsolidated sedimentary geological formations (quaternary deposits) across LMA, which was created by combining information from the Geological and Neotectonic Maps of Portugal.

Table 3 summarizes the definition of the hazard classes for the cases where seismic action is or is not amplified either by poorly consolidated sedimentary (Quaternary) deposits or by active faults, respectively, and Fig. 5 presents the spatial distribution of the hazard classes in the Lisbon Metropolitan Area.

3.2. The Vulnerability Module

3.2.1. Formulation of the Seismic Vulnerability Assessment Methodology

According to several authors (Ferreira, Mendes, and Silva 2019; Maio, Ferreira, and Vicente 2018; Vicente et al. 2014), the selection of seismic vulnerability assessment methods is typically based on

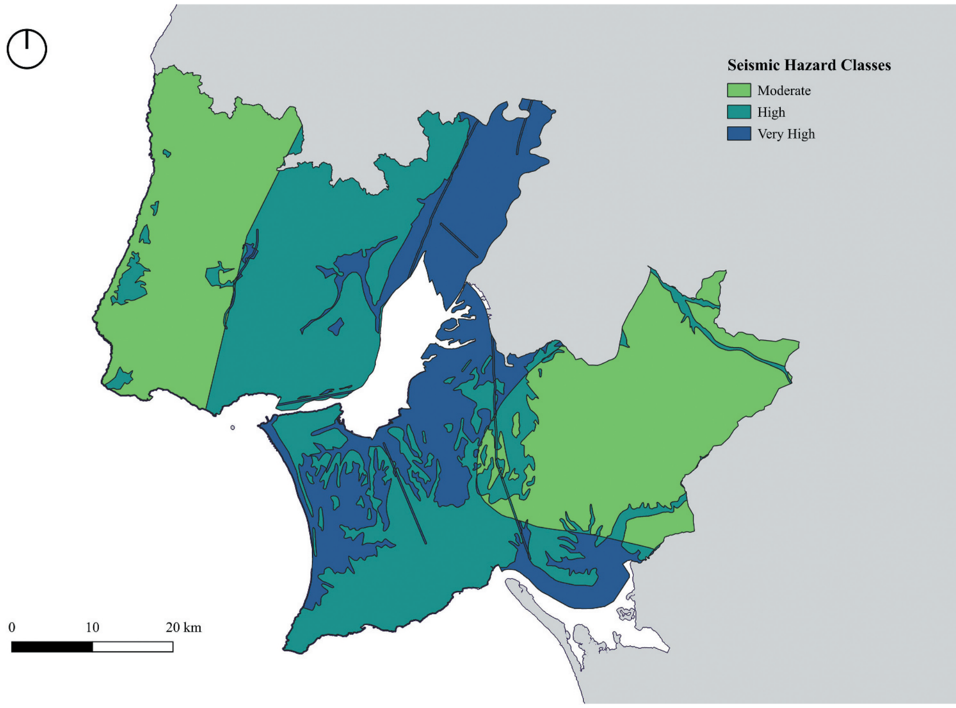

Figure 5. Seismic hazard classes across the LMA.

three main criteria: level of detail, type of output (or scale of evaluation), and quality of the input data and tools (or methods) used. When dealing with a large number of buildings at a national or urban scale where the resources and quantity of information required can be significant, the use of less sophisticated techniques or tools can be more practical and effective. As addressed in detail in many reviews on this topic, see, for example, Calvi et al. (2006) or Ferreira, Mendes, and Silva (2019), vulnerability assessment methodologies can be grouped into three main categories – first-level approaches, second-level approaches, and third-level approaches – according to their level of detail, the scale of evaluation, and the volume of data required. First-level approaches are preferable when assessing large areas and high number of buildings, since they primarily use qualitative information. Damage Probability Matrices (DPMs) like those proposed by Whitman, Reed, and Hong (1973), and rapid screening approaches like ATC-21 (1988) or GNDT II level (GNDT-SSN 1994) are representative examples of first-level approaches. Second-level approaches, on the other hand, are based on mechanical models, which typically require detailed geometrical and mechanical information to be applied. Finally, third-level approaches involve the use of complex numerical modelling techniques, which require a thorough understanding of the geometrical, material, and mechanical characteristics of the structure, and that is why they are mainly suited to be applied to assess individual buildings.

As mentioned before, the vulnerability index formulation applied in this work is based on the GNDT II level approach (GNDT-SSN 1994) that was developed for the vulnerability assessment of masonry buildings and is classified in the literature as a hybrid approach, combining the typological approach and the vulnerability index-based estimation. Initially formulated in Italy to assess the seismic behavior of residential masonry buildings, this methodology has been used in vulnerability studies at the urban scale over the last 30 years. It was used in the Portuguese built environment for the first time in 2011, in the historic city center of Coimbra (Vicente et al. 2011), and improved by introducing more detailed analysis for cases where adequate building data exist with new parameters related to the building's position and interaction between adjacent structures. Still, in what relates to Portuguese urban areas, additional studies were conducted in the city centers of Seixal (Ferreira et al.

2013), Faro (Maio et al. 2016), and Leiria (Blyth et al. 2020). The method was calibrated by Ferreira, Maio, and Vicente (2017) based on damage data collected in the aftermath of the magnitude VII 1998 Azores earthquake.

It is also worth noting that although the GNDT II level approach was initially developed for the seismic assessment of masonry buildings, this same approach was used by Ferreira, Rodrigues, and Vicente (2020) as the starting point for a methodology for the vulnerability assessment of RC buildings.

As in the original proposal, the methodology presented in this work evaluates the expected behavior of the building in the event of an earthquake by considering a few empirical parameters, as described below.

A singular innovation of the current methodology is the fact that it was explicitly tailored to be fed by the information available from the Portuguese 2011 Census data survey, which subsequently constituted the basis for selecting the adopted parameters. In fact, both the number and distribution of the population over the LMA and the various building typologies are characterized using information from Statistics Portugal, namely, data collected from the 2011 Population Census and the Buildings' Geographical Database (Statistics Portugal, Portuguese Census Survey 2011).

Each building parameter corresponds to a specific feature that affects the seismic response of a building, with a corresponding vulnerability class that is most applicable. These parameters are classified according to four vulnerability classes, C_{vi}, of A, B, C, and D and are associated with a weight, p_i, which defines the relative importance of each parameter to the overall seismic vulnerability of the building. It is important to note that the values for the weights given in Tables 4 and 5 for RC and URM buildings, respectively, have been initially set based on the authors' experience and expertise and then adjusted and validated following the procedure presented in Section 4. Regarding the vulnerability classes, they follow the typical structure of most of the parametric-based vulnerability assessment methodologies in the literature, including the GNDT II level approach (GNDT-SSN 1994), Vicente et al. (2011) and Ferreira, Rodrigues, and Vicente (2020).

A total vulnerability index, I_v^*, is calculated using Eq. (1), by computing the weighted sum of the four or five parameters, respectively, for RC or URM, multiplied by their specific weight assigned as a meaning of importance in terms of seismic response.

$$I_v^* = \sum_{i=1}^{n} C_{vi} \times p_i \tag{1}$$

For more straightforward interpretation and use, the vulnerability index, I_v^*, is then normalized to range between 0 and 100, assuming from that moment on the notation. The vulnerability level is given

Table 4. RC building parameters with vulnerability classes and weights.

		Class C_{vi}				Weight
	Parameter	A	B	C	D	p_i
P1	Building Position	0	5	20	50	1.5
P2	Period of Construction	-	5	20	50	2.0
P3	No. of Stories	0	5	20	50	0.75
P4	Ground Plan Configuration	0	-	-	50	2.5

Table 5. URM building parameters with vulnerability classes and weights.

