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Exposure and physical vulnerability indicators to assess seismic risk in urban areas: a step towards a multi-hazard risk analysis

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

[a]Institute for Sustainability and Innovation in Structural Engineering (ISISE), Department of Civil Engineering, University of Minho, Portugal; [b]Centre for Geographical Studies, Institute of Geography and Spatial Planning (IGOT), Associated Laboratory TERRA, University of Lisbon, Portugal; [c]Department of Geography and Environmental Management, University of the West of England, UK

ABSTRACT

Understanding the impacts of multi-hazard risk in urban areas is a fundamental step towards the adoption of resilience-enhancement and disaster prevention strategies, underpinning institutional adjustments aimed at improving the capacity of the authorities and stakeholders to manage risk. Within this framework, the work presented in this paper seeks to identify and analyze a set of exposure and buildings' physical vulnerability indicators to be used as input to a parametric-based seismic vulnerability assessment methodology for the unreinforced masonry (URM) building stock of Lisbon Metropolitan Area (LMA). For this approach, data from the 2011 Census survey are used to define the parameters describing the building's physical vulnerability and characterise the level of exposure in the study area. These results are then combined with the hazard component into a GIS tool. Seismic vulnerability results are presented for the URM building stock in LMA, and a more detailed analysis is conducted for the building stock of Setúbal municipality. Finally, risk outputs are presented and briefly discussed. Ultimately, understanding the impact and extent of multi-hazards can help prioritize resilience-increasing actions and disaster prevention measures to mitigate and manage natural hazards.

1. Introduction

Multi-hazard events, i.e. events that include more than one natural hazard, with or without causal relationships between them, with some degree of overlapping during the same time period, are usually much more impactful than a single hazard event,

CONTACT Tiago Miguel Ferreira ✉ Tiago.Ferreira@uwe.ac.uk

making it more likely that emergency response mechanisms are unable to respond efficiently and effectively. However, although there has been a focus and a significant amount of research work on single hazard assessments, there is still limited research data for multi-hazard analysis. Therefore, given the continued increase in urbanization (and ever-growing exposure both of population and buildings), it is essential to develop integrated risk assessment frameworks and tools for measuring, managing and mitigating the impacts of multiple natural hazards in urban areas.

Among the several natural hazards that have affected building stocks and infrastructure systems over the past few decades, often with severe economic and human consequences, earthquakes have been the most catastrophic ones. From an emergency planning point of view, the definition of seismic risk reduction strategies must be founded on a comprehensive understanding of the seismic vulnerability of the building stock (Chieffo et al. 2021), especially when dealing with unreinforced masonry (URM) buildings whose seismic performance is usually poorer. At the same time, the level of detail adopted for the analysis must be adjusted to the resources available and the amount of data resulting from the assessment, which makes simplified approaches more suited when the objective is to identify priorities in terms of vulnerability reduction intervention or to allocate resources to specific areas. Vulnerability Index-based methodologies are one of those simplified vulnerability assessment methodologies, which, in recent decades, have proved to be particularly suited when the objective is to carry out a first screening of the seismic vulnerability of large building stocks (Athmani et al. 2015).

The work presented in this paper aims to create a risk assessment framework for measuring the impacts of different natural hazards in urban areas by identifying, analyzing, and combining three core components: the seismic hazard, the exposure (i.e. built environment and population), and the seismic vulnerability of the exposed elements, in order to obtain risk hotspot areas, addressing the linkage between the building typologies and the respective physical vulnerability. Data from the 2011 Census was used herein to define a set of vulnerability assessment parameters used to evaluate the seismic vulnerability of the URM building stock of the Lisbon Metropolitan Area (LMA). After the parameters' validation and the seismic vulnerability assessment is concluded, the results are then combined with the seismic hazard of the area and integrated into a Geographic Information System (GIS), to generate seismic risk maps for the LMA municipalities.

This paper is organized as follows. After presenting the methodological framework that underpins the risk assessment approach adopted in this work, the exposed elements (buildings and population) in LMA are briefly characterized. The seismic vulnerability assessment methodology is then described, and an overview of the seismic vulnerability results is presented for the URM building stock in LMA, concerning mean, maximum, and minimum vulnerability values, as well as the overall distribution of the building stock across the vulnerability levels. A first analysis is then conducted aimed at identifying which municipalities are most vulnerable, and detailed results are described and analyzed for the case of the Setúbal municipality, showing how the classification of the building stock according to the proposed methodology leads to a deeper understanding of the building features influencing seismic

vulnerability at the urban scale. Additionally, risk outputs are presented and briefly discussed. Finally, some conclusions and remarks are highlighted, and proposals for future developments are suggested.

The novelty of the work presented in this paper lies in two main aspects. Firstly, the approach applied herein to assess the seismic vulnerability of the URM building stock in LMA, which was developed and validated specifically for this purpose. Among other particularities, it is worth noting that this approach was specifically developed to be applied at a very large scale – more than 150 thousand buildings in this case – using Census data. Secondly, although a single-hazard analysis (seismic) is carried out here, the methodology developed and applied in this work proved to be flexible enough to be adapted to assess other single hazards or integrated into more advanced frameworks involving, for example, multiple hazards.

2. Methodological framework: from hazard, exposure, and vulnerability analysis to risk assessment

The methodological framework adopted in this paper for the risk assessment is based on the approach presented by Ferreira and Santos (2020), including, besides a vulnerability and a hazard module, an exposure-related component.

The hazard level is obtained by combining three aspects: the seismic intensity, the PGA, and the ground/soil conditions. Considering a long-term time scale, it is the less dynamic or mutable component of the assessment. Subsection 2.1 presents an overview of the seismic hazard that characterizes the LMA, and the hazard levels considered in this seismic risk approach are explained in Subsection 2.2.

The exposure considered here is based on the identification of the elements at risk, namely buildings and population. 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 (created by Statistics Portugal with data from the 2011 Housing Census), respectively (Statistics Portugal 2011). Subsection 2.3 presents the characterization of the building typologies present in LMA and the spatial distribution of the population in LMA.

The seismic vulnerability level of the buildings is obtained through a parameter-based vulnerability assessment approach. From the evaluation of a few parameters of empirical nature, this approach allows obtaining a dimensionless index that measures the seismic vulnerability of the buildings into four levels with the corresponding vulnerability index ranging from low (0-25) and moderate (25-50) to high (50-75) and very high (75-100). Further details about the vulnerability assessment methodology can be found in Subsection 2.4.

Seismic risk is then computed using the risk matrix presented in Table 1, which combines the vulnerability of the building with the level of hazard in that specific location.

As can be seen in Table 1, five levels of seismic risk can result from this analysis, from 'Low' to 'Extreme'. As an example, if the level of hazard in a certain location is

Table 1. Seismic risk matrix.

Seismic risk		Hazard			
		L	Moderate	High	Very high
Vulnerability	Low	Low	Low	Moderate	High
	Moderate	Low	Moderate	High	Very high
	High	Moderate	High	Very high	Extreme
	Very high	High	Very high	Extreme	Extreme
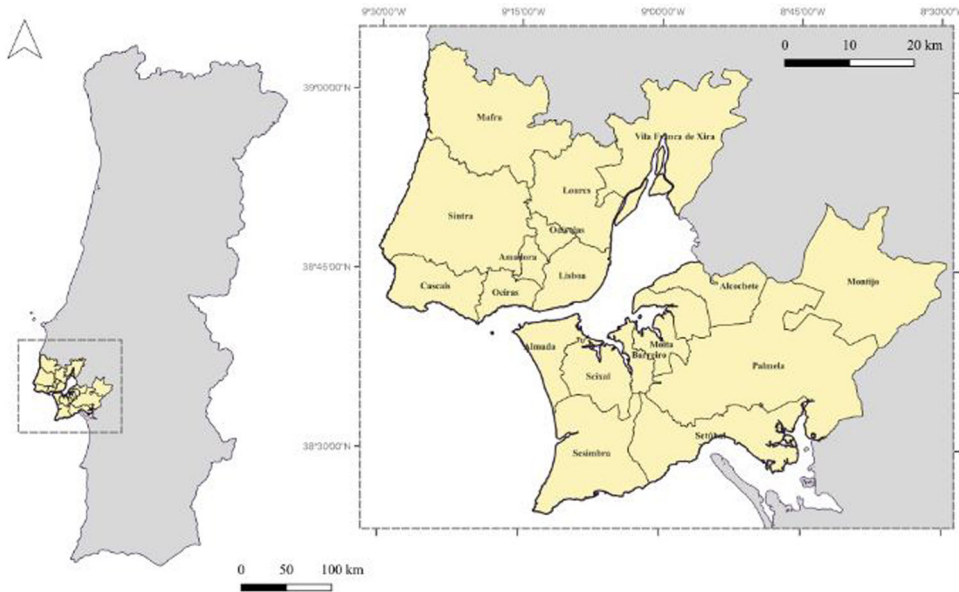
Figure 1. Division of the LMA into 18 municipalities.

tagged as 'low', but the vulnerability of the building stock is identified as 'very high', the final risk indicator is ranked as 'high'.

