On the Multi-hazard Risk Assessment of Urban Areas: Identification and Analysis of Exposure and Physical Vulnerability Indicators

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Abstract. The development of integrated decision-support tools, able to assess multiple hazards at the regional and local scales, is a fundamental step to enhance the preparedness of urban areas to mitigate present and future risks arising from climate change. Understanding multi-hazard risk can help prioritize resilience-increasing actions and disaster prevention measures and form the basis for exploring institutional adjustments that improve stakeholders' capacities to manage risk. Within this framework, the present research work aims to identify and analyze a set of exposure and buildings' vulnerability indicators to be used as input to a multi-hazard risk assessment methodology. Exposure is to be measured using a dimensionless score resulting from the quantitative identification of the elements at risk. Regarding the physical vulnerability of buildings, it is to be evaluated on a hazard-by-hazard basis using a large-scale parametric-based vulnerability assessment approach. Finally, the obtained exposure and physical vulnerability indicators are to be put together in order to create different data layers, which are then used to identify hotspot risk areas. The Metropolitan Area of Lisbon, Portugal, is used as a pilot study area to discuss the applicability and potential of the proposed indicators.

Keywords: Urban risk · Vulnerability assessment · Exposed elements · Seismic hazard

1 Introduction

The potential impact of multi-hazard events on urban areas, i.e., events that include more than one natural hazard with interrelationships between the hazards that impact the same

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location during the same time period, is, by definition, much more significant than the impact of a single hazard, making emergency response mechanisms 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. Hence, and given the increase in urbanization, it is essential to develop integrated risk assessment frameworks for measuring, managing, and mitigating the impacts of multiple natural hazards in urban areas.

Among the several natural hazards that in the past few decades have caused damages both to the building stock and infrastructure systems, as well as economic and human losses, earthquakes have been the most catastrophic ones.

The work reported in this paper aims to create a risk assessment framework for measuring impacts of multi-hazards in urban areas such as the Lisbon Metropolitan Area (LMA) 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, to finally obtain the risk hotspots areas, addressing the linkage between the building typologies and the respective physical vulnerability. The validated seismic vulnerability results and the seismic hazard components are 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 deals only with a single-hazard analysis (seismic), it establishes a simplified common methodology that can be applied to other natural hazards (such as floods and landslides) and will enable the creation of a framework for multi-hazard scenarios.

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 & Santos [1], including, besides a vulnerability and a hazard module, an exposure-related component.

The hazard level is obtained by combining three aspects: the maximum likely seismic intensity, PGA, and the geotechnical characteristics of the foundation soil. Considering a long-term time scale, it is the less dynamic component of the assessment.

The exposure is considered here based on the identification of the elements at risk, namely buildings and population. The various building typologies presented in the LMA are characterized, as is the number and the distribution of the population over the 3,015 km^2 that compose the LMA, see Subsect. 2.1.

The level of the physical vulnerability 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 level of vulnerability of the building. Further details about the vulnerability assessment methodology can be found in Subsect. 2.2, and some representative vulnerability outputs obtained for the LMA are presented and commented in Sect. 4.

Seismic risk is then computed using the vulnerability-hazard matrix presented in Table 1, which combines the hazard and vulnerability results obtained using the above-described approaches.

Table 1. Seismic risk matrix.

Seismic Risk		Hazard			
		Low	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

2.1 Identification of the Exposed Elements (Buildings and Population)

With 18 municipalities, 211 parishes, and near 2,813,000 inhabitants [2], the Lisbon Metropolitan Area (LMA) is the largest urban area in Portugal. According to the 2011 Census, the building stock in the LMA comprises 449,573 buildings spatially distributed by the 18 municipalities, as illustrated in Fig. 1. From these 449,573 buildings, 65% correspond to Reinforced Concrete (RC) structures and 34% to Unreinforced Masonry (URM) structures. The distribution of these two structural typologies within each one of the municipalities of the LMA is also provided in Fig. 1.

