18TH WORLD CONFERENCE ON EARTHQUAKE ENGINEERING
WCEE2024
MILAN

MILAN, ITALY
30TH JUNE - 5TH JULY 2024

www.wcee2024.it

A MULTI-HAZARD MODEL FOR THE CITY OF LISBON, PORTUGAL

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Abstract: *In recent decades the topic of exposure to natural hazards has gained prominence due to the rise in natural and man-made disasters that might particularly damage urban areas. Population growth, urbanization and climate change are just a few of the reasons that have led to an increase in catastrophes, as well as increased community awareness of the issue. To effectively mitigate these phenomena, it is required a comprehensive assessment of the various hazards that often affect a region. The relevance of the topic is contained in the international development agenda concerning the assessment of multi-hazard risks as one of the guiding concepts in the Sendai Framework 2015-2030, therefore several approaches for assessing vulnerability and risk have been presented throughout the years. However, the majority of them only analyse one hazard at a time, and there are currently few approaches that examine many threats at the same time. Disaster mitigation plans must thus consider all the hazards as a whole to preserve the built environment and reduce both economic and human losses. The current study aims to propose a multi-risk model for the city of Lisbon, which, like many other cities throughout the world, faces several threats that endanger its population, infrastructure, and economy. To limit these risks and build effective disaster response plans, a comprehensive multi-risk assessment that accounts for earthquakes and floods has been evaluated. To achieve these results, the proposed study utilised satellite remote sensing technique data and GIS tools to obtain a spatial distribution of the elements at risk. Flood and earthquake vulnerability have been evaluated for every building in the study area and damage scenario has been assessed for each return period. For the evaluation of seismic vulnerability, the Risk-UE method has been applied while for the flood vulnerability assessment, a complex hydrological model for rainfall scenario was considered. Furthermore, the expected losses have been estimated and combined for a multi-risk evaluation. This process enables the city's most vulnerable areas to be prioritised. The main outcomes gained constitute a significant step forward in the implementation of community preparedness programmes, as well as the adoption of appropriate urban mitigation strategies that account for potential hazards to increase cooperation between responders and local authorities.*

Keywords: Multi-hazard, Multi-vulnerability assessment, Seismic vulnerability, Flood vulnerability, Damage scenario, Loss estimation.

1. Introduction

1.1. State of the art

The issue of natural hazard exposure has grown in importance in recent decades, not only because humans are more aware of it, but also because some phenomena, such as population growth, uncontrolled urban development, poor multi-level governance and climate change have contributed to the increased frequency and severity of disasters (Javadinejad et al., 2019; Julià & Ferreira, 2021). Climate change has been observed for several decades, and the consequences are proving to be disastrous for communities. Human activities, the primary cause of this phenomenon, have significantly increased greenhouse gas emissions, resulting in a large rise in the global average temperature. It is predicted that by 2100, the Earth's temperature will rise by 1° to 5°, causing serious problems such as water scarcity, landslides, floods, heat waves and fires (Sesana et al., 2018; Javadinejad et al., 2019). In the years 2005-2015, more than 1.5 billion people were affected by natural disasters: more than 700.000 lost their lives, 1.4 million were injured, and about 23 million lost their homes plus other people who were affected in other ways by these catastrophes (UNISDR, 2015). For these reasons the UN Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015), emphasised the need for understanding, assessing and managing risks in exposed urban areas (UNISDR, 2015; Julià & Ferreira, 2021). The concept of risk, defined as "*the combination of the probability of an event and its negative consequence*" (UNISDR, 2009), is made by the composition of three terms: hazard, vulnerability and exposure (Grünthal et al., 2006). According to the same UN Sendai statement, risk must be minimised through an evaluation of vulnerability and exposure to various hazards, specifically referring to the concept that risk reduction practises must be as "*multi-hazard and multisectoral*" as possible. Indeed, among the guiding concepts contemplated, point (g) reiterates that the "*multi-hazard approach*" is the foundation for an effective Disaster Risk Reduction, DDR, (UNISDR, 2015).

Since risk mitigation has become an increasingly essential matter of focus, several approaches for assessing vulnerability and risk have been presented throughout the years. However, the majority of them only analyse one hazard at a time, with fewer approaches that examine many threats at the same time, especially when it regards historical city centres (Kappes et al., 2012; Ciurean et al., 2018; Arrighi et al., 2022). This is because the topic is still challenging to develop because of the technical understanding and expertise necessary, the significant financial investment required, as well as the difficulties in assessing vulnerability and losses that may arise due to different metric systems and process characteristics for each hazard. These concerns are exacerbated in historic city centres, where the complexity of the built environment emphasizes the difficulties of the conservation objective (Kappes et al., 2012; Julià & Ferreira, 2021; Arrighi et al., 2022). The topic is very complex since multi-hazard analyses are more than the sum of the individual hazards examined and the total level of risk may be affected by hazard interrelations that result from the spatial and temporal overlap of multiple hazards (Kappes et al., 2012; Tilloy et al., 2019). As a result, developing a standardised technique that takes into consideration the many possibilities of hazard interactions is still scarce (Kappes et al., 2012). To overcome this issue, some authors (Gallina et al., 2016; Gill & Malamud, 2016; Tilloy et al., 2019) have also tried to clarify the terminology about a multi-hazard topic. According to (Gill & Malamud, 2016) the term "*multi-layer single-hazard*" refers to the independent examination of different hazards over an area, as well as to the identification of areas where different hazards overlap, while the term "*multi-hazard*" should consider the relationships between the various hazards rather than just overlapping them. (Gallina et al., 2016) distinguish the two concepts of "*multi-hazard*", when two or more hazards overlap geographically or temporally and "*multi-vulnerability*", i.e. when an asset can exhibit a different vulnerability degree to different hazards or when the vulnerability changes over time. These two concepts are elements within the broader framework of "*multi-risk*". In this framework, each hazard is individually analysed for exposure and vulnerability, and these analyses are then integrated into a comprehensive assessment that considers all potential hazard-vulnerability interactions.

