



Multi-attribute-based procedure for seismic loss scenario in a historical area

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Abstract

Seismic events have shown to be exceedingly damaging to structures over time, with serious social and economic consequences. As a result, large-scale seismic risk assessments are essential for reducing the potential damage from future earthquakes. Therefore, the proposed study attempts to examine the vulnerability and risk of unreinforced masonry buildings (URM) placed in aggregate conditions in a historical area of the city centre of Lisbon. To this purpose, a comprehensive exposure model was developed combining satellite remote sensing, GIS software, and census data. Subsequently, seismic hazard was evaluated in the area, considering both Peak Ground Acceleration (PGA) and macro-seismic intensity for different return periods (i.e. 2-50-100-475-975-2500-5000 years). Vulnerability was assessed by introducing a novel approach to earthquake risk assessment using Multi-Criteria Decision-Making methodologies. Specifically, the method employs the Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) computational methods to evaluate parameter weights and vulnerability index. Damage scenarios, fragility curves and mean damage ratios curves were provided to offer an overview of the vulnerability of the assets exposed to risk. Finally, the expected consequences were evaluated in terms of direct economic losses showing an economic loss of 595 M€ for a 475-years return period, while 1108 M€ for 5000-years. This study significantly enhances seismic analysis for urban areas by introducing a Multi-Criteria Approach. This method simplifies vulnerability assessment, ensuring ease of application and reproducibility. Its insights offer valuable support for disaster risk management decisions, facilitating the implementation of resilience and risk-reduction strategies.

Keywords Seismic vulnerability · Index-based methodology · Loss estimation · Multi-criteria analysis

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1 Introduction

Seismic occurrences of varying intensities have caused structural damage throughout time, resulting in significant social and economic costs (Li and Gardoni 2024). For example, the Northridge earthquake in California (US) in 1994 caused roughly US\$14 billion in insured losses, but the Kobe earthquake in Japan in 1995 caused absolute losses of US\$150 billion (Calvi et al. 2006). In more recent years, seismic losses have been high: after the L'Aquila earthquake on April 6, 2009 (Italy), more than 10 billion euros were spent on emergency and restoration (Del Gaudio et al. 2019b). Also, the 2023 Kahramanmaraş earthquake sequence in Turkey resulted in enormous economic and demographic losses. This most recent disaster resulted in 50 thousand fatalities, around 110 thousand injured persons, and major damage to buildings and infrastructures, with total economic losses, considering indirect as well as direct costs, projected to surpass US\$100 billion (Sagbas et al. 2024). According to (McGlade et al. 2019), earthquakes caused 12.5% of overall economic losses between 2005 and 2015. As a result, large-scale seismic risk evaluations are essential for minimising potential damages from future earthquakes, since the major purpose of risk assessments is to estimate and map territorial damage and losses (Barbat et al. 2010; Silva et al. 2015).

Seismic risk assessment typically consists of three main elements: hazard, which refers to possible loss-causing occurrences; vulnerability, which quantifies the percentage of loss associated with different intensity measures; and exposure, resulting in identifying the spatial distribution of assets vulnerable to the hazard (Silva et al. 2015; UNISDR 2009). Portugal's seismic hazard characteristics (large to very large offshore earthquakes and moderate to large onshore earthquakes), as well as its building stock (the larger part of which is made up of masonry buildings), result in significant seismic risk, even when only moderate events occur (Silva et al. 2015; Vilanova and Fonseca 2007). Such problems highlight the importance of conducting a complete evaluation of seismic risk in Portugal, which will serve as the foundation for implementing risk-reduction measures (Silva et al. 2015).

Asset risk can theoretically be mitigated by intervening in one of the three key risk factors. However, while talking about earthquakes, it is important to note that reducing the hazard is impossible since it is reliant on the characteristics of the location, and decreasing exposure may be challenging owing to the high costs of moving assets and people. Therefore, the vulnerability allows for relatively agile action: reducing the vulnerability of structures to a certain seismic event implies lowering the risk (Barchetta et al. 2023; Pagliacci and Russo 2019). As a result, the problem of large seismic losses is strictly connected to the high level of vulnerability that structures have traditionally exhibited. This is particularly true for old masonry buildings, which constitute a large portion of the built environment despite not exhibiting box-like behaviour but just designed to support gravity loads, owing to the simplicity with which the materials could be found and assembled (Colajanni and D'Anna 2024; Salvalaggio and Valluzzi 2022). Over the years many vulnerability assessment methods have been developed which, according to literature (Calvi et al. 2006; Sandoli et al. 2021), can be classified into empirical, mechanical/analytical, hybrid and expert judgement methods.

Empirical methodologies, for instance (Benedetti and Petrini 1984; Brando et al. 2017; Del Gaudio et al. 2019a), began to develop in the early 1970s, relying on data-driven approaches based on historical post-earthquake damage distribution information. In these approaches, buildings are divided into typological classes, (or “vulnerability classes” based

on a few fundamental typological and structural characteristics), and a vulnerability model for each class may be calibrated using statistical elaborations based on past earthquake damage observations. Then, field observations offer the necessary knowledge to estimate the vulnerability of a certain typological class within a generic building stock (Calvi et al. 2006; Sandoli et al. 2021).