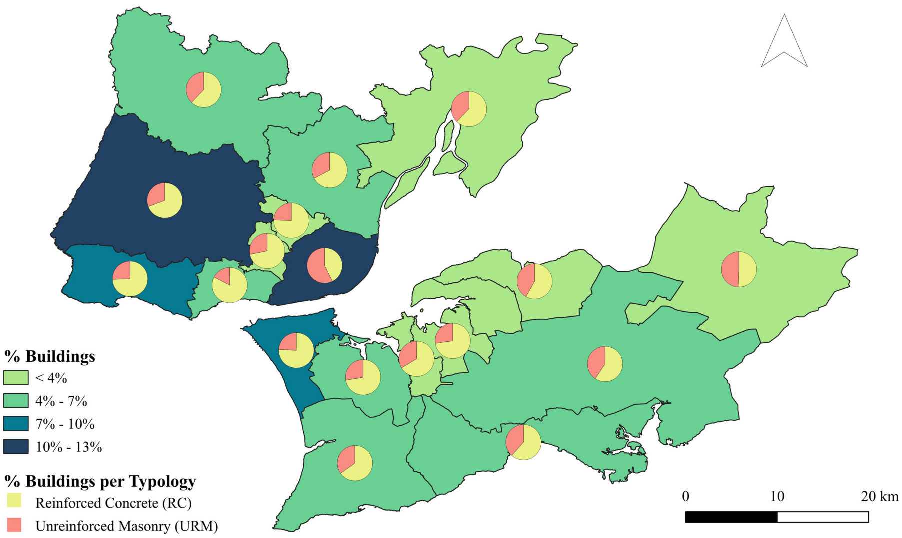

Fig. 1. Distribution of building stock and typologies per municipality.

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 [3, 4]:

- '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 (see Fig. 2, on the left).
- '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 in shape window openings (see Fig. 2, 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 (see Fig. 3, on the left).
- '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 (see Fig. 3, on the right).

Fig. 2. Unreinforced masonry buildings in the Lisbon Metropolitan Area: 'Pre-Pombalino' buildings (on the left) and 'Pombalino' buildings (on the right).

Fig. 3. Unreinforced masonry buildings in the Lisbon Metropolitan Area: 'Gaioleiro' buildings (on the left) and 'Placa' buildings (on the right).

Regarding the resident population in the LMA, its distribution is presented in Fig. 4. The distribution of the resident per building typology (URM and RC) is also provided in the figure. As can be observed in Fig. 4, 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 near 57%.

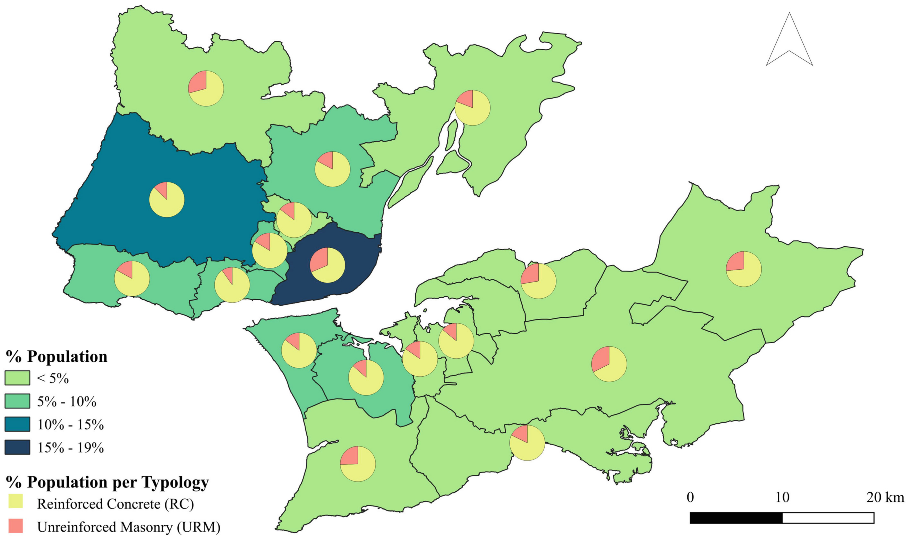

Fig. 4. Distribution of population per municipality and building typology.