Due to the complexity of the problem, some literature reviews on multi-hazard methodologies have been carried out, contributing to creating a general framework for the multi-hazard context (Kappes et al., 2012; Gallina et al., 2016; Ciurean et al., 2018; Tilloy et al., 2019; Julià & Ferreira, 2021). Methodologies can be classified using a different conceptual framework depending on the actual state of the art. For example, the classification proposed by (Ciurean et al., 2018) divides methodologies into qualitative (De Pippo et al., 2008; Karatzetzou et al., 2022), semi-quantitative (Araya-Muñoz et al., 2017; Pilone & Demichela, 2018), and quantitative (Chen et al., 2016; Nishino, 2023). However, the subdivision proposed by (Kappes et al., 2012) classifies the various methods according to the evaluation phase of the multi-risk assessment: multi-hazard analysis (El Morjani et al., 2007; Barrantes, 2018), vulnerability to multiple hazards analysis (Zuccaro et al., 2008; Xu et al., 2021) and multi-hazard risk analyses (Grünthal et al., 2006; Tocchi et al., 2023).

The preservation of historical city centres is considered an essential matter of interest due to the tangible and intangible values such as historical, social, identity, and economic worth that are widely understood and recognised. Indeed, city centres must be safeguarded because of their historical relevance, social identity, and economic value to communities. In this view, risk assessment is an essential step towards reducing economic and human losses, as well as preserving historic centres and their immaterial significance (Sesana et al., 2018; Arrighi et al., 2022). The present study aims to provide a multi-risk assessment approach for Lisbon's historic city centre, taking earthquake and flood hazards into account. The case study assesses the vulnerability and risk of ordinary unreinforced masonry buildings (URM) in an important historical area of the case study area, namely Baixa Pombalina. Firstly, the exposure model was developed through remote sensing techniques and integrated into the GIS tool. Then seismic and flood vulnerability has been properly evaluated considering the Risk-UE method and flood state-damage curves available in the literature. A multi-risk assessment was carried out, which included an evaluation of building economic losses to evaluate the expected financial implications.

1.2. Study area

The vulnerability and risk assessment in a multi-hazard context is developed for a subsector of the historical city centre of Lisbon, prone to different hazards. Lisbon, as a historically vulnerable city, has consistently been exposed to a variety of risks throughout time, as addressed in the following chapter (refers to § 2). Lisbon is situated in the south part of the country on the right side at the estuarine of the Tagus river and it has a total land area of 100.1 km^2, with Earth's surface of 86.43 km^2, subdivided into 24 parishes. The population count of 545.796 inhabitants (291.617 women and 254.179 men), with a total number of 49.223 buildings, according to 2021 Census data (Instituto Nacional de Estatística, IP - Portugal, n.d.).

The case study specifically focuses on the Baixa Pombalina area (Figure 1), the downtown region of Lisbon located between the Rua Nova do Almada (West), Praça Dom Pedro IV and Praça da Figueira (North), Rua da Madalena (Est) and Praça do Comércio (South).

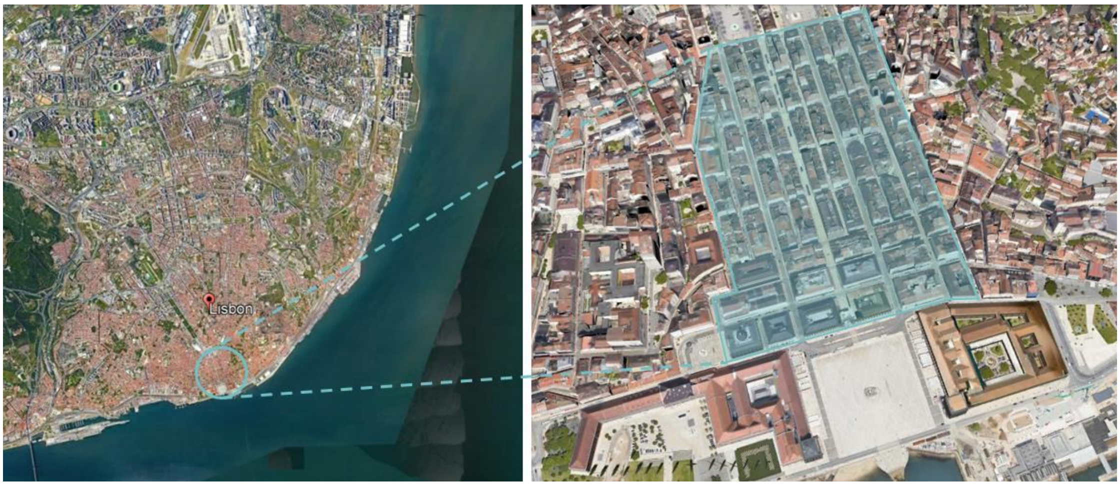


Figure 1. The case study area: Baixa Pombalina (Lisbon). Adapted from (Google Earth, n.d.).