Mechanical/analytical methodologies allow for a more detailed assessment of vulnerability based on the building's geometry and mechanical properties (Del Gaudio et al. 2015; Milani 2019; Ramos and Lourenço 2004). These methods, which use building modelling procedures, evaluate vulnerability by comparing structural capacity to seismic demand. Analytical or mechanical approaches with varying levels of detail are frequently used to assess the vulnerability of single existing buildings before undertaking structural rehabilitation interventions (Leggieri et al. 2021; Puncello and Caprili 2023).

The hybrid methods, for instance (Barbat et al. 1996; Kappos et al. 2006; Sandoli et al. 2021), combine the results of simulated damage statistics from an analytical model, for certain building typology, with post-earthquake damage data. Finally, the expert-judgement methods, such as (ATC 1985), provide typological seismic fragility curves by estimating the damage level and structural behaviour for building classes based on the judgement provided by technicians with experience in the field (Calvi et al. 2006; Sandoli et al. 2021).

Remaining in the field of large-scale evaluations, it is important to highlight that, because of their empirical component, empirical methodologies are quick to assess vulnerability on a larger sample of buildings, making them particularly suited for large-scale vulnerability assessments. In contrast, in the field of large-scale assessment, mechanical methods, which are better suited to single-building analysis due to their higher level of detail, can compensate for the limitations of empirical approaches caused by the scarcity of data collected for earthquakes of both high and low intensity due to their low-frequency of occurrence. The expert-judgement technique can also be used to evaluate many buildings; however, the results can be affected by the limited knowledge of the building stock features, as well as by the personal experience and familiarity with structural engineering of team members. Finally, hybrid techniques attempt to address the constraints of empirical, mechanical, and expert-judgment approaches, namely a lack of adequate data, computational effort, and subjectivity, respectively (Sandoli et al. 2021).

Analysing the seismic vulnerability of buildings in historical city centres has proven to be a highly interesting task. Indeed, historical sites are particularly susceptible because of their physical or tangible, as well as immaterial or intangible value. In addition to their economic value, historic centres, as part of cultural heritage, allow people to understand and experience culture, customs and traditions, art, religion, and history, as well as contribute to community identity and memory, and a sense of belonging (Fontenele et al. 2023; Puncello and Caprili 2023).

Assessing the seismic vulnerability of structures in historic areas is very difficult for a variety of reasons. One of the most difficult issues when working with old buildings is the lack of knowledge regarding the geometry, structural features, and construction type of buildings. Another issue is the architectural environment in historic city centres which is both intricate and diversified, with complex geometry and a wide range of construction techniques and materials. Furthermore, the structures have been exposed to a range of alterations throughout the years, including additional floors and plan expansions, which have affected their structural behaviour. As a result, the urban morphology of historical centres

is defined by the aggregate condition, in which the complicated interconnections between various structures within the same cluster provide extra challenges. When it comes to building aggregate, there are various factors to consider. One example is structural heterogeneity, which is characterised by the presence of diverse materials and construction techniques amongst cells. Furthermore, the difference in height between nearby buildings is a problem that aggregates present: the dynamic response of each cell is heavily influenced by the surrounding cells, so variable building or inter-story heights, as well as the position of the building within the aggregate, should be carefully considered (Chieffo et al. 2023; Formisano et al. 2015). Some studies explored the vulnerability of building aggregates, which may be classified as empirical (Colajanni and D’Anna 2024; Vicente et al. 2011) or mechanical (Angiolilli et al. 2021; Ferrito et al. 2016; Leggieri et al. 2021). Empirical approaches are more suited to assessing huge numbers of structures on an urban scale since they require less data and can be processed faster. Furthermore, they are especially useful when the objective is to provide straightforward tools for decision-makers, such as municipalities, to reduce and mitigate catastrophe risk (Formisano et al. 2015; Leggieri et al. 2021).

Municipalities face the challenge of managing risk on a large scale, necessitating simple approaches that allow them to prioritise interventions and mitigation strategies against various objectives, and they are typically required to make decisions based on specific criteria. However, this may be managed using approaches such as Multi-Criteria Decision Making (MCDM) procedures, which allow experts to analyse a plan by taking into consideration multiple interests, as well as the interplay of several, often conflicting, objectives and decision criteria (Alizadeh et al. 2018; Dean 2022; Fontenele et al. 2023). As a result, the current study deals with evaluating the seismic vulnerability of the existing building stock using a feasible, robust and reproducible MCDM approach that explicitly incorporates multiple objectives and decision criteria into the analysis.