2.1. The Lisbon metropolitan area

Centred in the Portuguese capital city of Lisbon, the Lisbon Metropolitan Area (LMA) is the largest urban area in the country, covering an area of 3,001 km2 and being home to near 2,813,000 inhabitants (approximately 27% of the Portuguese population). With 18 municipalities (Figure 1) and 211 parishes, it covers part of the Districts of Lisbon and Setúbal, on the northern and southern side of the Tagus River, respectively. According to the 2011 Census survey, the LMA has a density of 935 inhabitants per km2 and a property concentration of 449,573 buildings. Lisbon records the highest average levels of income per capita in Portugal and, with a GDP of €66.5bn in 2016 (EUROSTAT), it is the most important contributor to the national GDP (35.9%).

The Lisbon Metropolitan Area is generally considered one of the most critical seismic regions in Portugal, in great part due to the proximity of the Africa-Eurasia plate boundary. This location makes the region prone to devastating offshore and onshore

earthquakes (Custódio et al. 2015; Wronna et al. 2021), which is especially important given the economic and demographic relevance of this region in the country's context. Several large earthquakes have occurred in the past, namely in 1755, 1816, and 1969. The 1755 Lisbon earthquake, in particular, was the largest known historic earthquake to impact Europe and northern Africa, with an estimated magnitude of 8.5 to 9 and an epicentre at about 300 km to 400 km southwest of Lisbon in the Gorringe Bank, along the Africa-Eurasia plate boundary (Franco and Shen-Tu 2009). The proximity of the Africa-Eurasia plate boundary impacts the area's seismicity in yet another way by triggering a number of onshore crustal faults, of which the most relevant to LMA is the Lower Tagus Valley (LTV) fault, passing through Lisbon (Vilanova and Fonseca 2004). Several large historical earthquakes, namely in 1531, 1909, and possibly 1344, occurred on the LTV, causing significant damage in the Lisbon area.

2.2. Hazard assessment

The seismic hazard was assessed by combining three components: the earthquake intensity (obtained from the seismic intensity map created by the Portuguese Institute for Sea and Atmosphere), the Peak Ground Acceleration for a return period of 475 years (obtained from Montilla and Casado 2002), 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, from the Geological Map of Portugal and the Neotectonic Map of Portugal.

Considering the seismic intensity map in Figure 2(a), it is estimated that about 40% of the Lisbon and Tagus Valley (LVT) 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).

As to the distribution of maximum ground accelerations represented in Figure 2(b), adopted from Montilla and Casado (2002), PGA range from 3.2 to 4.0 m/s^2, from 2.4 to 3.2 m/s^2, and from 1.6 to 2.4 m/s^2 in 41.4%, 46.3% and 12.3% of the LVT Region, respectively. Figure 2(c) shows the unconsolidated sedimentary geological formations, namely the Quaternary deposits (which occupy about 22.7% of the territory) and the active faults in the zone.

Tables 2 and 3 illustrate the definition of the hazard classes for the cases where seismic action is amplified either by poorly consolidated sedimentary deposits or by active faults. Moreover, Figure 3 presents the spatial distribution of the hazard classes in the Lisbon Metropolitan Area.

2.3. Identification of the exposed elements: buildings and population

According to the 2011 Census survey, the building stock in the LMA comprises 449,573 buildings spatially distributed by the 18 municipalities, as illustrated in Figure 4. Of these 449,573 buildings, 65% correspond to Reinforced Concrete (RC) structures and 34% to Unreinforced Masonry (URM) structures. The distribution of
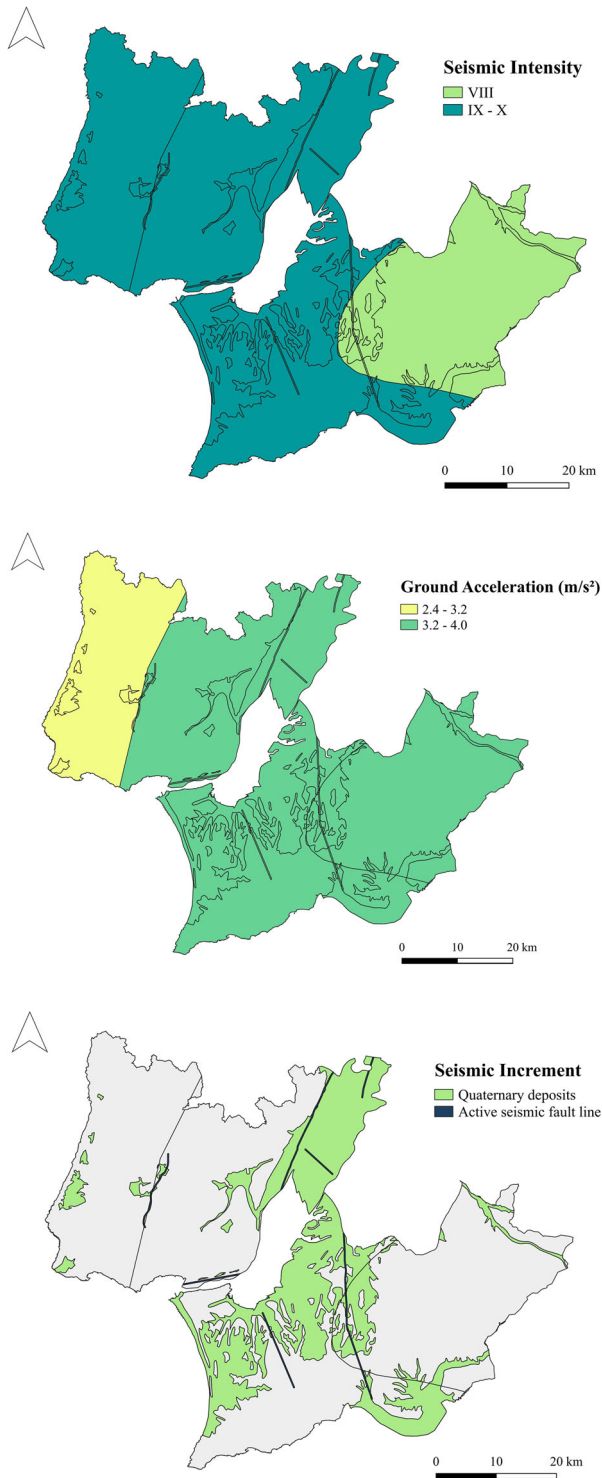
Figure 2. Seismic intensity (a) and maximum peak ground acceleration (b) maps for the Lisbon and Tagus Valley region for a return period of 475 years, and sedimentary consolidation deposits and active faults map (c).

Table 2. Hazard levels (presence of poorly consolidated sedimentary deposits or active faults).

		Peak ground acceleration (m/s²)		
Hazard		1.6–2.4	2.4–3.2	3.2–4.0
Seismic intensity zone	VIII	Moderate	Moderate	High
	IX	–	High	Very high
	X	–	High	Very high

Table 3. Hazard levels (no seismic amplification induced by poorly consolidated sedimentary deposits or active faults).