2.2 Characterization of the Physical Vulnerability of the Building Stock

According to several authors [5–7], the selection of seismic vulnerability assessment methods 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) used. When dealing with a large number of buildings over a national or urban scale, the resources and quantity of information required are significant, and so the use of less sophisticated techniques or tools is more practical and necessary. Thus, methodologies for vulnerability assessments at a large scale should be based only on a few parameters, some of empirical nature.

The vulnerability index formulation applied in this work is based on the GNDT II level approach [8] 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. The seismic vulnerability methodology is based on post-earthquake damage observation and survey data covering several structural elements, which focuses on the most important aspects that define building damage, translated into a few parameters of empirical nature. It was 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 [9].

As in 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. 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}) of A, B, C and D, and are associated with a weight (p_i) that defines the relative importance of each parameter to the overall seismic vulnerability of the building.

The current methodology was explicitly tailored to be fed by the Portuguese 2011 Census data survey, which subsequently constituted the basis for selecting the adopted parameters. Therefore, the following parameters in Table 2 were identified.

Table 2. Building parameters with vulnerability classes and weights.

Parameters		Classes C_{vi}				Weight
		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 storeys	0	5	20	50	0.5
P5	Ground plan layout	0	–	–	50	0.5

A total vulnerability index, I_v^*, is calculated using Eq. (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 then normalized to range between 0 and 100, assuming from that moment on the notation.

The parameters that mostly influence the seismic vulnerability of the URM buildings 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 parameter weights corresponding to the above mentioned are 2.5 and 1.0, 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.

3 Analysis of the Physical Vulnerability Results

Based on the methodology described earlier in Subsect. 2.2, once all the seismic vulnerability indices per URM building have been computed, the results were spatially distributed using the GIS application software (QGIS 3.16.8-Hanover). Given the large scale of the Census building data, the physical vulnerability results were discretized per municipality, as displayed in Fig. 5.

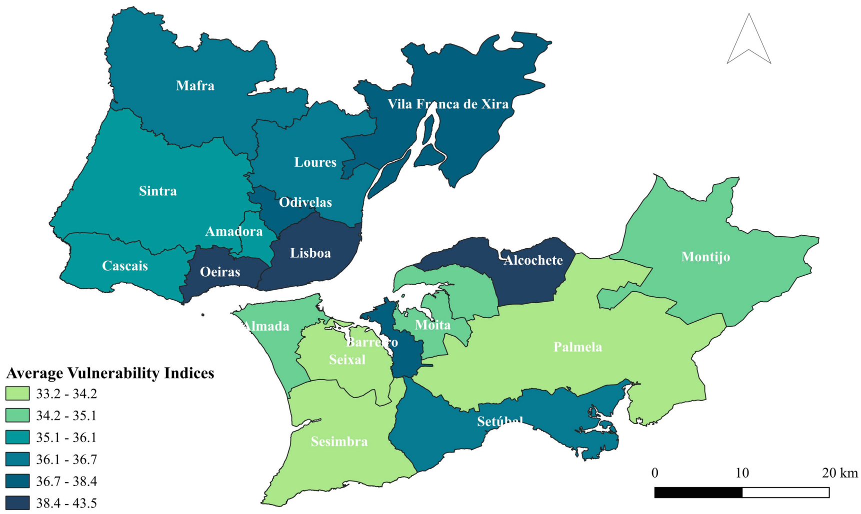

Fig. 5. Distribution of the average vulnerability indices obtained for the LMA municipalities.

Then, a representative selection of the most vulnerable municipalities related to the URM building typology was carried out based on the combination of the vulnerability outputs presented in Fig. 5 and the analysis of the portion of the buildings within the municipality whose vulnerability index value exceeds 50, given in Fig. 6.