Thus, the proposed study investigates the seismic vulnerability and risk of typical ordinary unreinforced masonry structures (URM) at an important historical area in Lisbon known as Baixa Pombalina. To begin, the exposure model was developed using remote sensing techniques and then integrated into a GIS environment. Then, earthquake scenarios with different return periods were simulated. The seismic vulnerability was evaluated using a proposed index approach based on characteristics related to data availability and context-specific features. This task was achieved by carefully selecting parameters and introducing new vulnerability classifications and weights through the MCDM technique, followed by a risk assessment. The approach herein proposed, innovatively adopts the MCDM methods to build a new seismic-based vulnerability index approach for the Lisbon area. Furthermore, the application of MCDM techniques reduces subjectivity in evaluation, making the method more adaptable in different contexts and even in circumstances of a lack of data.

Thus, the paper is organised as follows: in Sect. 2 the case study is introduced; in Sect. 3 the exposure model for the case study area is provided; in Sect. 4 seismic hazard assessment is performed and the results are compared with the European Seismic Hazard Model; Sect. 5 introduces the seismic vulnerability evaluation through MCDM methods, in Sect. 6 the evaluation of building economic losses is addressed and, finally, in Sect. 7 the main outcomes are carefully discussed.

2 Case study area

The seismic loss evaluation was conducted for an urban neighbourhood situated in the Baixa Pombalina (Lisbon downtown), as presented in Fig. 1. The region is the result of post-1755 earthquake reconstruction, which emphasises its vulnerability to earthquakes due to the presence of historic masonry buildings. The district is a cultural and economic centre where tourists may experience the city's cultural identity and historic dynamism. The buildings in the area have commercial uses on the ground floor and residential purposes on the higher levels (Barchetta et al. 2023; Martins et al. 2018; Mascheri et al. 2024).

The Baixa Pombalina district was destroyed by the generally referred to as “The Great Lisbon Earthquake”, of November 1, 1755, (estimated magnitude around 8.5 on Richter scale located offshore), followed by a tsunami and fires. This earthquake destroyed approximately 85% of the structures and killed roughly 20% of the inhabitants of Lisbon at the time (30,000 to 40,000 casualties), (Bernardo et al. 2021). After the earthquake, the destroyed buildings were rebuilt under the leadership of the Prime Minister Marquis of Pombal. The reconstruction marked the introduction of the so-called building typology “Pombalino”, which was characterised by the introduction of specific structural peculiarities aimed at improving their seismic performance and other features. Indeed, the structural system consists of a timber frame forming a triangular geometry filled with low-quality masonry for interior walls (known as “frontal” walls), which are joined to the orthogonal walls by vertical studs in the corners. The façades, as well as the walls between adjacent structures, are usually built with rubble stone masonry, however, higher-quality masonry can be found on the ground levels and at angles. The slabs were constructed using a system of wooden beams and planks, with wall-to-floor connections secured by simply fixed anchors (Barchetta et al. 2023; Bernardo et al. 2021; Mascheri et al. 2024). Examples of the main structural elements of the typical Pombalino typology are reported in Fig. 2.

However, in the Baixa Pombalina area, some buildings can be identified as reinforced concrete buildings, as a consequence of interventions throughout the years.



Fig. 1 The Baixa Pombalina area. Maps: adapted from (Google Earth 2024); where in the red and blue frames are reported two examples of the inspected buildings



Fig. 2 Main structural elements (slabs and internal walls) of the inspected typical Pombalino buildings

Given these characteristics, two building typologies have been identified: Pombalino and reinforced concrete, which have been classified, for this study, using the Risk-UE project's Building Typology Matrix (BTM), (Milutinovic and Trendafiloski 2003). The Risk-UE BTM identifies the key features of European building stock by identifying certain common building typologies.

In the current work, it has been given a typology M3.1, i.e. URM-wooden slabs, to Pombalino structures; and RC1, i.e. RC moment frames, to the identified reinforced concrete buildings; however, the latter was excluded from the analysis and has not been further investigated.

3 Seismic exposure model

In an urban risk assessment method, a crucial phase in predicting possible losses is to develop an exposure model for all assets that may be subject to hazards, such as people, properties, and economic activities. Buildings, in particular, require the identification of their position and monetary value; hence, the exposure model serves also as a geographical data layer for risk assessment (Arrighi et al. 2023; Sterlacchini et al. 2014). As already outlined in (Mascheri et al. 2024), the area of interest is composed of 393 ordinary buildings in aggregate conditions, see Fig. 3. However, only ordinary unreinforced masonry (URM) structures were identified, classified, and structured into an inventory containing the most essential building attributes.

To store and spatially represent the gathered data about the examined buildings, a typological database was created using QGIS software (Graser 2013), which allowed for the analysis of a consistent range of building attributes, e.g., building typology, number of storeys, physical condition, position in the aggregate, (see Fig. 4), as well as statistical analysis of the building sample and geographical visualisation. Data on building typology features as well as on spatial and geomorphological information were acquired through literature review, Google Maps, Google Earth, and GIS (Nascimbene 2024), while census data provided monetary exposure is found in (Mascheri et al. 2024).