		Peak ground acceleration (m/s²)		
Hazard		1.6–2.4	2.4–3.2	3.2–4.0
Seismic intensity zone	VIII	Low	Low	Moderate
	IX	–	Moderate	High
	X	–	Moderate	High
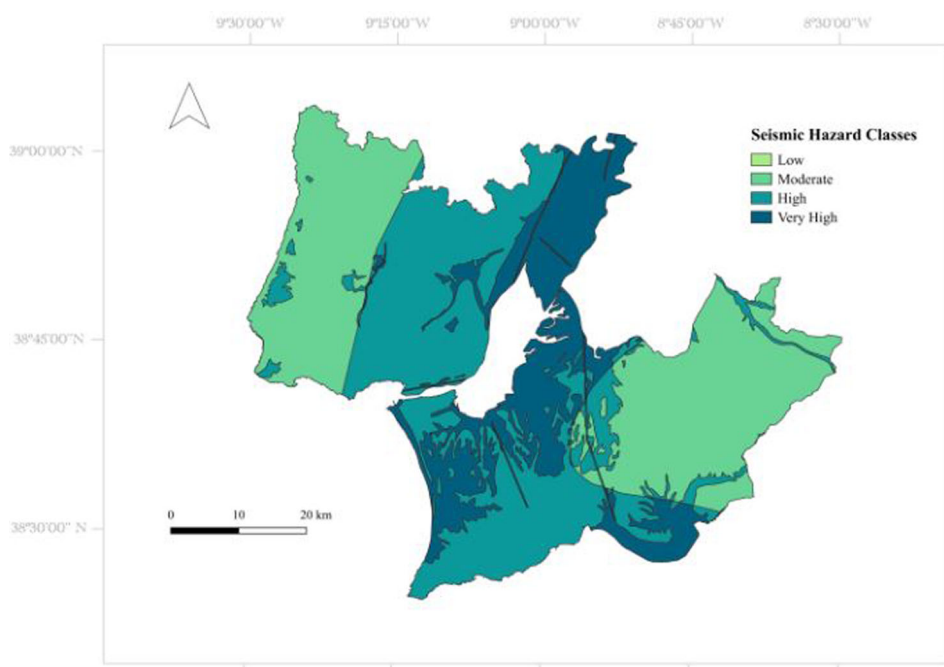
Figure 3. Spatial distribution of the hazard classes in LMA.

these two structural typologies within each one of the municipalities of the LMA is also provided in Figure 4.

Focusing specifically on the URM buildings, which is the typology addressed in this paper, four main types of unreinforced masonry buildings can be identified in the LMA (Simões et al. 2012; Bernardo et al. 2021):

- 'Pre-Pombalino' buildings – dating back to the period before the 1755 Lisbon Earthquake, these structures are characterized by irregular geometry, reduced dimensions in a plan, and narrow facades. With up to four stories, these buildings' walls are generally of poor-quality masonry (Figure 5(a)).
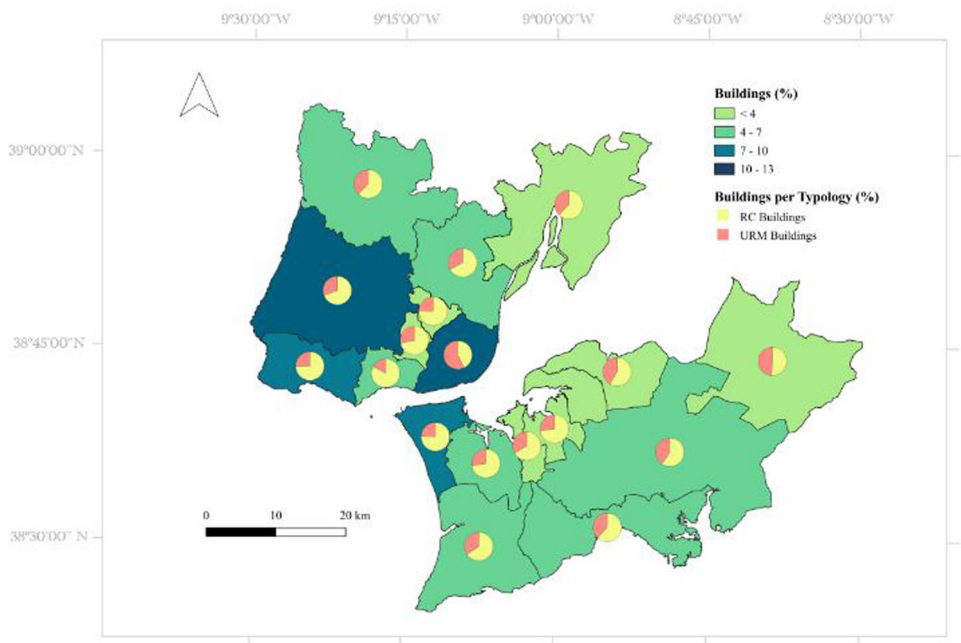
Figure 4. Distribution of building stock and typologies per municipality.

Figure 5. Unreinforced masonry buildings in the Lisbon Metropolitan Area: 'Pre-Pombalino' buildings (a) and 'Pombalino' buildings (b).

- 'Pombalino' buildings – built in the aftermath of the 1755 Earthquake, the most distinctive feature of these buildings is the "Gaiola Pombalina," a timber-framed wall truss idealized to absorb the impact of horizontal seismic forces. These buildings typically present up to five stories, regular geometry, and large and regular shape window openings (Figure 5(b)).

Figure 6. Unreinforced masonry buildings in the Lisbon Metropolitan Area: 'Gaioleiro' buildings (on the left) and 'Placa' buildings (on the right).

- 'Gaioleiro' buildings – built between 1870 and 1930, these buildings can be seen as a downgrade compared to the previous "Pombalino" typology, with a lower level of construction quality (Figure 6(a)).
- 'Placa' buildings – these report to a group of structures built during a very specific time period, mainly between 1930 and 1960, representing a structural solution characterized by a combination of masonry walls and reinforced concrete elements, such as concrete floor slabs (without any slab continuity). This is a transition structural typology between the traditional masonry structures and the modern reinforced concrete building construction (Figure 6(b)).

The distribution of the resident population in the LMA is presented in Figure 7, as well as its distribution per building typology (URM and RC). As shown in Figure 7, Lisbon and Sintra are the two municipalities with the highest number of inhabitants, with 548,358 and 377,823 (respectively 19% and 13% of the total population of the LMA). When breaking down the population distribution per building typology, it is possible to observe that around 80% of the LMA's inhabitants live in RC buildings and 20% in URM buildings. In relative terms, Oeiras is the municipality that presents a higher percentage of RC buildings, about 83% of Oeiras building stock, whereas Lisbon is the one with a higher percentage of URM buildings, with nearly 57%.

2.4. Methodology for the seismic vulnerability assessment of the unreinforced masonry building stock

It is generally considered that the selection of a seismic vulnerability assessment method to use in a specific analysis should be based on three main essential criteria: level of detail, type of output (or scale of evaluation), and quality of the input data and tools (or methods) (Vicente et al. 2014; Maio et al. 2018; Ferreira et al. 2019). The vulnerability index formulation applied in this work is based on the GNDT II level approach (GNDT-SSN 1994) for the vulnerability assessment of masonry buildings, which is an approach classified in the literature as a hybrid one, combining the typological approach and the vulnerability index-based estimation. This approach was
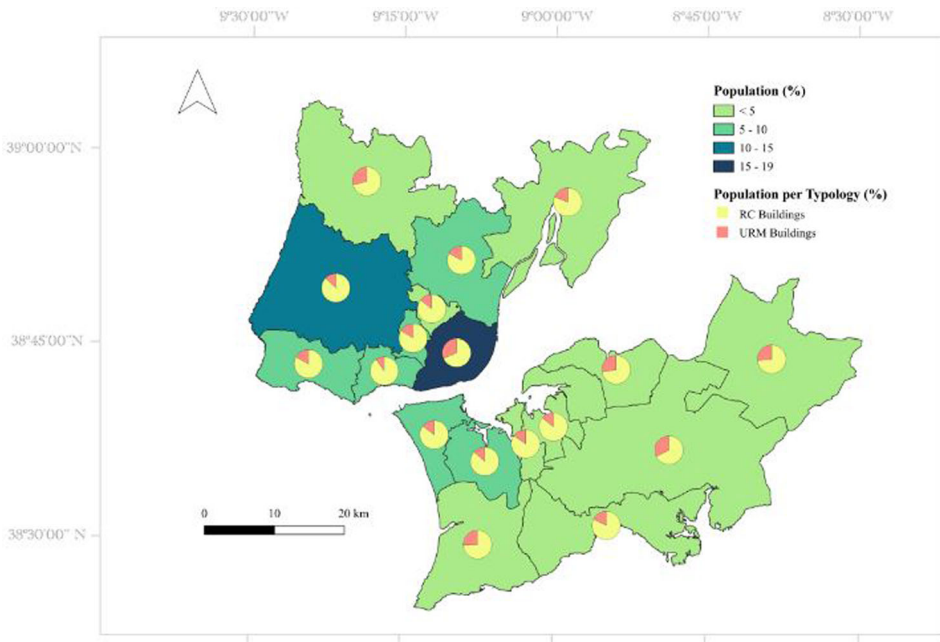
Figure 7. Distribution of population per municipality and building typology.