The aforementioned area consists of 393 ordinary buildings erected in aggregate conditions. The selected urban sector is indicative of the ancient city centre of Lisbon, which is recognised to be very vulnerable to many threats due to the presence of ancient masonry buildings and the coastal setting along the Tagus River. The features of this part of town make Lisbon a tourist attraction, where visitors may learn about the cultural identity and history of the city (Martins et al., 2018), which is a recognised heritage that should be preserved. As confirmation of the area's relevance for Lisbon, the comprehensive historical conservation plan Plano de Pormenor de Salvaguarda da Baixa Pombalina (PPSBP) was implemented in 2011, as reported in (Barchetta et al., 2023). The majority of buildings in this area are unreinforced masonry buildings (URM) built according to the "Pombalino" style (82% of the cases), and many others in reinforced concrete, RC, (18% of the sample) as a result of interventions throughout the years. The occupancy is predominantly mixed, with commercial activities on the ground floor and residential functions on the upper floors (Barchetta et al., 2023).

The Baixa Pombalina neighbourhood is one of the most iconic areas of the Lisbon earthquake of 1st November 1755, because this part of the city was entirely devastated by this event followed by tsunami and fires (Martins et al., 2018; Catulo et al., 2018). Following this disaster, under the direction of the Marquis of Pombal, all of the destroyed buildings were rebuilt (Catulo et al., 2018; Martins et al., 2018). The Pombaline reconstruction was distinguished by the introduction of “Pombalino”, a building type characterised by its robustness, regularity and uniformity (Bernardo et al., 2021; Barchetta et al., 2023). The “Pombalino” structures marked the introduction of specific structural peculiarities aimed at improving their seismic performance. Indeed, the structural system called the “Pombalino cage”, in Portuguese “Gaiola Pombalina”, consists of a set of internal walls, called “frontal” walls, with a three-dimensional timber structure forming a triangular geometry filled with poor quality masonry, that are connected with the orthogonal walls by vertical studs in the corners. Together with the timber floors the structure ensure the bracing of exterior stone masonry walls and the resistance to forces in any direction (Barchetta et al., 2023; Bernardo et al., 2021; Catulo et al., 2018).

2. Hazard

Hazard is a potential threat that can cause economic, social, and environmental loss (UNISDR, 2009). The city of Lisbon has already experienced multiple hazards including earthquakes and floods. Lisbon's seismic risk indicates a moderate to high earthquake magnitude (Bernardo et al., 2021); furthermore, due to its coastal location, Lisbon is prone to flooding risk, as demonstrated by the devastating event in 1967 (Trigo et al., 2016).

1.3. Earthquakes

The tectonic activity in the Lisbon region significantly influences the seismic risk faced by the city, since it is situated on the Eurasian plate near the boundary with the African plate. This hazard primarily results in very large offshore earthquakes and moderate to large onshore earthquakes (Bernardo et al., 2021; Vilanova & Fonseca, 2007). According to (Vilanova & Fonseca, 2007), the mean hazard map for the whole of Portugal shows PGA values in rock ranging from 0.05g to 0.20g with a 10% exceedance probability in 50 years, corresponding to a return period of 475 years; however, the greatest PGA values are in the Lower Tagus Valley region (Lisbon area) and the Algarve region (Figure 2).

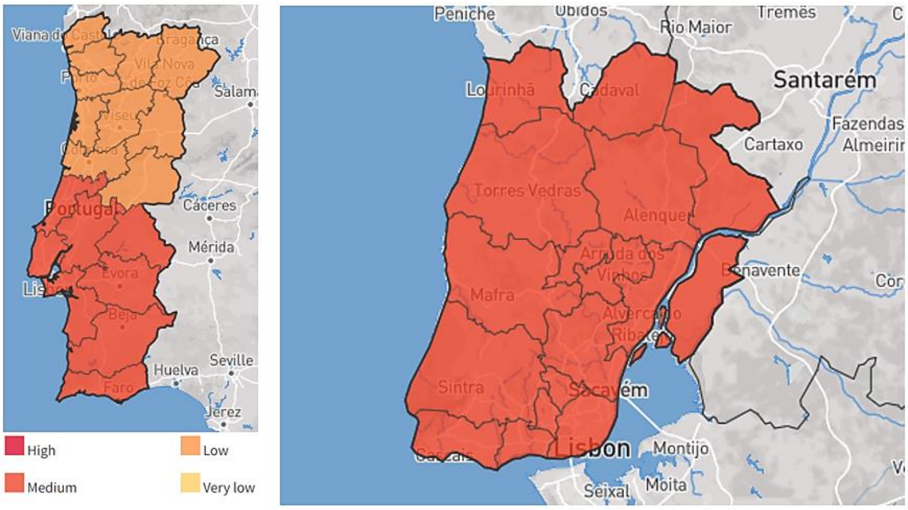


Figure 2. Seismic hazard in Portugal and Lisbon. Available at www.thinkhazard.com (GFDRR, n.d.).

Historically Portugal, and consequently the Lisbon area, has experienced many earthquakes. According to the records, an earthquake of an estimated magnitude between 6.0 and 6.6 struck Lisbon on January 26, 1531. This event caused significant damage in Lisbon's downtown and surrounding areas, damaging around one-third of the city's building stock and killing between 1,000 and 30.000 people (Sá et al., 2018). The most significant earthquake in Portugal, with subsequent tsunami and fire events, happened in 1755, often known as "The Great Lisbon Earthquake", with an estimated magnitude of roughly 8.5 on the Richter scale. This earthquake damaged around 85% of the structures, with around 30,000 to 40,000 people killed (Bernardo et al., 2021). The Benavente earthquake (1909), estimated magnitude of 6.0 around 30 km northeast of Lisbon, caused 46 fatalities.