The majority of the buildings are unreinforced masonry of the “Pombalino” type (82% of the cases, 324 buildings), and some are reinforced concrete (18% of the sample), (Fig. 4a). Regarding the number of floors, 96% of buildings have between 5 and 7 levels. In terms of building position within the aggregate, see Fig. 4b, the majority of them are in the intermediate position (58%), i.e. enclosed among two internal structural cells within the aggregate,



Fig. 3 Identification of the buildings in the case study area

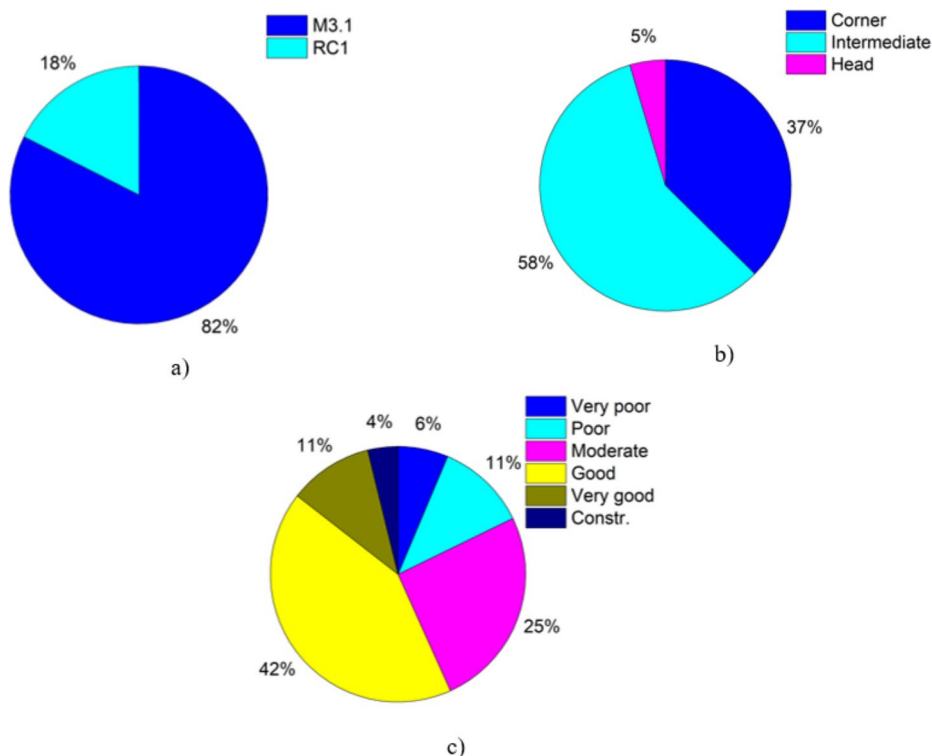


Fig. 4 Study area attributes **a** building typology; **b** position in the aggregate; **c** physical condition

37% are in the corner position, i.e. between two buildings in the corner of the aggregate, and only a few of them in head position (5%), i.e. at the ends of the aggregate. The physical state of the buildings (see Fig. 4c) demonstrates that 53% of the sample is in good or very good condition, with a significant majority (43% of the sample) in moderate to very poor condition. It is worth noting that “Constr.” indicates that some structures were undergoing renovation at the time of the survey.

The monetary exposure of the buildings is evaluated by multiplying the market value, the floor area, and the number of floors, according to the following formula (Mascheri et al. 2024):

$$E_i = \sum_{j=1}^n V_{m,j} \cdot A_j \cdot n_j \quad (1)$$

where E_i is the monetary value of the i -building, $V_{m,j}$ is the market value expressed in €/m², A_j is the building area and n_j is the number of floors. Data about the market value has been found in the census statistics, particularly (INE 2023) database indicates a market value of 5200 €/m² for commercial areas and 3788 €/m² for residential areas (Mascheri et al. 2024).

4 Seismic hazard model

Because of its location on the Eurasian plate near the African plate boundary, as stated, the Portuguese mainland is vulnerable to seismic activity, resulting in very large offshore earthquakes and moderate to large onshore earthquakes. Particularly, the Algarve region (south of Portugal) and Lower Tagus Valley region (Lisbon area) present the highest seismic hazard, respectively, offshore and onshore (Bernardo et al. 2021; Vilanova and Fonseca 2007). During its history, Lisbon has already experienced important earthquake events. Besides the already mentioned “Great Lisbon Earthquake”, other events are worthy of mention such as the “Lower Tagus Valley earthquake” on January 26, 1531, of an estimated magnitude between 6.5 and 7.1 (Custódio et al. 2015; Sá et al. 2018); the onshore “Benavente earthquake” in 1909 with a magnitude of 6.3, which occurred around 60 km northeast of Lisbon; and the “Algarve earthquake” in 1969, which had a magnitude of 7.8 and was centred offshore to the south of Algarve (Bernardo et al. 2021). Usually, to define the seismic scenario, macroseismic intensity or Peak Ground Acceleration (PGA) are the type of intensity measure most used (Calvi et al. 2006). In the current work, to assess the seismic hazard, the PGA values associated with the different return periods have been calculated according to the following formula (Lantada et al. 2018):