originally proposed in Italy and has been applied over the last 30 years in many large-scale analyses. In 2011, it was adapted to the Portuguese masonry construction and improved further 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 (Vicente et al. 2011). Further developments were made by Ferreira et al. (2017), who calibrated the method according to damage data collected in the aftermath of the 1998 Azores earthquake. In Portugal, it has been applied to the historical city centres of Coimbra (Vicente et al. 2011), Seixal (Ferreira et al. 2013), Faro (Maio et al. 2016), and Leiria (Blyth et al. 2020). Similar to the original proposal, the methodology presented in this work can be used to obtain a seismic vulnerability index of buildings based on the evaluation of a few parameters of empirical nature. A singular innovation of the current methodology is the fact that it was explicitly tailored to be fed by the available Portuguese 2011 Census data survey, which subsequently constituted the basis for selecting the adopted parameters, as per Table 4. Each of these parameters 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}), A, B, C, and D, which are then associated with a weight (p_i) that defines the relative importance of each parameter to the overall seismic vulnerability of the building.

The parameters that mostly influence the seismic vulnerability are parameter P1, which refers to the structural systems (including construction materials), and parameter P3, related to the relative position of the building within the aggregate. The weights corresponding to the above-mentioned parameters are 2.5 and 1.0,

Table 4. Building parameters with vulnerability classes and weights.

Parameters		Classes C_{vi}				Weight p_i
		A	B	C	D	
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 storeys	0	5	20	50	0.5
P5	Ground plan layout	0	–	–	50	0.5

respectively. Although less significant in terms of weights, the role of the other three parameters – P2 (Period of Construction), P4 (Number of stories), and P5 (Ground plan layout) – is also essential, contributing to capturing the overall seismic vulnerability of the building.

A vulnerability index, I_v^*, is calculated using Equation (1) by computing the weighted sum of the parameters multiplied by their specific weight assigned as a meaning of importance in terms of seismic response.

$$I_v^* = \sum_{i=1}^{5} C_{vi} \times p_i \tag{1}$$

For more straightforward interpretation and use, the vulnerability index, I_v^* is usually normalized to range between 0 and 100, assuming from that moment on the notation. In the following, each of the parameters presented in Table 2 is described in more detail.

2.4.1. Parameter P1: structural system

Parameter P1 refers to the type of the structural system classifying the URM in different typologies that are prevalent in the LMA and consequently with varying levels of vulnerability. The adopted typological discretization and the vulnerability classes assigned are presented in Table 5. Generally speaking, adobe and rubble stone buildings are the two most vulnerable building typologies, being accordingly assigned to the most unfavourable vulnerability class (D). Conversely, regardless of the building typology, main construction material, the floor's stiffness and the effectiveness of the connections between the vertical (i.e. walls) and horizontal elements (i.e. floors) play a critical role in the seismic performance 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 this class. Looking into the remaining types of unreinforced masonry buildings that are present in LMA, a division was made between URM buildings with timber and concrete floors, considering that the former are less vulnerable than the latter due to the nature of the timber-framed wall structure, which is connected to the timber floors and ensures a global seismic response, while (as described in Subsection 2.3) 'placa' buildings display no slab continuity.

2.4.2. Parameter P2: period of construction

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 design code requirements at the time the building

Table 5. Classes definition for parameter P1.

Class	Structural system
A	–
B	URM building with timber floor
C	URM building with concrete floor slabs
D	Adobe or rubble stone building

Table 6. Classes definition for parameter P2.

Class	Period of design and construction
A	1981–2011
B	1961–1980
C	1945–1960
D	before 1945

Table 7. Classes definition for parameter P3.

Class	Building position
A	Terraced buildings
B	Isolated buildings
C	Classic buildings
D	Semi-detached or edge buildings

was built, as well as the ageing 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 the older ones. Table 6 presents the classes and respective periods of construction chronologically.

2.4.3. Parameter P3: building position

Masonry buildings are frequently inserted in aggregates of buildings. Parameter P3 is related to the building's relative position and interaction with the adjacent neighbouring 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: post-earthquake damage observation has allowed understanding that corner and row-end buildings are generally more vulnerable than those located in the middle of the block, something that 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 7.

2.4.4. Parameter P4: number of stories

Parameter P4 is referred to the number of stories as a measure of the height of the building. The building height does affect the seismic vulnerability of the building in terms of both the drift at roof level and the potential pounding effect with adjacent buildings, as previously considered in parameter P3. Therefore, the seismic vulnerability of a building typically increases with the additional number of stories, as per Table 8.

Table 8. Classes definition for parameter P4.

Class	No. of storeys
A	1 floor
B	2–3 floors
C	4–5 floors
D	>6 floors

Table 9. Classes definition for parameter P5.

| Class	Ground plan configuration
A	Regular buildings
B	–
C	–
D	Irregular buildings

2.4.5. Parameter P5: ground plan configuration

Parameter P5 evaluates the plan irregularity on the ground floor. In the case of URM residential buildings with commercial use on the ground floor, the most common alterations through time are the replacement of the front façade masonry walls with full height glazing windows and the open plan layout area, reducing the area of internal walls. These changes create 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 classified conservatively in the most vulnerable class D, considering the significant number of buildings included in the analysis and the uncertainty of what they may represent. On the other hand, Class A represents the least vulnerable cases of regular buildings, as per Table 9.

2.5. Validation of the simplified methodology

The validity of an index-based seismic vulnerability assessment methodology that is developed for a specific building stock depends, besides the parameters that were chosen, on the weights assigned to each one, reflecting their relative importance. Such weights must be carefully assessed, either by experts' opinion or by a validation process that necessitates post-earthquake damage data, something that is not available for the Lisbon Metropolitan Area. In the absence of post-earthquake data, the validity of this methodology was assessed considering that a similar methodology has been pre-calibrated based on URM building typologies from the historical city centre of Leiria (Blyth et al. 2020), which share similar constructive and geometrical features to the LMA's unreinforced masonry building stock. An index-based methodology considering fourteen parameters was applied to a pre-calibrated original sample consisting of 103 URM buildings. The features represented in the five parameters adopted in this simplified methodology were also considered in the methodology adopted for the historical city centre of Leiria. Figure 8 illustrates the comparison of vulnerability indexes obtained with the original and the simplified vulnerability assessment approach for the URM buildings, from which a fairly good correlation was obtained, with a coefficient of determination, R^2, of approximately 0.711, which allows validating the weights assigned to the five parameters used for the 152,916 URM buildings.
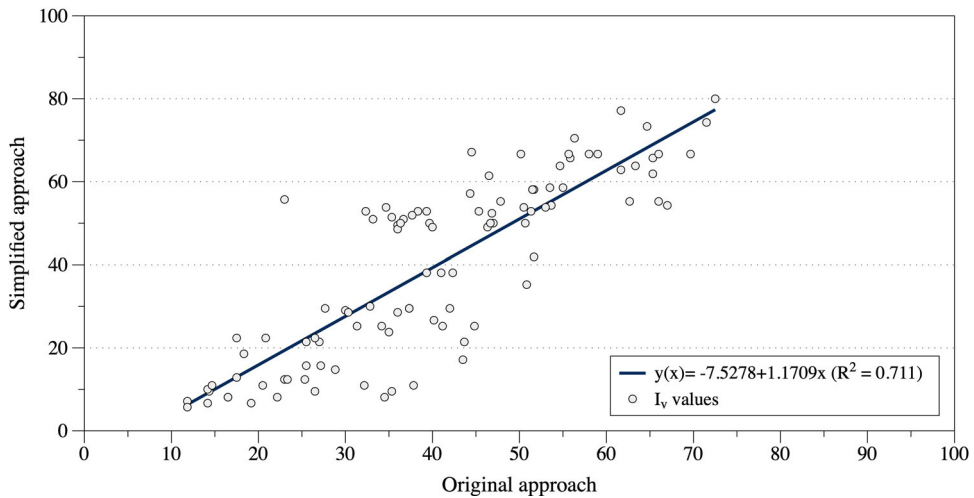
Figure 8. Correlation of vulnerability indexes between the original and the simplified vulnerability assessment approach for the URM buildings.