		Class C_{vi}				Weight
	Parameter	A	B	C	D	p_i
P1	Structural System	-	5	20	50	2.5
P2	Period of Construction	0	5	20	50	0.75
P3	Building Position	0	5	20	50	1
P4	No. of Stories	0	5	20	50	0.5
P5	Ground Plan Configuration	0	-	-	50	0.5

directly by the seismic vulnerability index. As to its link to the vulnerability classes in the seismic risk matrix represented in Table 1, vulnerability indices ranging between 25 and 50 and between 50 and 75 were defined as "moderate" and "high," respectively. It should be noted that the value of 50 is often used in index-based vulnerability assessment approaches as a threshold for high vulnerability. The following subsections analyze in more detail each of the parameters for RC and URM buildings, respectively.

3.2.2. Analysis of RC Building Parameters

Parameter P1 is related to the building's relative position and interaction with the adjacent buildings, which can potentially lead to pounding effects. According to the available Census data, four different building positions were considered, with each one corresponding to a different vulnerability class, as defined in Table 6. Given the uncertainty regarding how the "Classic" and "Other" buildings are positioned within the aggregate or with respect to the adjacent buildings, both were conservatively assigned to class C.

Parameter P2 addresses the period of design and construction of the building relative to the seismic design code provisions, as per Table 7. Given the absence of any field data related to the quality of RC building design and their structural systems, the vulnerability classes were ranked conservatively based on the evolution of the Portuguese seismic codes and regulations.

Parameter P3 refers to the height of the building, as represented by the number of stories, which affects the seismic vulnerability of the building in several ways. For example, taller buildings lead to greater top story displacement/drift ratio demands, which in turn requires appropriate seismic detailing in order to assure an adequate displacement ductility capacity. Taking this into account, the seismic vulnerability tends to increase with the additional number of stories, as illustrated in Table 8.

Finally, parameter P4 evaluates the vertical irregularity, a characteristic that is important to consider when the layout of vertical structural elements (i.e. wall layout) on the ground floor level changes in relation to the upper floors, for instance, as a result of an open plan area for commercial use or car parking spaces. This building typology, often known as "piloti" building, is prone to the soft-story mechanism at ground level affecting the strength or stiffness between the ground and the upper floors.

Table 6. Class definition for parameter P1.

Class	Building Position
A	Row or Terraced buildings
B	Isolated buildings
C	Classic buildings*
D	Semi-detached/Edge buildings

*(The 'Other' buildings are also included).

Table 7. Class definition for parameter P2.

Class	Period of design & construction
A	After 2018: Modern Seismic Codes
B	1981–2018: Current Seismic Codes
C	1961–1980: Minor Seismic provisions
D	Before 1960: No Seismic Codes

Table 8. Class definition for parameter P3.

Class	No. of Stories
A	1–2 floors
B	3–7 floors
C	8–15 floors
D	>15 floors

Table 9. Class definition for parameter P4.

Class	Ground Plan configuration
A	Regular Buildings
B	-
C	-
D	Irregular Buildings*

*Including the 'Non-evaluated' buildings.

Also, this type of irregularity could easily lead to a concentration of higher force demands to lesser structural elements and, therefore, increased deformation demands at the first-floor level. This, in turn, results in a shear failure mechanism on the ground-level columns and/or walls, making such buildings particularly vulnerable seismically. Two classes were defined for this parameter, with Class D being the most vulnerable one and Class A representing regular buildings, as per Table 9. Consequently, the potentially devastating effect of a soft-story mechanism, the non-evaluated buildings were classified conservatively in class D.

3.2.3. Analysis of URM Building Parameters

Parameter P1 refers to the type of structural system classifying the URM in different typologies (according to the building types that are prevalent in the LMA) and, therefore, with varying levels of vulnerability. The typological discretization adopted with the assigned classes is presented in Table 10. As generally considered, both adobe and rubble stone buildings revealed poorer behavior to seismic actions and were accordingly assigned to the most vulnerable class D. It is also acknowledged that regardless of the building typology, both the floor's stiffness and the efficient connection between the vertical (i.e. walls) and horizontal elements (i.e. floors) are important characteristics, which govern the overall seismic response of the building. Taking this into account and considering the weights assigned to class A, a decision was made not to assign any typology to the least vulnerable class A. Looking into the remaining types of URM buildings that are present in LMA, a division was made between URM buildings with timber and concrete floors, considering that the formers are less vulnerable than the latter ones. This is based on the fact that the "*placa*" buildings, consisting of concrete floor slabs instead of timber flooring, typically have no adequate connections to the masonry walls and between slab sections to guarantee a continuous diaphragm action and transfer of horizontal loading to the walls.

Parameter P2 addresses the period of design and construction of the building. This parameter reflects the expected safety level of the building when subjected to seismic actions, taking into account the technical and legal requirements at the time the building was built, as well as the aging of the construction materials, reflecting both material decay and possible lack of maintenance through time. The classes were defined according to time periods that are representative of the evolution of Portuguese seismic legislation and ordered chronologically, assuming that the most recent buildings are less vulnerable than older ones. Table 11 presents the classes and respective periods of construction.

Table 10. Class definition for parameter P1.

Class	Structural System
A	-
B	URM with timber floor
C	URM with concrete floor slabs
D	Adobe & Rubble

Table 11. Class definition for parameter P2.

Class	Period of design & construction
A	1981–2011 (Post-code: > 1983)
B	1961–1980 (Mid-code: 1958–1983)
C	1945–1960 (Pre-code: < 1958)
D	<1945 (Pre-code: < 1958)

Parameter P3 takes into consideration the building's relative position and interaction with the adjacent neighboring buildings, bearing in mind either a possible pounding effect or the fact that buildings sustain different levels of damage based on their position within the aggregate. In fact, post-earthquake damage observation has allowed to verify that corner and row-end buildings are generally more vulnerable than those located in the middle of the building block, which was also observed by Vicente et al. (2011). According to the available Census data, four different building positions were considered, each one corresponding to a different vulnerability class, as defined in Table 12. Given the uncertainty on how the "Classic" and "Other" buildings are positioned within the aggregate and relative to the adjacent buildings, they were both classified conservatively within Class C.

Parameter P4 is referred to the number of stories (a measure of the height of the building), which affects the seismic vulnerability of the building in terms of both the displacement/drift at roof level and the potential pounding effect with adjacent buildings of different heights if present. Hence, the seismic vulnerability of a building typically increases with the additional number of stories, as per Table 13.

Parameter P5 evaluates the plan irregularity on the ground floor. In the case of URM buildings in urban areas, a common alteration through time is the replacement of the front façade masonry walls with full-height glazing windows, namely in buildings with commercial use on the ground floor. The internal wall layout can also change at ground level in such buildings. This creates a potential eccentricity and torsional effect, increasing the in-plane shear demand on the remaining masonry walls at ground floor level. Consequently, this type of structural irregularity is assigned to class D. The "non-evaluated" portion of the building stock has also been conservatively assigned to class D, taking into account the significant number of these buildings and the uncertainty of their behavior in the event of an earthquake. On the other hand, Class A represents the least vulnerable cases of regular buildings, as per Table 14.

4. Validation of the Proposed Methodology

As discussed in detail by Ferreira, Maio, and Vicente (2017), the application of any index-based methodology for the seismic vulnerability assessment of existing buildings requires the accurate

Table 12. Class definition for parameter P3.

Class	Building Position
A	Row/Terraced buildings
B	Isolated buildings
C	Classic buildings*
D	Semi-detached/Edge buildings

* (The 'Other' buildings are also included).

Table 13. Class definition for parameter P4.

Class	No. of Stories
A	One floor
B	2–3 floors
C	4–5 floors
D	>6 floors

Table 14. Class definition for parameter P5.