$$a_b|_{PR=t} = a_b|_{PR=T} \cdot \left(\frac{t}{T} \right)^{0.37} \quad (2)$$

where $a_b|_{PR=t}$ is the basic acceleration for a generic return period t and $a_b|_{PR=T}$ is the basic acceleration for the reference return period T . Subsequently, a formula that relates Peak Ground Acceleration (PGA) with EMS-98 intensity has been used (Lantada et al. 2018):

$$\log_{10}(a_b) = 0.301030 \cdot I - 0.2321 \quad (3)$$

where a_b is the basic acceleration and I is the macroseismic intensity according to the EMS-98 scale (Grünthal 1998). Based on the data from the (IPQ 2010) Portuguese National Annex, the expected PGA value in rock for Lisbon is around 0.17g associated with a 10% probability of exceedance in 50 years (i.e. return period of 475 years). Starting from this value, the acceleration for different return periods (T_R), i.e. 2-50-100-475-975-2500-5000 years have been estimated through Eq. (2), see Fig. 5a. Subsequently, the PGA has been converted into EMS-98 macroseismic intensity through the empirical correlation of Eq. (3), see Fig. 5b.

The PGA estimates obtained from the empirical formulation described in (Lantada et al. 2018) may be assumed reliable because it results in a safety condition for the calculated PGA values concerning the 2020 European Seismic Hazard Model (ESHM20) (Danciu et al. 2021), see Table 1.

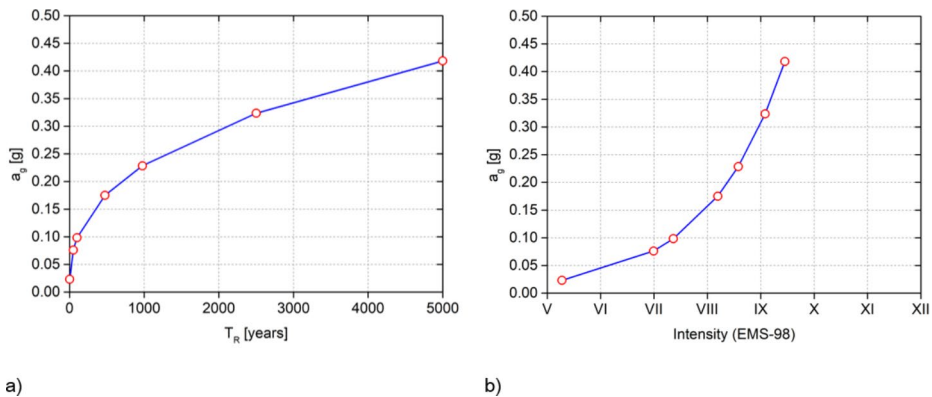


Fig. 5 Seismic hazard: **a** relation T_R -PGA; **b** relation EMS-98 macroseismic intensity-PGA

Table 1 Comparison of the PGA used in this study to the PGA from ESHM20 for the Lisbon area

Return period (T_R)	PGA values (Lantada et al. 2018)	PGA values (Danciu et al. 2021)
2	0.02g	Not provided
50	0.07g	$0.025g < PGA < 0.05g$
100	0.10g	$0.05g < PGA < 0.075g$
475	0.17g	$0.125g < PGA < 0.15g$
975	0.22g	$0.15g < PGA < 0.20g$
2500	0.31g	$0.25g < PGA < 0.30g$
5000	0.41g	$0.30g < PGA < 0.40g$

5 Seismic vulnerability model

The vulnerability of an exposed asset to a specific hazard intensity can be expressed as a percentage of loss on a scale of 0 (no damage) to 1 (collapse) (Sterlacchini et al. 2014). Empirical index-based methodologies are frequently utilised for vulnerability assessments in urban environments since they are simple to use and time-saving when analysing a large number of buildings. The vulnerability index method (VIM) is based on specific survey forms that allow for the correct evaluation of typological, structural, and material characteristics of buildings, which are then utilised to generate a synthetic index reflecting the expected level of vulnerability (Chieffo et al. 2023). The index is a weighted average of many criteria that indicate how certain building characteristics affect the seismic response. To begin, a set of parameters must be chosen, and weights assigned to each parameter based on their relative relevance in the building's seismic response. A survey form is utilised to gather data for each building and then, for each parameter, a class from A (less vulnerable) to D (more vulnerable) is assigned. Finally, the vulnerability index of each building is assessed by adding the weighted parameters (Puncello and Caprili 2023). This method was first developed in 1984 by (Benedetti and Petrini 1984) and has been widely applied and modified over the years, such as in (GNDT 1993) which revised and recalibrated parameters and scores, developing a survey form based on post-damage observations for masonry and reinforced concrete buildings. Originally, the main drawback of this method was that it only allowed for calculating the vulnerability of single buildings while neglecting building

aggregates, which are common in European historic cities. As a result, the initial method was considerably expanded to incorporate masonry building aggregates, allowing for the effects of interaction between adjacent structures to be accounted for (Chieffo et al. 2023). Indeed, (Formisano et al. 2009) added five parameters to the original Benedetti and Petrini's form, to account for aggregate effects, later calibrating the scores and weights using a 3D analytical model (Formisano et al. 2015) and subsequently widely applying the methodology, see (Chieffo et al. 2022, 2023; Formisano and Chieffo 2022). The same issue was investigated by the study proposed by (Vicente 2008), later presented by (Vicente et al. 2011) and re-calibrated by (Ferreira et al. 2017), which proposed 14 parameters for taking into account building interactions.