Near the epicenter approximately 80% of buildings were unusable; while in Lisbon the earthquake mainly damaged the eastern part of the city producing minor damages (Teves-Costa et al., 2017). The last important earthquake that affected Lisbon was in 1969, with a magnitude of 7.8 located offshore from the south of the country. This earthquake caused 13 fatalities and the collapse of over 400 structures in the south of Portugal, while in Lisbon, the fall of chimneys was the most severe loss observed (Bernardo et al., 2021).

The seismic hazard for the study area is identified starting from the study proposed by (Vilanova & Fonseca, 2007) which identified the mean hazard map for Portugal with PGA values in rocky soil ranging from 0.05g to 0.20g for a return period of 475 years. So, considering an initial PGA of 0.20g associated with a 475-year return period, the PGA values for different specified return periods (2, 5, 10, 20, 50, and 100 years) using mathematical formulas found in (Lantada et al., 2018) was computed. Then, the obtained PGAs associated with each estimated return period are correlated to the expected macroseismic intensities as reported by (Lantada et al., 2018) for quantifying the potential seismic impact on buildings and providing critical information for seismic risk assessment.

1.4. Floods

In Portugal, coastal regions contain a significant percentage of the population, and towns such as Lisbon, as well as many other major metropolitan centres, are located near estuaries. This geographical layout in Portugal gives a unique challenge to assessing flood risk, as indicated in Figure 3 (Rilo et al., 2015).

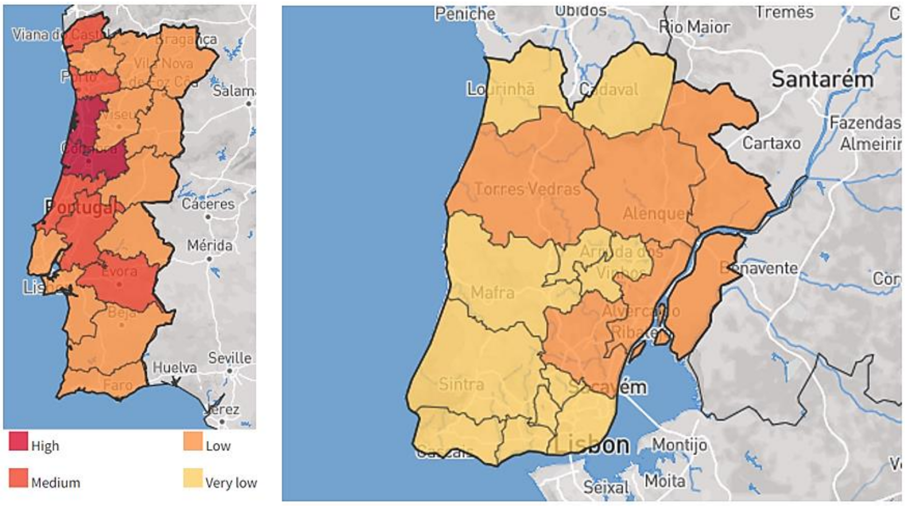


Figure 3. Urban flood hazard in Portugal and Lisbon. Available at www.thinkhazard.com (GFDRR, n.d.).

According to (Leal et al., 2018) the three most significant flood events in Lisbon were recorded on November 25-26th, 1967; November 18-19th, 1983; and February 18, 2008. In November 1967, Lisbon experienced the deadliest natural disaster since the devastating earthquake of 1755. Severe rains with extraordinary intensity fell on the Lisbon Metropolitan Area, causing flash floods and landslides. The November 1967 event set daily rainfall records (137 mm) that were significantly more than the normal average for that month (100.5 mm). This event had significant socioeconomic consequences: the official estimate of fatalities was 495; nearly 900 people lost their homes, and several road and train connections were interrupted (Leal et al., 2018; Trigo et al., 2016). In the same month, but several years later, an extraordinary precipitation event in November 1983 affected the Lisbon area. This event set daily rainfall records (163.7 mm) with much more respect to the normal average for that month. This high rainfall event resulted in a variety of negative effects, including urban floods and landslides. The reported overall number of fatalities was 10, with huge economic losses as a result of power block and interruption of road and rail lines (Leal et al., 2018; Liberato et al., 2012). In more recent years, on 18th February 2008, another intense flood struck Lisbon with a daily rainfall record of 140.9 mm (89.4 mm is the normal average for that month). There is no official assessment of the entire economic damage but the National Authority of Civil Protection reported 4 deaths, 65 individuals displaced, and 121 evacuated (Fragoso et al., 2010; Leal et al., 2018).

Concerning the flood hazard, the flood depth maps for different occurrence probability scenarios (2, 5, 10, 20, 50, 100, 500 years) have been simulated considering a proper pluvial flood model developed in HEC-RAS software (Hydrologic Engineering Center, 2021), starting from observed rainfall data for the Lisbon area (Brandão et al., 2001). The hydrological model is based on the IDF curves (intensity-duration-frequency) for Lisbon, and then, through the Soil Conservation Service-Curve Number (SCS-CN) method (SCS, 1993) the hydrographs are considered, which served as input data for the rainfall model.