2.6. Implementation of a GIS tool

The volume of data originating from an analysis that incorporates the impacts of several natural hazards and is furthermore conducted at the regional scale can be significant, and thus a general planning tool is important in the decision-making process. Geographic Information Systems (GIS) can be versatile tools to store, manage and present information in an intuitive way, allowing for constructing scenarios, testing hypotheses, and drawing conclusions to get a general view of the area being analyzed.

The processing of the seismic vulnerability data and hazard results were manually inputted into a spreadsheet database to create a digital record, which was then implemented and processed using the open-source Geographic Information System software QGIS. Geo-referenced graphical data (i.e. vectorised information and orthophoto maps) and 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. Analysis of the seismic vulnerability results for the URM buildings in the LMA

The application of the seismic vulnerability methodology described earlier to the entire 152,916 URM building stock in LMA allows plotting the histogram in Figure 9, which shows the distribution of URM buildings across the Vulnerability Index ranges.

Vulnerability index values range from 14.3 to 91.4, with a mean seismic vulnerability index, $I_{v,mean}$, of 37.2, and an associated standard deviation, σ_{I_v}, of 12.8. According to the histogram in Figure 9, 47% of the URM buildings fall within the 30-40 Vulnerability index range, about 19% of the buildings have an I_v value within the range of 40-50, and 10% are distributed between 50 to 80. Once all the seismic vulnerability indices per URM building had been computed, the results were spatially
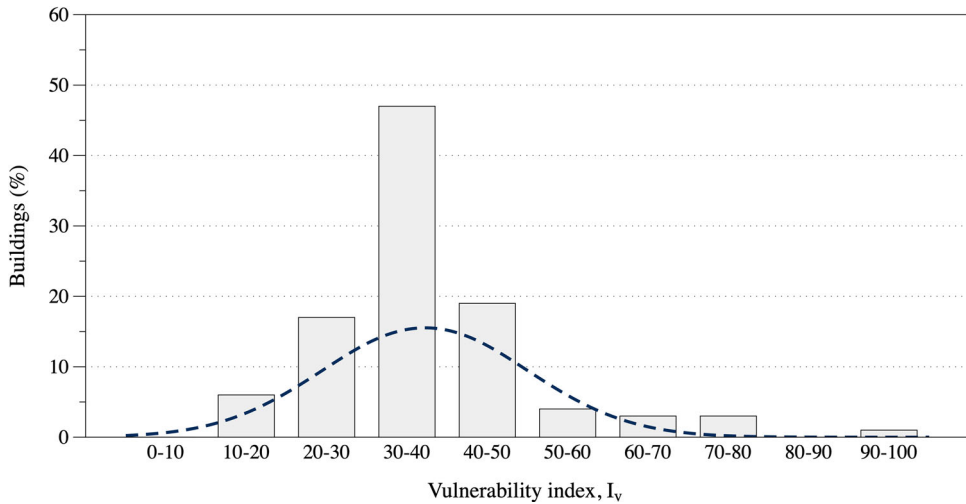
Figure 9. Vulnerability Index distribution of the URM building stock in LMA: histogram and best-fit normal distribution curve.
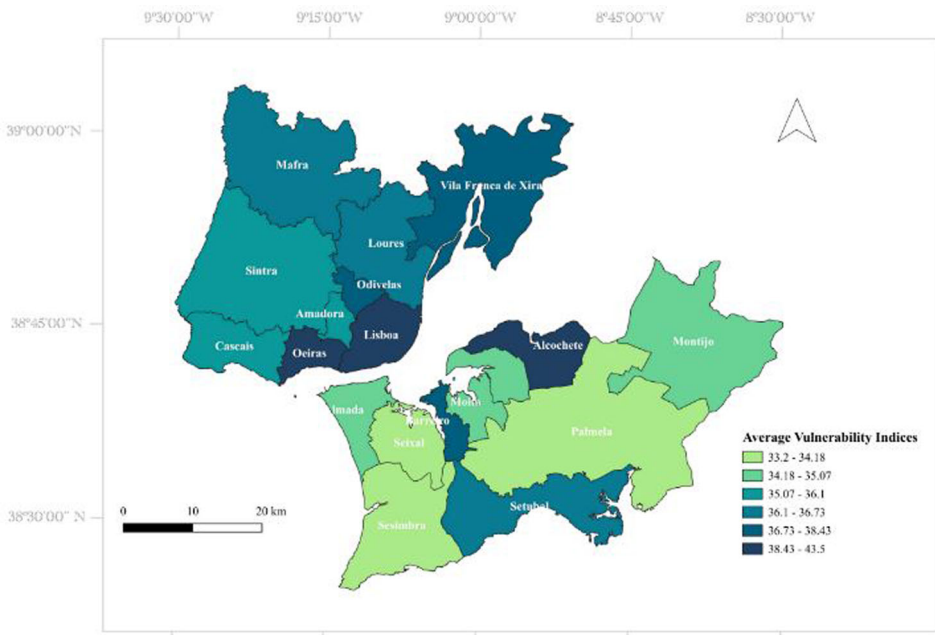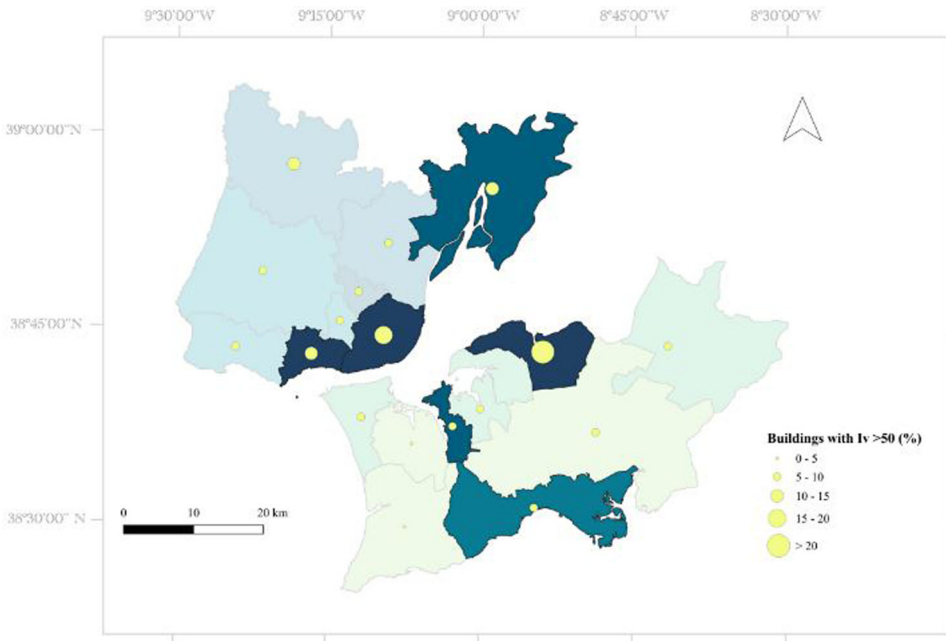

Figure 10. Distribution of the average vulnerability indices obtained per municipality for the LMA.

distributed using the GIS application software (QGIS 3.16.8-Hanover). Given the large scale of the Census building data, seismic vulnerability indices were discretized per municipality, as displayed in Figure 10.