Class	Ground Plan configuration
A	Regular Buildings
B	-
C	-
D	Irregular Buildings*

*Including the 'Non-evaluated' buildings.

calibration of the weights associated with the vulnerability parameters. When such does not happen, and inaccurate assumptions are made, changes are that the vulnerability values obtained are not actually representative of the actual physical vulnerability of the buildings. Such calibration is typically made by resorting to post-earthquake damage data, which, unfortunately, is not available for the LMA. However, the fact that comparable methodologies have been pre-calibrated for RC and URM building typologies – refer to (Ferreira, Rodrigues, and Vicente 2020) and (Blyth et al. 2020), respectively – opened the possibility to adopted here an alternative validation approach based on the comparison between the vulnerability indices obtained with those methodologies, which are methodologically more complex and with more evaluation parameters, and the ones calculated with the simplified vulnerability assessment methodologies proposed in this investigation. It must be stressed that more than trying to find a perfect fit between the vulnerability values obtained with the original and the simplified methodologies, the chief objective of this validation exercise is to investigate whether there is a positive tendency between methodologies, i.e. if a building flagged as highly vulnerable by the detailed methodologies would also be glad as highly vulnerable by the simplified ones. Such a tendency is plotted in Fig. 6, where the vulnerability indices obtained with the different methodologies for the RC and URM buildings are compared. The ratios between the indices obtained using the original and the simplified methodologies, measured in terms of percentage differences, are also included in the figure through a color scheme, as well as the linear fit results and 95%ile confidence intervals.

As can be observed in the plots given in Fig. 6, there is a good correlation between the vulnerability indices calculated with the original and the simplified methodologies, as the values obtained for the coefficients of determination – $R^2 = 0.729$ for the RC buildings and $R^2 = 0.711$ for the URM buildings – suggest. Furthermore, the ratios between the indices obtained using the original and the simplified methodologies allow one to get a feeling of the relative difference between those indices, though such a difference is not determinant in the scope of this work since these vulnerability indicators will only be used to identify relative vulnerability among buildings, not to estimate damages. As displayed in Fig. 6, those ratios are significantly more dispersed for RC buildings, with a mean average, a median and a standard deviation of about 66.9%, 71.41% and 44.19, respectively – compared to 5.8%, 1.32% and 35.80 for the URM buildings. It is worth noting that, although these values seem to indicate a big deviation between the original and the simplified methodologies, in particular for the one for RC buildings, the fact is that in most cases, we are working with small numbers which, when put in relative terms, result in misleadingly large values. Moreover, these differences do not have a direct physical meaning, which makes them not very relevant in the context of the present research. More relevant is certainly to understand whether the results obtained with the simplified methodologies are conservative or nonconservative, i.e. if they are overestimating or underestimating the vulnerability compared with the original

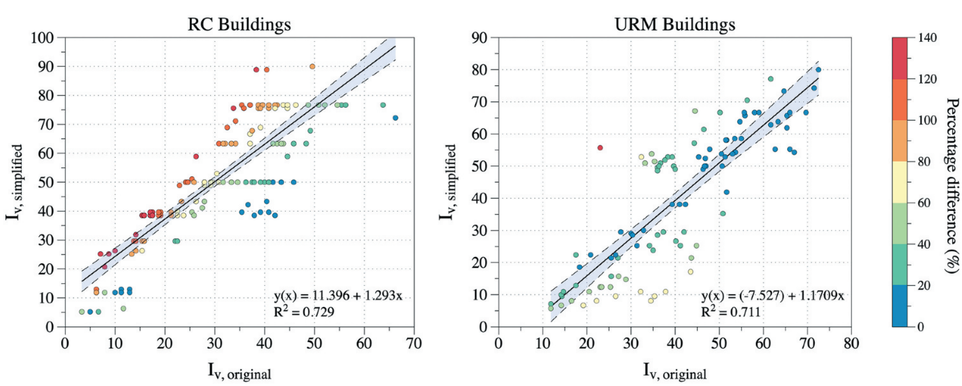

Figure 6. Correlation of the vulnerability indices obtained with the original and the simplified vulnerability assessment methodologies, fit results and 95-confidence intervals.

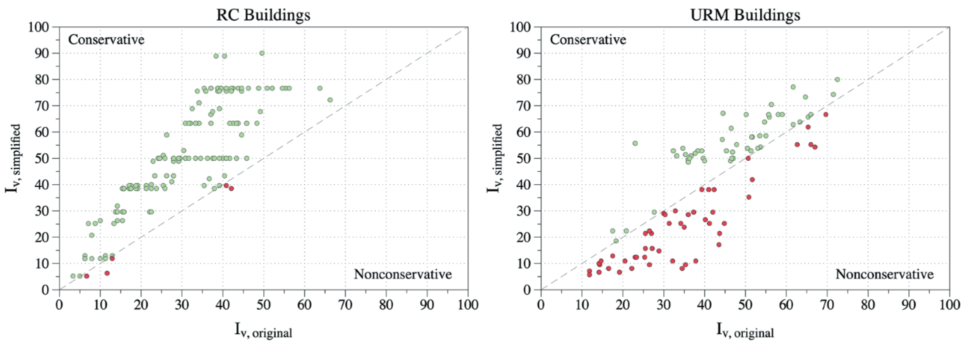

Figure 7. Identification of the conservative and nonconservative observations.

methodologies. That is presented in Fig. 7, where the conservative and nonconservative results are highlighted with different colors. As can be observed, a conservative result has been observed in about 97% of the cases for the RC buildings. As for the URM buildings, such a figure drops to about 50%. Since the proposed methodology is composed of fewer parameters than the original one, a tendency to overestimate the vulnerability results is acceptable and desirable.

5. Vulnerability and Risk Results

Once all the seismic vulnerability indices per building had been computed, the results were spatially distributed using the GIS application software (QGIS 3.16.8-Hanover) and combined with the hazard to obtain the risk levels. This allows for an intuitive perception of the vulnerability and risk levels across the Lisbon Metropolitan Area. Given the large scale of the Census building data, seismic vulnerability indices were discretized per municipality. This section presents and discusses the seismic vulnerability and risk results for the whole LMA, with additional analysis output for the municipality of Lisbon.

5.1. Lisbon Metropolitan Area

5.1.1. Vulnerability Assessment Results

The application of the vulnerability index-based method herein refers to the entire building stock of 292,978 RC buildings and 152,916 URM buildings in the LMA. In addition, the RC buildings show a mean seismic vulnerability index of 50.7 with an associated standard deviation of 15.6, while the URM buildings have values of 37.2 and 12.8, respectively. As to maximum and minimum vulnerability index values, the RC buildings range from 11.85 to 93.3, whereas the URM buildings present a smaller range between the maximum and the minimum value: 14.3 to 91.4.

According to the histograms plotted in Fig. 8, 39% of the RC building stock falls within the 40–50 vulnerability index range, making this the vulnerability range with the greater percentage of building in it. Moreover, 22% of the RC buildings present a vulnerability index within the 50–60 range, about 15% are within the range of 60–70, and 11% have a vulnerability index above 70. Comparatively, the histogram obtained for the URM buildings is noticeably more skewed to the left, with 48% of the URM buildings falling within the 30–40 vulnerability index range, about 12% between 40 and 50, and 18% ranging between 50 and 100.

Figure 9 illustrates the average vulnerability index for the entire building stock, including both RC and URM buildings per municipality. Hence, the municipalities of Oeiras and Moira appear to have the highest vulnerability index score, while Palmela and Montijo are on the lower end of the spectrum.

Figure 10 highlights, for each municipality, the portion of the building stock with vulnerability index values greater than 50, which is defined as the threshold for high seismic vulnerability, as per

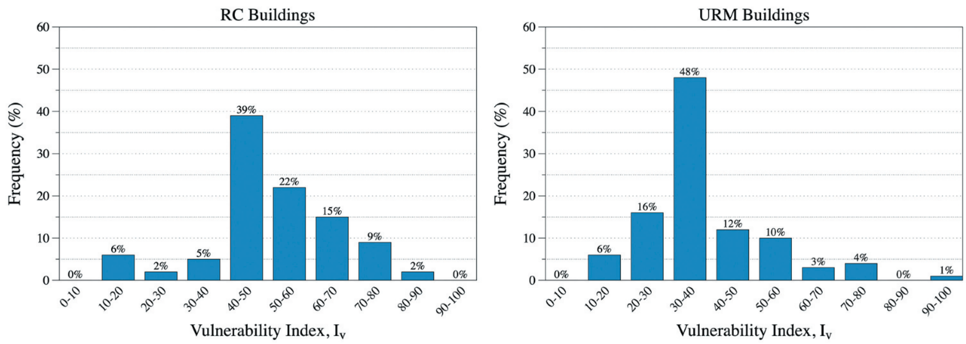

Figure 8. Vulnerability index distribution of the RC and URM building stock in the LMA.