3. Exposure model

According to the (UNISDR, 2009) definition, the exposure is "*people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses*". Therefore, normally the exposure of buildings is represented by their position and monetary value (Arrighi et al., 2022). In light of this, the development of an assets inventory for the evaluated area, encompassing assets potentially vulnerable to different hazards, is a fundamental undertaking in the assessment of expected losses (Grünthal et al., 2006). In the present study, the exposure model was carefully developed by gathering a detailed inventory of the analysed buildings, which was then visualised within the QGIS framework (Graser, 2013). The database for the case study area was meticulously made including a consistent range of building attributes.

This inventory facilitated the statistical analysis of the most important building features (as reported in Figure 4), as well as their spatial visualization using GIS maps (as reported in Figure 5).

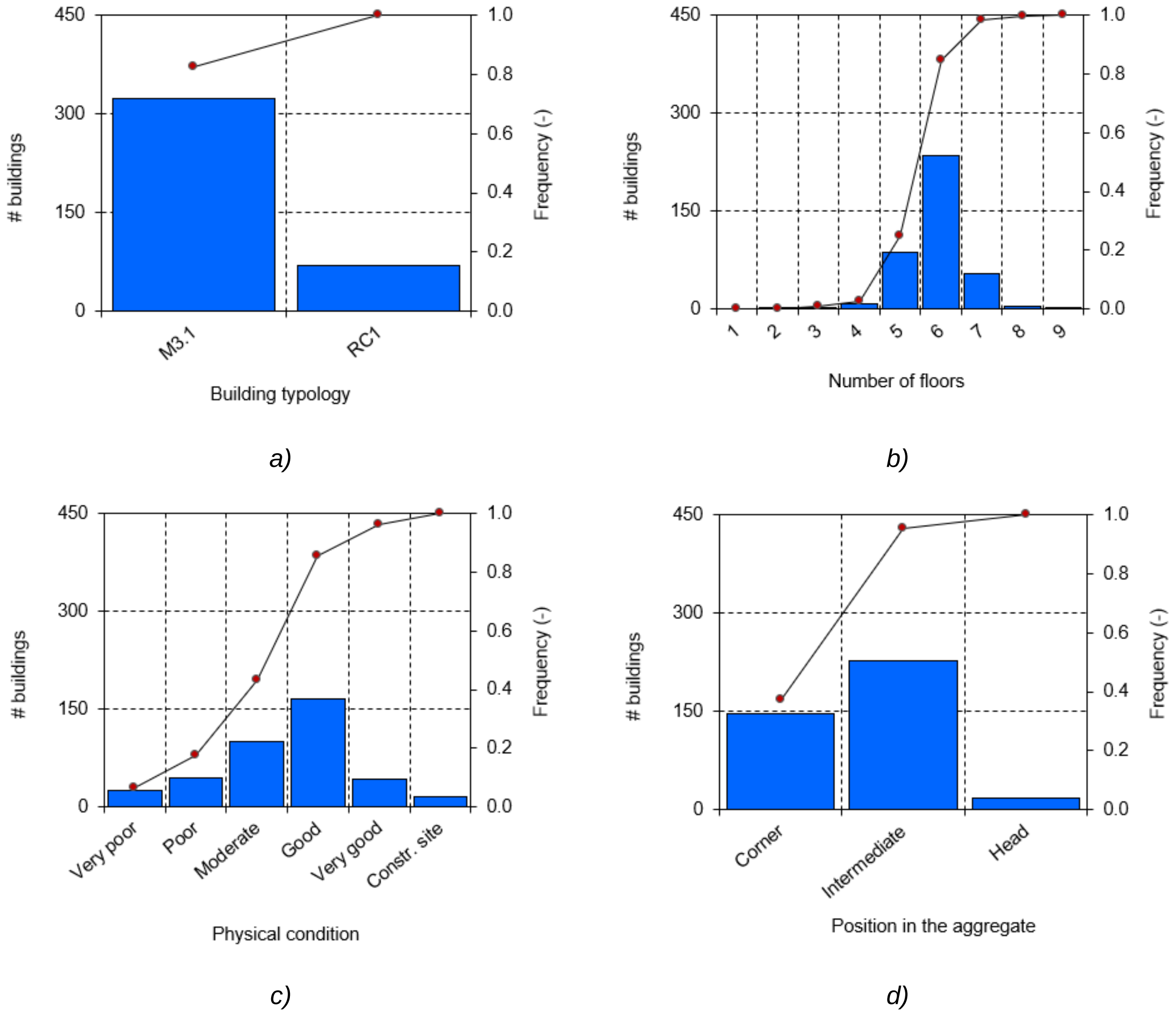
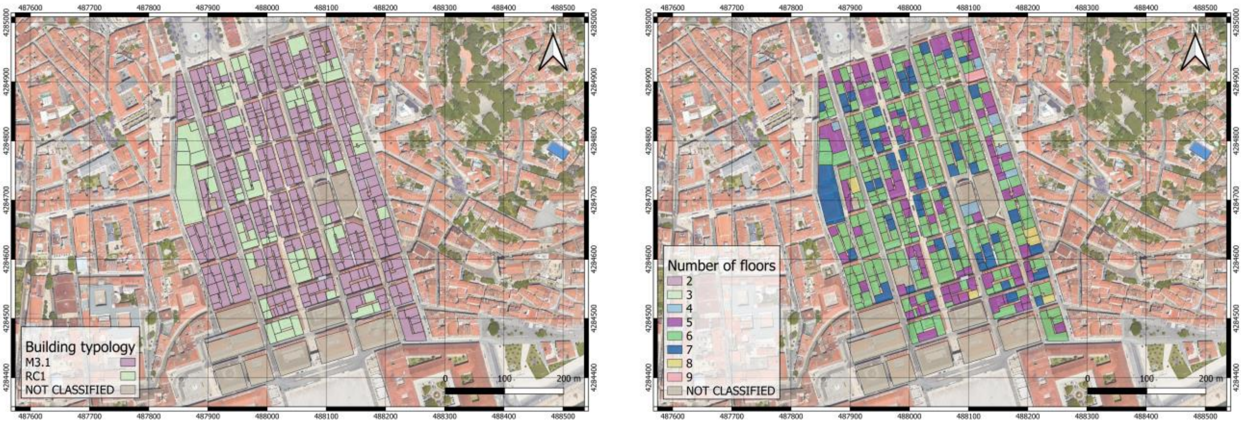