5.1 Proposed vulnerability index

In the present work, a vulnerability index evaluation was properly evaluated to analyse the seismic vulnerability of ordinary URM buildings in the Baixa Pombalina area, intending to produce an index approach that is well-suited and easy to apply to the case study. Given the frequent challenge of lack of data, the proposed study aims to offer a methodology tailored for extensive assessments, even under constraints of limited data availability, time, and financial resources. This approach eliminates the need for laborious and time-consuming on-site inspections (Barchetta et al. 2023). The study focuses on the potential of remote sensing techniques for data collecting and proposes an approach that is reproducible and adaptable even in different contexts with varying characteristics, data, and resource availability. To determine the parameters for the index-based evaluation, two stages are required: (i) selecting parameters that are particularly relevant to the case study from a vast number of indicators provided in the literature, and (ii) assessing class scores and parameters weight.

5.1.1 Parameters selection

Based on a review of the literature (Brando et al. 2017; Formisano et al. 2015; GNDT 1993; Milutinovic and Trendafiloski 2003; Stefanini 2020; Vicente 2008), the authors selected the most representative parameters for the case study area for which data were available. Specifically, 14 parameters have been organised into 5 main groups: (i) structural system; (ii) regularities; (iii) aggregate interactions; (iv) conservation status and (v) urban interaction among existing aggregates. For each parameter, four vulnerability classes were defined, ranging from A (less vulnerable) to D (more vulnerable). Table 2 summarises the parameters chosen, as well as the primary sources where the parameters may be found, and the Appendix gives a further explanation only for the parameters that are novel in comparison to the current relevant literature. It is worth noting that the description of parameter 14-Aggregate distance can be found slightly different in (Brando et al. 2017) under the name of “Non-seismic external hazard”, which takes into account the potential influence of other surrounding structures.

It is worth noting that the (i) structural system aims at describing the seismic response of masonry buildings. Over time, damage observed following an earthquake has shown that the collapse of masonry buildings is frequently characterised by out-of-plane mechanisms. This vulnerability is exacerbated by the lack of adequate connections between walls as well as between walls and horizontal diaphragms. Indeed, if the connections are poor, the global

Table 2 Vulnerability parameters

	Parameter	Source
Structural System		
1.	Nature of vertical structures	(Banica et al. 2017; Brando et al. 2017; Formisano et al. 2015; GNDT 1993; Milutinovic and Trendafiloski 2003; Ortega et al. 2019a; Preciado et al. 2020; Stefanini 2020; Vicente 2008)
2.	Conventional strength	(Formisano et al. 2015; GNDT 1993; Vicente 2008)
3.	Topographic condition	(Brando et al. 2017; Formisano et al. 2015; GNDT 1993; Milutinovic and Trendafiloski 2003; Preciado et al. 2020; Stefanini 2020; Vicente 2008)
4.	Number of floors	(Banica et al. 2017; Brando et al. 2017; Milutinovic and Trendafiloski 2003; Ortega et al. 2019a; Stefanini 2020; Vicente 2008)
5.	Horizontal diaphragms	(Brando et al. 2017; Formisano et al. 2015; GNDT 1993; Ortega et al. 2019a; Preciado et al. 2020; Stefanini 2020; Vicente 2008)
Regularities		
6.	In-plane regularity	(Brando et al. 2017; Formisano et al. 2015; GNDT 1993; Milutinovic and Trendafiloski 2003; Preciado et al. 2020; Stefanini 2020; Vicente 2008)
7.	Vertical regularity	(Brando et al. 2017; Formisano et al. 2015; GNDT 1993; Milutinovic and Trendafiloski 2003; Preciado et al. 2020; Stefanini 2020; Vicente 2008)
8.	Wall façade openings and alignments	(Stefanini 2020; Vicente 2008)
Aggregate interactions		
9.	Presence of adjacent buildings with different height	(Formisano et al. 2015; Milutinovic and Trendafiloski 2003; Stefanini 2020)
10.	Position of the building in the aggregate	(Brando et al. 2017; Formisano et al. 2015; Milutinovic and Trendafiloski 2003; Stefanini 2020; Vicente 2008)
11.	Structural or typological heterogeneity among adjacent structural units	(Formisano et al. 2015; Stefanini 2020)
12.	Percentage difference of opening areas among adjacent façades	(Formisano et al. 2015)
Conservation status		
13.	Conservation status	(Banica et al. 2017; Formisano et al. 2015; GNDT 1993; Milutinovic and Trendafiloski 2003; Ortega et al. 2019a; Preciado et al. 2020; Stefanini 2020; Vicente 2008)
Urban interaction among existing aggregates		
14.	Aggregate distance	(Brando et al. 2017)