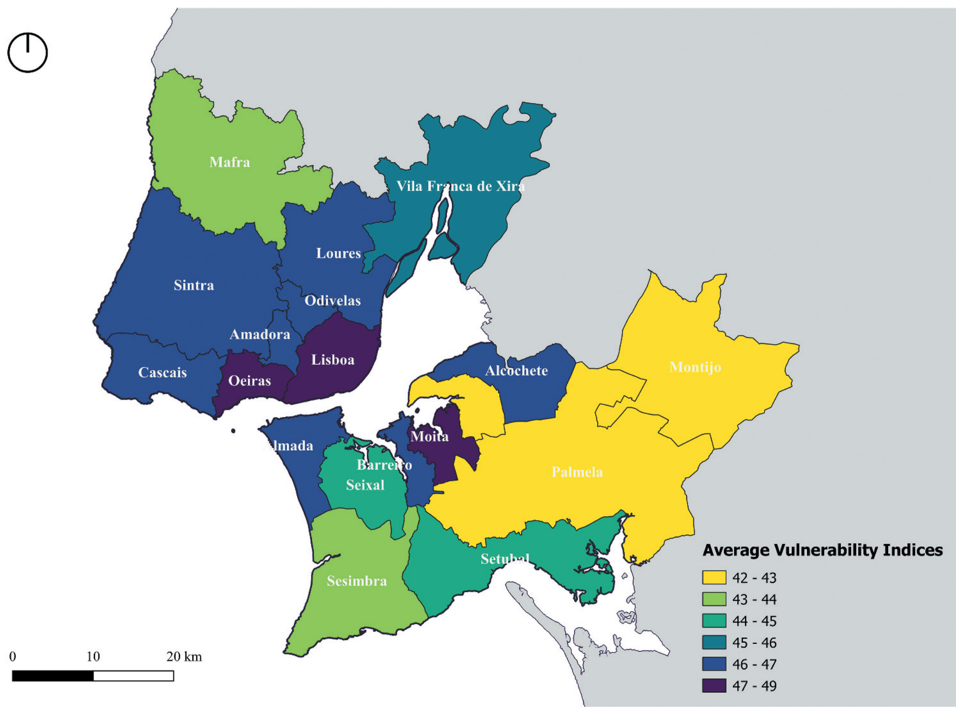

Figure 9. Spatial distribution of the average vulnerability indices obtained for the entire building stock per municipality in the LMA.

Section 2. It appears that the most vulnerable buildings ($I_v > 50$) are located in Oeiras, Lisboa, Amadora, and Barreiro.

5.1.2. Risk Analysis

As mentioned in Section 3, the seismic hazard and the vulnerability results, as first-order outputs, are combined to perform a risk assessment. The spatial distribution of the second-order analysis resulting from that integration is illustrated in Fig. 11, highlighting the range of risk levels across the LMA. As can be seen, the municipalities with the higher seismic risk are Lisbon, Cascais, Amadora, Seixal, and Moita.

The conceptual framework described in Section 3, underpinning the risk analysis that was carried out, allows an understanding of the interaction of the first-order hazard and vulnerability levels. One of the conclusions that emerge from this interaction is the fact that areas or municipalities of high or

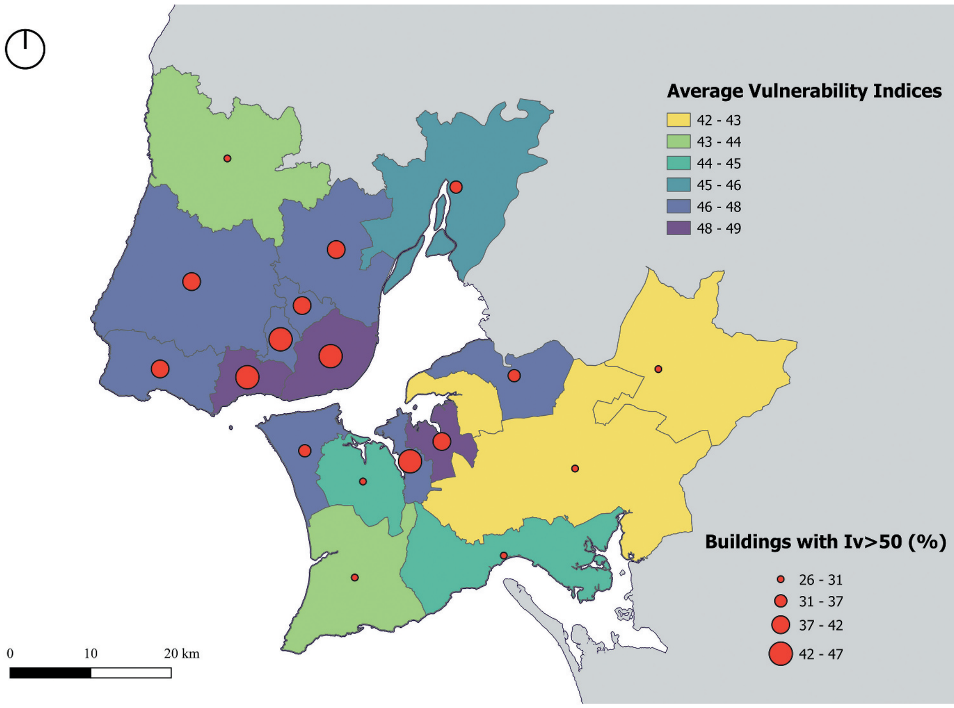

Figure 10. Spatial distribution of the building stock percentage with a vulnerability index higher than 50.

very high hazard and low to moderate vulnerability may easily result in a high or very high level of risk, which would not have been expected considering only their vulnerability level. Typical examples are the Barreiro, Loures or Setúbal municipalities.

Another second-order analysis output is the correlation of risk levels with population density. The following Fig. 12 illustrates the average distribution of population across all the municipalities of LMA, from which it can be seen that the most populated areas present moderate to very high or extreme risk levels.

This correlation between risk levels and population density can be very useful in supporting the planning and development of suitable and effective disaster risk management strategies aimed at reducing the impact of natural hazards on vulnerable buildings and communities. Hence, as a matter of priority in future risk mitigation plans for the resilience and preparedness of local communities, particular attention should be given to municipalities with high population densities and high-risk levels, such as Lisbon.

5.2. Lisbon Municipality

5.2.1. Vulnerability Assessment Results

Before going into the vulnerability results, summarised in Fig. 13, it is worth analyzing with some detail the distribution of the vulnerability classes obtained for each one of the vulnerability parameters since that information alone can provide valuable insight into the features that are contributing the most to the vulnerability of the building stock. Such a distribution is illustrated in Fig. 14 and discussed in the paragraphs below.