Figure 4. A statistical representation of main attributes for the study area: a) building typology; b) number of floors; c) physical condition; d) position in the aggregate.

Figure 4 illustrates that most buildings in the area are of URM, accounting for 82% of the sample, while 18% are made of RC. These buildings vary in height from 2 to 9 floors, with a significant majority (96%, i.e. 376 buildings) having 5 to 7 floors; concerning the physical condition, the buildings are classified as good or very good which corresponds to the 53% of the sample, while a considerable percentage (42%) is in a moderate to very poor condition. In terms of the position within the aggregate, which typically consists of an average of 8 buildings per aggregate, the intermediate category constitutes the highest proportion (58%), followed by the corner (37%), and a smaller percentage of buildings classified as head (5%) types.



a) *b)*

Figure 5. Spatial representation of main attributes for the study area: a) building typology; b) number of floors.

The monetary exposure, E_i for the analyzed buildings sample, is determined by multiplying the floor area, A_i, by the market value, V_m, and the number of floors, n_i. According to the (Instituto Nacional de Estatística, IP - Portugal, n.d.), the market value has assumed 5200 €/m^2 for commercial areas and 3788 €/m^2 for residential areas; consequently, the monetary exposure is then calculated by the following equation:

$$E_i = \sum_{i=1}^{n} V_m \cdot A_i \cdot n_i \quad (1)$$

4. Vulnerability

Vulnerability is "*the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard*" (UNISDR, 2009). Seismic and flood vulnerability has been investigated with two different methodologies, later detailed since the two hazards have different metrics (flood depth and macroseismic intensity), as depicted in (Arrighi et al., 2022). The seismic vulnerability has been investigated according to the procedure developed in the framework of the Risk-UE project (Milutinovic & Trendafiloski, 2003). The Risk-UE project, financed by the European Union, had as its principal goal to encourage the development of a comprehensive seismic risk assessment technique shared by the European countries. This project introduced an index-based methodology that was evaluated in seven different cities throughout the continent (Kassem et al., 2020). In this methodology the buildings are divided into typological classes according to the classification of the Building Typology Matrix (BTM) and the damage levels are the ones derived from the European Macroseismic Scale (EMS-98) by (Grünthal, 1998). The vulnerability of each building is calculated through the following equation:

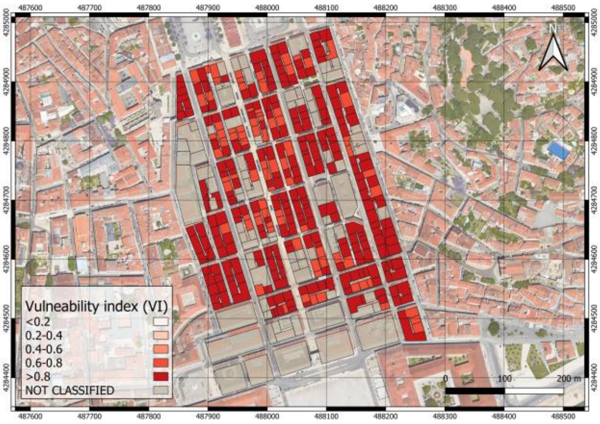
$$\overline{V}_I = V_I^* + \Delta V_R + \Delta V_m \quad (2)$$

Where V_I^* is the most probable value of the vulnerability index V_I of the corresponding building class (M3.1=0.74), ΔV_R is the regional vulnerability factor i.e. a measure of how susceptible a region is to damage from a natural hazard, ΔV_m is the sum of behaviour modifiers that alters the vulnerability index for each single building taking into account specific characteristics, such as the plan regularity, type of foundations, state of preservation and so on. For the area under consideration, 324 masonry buildings of the "Pombalino" type have been identified and have been assigned an M3.1 BTM typology (i.e. wooden slabs URM). Following this, the mean damage grade (μ_D) was estimated by calculating $\overline{V}_I$ using a semi-empirical formulation that relates the expected mean damage to vulnerability for a given intensity level, I.

$$\mu_D = 2.5\left[1+\tanh\left(\frac{I+6.25\,\bar{V}_I-13.1}{2.3}\right)\right] \tag{3}$$

Next, the pluvial flood vulnerability model was developed by adopting the stage-damage curves which relate the intensity parameter (flood depth in meters) with the relative physical damage ($D_{\%}$). The proposed research adopted the stage-damage curves reported by (Dias et al., 2010) who applied the flooding procedure for the same urban area. The curves reported by (Dias et al., 2010) assess the damage to buildings classifying the structures with or without a basement and with two or fewer floors and three or more floors. Furthermore, according to (Arrighi et al., 2022), it was assumed that for a water level less than 0.25m, no damage is experienced by the case study historical buildings. Indeed, due to the variable ground elevations in the area, the above-mentioned threshold represents the average height of the building's entry door above the road level.