response of the building cannot be guaranteed, leading the different elements to behave independently, resulting in local collapse mechanisms, such as wall overturning. The global response can be ensured by activating the in-plane strengths of earthquake-resistant components through an adequate transfer of seismic actions to parallel walls. This behaviour, known as box behaviour, may be ensured by using diaphragms with sufficient in-plane stiffness as well as adequate wall-to-wall and wall-to-floor connections (Celano et al. 2021; Ortega et al. 2019a). In light of these considerations, wall-to-wall and wall-to-floor connections are of considerable attention in assessing the seismic vulnerability of masonry buildings. However, the lack of data and the quick-based nature of the large-scale assessment for Baixa Pombalina made it difficult to consider these aspects at this stage. Some information can be derived from the literature; however, when more specific information is available, the

connections can be added to the list of parameters as additional ones, to which weight can subsequently be assigned using the AHP technique. Alternatively, they can be incorporated in the assignment of classes of other parameters (such as vertical structures), in this case, the weight of the more detailed parameter can be re-evaluated.

5.1.2 Classes scores and parameters weights evaluation

For the evaluation of class scores and parameter weights, an MCDM technique was used, specifically the Analytic Hierarchy Process (AHP) introduced by (Saaty 1980). Many researchers used the AHP technique, which requires expert judgement to determine weight parameters, see (Alizadeh et al. 2018; Bahadori et al. 2017; Fontenele et al. 2023). According to (Dean 2022), the AHP method requires that the relative importance of each criterion concerning the objective is determined by a series of pairwise comparisons of criteria. This can be done by assigning a subjective judgement of the importance of the various criteria subsequently transformed into quantitative scores through a discrete scale ranging from 1 (equally preferred) to 9 (extremely preferred), see Table 3. Then, the results of the pairwise comparisons of different criteria are displayed in a matrix, from which weights can be obtained by calculating the maximum eigenvalue (λ_{max}) of the matrix (Dean 2022). A further explanation of the well-known method can be found in the literature, e.g. (Cahyapratama and Sarno 2018; Dean 2022; Pathan et al. 2022).

The AHP method allows to check the consistence of the subjective choice through the Consistency Ratio (CR) as follows (Pathan et al. 2022):

$$CR = \frac{CI}{RI} \quad (4)$$

which indicates if the decision on the criterion's relative importance can be defined as consistent (for CR values less than 0.10). The CI is the consistency index and is given by the formula (Pathan et al. 2022):

$$CI = \frac{(\lambda_{max} - n)}{n - 1} \quad (5)$$

where n is the number of parameters and λ_{max} is the maximum eigenvalue. RI is the Index of Random Consistency which is based on the number of n , and can be found in the table in the literature, see (Pathan et al. 2022).

This procedure was firstly applied to each parameter to derive the scores of each class (from A, less vulnerable, to D, more vulnerable), and the results are presented in Table 4.

Table 3 Scale for pairwise comparison (Alizadeh et al. 2018)

Importance	Subjective judgements
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred
2, 4, 6, 8	Intermediate values
Reciprocals	For inverse judgments

Then, the same procedure has been applied for the calculation of the parameter weights, the results are displayed in Table 5.

5.2 Vulnerability evaluation

Once the class scores and parameter weights are determined, the proposed index-based method, rooted in the key parameters of the GNDT approach (GNDT 1993), can be applied to evaluate the vulnerability index (I_V). Additionally, the TOPSIS method, another MCDM methodology, can be employed to estimate (I_V), which initially falls within the range of 0 to 1, and to rank buildings accordingly. The European macroseismic approach (Lagomarsino and Giovinazzi 2006; Milutinovic and Trendafiloski 2003) uses the vulnerability to estimate the mean damage grade of a building μ_d , for a specific intensity measure (specific return period). However, to calculate the μ_d , the vulnerability index (I_V) from the (GNDT 1993) approach must be translated into the vulnerability index (V) from the macroseismic approach (Lagomarsino and Giovinazzi 2006). Therefore, before performing this combined approach, a GNDT-Macroseismic correlation is required. After determining the correlation, the vulnerability index (V) may be used to calculate μ_d and to evaluate the damage scenario (Vicente et al. 2011).