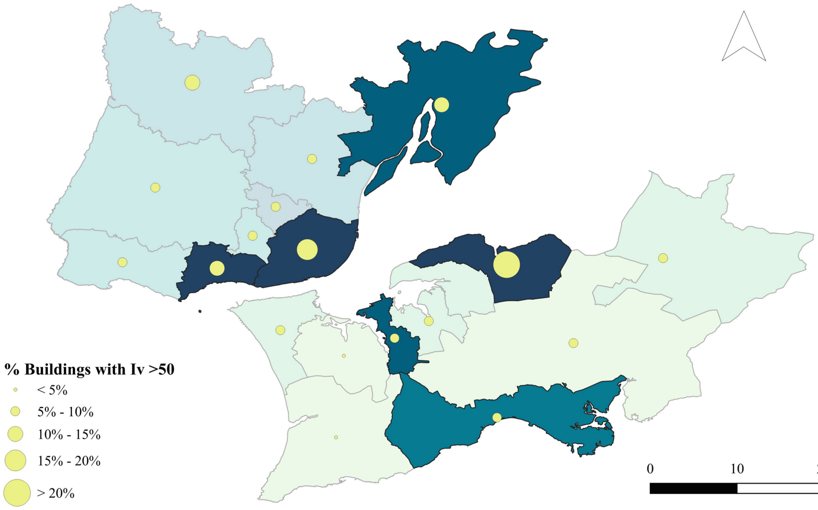

Fig. 6. Distribution of the percentage of URM buildings within the LMA municipalities with vulnerability index values higher than 50, with the identification of the six municipalities identified as the most vulnerable.

The six municipalities flagged in this first stage of analysis, namely Alcochete, Barreiro, Lisboa, Oeiras, Setúbal, and Vila Franca de Xira, should be therefore subjected to a more detailed assessment where all the factors that are contributing to this vulnerability must be carefully analyzed and understood. An example of this is provided in Fig. 7, where the spatial distribution of the physical vulnerability of Setubal municipality is displayed, highlighting with red color the areas in which the concentration of physical vulnerability is more significant.

As can be concluded from the observation of Fig. 7, most of the physical vulnerability hotspots identified in the municipality of Setubal are concentrated around Setubal city, a result that was already expected since this area concentrates most of the buildings. Despite that, it is possible to identify other urban areas where the level of physical vulnerability is also meaningful, such as São Sebastião and Brejos de Azeitão.

4 Final Remarks

The great advantage of this approach is the identification of the most vulnerable areas within the LMA, providing decision-makers and planners with valuable information for the higher risk areas, cities/towns, and even blocks or buildings (depending on the scale of the assessment carried out) on which retrofitting measures can be carried out.

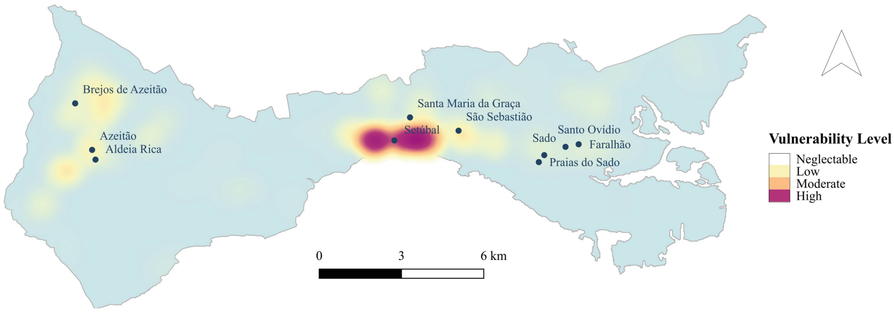

Fig. 7. Distribution of the physical vulnerability in Setúbal municipality.

As to the uncertainty inherent in the assignment of the vulnerability classes to each building parameter with the associated weights, it might be overcome (or reduced) with additional fieldwork, gathering detailed site information on specific building categories and locations of medium to high hazard levels.

In future work, it is recommended to refine further any uncertainties regarding unknown building characteristics from the 2011 Census data with carefully planned fieldwork focusing on specifically high vulnerable and risk areas with the most vulnerable building typologies. This would lead to a more detailed and robust database of the building vulnerabilities and possibly even to re-evaluate the parameters' weights.

The work presented in this paper is a part of a larger project aiming at developing an integrated risk assessment framework for measuring impacts of multiple natural hazards in urban areas, based on the 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 measure aggregated urban risks and to accurately investigate the potential impact of pre and post-disaster strategies. Accordingly, this project will contribute to improving the protection of vulnerable communities to the impact of natural disasters.

The methodologies applied here for the seismic vulnerability 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 can then be utilized by local emergency and risk mitigation planners to reduce the impact of any natural hazards to the most vulnerable communities.

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