According to the above-introduced procedure, the seismic and flood vulnerability for the Baixa Pombalina area has been estimated. Figure 6 shows the seismic vulnerability index, seismic damage, and flood-water depths scenarios for the examined building stock.



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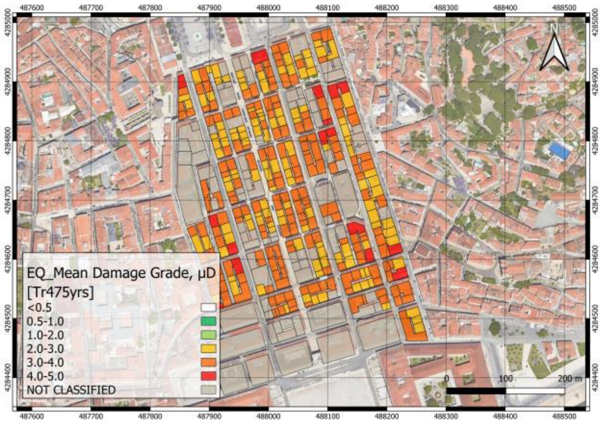

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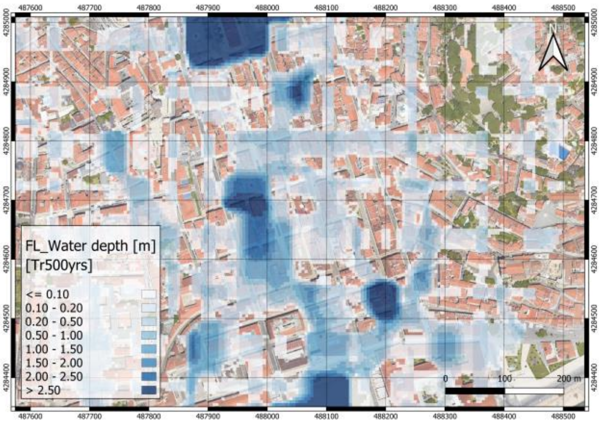
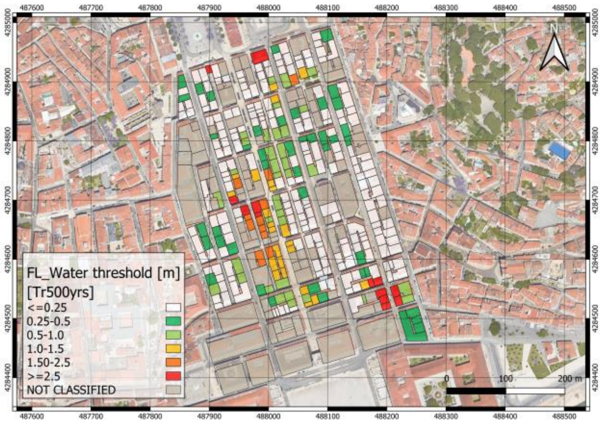


c)



d)

Figure 6. Vulnerability estimation: a) seismic vulnerability index $\bar{V}_I$; b) earthquake damage grade for a return period of 475 years; c) water depth for a return period of 500 years; d) water depth associated to a damage level for a return period of 500 years.

5. Risk

The risk has been calculated for the two hazards considering them with no interactions (independent), then a multi-risk assessment is performed to understand the total level of risk that, as depicted in (Tocchi et al., 2023), could be useful when two hazards occur within a short period from one another. In line with the terminology described in Section 1, this multi-risk assessment aligns with a multi-layer single-hazard risk evaluation.

This classification arises because the two distinct hazards overlap in this scenario, resulting in the summation of the individual risks associated with each hazard.

The total seismic building losses have been calculated by multiplying the monetary exposure E_i, evaluated according to equation (1), (see section 3), by the corresponding damage levels achieved by the buildings in the simulated scenario. In the absence of specific data for the case study area, the reconstruction value is herein assumed to be equal to the market value proportionally reduced to the corresponding damage threshold, D_i= 1, 2.,..5, reached by the building, as explained in (Roca et al., 2006). Similarly, the total flood building losses were calculated by multiplying the monetary exposure E_l by the relative physical damage ($D_{\%}$). Based on these assumptions, the Loss Exceedance Curve was evaluated. This curve relates the mean annual frequency of exceedance of a given hazard to the corresponding expected losses (Tocchi et al., 2023), which is defined according to:

$$v\,(p) = \sum_{i=1}^{Events} Pr(P > p \mid Event_i) \cdot F_A(Event_i) \qquad (4)$$

where v (p) is the exceedance rate of loss, p; $F_A(Event_i)$ is the annual frequency of occurrence of the $Event_i$; and $Pr(P>p \mid Event_i)$ is the probability of the loss to be greater than or equal to p, conditioned by the occurrence of the $Event_i$. Figure 7 represents the Loss exceedance Curve gained from the present case study in terms of annual frequency (a) and return period (b).