Regarding the structural system of URM buildings (parameter P1), 42% of the buildings are assigned to the two most vulnerable classes ("placa" buildings, in Class C, and adobe or rubble masonry buildings, in Class D), while URM buildings with timber floors account for 58% of the

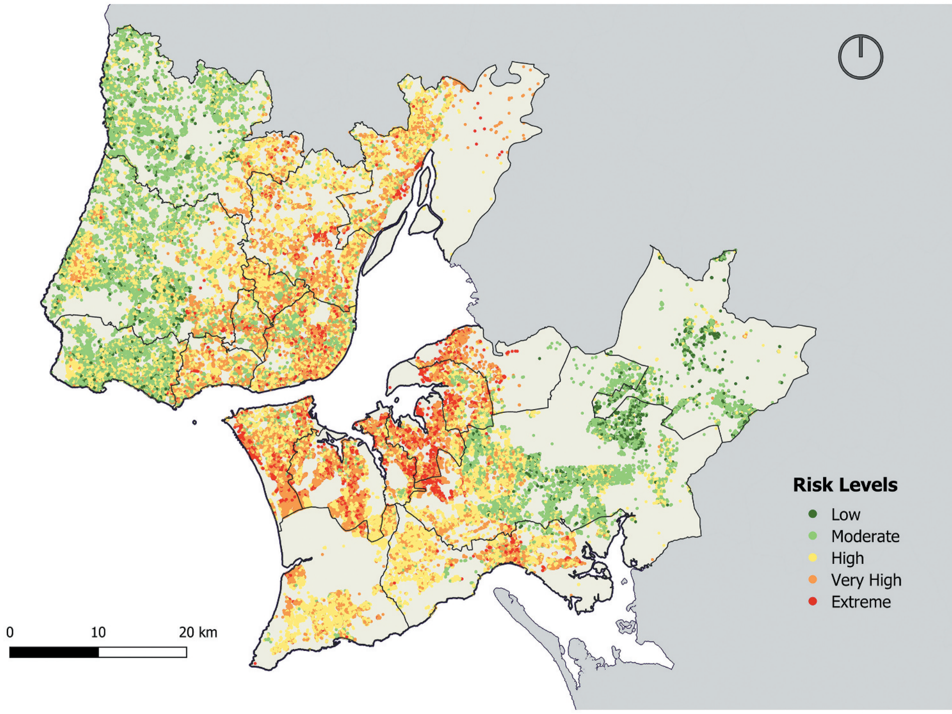

Figure 11. Spatial distribution of the risk assessment for the residential RC & URM buildings of the LMA.

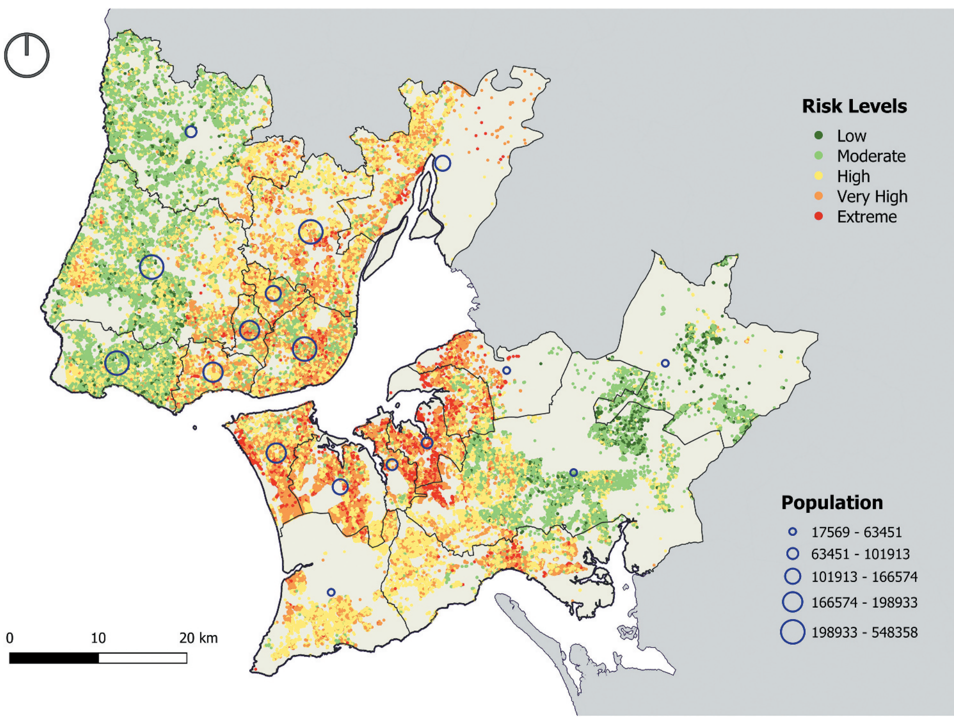

Figure 12. Spatial distribution of the risk assessment for the residential RC & URM buildings along with the population density over the LMA.

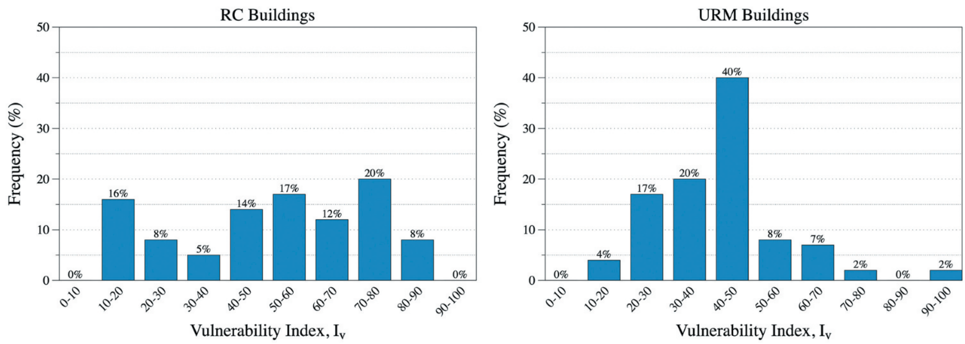

Figure 13. Vulnerability index distribution of the RC and URM buildings at Lisbon municipality.

building stock. In what concerns the building's position (as reflected by parameters P1 in RC buildings and P3 in URM buildings), a considerable portion of the RC building stock (71%) is assigned to Class C, being that 69% of these are "Classic" buildings and 2% are "Other." As to URM, buildings in the two most vulnerable classes account for just over two-thirds of the building stock, with vulnerability class D (semi-detached and edge buildings) accounting for 13% of the building stock and "Classic" buildings representing 55%. Regarding the period of construction (parameter P2 for both RC and URM buildings), the RC building stock is roughly evenly distributed (ranging from 30–35%) in the classes B, C, and D, which indicates an even distribution and development of the RC building stock in Lisbon municipality for each of the three periods considered. As for URM, buildings dated before 1945 (Class D) represent 60% of the building stock, while those constructed between 1945 and 1960 (Class C) account for 24%. From this, it can be seen that a substantial fraction of the URM buildings in the Lisbon municipality were built before the publication of the first Portuguese seismic code in 1958 and are expected to display the characteristic deficiencies generally attributed to traditional masonry buildings designed with no seismic provisions.

As for the height of the building, over half (54%) of the RC buildings are mid-rise buildings (with three to seven floors), corresponding to (parameter P3) Class B, while in the case of URM buildings (parameter P4) 40% of the buildings have two or three floors, and are thus assigned to Class B. Both low-rise (Class A) and high-rise (Class C) buildings, with one and four or more floors, respectively, account for 28% each.

Structural irregularities are considered in both RC buildings parameter P4 (soft story mechanisms at ground level) and URM buildings parameter P5 (structural irregularity due to the ground plan layout). In the first case, Class D remains the dominant vulnerability class, with about 71% of the buildings, including both irregular (41%) and non-evaluated (30%) buildings. Buildings classified as regular account for 29% of the building stock. As regards URM buildings, the vast majority (95%) are assigned to Class D, the most vulnerable, with the remainder 5% in the least vulnerable class (A).