Figure 11 shows a representative selection of the most vulnerable municipalities in what concerns the URM buildings, based on the combination of the vulnerability outputs, presented before in Figure 7, and the portion of buildings whose vulnerability index values exceed 50. This score represents a threshold for high vulnerability, as

Figure 11. Distribution of the percentage of URM buildings for vulnerability index values higher than 50 per municipality.

introduced in Section 2 and in agreement with the current practice when working with index-based vulnerability assessment approaches.

From this first analysis, six municipalities (namely Alcochete, Barreiro, Lisboa, Oeiras, Setúbal, and Vila Franca de Xira) emerge as requiring a more detailed assessment where all the factors that are contributing to this vulnerability must be carefully analyzed and understood. Taking these preliminary results into account, the municipality of Setúbal (the seat of the Setúbal District, which includes the LMA's municipalities located south of the Tagus River) is used in the following section to show the type of outputs that can be obtained from the vulnerability assessment methodology presented in this paper, as well as what kind of detailed analysis can be performed based on those. It is worth noting that, although the municipality of Setúbal does not appear to have the highest seismic vulnerability index compared to other municipalities, as per Figure 11, it has a considerable percentage of buildings (over 50%) within the 30-40 index range, as described below and illustrated in Figure 12. Also, considering that the most populated area of Setúbal city centre lies within a high seismic hazard zone (ranging from high to very high, as per Figure 3), it was deemed necessary to select this municipality and explore further its level of seismic vulnerability and risk.

4. Analysis of the seismic vulnerability results in Setúbal municipality

The seismic vulnerability index results plotted in Figure 12 provide a mean seismic vulnerability index, $I_{v,mean}$, of 36.7 and an associated standard deviation, σ_{I_v}, of 12.3, with the minimum and maximum values of 14.3 and 91.4, respectively. According to the histogram in Figure 12, about 90% of the URM buildings have an I_v value below
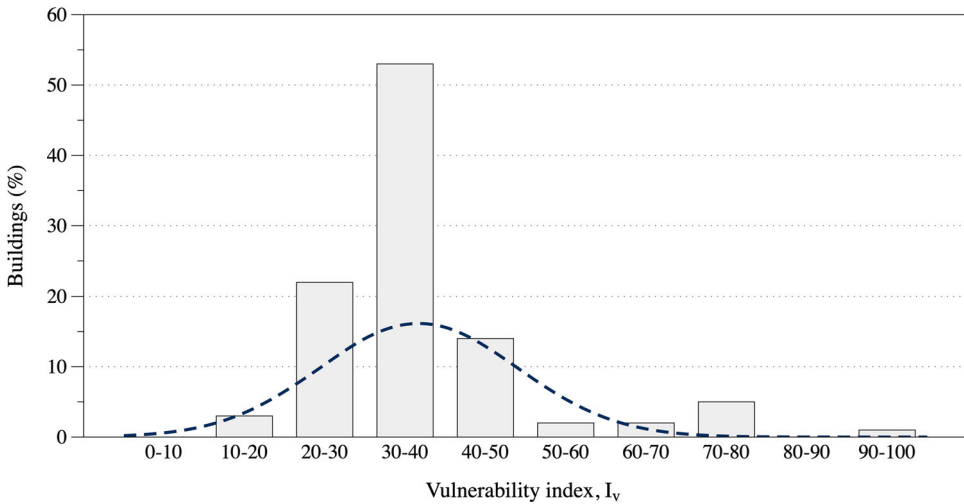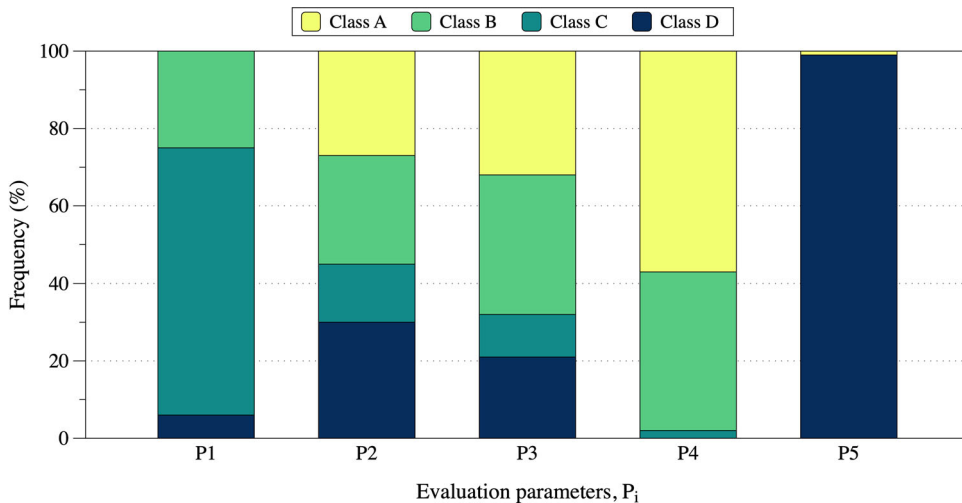
Figure 12. Vulnerability Index distribution of the URM building stock in the municipality of Setúbal: histogram and best-fit normal distribution curve.
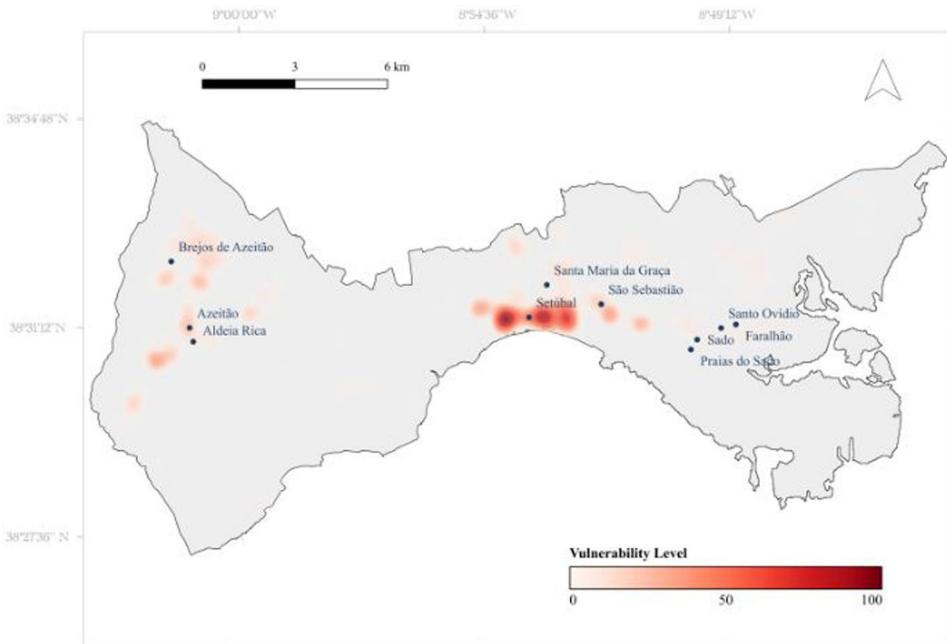
Figure 13. Heatmap of the seismic vulnerability in Setúbal municipality.

50, with 53% of buildings within the 30-40 vulnerability index range and only about 10% representing a vulnerability range above 50.

Figure 13 displays the spatial distribution of the seismic vulnerability of Setúbal municipality, highlighting the areas in which the concentration of seismic vulnerability is more significant, such as around Setúbal city, something that is expected given the concentration of buildings in this area. It is possible to identify other urban areas

Figure 14. Vulnerability class distribution of each parameter.

where the level of seismic vulnerability is also considerable but with a lesser concentration of buildings; see, for instance, São Sebastião and Brejos de Azeitão.