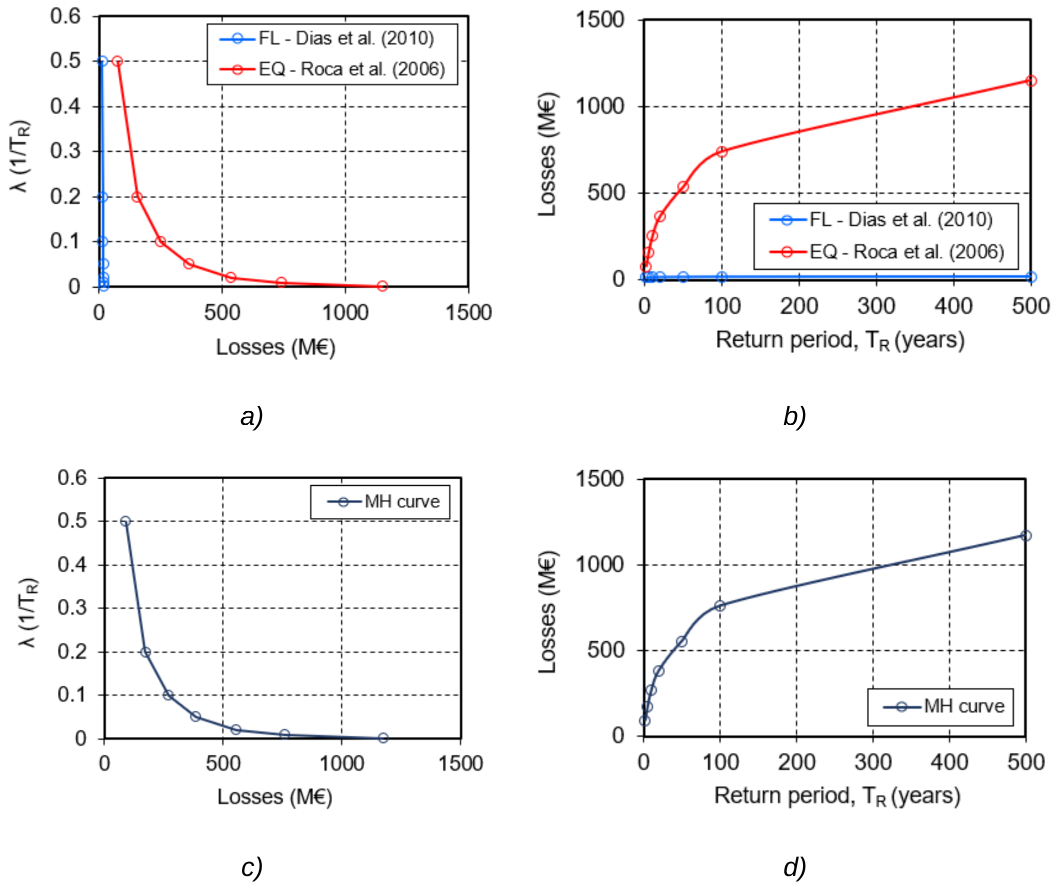


Figure 7. Loss Exceedance Curve: a) annual frequency; b) return period; c) multi-hazard annual frequency and d) multi-hazard return period.

As shown in Figure 7 the two single-hazard risk curves (EQ and FL) indicate that the building losses due to earthquakes are much greater than the ones due to floods. As an example, for a return period of 500 years, the building losses are approximately 1150 M€ for earthquakes and 21 M€ for floods. Earthquake damage to structures is much more severe than flood damage since flood damage to buildings with three or more floors can reach a maximum of 10% for water depths of 3 meters, as reported in (Dias et al., 2010).

Additionally, for a comprehensive grasp of the global expected losses within the study area, a multi-hazard curve has been proposed and presented in Figure 7 c) and d). These curves, defined as the cumulative impact of the individual events under consideration, offer a global overview of the potential losses resulting from the considered hazards.

6. Conclusion

This paper proposed a multi-risk model for the city of Lisbon taking earthquake and pluvial flood hazards into account. Lisbon, like many other cities throughout the world, has experienced several threats that put at risk its population, infrastructure, and economy. The case study focused on the assessment of ordinary URM buildings in a subsector of the historic city centre of Lisbon, more precisely in a coastal area called Baixa Pombalina. The main outcomes of the proposed study are presented below:

- The exposure model, using remote sensing and GIS data, reveals the building characteristics: 82% are Pombalino type, 18% reinforced concrete, 96% of the total examined sample have 5-7 floors, 53% are in good or very good condition, and 42% in moderate to very poor condition. They are distributed as 58% intermediate, 37% corner, and 5% head positions. This data is essential for assessing collective building behaviour during natural disasters.
- The results provided by the application of the Risk-UE method show that 75% of URM buildings have a V_I>0.8 (very high), while 25% fall between 0.6-0.8 (high). For a 475-year return period, damage grades are as follows: 38% at D3 ($2<\mu_D<3$), 57% at D4 ($3<\mu_D<4$), and 5% at D5 ($4<\mu_D<5$).
- Concerning the rainfall scenario, stage-damage curves from the literature were used for flood vulnerability assessment. For a 500-year return period, 61% of URM buildings had water depths below 0.25m, while just 4% faced depths over 2.50m.
- For a 500-year return period, expected building losses were calculated at approximately €1150M for earthquakes and €21M for floods. The earthquake losses are significantly higher, likely due to structural damage being a larger component compared to pluvial floods, where content damage typically plays a greater role. Future research could address this by considering content damage.

The methodology presented here offers a structured framework for prioritizing forthcoming risk mitigation efforts and streamlining the execution of community disaster response plans. By embracing this approach, urban areas can effectively confront potential threats through tailored urban mitigation strategies. This methodology brings several benefits, such as improving decision-making processes, directing resources towards targeted risk reduction measures, and strengthening community preparedness and resilience. Finally, the adoption of this methodology plays an essential role in minimizing the potential consequences of future risks while fostering sustainable and resilient urban development.

Acknowledgement

This work was partly financed by FCT / MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB / 04029/2020, and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020.

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