Analyzed the distribution of the vulnerability classes, one can now better appreciate the distributions of the vulnerability results obtained for the RC and the URM buildings of Lisbon municipality, both given in Fig. 13. Starting with the RC buildings, as can be seen in the figure, the level of vulnerability is quite heterogenous, with 57% of the buildings presenting a vulnerability index within the range of 50–90. The vulnerability range with more buildings, 20%, was found to be 70–80, followed by 50–60 and 10–20 with 17% and 16% of the buildings, respectively. These results led to an average mean value of 52.6 and a standard deviation of 23.7. The minimum and maximum values are 11.85 and 93.3, respectively. As for the distribution of the URM buildings, it is noticeably more homogeneous than the one found for the RC buildings, with 40% of the URM buildings concentrated in the 40–50 vulnerability range. As a result of that, the average mean value of this distribution is 43.5 and the standard deviation is 13.5. Finally, the minimum and maximum values were found to be 14.3 and 91.4, respectively. Only 19% of the URM buildings have a vulnerability index within the range of 50–100,

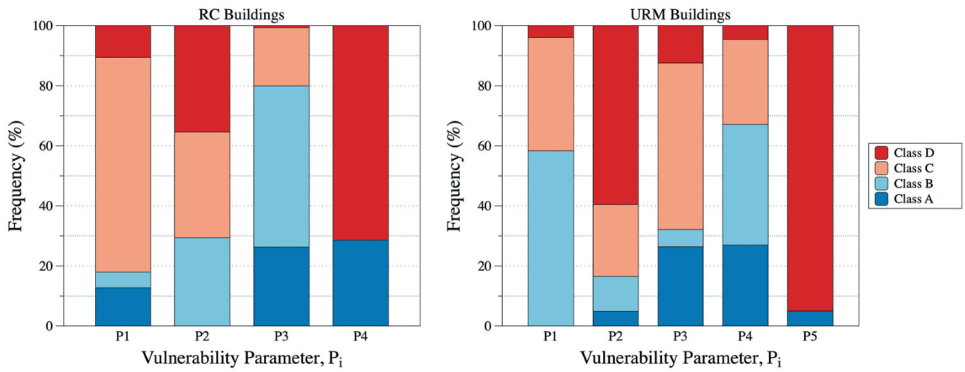

Figure 14. Distribution of the vulnerability classes across the vulnerability parameters.

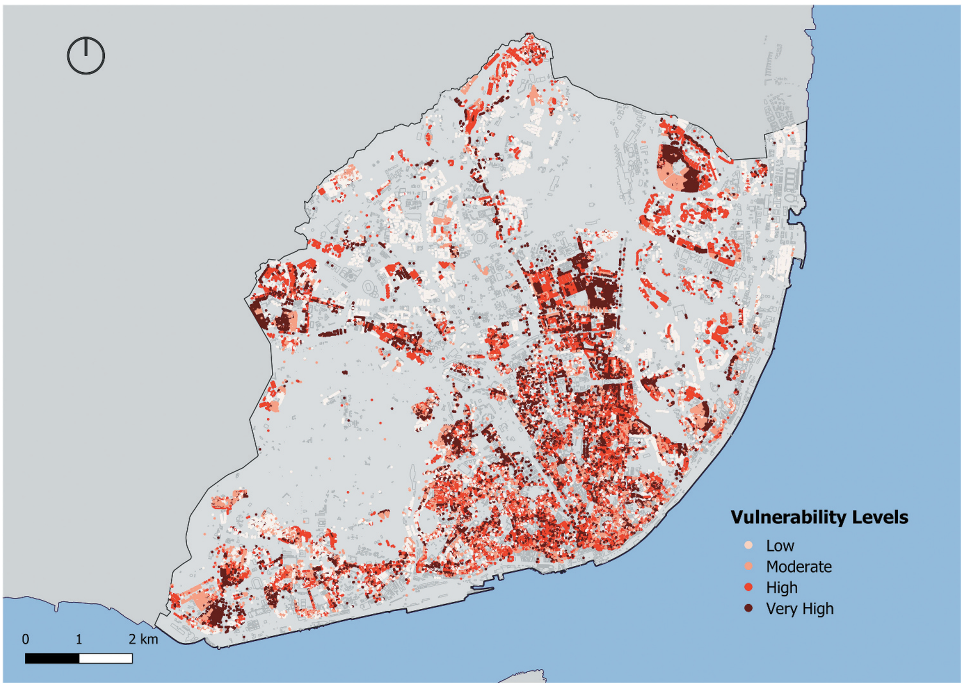

Figure 15. Spatial distribution of seismic vulnerability of residential building stock in Lisbon municipality.

which seems to suggest that only a relatively small fraction of the URM building stock in the Lisbon municipality is of high to very high seismic vulnerability.

Figure 15 presents the spatial distribution of seismic vulnerability for residential RC and URM buildings in Lisbon municipality, with Fig. 16 zooming in on a localized area of the historical part.

Based on the two above figures, it becomes evident that the high vulnerability areas are not only present in the historic center because of the older URM buildings. On the contrary, it is actually spread on the outskirts within newer residential developments, which is an indication of the number and high vulnerability of RC buildings.

5.2.2. Risk Analysis

In the specific case of the municipality of Lisbon, although its greater extent is mostly at high seismic hazard, as represented in Fig. 5, the consideration of the vulnerability levels results in buildings

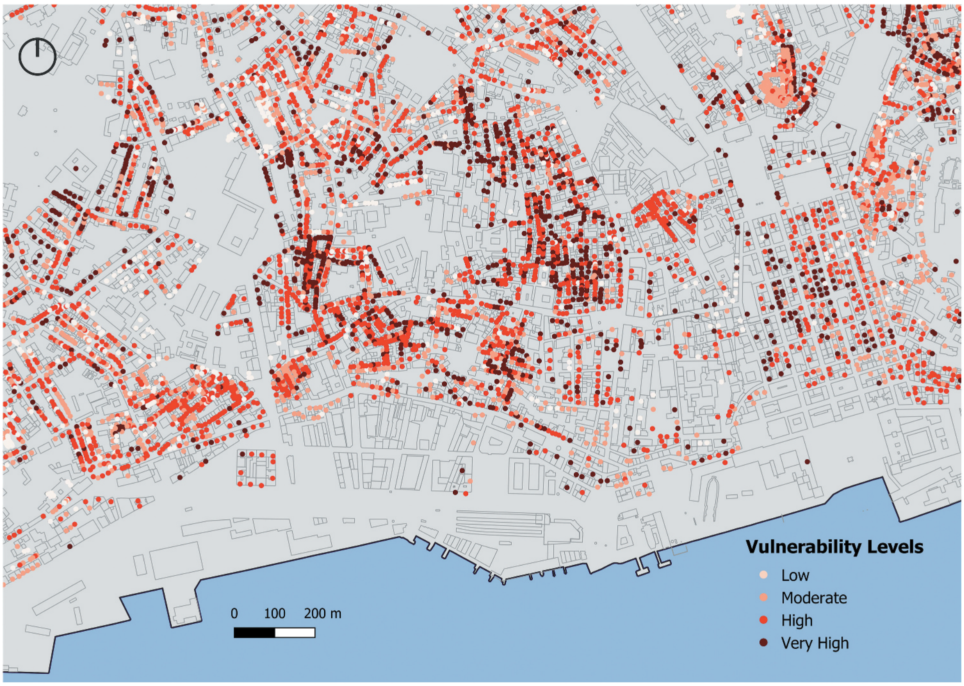

Figure 16. Spatial distribution of vulnerability of residential building stock in a localized area of Lisbon.