Figure 14 represents a combined distribution of the URM buildings based on their vulnerability classes for each of the five parameters.

From the analysis of this distribution, some important points can be made regarding the building stock's characteristics in the Setúbal municipality, namely, considering how they impact the building's seismic vulnerability.

Regarding the structural system, 75% of the buildings are classified in the two most vulnerable classes, with 69% corresponding to 'placa' buildings (Class C), and 6% to adobe or rubble masonry buildings (class D, the most vulnerable). URM buildings with timber floors, assigned to class B (which is the least vulnerable of the classes considered), account for 25% of the URM buildings.

As regards the period of construction, buildings dated before 1945 (Class D) represent 29% of the building stock, and those constructed between 1945 and 1960 (Class C) account for 15%. From this, it can be concluded that a significant portion (almost half) of the URM building stock in the Setúbal municipality was built before the publication of the first Portuguese seismic code, enacted in 1958. The remaining portion (55%) was built after the 1960s, with an almost identical distribution for the mid-code (1958-1983) and post-code (after 1983) periods, with 28% and 27%, respectively.

On the subject of the buildings' position within the aggregate, reflected by Parameter P3, buildings in the two most vulnerable classes account for almost one-third of the building stock (vulnerability class D buildings accounts for 21% of the buildings, while 'Classic' buildings represent 11%). The other 68% of the buildings present a roughly similar distribution, with 'isolated' (class B) buildings accounting for 36% and 32% classified as 'row/terraced' buildings (class A).

In what concerns the number of stories (Parameter P4), more than half (57%) of the buildings are assigned to the least vulnerable class (class A), as they have only one floor and are thus considered low-rise buildings. Another significant portion (40%) of the buildings have two or three floors and thus are mid-rise, which are
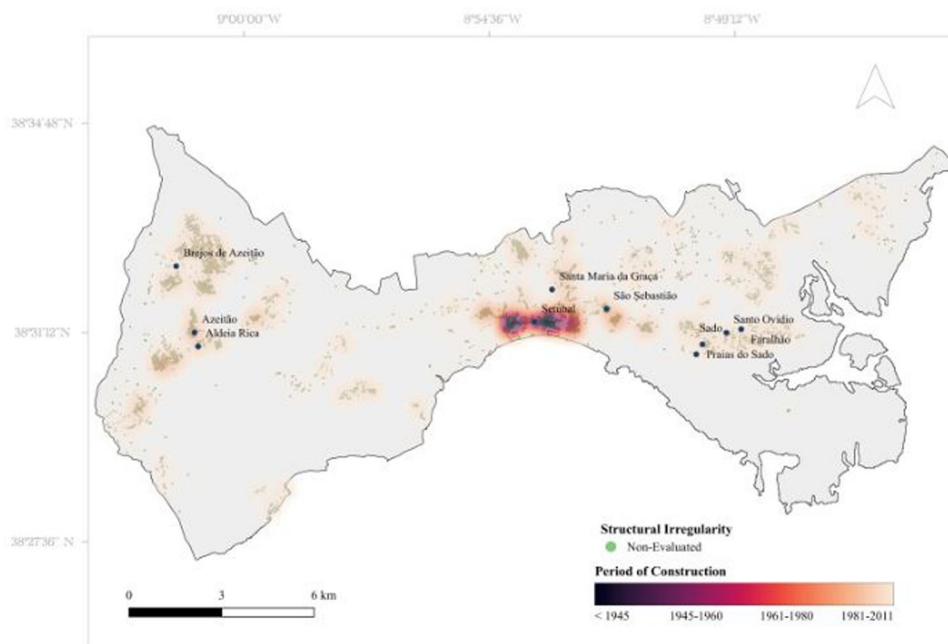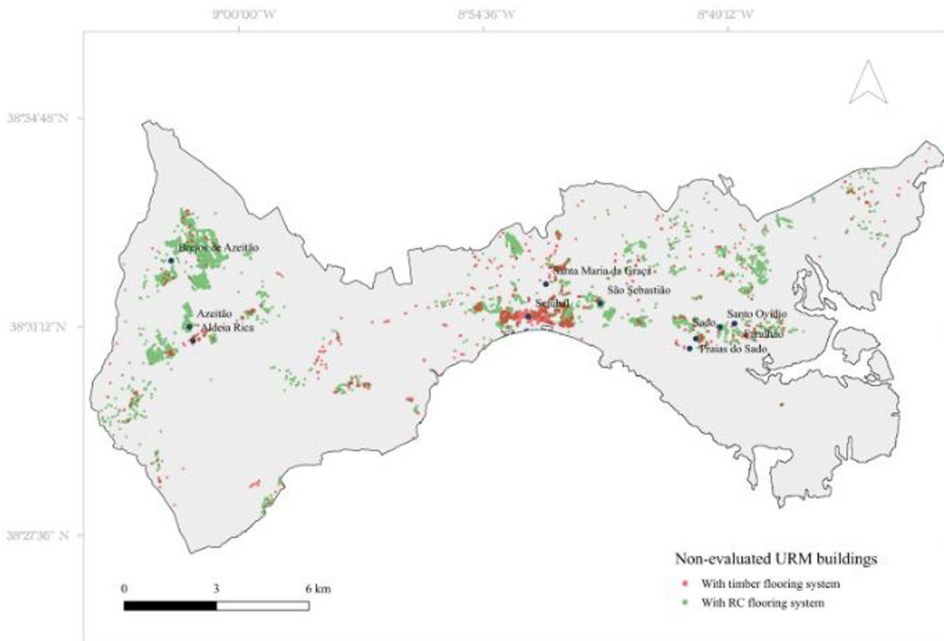
Figure 15. Spatial distribution of the 'non-evaluated' buildings with the period of construction.

assigned to vulnerability Class B). Buildings with four or more floors (representing Classes C and D) account for just 2% of the building stock. In short, and considering the number of stories, it can be said that the URM buildings in the Setúbal municipality pose a low seismic vulnerability.

As to the structural irregularity due to the ground plan layout (Parameter P5), by far the larger portion of buildings (99% of the building stock) are assigned to Class D, the most vulnerable, with the remainder 1% in the least vulnerable class (A). When analyzing the P5's distribution in further detail, it is possible to observe that the buildings assigned to class D correspond both to 'irregular' (6%) and to 'non-evaluated' buildings (93%). By and large, and in what concerns the building appraisal related to structural irregularity adopted in this methodology, URM buildings in the Setúbal municipality display a significant seismic vulnerability.

Considering the above-mentioned distribution, and with a view to identifying the nature of 'non-evaluated' buildings, Figures 15 and 16 illustrate the distribution of these 'non-evaluated' URM buildings against the backdrop of the period of construction and the structural systems.

Therefore, based on Figure 15, it is evident that the older URM buildings (i.e. prior to 1960) are mostly found in the centre of Setúbal city, which is expected to be historically the older settlement. The majority of the 'non-evaluated' buildings relate more to those built after 1960, which, according to parameter P2 described above, represent the majority (55%) and are categorized in Class B and A as less vulnerable than the older ones. Hence, considering the age group that the 'non-evaluated' buildings represent, it could be argued that classifying them into Class D (of Parameter P5) may be slightly over-conservative for a certain portion in the case of Setúbal.

Figure 16. Spatial distribution of the 'non-evaluated' buildings with the structural systems.

According to Figure 16, regarding the main URM building typologies in relation to the 'non-evaluated' buildings, it can be concluded that the traditional URM buildings with the timber floor relate to the older form of URM typology (together with adobe/rubble masonry), which is typically found in the older historical centres (like in the main Setúbal city). Consequently, the younger URM typology with concrete slabs (i.e. placa buildings) replacing the original timber flooring systems spreads beyond the main historic centres covering the remaining URM buildings within the municipality. In that respect, based on the dominant 'URM with placa' typology, it can be said that the 'non-evaluated' buildings represent the most vulnerable typology and would be fair to rank those in Class C or D (for parameter P5).