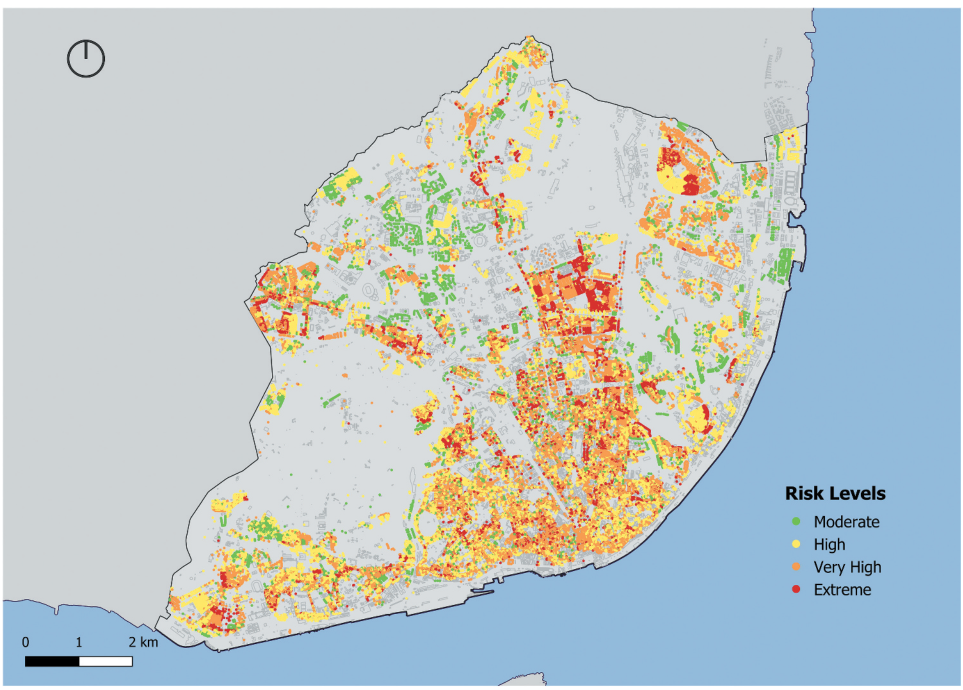

Figure 17. Spatial distribution of the risk assessment for the residential building stock of Lisbon municipality.

exposed to seismic risk levels that range from moderate to extreme. Figure 17 presents the spatial distribution of the seismic risk for the residential RC and URM buildings of Lisbon municipality, while Fig. 18 shows this analysis for a localized area. As mentioned before regarding the LMA, the

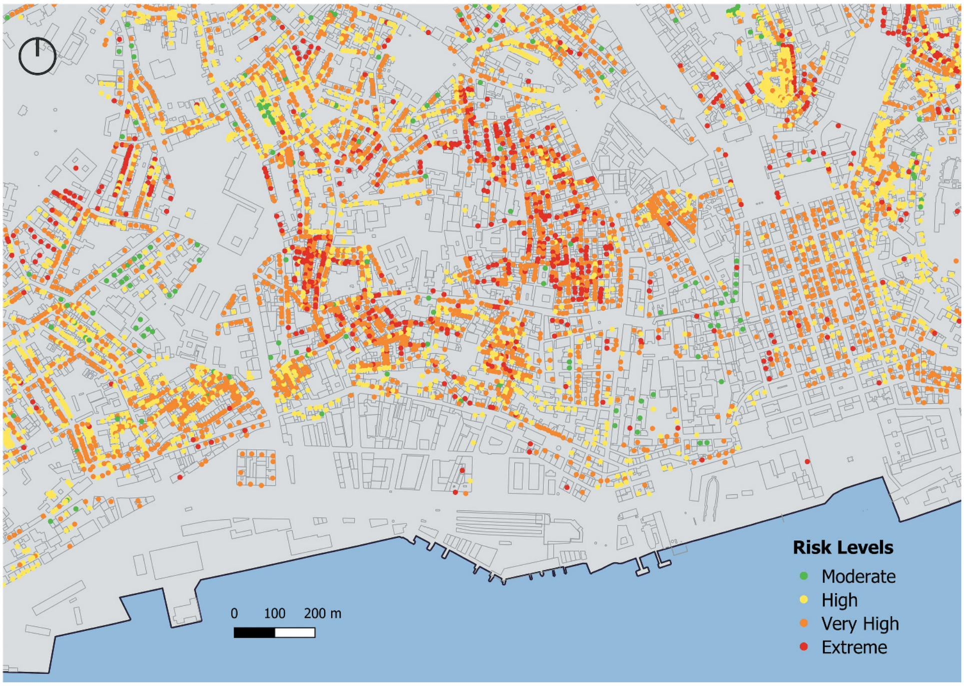

Figure 18. Spatial distribution of the risk assessment for the residential building stock in a localized area of Lisbon.

consideration of vulnerability level alone can lead to flawed conclusions regarding the impacts a seismic event could have on the building stock. Hence, a seismic risk assessment is paramount in order to devise strategies that mitigate the impacts of future earthquakes. At the same time, and chiefly in the case of the extremities considered in these scales, some correspondence can be found, with low and very high vulnerability often leading to moderate and extreme seismic risk, respectively.

5.3. Synthesis and Further Remarks

The vulnerability analysis conducted at the LMA urban scale shows that RC buildings display an average vulnerability index of 50.7, with the majority of RC buildings distributed above the 40–50 index range, while URM buildings appear to be less vulnerable, with a vulnerability index of 37.2 and the majority of buildings distributed below the 40–50 range. At the scale of the Lisbon municipality, the mean vulnerability values of RC and URM buildings are 52.6 and 43.5, respectively. Although the URM buildings are typically more vulnerable because of their age, material decay, and lack of connectivity between floors and walls, the RC buildings present a higher vulnerability in the current study. This can be justified, at least in part, considering the dominant portion of buildings on each typology that are classified in the most vulnerable class, which will essentially govern the overall vulnerability outcome. For instance, the majority of the RC buildings were built before the publication of the 1983 seismic code and present minor or no seismic provisions, which makes them particularly vulnerable to seismic actions. The "placa" buildings, on the other hand, represent a much smaller fraction of the URM building stock as compared to the most vulnerable RC typology (low- to medium-rise buildings constructed before 1983). As a result, URM buildings have a smaller impact on the overall vulnerability assessment of the LMA building stock, and therefore a direct comparison between the two main typologies of URM and RC is not realistic and representative in that case.

6. Conclusions

Given the increased exposure resulting from the urban expansion and population growth in the Lisbon Metropolitan Area in the last two centuries, it is expected that a presumed recurrence of the 1755 Lisbon earthquake would result in a more severe loss scenario for the surrounding urban areas. The likelihood of such a scenario emphasizes, even more, the need for developing suitable and efficient tools that can be used to assess the vulnerability of these areas and to create efficient and effective risk mitigation strategies.

In the context of a larger research project aimed at developing a multi-hazard integrated framework, this paper described a simplified index-based seismic vulnerability assessment methodology, specifically adapted to be fed with data from the Portuguese Census data of the 2011 survey. The great advantage of this simplified approach is the ability to identify fairly quickly and with a reasonable effort, given the scale of the analysis, the most vulnerable areas and building typologies within the LMA. In the absence of post-earthquake damage with which to calibrate the parameters' weights, a comparative analysis was made with results from similar methodologies that were used in urban areas whose building stock has similar constructive and geometrical features to those of LMA, which validated the adopted parameters' weights. This methodology was then applied to the Lisbon Metropolitan Area, taking into account its most representative building typologies. In total, 292,978 RC and 152,916 URM buildings were assessed. The analysis allowed obtaining the vulnerability levels across the Lisbon Metropolitan Area, discretized by the municipality, as well as providing an overview of the distribution of the buildings across their vulnerability range.

The vulnerability results were then integrated with the hazard levels in a GIS tool in order to provide an understanding of the vulnerability and hazard interaction, as well as to identify the areas with more seismic risk. The spatial distribution of the risk assessment results provides an easy way to communicate to decision-makers and risk mitigation planners which communities are more vulnerable and should therefore be given priority in devising risk management plans.

The uncertainties regarding the building characteristics, inherent to the 2011 Census data (in what concerns, for instance, the ground plan configuration layout, which affects the mass and stiffness regularity of the building, and the building position within the aggregate, which can be used to illustrate the interaction between adjacent buildings), can easily impact the overall vulnerability of the building stock, as the buildings were not inspected and recorded in detail. One way to improve the quality of the input data would be to conduct some carefully planned fieldwork, focusing on a small sample of specific building typologies in the areas with higher vulnerability and risk levels, which could also shed some light and refine the vulnerability levels, mainly in what concerns the RC building typologies. This would enable a more detailed and robust database of the RC building vulnerabilities and possibly even re-evaluate the parameters' weights for the vulnerability assessment methodology.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Funding

The project "MIT-RSC - Multi-risk Interactions Towards Resilient and Sustainable Cities" [MIT-EXPL/CS/0018/2019] leading to this work is co-financed by the ERDF - European Regional Development Fund through the Operational Program for Competitiveness and Internationalization - COMPETE 2020, the North Portugal Regional Operational Program - NORTE 2020 and by the Portuguese Foundation for Science and Technology - GCT under the MIT Portugal Program at the 2019 PT call for Exploratory Proposals in "Sustainable Cities". Pedro Pinto Santos was financed through FCT I.P., under the program of 'Stimulus of Scientific Employment – Individual Support within the contract CEECIND/00268/2017.

ORCID

Maria Xofi http://orcid.org/0000-0002-4703-0659
Tiago Miguel Ferreira http://orcid.org/0000-0001-6454-7927
José Carlos Domingues http://orcid.org/0000-0002-7934-3756
Pedro Pinto Santos http://orcid.org/0000-0001-9785-0180
Susana Pereira http://orcid.org/0000-0002-9674-0964
Sérgio C. Oliveira http://orcid.org/0000-0003-0883-8564
Eusébio Reis http://orcid.org/0000-0001-8367-1835
José Luís Zêzere http://orcid.org/0000-0002-3953-673X
Ricardo A.C. Garcia http://orcid.org/0000-0002-1036-6271
Paulo B. Lourenço http://orcid.org/0000-0001-8459-0199

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References

ATC-21 Rapid Visual Screening of Buildings for Potential Seismic Hazards. 1988. Washington DC, USS: Federal Emergency Management Agency.

Bernardo, V., A. Campos Costa, P. Candeias, and A. Costa. 2022. Seismic vulnerability assessment and fragility analysis of pre-code masonry buildings in Portugal. *Bulletin Earthquake Engineering* 20 (11):6229–65. doi:10.1007/s10518-022-01434-8.

Bernardo, V., R. Sousa, P. Candeias, A. Costa, and A. Campos Costa. 2021. Historic appraisal review and geometric characterization of old masonry buildings in Lisbon for seismic risk assessment. *International Journal of Architectural Heritage* 16 (12):1–21. doi:10.1080/15583058.2021.1918287.

Blyth, A., A. Di Napoli, F. Parisse, Z. Namourah, E. Anglade, A. -M. Giatreli, H. Rodrigues, and T. M. Ferreira. 2020. Assessment and mitigation of seismic risk at the urban scale: An application to the historic city center of Leiria, Portugal. *Bulletin Earthquake Engineering* 18 (6):2607–34. doi:10.1007/s10518-020-00795-2.

Calvi, G. M., R. Pinho, G. Magenes, J. J. Bommer, and H. Crowley. 2006. Development of seismic vulnerability assessment methodologies over the past 30 years. *ISET Journal of Earthquake Technology* 43:75–104.

Ferreira, T. M., R. Maio, and R. Vicente. 2017. Seismic vulnerability assessment of the old city centre of Horta, Azores: Calibration and application of a seismic vulnerability index method. *Bulletin Earthquake Engineering* 15 (7):2879–99. doi:10.1007/s10518-016-0071-9.

Ferreira, T. M., N. Mendes, and R. Silva. 2019. Multiscale seismic vulnerability assessment and retrofit of existing masonry buildings. *Build* 9 (4):91. doi:10.3390/buildings9040091.

Ferreira, T. M., H. Rodrigues, and R. Vicente. 2020. Seismic vulnerability assessment of existing reinforced concrete buildings in urban centers. *Sustainability* 12 (5):1996. doi:10.3390/su12051996.

Ferreira, T. M., R. Vicente, J. A. R. M. Silva, H. Varum, and A. Costa. 2013. Seismic vulnerability assessment of historical urban centres: Case study of the old city centre in Seixal, Portugal. *Bulletin Earthquake Engineering* 11 (5):1753–73. doi:10.1007/s10518-013-9447-2.

GNDT-SSN. 1994. Scheda di esposizione e vulnerabilità e di rilevamento danni di primo livello e secondo livello (muratura e cemento armato). Gruppo Nazionale per la Difesa dai Terremoti, Roma, Italy.

Kassem, M. M., F. Mohamed Nazri, and E. Noroozinejad Farsangi. 2020. The seismic vulnerability assessment methodologies: A state-of-the-art review. *Ain Shams Engineering Journal* 11 (4):849–64. doi:10.1016/j.asej.2020.04.001.

Lamego, P., P. B. Lourenço, M. L. Sousa, and R. Marques. 2017. Seismic vulnerability and risk analysis of the old building stock at urban scale: Application to a neighbourhood in Lisbon. *Bulletin Earthquake Engineering* 15 (7):2901–37. doi:10.1007/s10518-016-0072-8.

Maio, R., T. M. Ferreira, and R. Vicente. 2018. A critical discussion on the earthquake risk mitigation of urban cultural heritage assets. *International Journal of Disaster Risk Reduction* 27:239–47. doi:10.1016/j.ijdrr.2017.10.010.

Maio, R., T. M. Ferreira, V. Vicente, and J. Estêvão. 2016. Seismic vulnerability assessment of historical urban centres: Case study of the old city centre of Faro, Portugal. *Journal of Risk Research* 19 (5):551–80. doi:10.1080/13669877.2014.988285.

Montilla, J. A., and C. L. Casado. 2002. Seismic hazard estimate at the Iberian Peninsula. *Pure and Applied Geophysics* 159 (11–12):2699–713. doi:10.1007/s00024-002-8754-3.

Morgado, M. J. 2017. Lisbon and Lisbon Metropolitan Region: Population context at the core of the urban food system. CEACT/UAL - Centro de Estudos de Arquitetura, 22.
Silva, V., H. Crowley, H. Varum, and R. Pinho. 2015. Seismic risk assessment for mainland Portugal. *Bulletin of Earthquake Engineering* 13 (2):429–57. doi:10.1007/s10518-014-9630-0.
Simões, A. G., J. G. Appleton, R. Bento, J. V. Caldas, P. B. Lourenço, and S. Lagomarsino. 2017. Architectural and structural characteristics of masonry buildings between the 19th and 20th centuries in Lisbon, Portugal. *International Journal of Architectural Heritage* 11 (4):457–74. doi:10.1080/15583058.2016.1246624.
Simões, A. G., R. Bento, S. Lagomarsino, S. Cattari, and P. B. Lourenço. 2020. Seismic assessment of nineteenth and twentieth centuries URM buildings in Lisbon: Structural features and derivation of fragility curves. *Bulletin Earthquake Engineering* 18 (2):645–72. doi:10.1007/s10518-019-00618-z.
Statistics Portugal, Portuguese Census Survey. 2011. Accessed October 30, 2021. http://censos.ine.pt/.
Vicente, R., D. D′ayala, T. M. Ferreira, H. Varum, A. Costa, J. A. R. M. Silva, and S. Lagomarsino. 2014. Seismic vulnerability and risk assessment of historic masonry buildings. In *Structural rehabilitation of old buildings. Building pathology and rehabilitation*, ed. A. Costa, J. Guedes, and H. Varum, Vol. 2, 307–48. Berlin: Springer.
Vicente, R., S. Parodi, S. Lagomarsino, H. Varum, and J. A. R. M. Silva. 2011. Seismic vulnerability and risk assessment: Case study of the historic city centre of Coimbra, Portugal. *Bulletin Earthquake Engineering* 9 (4):1067–96. doi:10.1007/s10518-010-9233-3.
Whitman, R. V., J. W. Reed, and S. -T. Hong. 1973. Earthquake damage probability matrices. *Proceedings of the Fifth World Conference Earthquakes Engineering*, Rome, Italy, June 25–29.