Essentially, both of these aspects (i.e. period and structural systems) provide an indication of the expansion of built and populated areas and development of construction systems over time. Having the majority (69%) of the URM buildings being the 'URM with placa' buildings with their inherent increased vulnerability of poor structural connections of the concrete floor into the masonry walls, they end up affecting the overall seismic vulnerability of URM typology.

5. Analysis of the seismic risk results in Setúbal municipality

As previously described in Section 2, the seismic hazard and the vulnerability results, as first-order outputs, are combined to get the risk assessment results of Setúbal municipality. The spatial distribution of the second-order analysis from that integration is illustrated in Figure 17, highlighting the different range of risk levels across the Setúbal
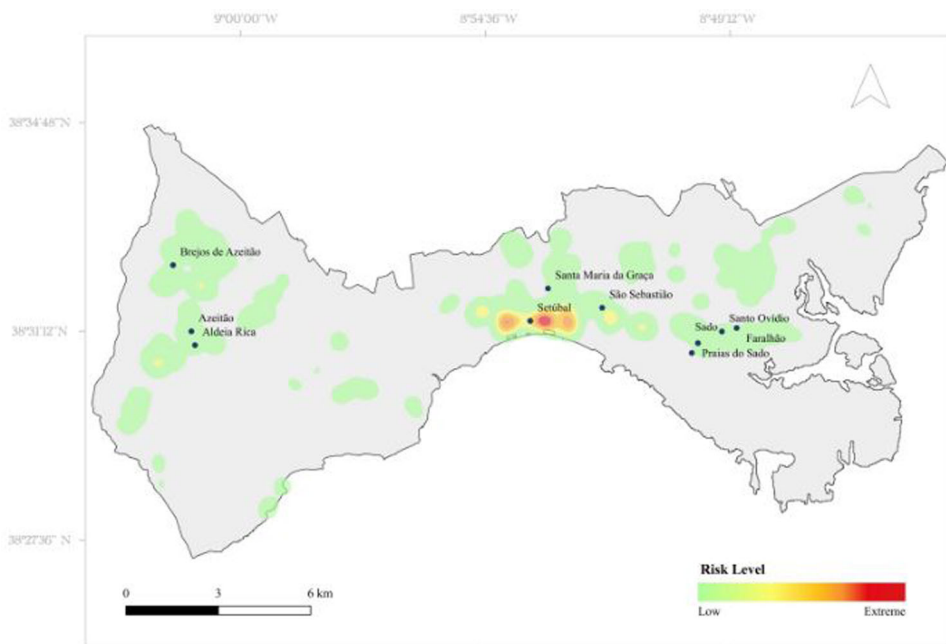
Figure 17. Spatial distribution of the risk analysis for the URM of Setúbal municipality.
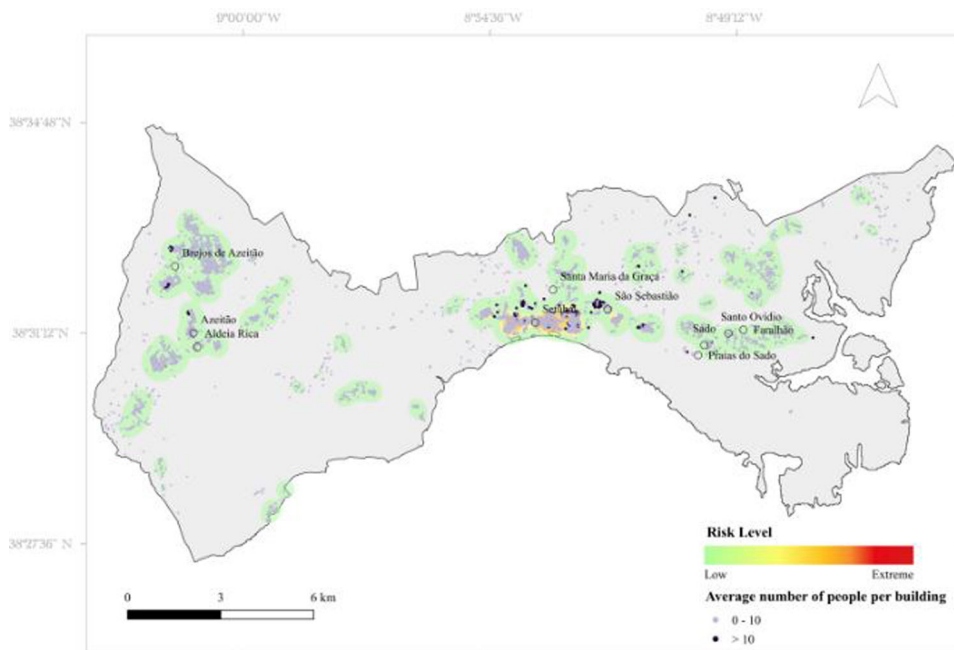

Figure 18. Spatial distribution of the population in Setúbal municipality.

municipality with the least and most risky areas or cities. Based on the methodological framework described in Section 2 and particularly on the risk matrix approach, it is worth confirming the spatial interaction of the hazard and the vulnerability output

levels. In particular, although Setúbal municipality is mostly at 'high' and 'very high' seismic hazard (see Figure 3), the areas of 'low' seismic vulnerability (given in Figure 13) ended up resulting in 'low' to 'moderate' risk levels, as per Figure 17.

Another worth mentioning result is the correlation between the risk output and the population distribution. Figure 18 shows the average population distribution per building across the Setúbal municipality in relation to the risk levels.

Hence, it is apparent from Figure 18 that the most populated towns are mostly related to areas of moderate to very high or extreme risk levels. This realization becomes of particular interest and priority to risk mitigation plans to ensure the preparedness and resilience of the most affected communities.

6. Conclusions

The seismic vulnerability assessment methodology presented in this paper allowed identifying not only the most seismically vulnerable areas within the Lisbon Metropolitan Area but also the spatial distribution and correlation of building parameters, which affect and contribute to the estimation of vulnerability index results. In the case of Setúbal, it could be argued that the assignment of 'non-evaluated' buildings regarding their structural irregularity to Class D (in Parameter P5) might be partly a conservative approach, overestimating the overall vulnerability index outcome. Therefore, it is recommended to refine further any uncertainties related to building characteristics inherent in the 2011 Census survey data with some carefully planned fieldwork focusing on specifically highly vulnerable and risky areas, as highlighted above, together with the most vulnerable building typology (i.e. the URM with 'placa' buildings). Hence, any additional fieldwork would lead to a more detailed and robust database of the building vulnerabilities and could even allow re-evaluating the associated parameters' weights on the vulnerability index estimation.

The work presented in this paper is part of a larger project aiming at developing an integrated risk assessment framework for measuring the impacts of multiple natural hazards in urban areas and is based on a comprehensive analysis of their direct and indirect interrelations and consequences. Such a framework is intended to constitute a useful decision-support tool, providing a singular standardized metric to accurately measure aggregated urban risks and investigate the potential impact of pre- and post-disaster strategies. Despite any uncertainties on the available data that need to be refined and enriched, it is evident that the great advantage of this vulnerability index-based methodology is the fairly quick identification of the most vulnerable areas at the urban scale of the LMA. This simplified approach can easily provide decision-makers and planners valuable information for the higher risk areas, cities/towns, or even blocks of buildings (depending on the scale of the assessment carried out and the available data) on which retrofitting measures can then be carried out making the buildings and population more resilient and prepared towards future natural hazard events.

The methodologies applied here for the seismic vulnerability and risk assessment will also be developed and applied to assess flood, landslide, and fire vulnerability. Ultimately, this will allow for the creation of a multi-hazard framework, which local

emergency and risk mitigation planners can then utilize to reduce the impact of any natural hazards on vulnerable communities.

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Data availability statement

The data that support the findings of this study are available from the corresponding author.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Maria Xofi 🄳 http://orcid.org/0000-0002-4703-0659
José Carlos Domingues 🄳 http://orcid.org/0000-0002-7934-3756
Pedro P. 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
Tiago Miguel Ferreira 🄳 http://orcid.org/0000-0001-6454-7927

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