5.2.1 TOPSIS method

The vulnerability index was evaluated using an MCDM technique, namely the TOPSIS method (Hwang and Yoon 1981), which, due to its simplicity, is one of the most widely used approaches in decision-making, see (Gulum et al. 2021; Pathan et al. 2022). The TOPSIS method is a type of Multiple Attribute Decision Making (MADM) approach based on the concept that the best solution has the shortest distance from the positive ideal solution and the longest from the ideal negative one (Gulum et al. 2021). According to (Chakraborty 2022) the general MADM procedure starts with three elements: a set of alternatives $A_i (i = 1, 2, \dots, I)$, which represents the available options for the decision maker that needs to be ranked (in this case the buildings); the chosen attributes $C_j (j = 1, 2, \dots, J)$, which represent the factors that can influence the choice of the decision makers in ranking the alternatives (in this case the 14 parameters), and the weights of the parameters $W_j (j = 1, 2, \dots, J)$, which represents the relative importance of the attributes C_j respect to the objective of the decision-making process (in this case the calculated weights). Once these three components are identified, the TOPSIS method may be outlined, see (Chakraborty 2022) for a detailed explanation of the method.

The final step of the procedure allows to calculate the overall preference score V_i for each alternative A_i .

In the current study, the overall preference score V_i indicates how far an alternative is from the ideal negative solution: values close to 0 means that it is very close, i.e. the alternative is negative; values close to 1 mean that it is very far, i.e. the alternative is positive. In the present work, all attributes are taken as cost attributes, making the positive ideal solution the minimum value of performance ratings v_{ij} , see (Chakraborty 2022). So, the best alternative should be the one with the shortest distance from the ideal positive solution and the longest from the negative one. Due to this, the overall preference score gives back the highest values for the best alternatives (highest distance from the negative solution) and the lowest values

Table 4 Classes scores for the 14 parameters

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	0.041	0.055	0.051	0.065	0.044	0.081	0.066	0.046	0.072	0.071	0.061	0.074	0.052	0.059
B	0.094	0.118	0.087	0.136	0.096	0.114	0.121	0.070	0.123	0.110	0.128	0.138	0.076	0.083
C	0.219	0.263	0.205	0.317	0.302	0.249	0.232	0.282	0.218	0.239	0.181	0.275	0.233	0.321
D	0.645	0.564	0.657	0.482	0.557	0.556	0.581	0.602	0.587	0.581	0.629	0.513	0.638	0.537

for the worst (lowest distance from the negative solution). However, the concept of the vulnerability index is the opposite: the highest value of the vulnerability index means the worst alternative and the lowest value of the vulnerability index means the best alternative. Therefore, the subsequent transformation becomes necessary:

$$I_V = 1 - V_i \quad (6)$$

5.2.2 GNDT-macroseismic correlation

The present study adopted a vulnerability index I_V composed of 14 parameters selected based on the available data for the case study area. Even if the parameters used are different, the approach may be carried out in a similar way to the one proposed by GNDT (GNDT 1993), as explained in (Vicente et al. 2011). However, the proposed method utilizes the Macroseismic Method (Lagomarsino and Giovinazzi 2006) to calculate vulnerability curves and the corresponding mean damage grade μ_D , so that a correspondence between the two methodologies must be established. As explained in (Kassem et al. 2020) the GNDT method originally consisted of 11 criteria that indicate the most critical characteristics of a structure that may influence its seismic response. Each parameter has four vulnerability classes ranging from less vulnerable to most vulnerable (A, B, C, D), with respective scores. Then to each parameter, a weight is assigned to represent the importance of the parameter in the seismic vulnerability of the building. Finally, the weighted sum of the parameters represents the vulnerability index I_V , which is usually normalized between 0 (less vulnerable) and 100 (more vulnerable). The vulnerability index I_V may then be correlated with the damage factor (d) using the vulnerability functions provided by (Benedetti and Petrini 1984), derived from past-earthquake data. Here, d ranges from 0 (no damage) to 1 (total damage), and represents the ratio of repair cost to replacement cost (Kassem et al. 2020). Instead, the Macroseismic method, developed for vulnerability assessment in Europe, is also known as the RISK-UE project (Milutinovic and Trendafiloski 2003). The Risk-UE project, funded by the European Union, aimed to facilitate the development of a comprehensive seismic risk assessment method shared by European countries. As a result, this study used an index-based approach, which was evaluated in seven cities throughout the continent (Kassem et al. 2020). As explained in (Kassem et al. 2020), in this methodology, buildings are classified into typological classes, i.e., masonry, reinforced concrete, steel, and timber, based on the Building Typology Matrix (BTM), and then distributed into six vulnerability classes (A to F), from most vulnerable to least vulnerable. Furthermore, the damage levels are derived from the European Macroseismic Scale (EMS-98), (Grünthal 1998).

The vulnerability of each building is calculated starting from a vulnerability index for the corresponding building class V_I^* , which is modified by adding a regional vulnerability factor ΔV_R , i.e. a measure of how susceptible a region is to damage from a natural hazard, and some behaviour modifiers ΔV_m that alters the vulnerability index by taking into account specific characteristics, such as the plan regularity, construction quality or state of preservation (Kassem et al. 2020; Milutinovic and Trendafiloski 2003). Then, the mean damage grade (μ_D) can be estimated by using the formulation proposed by (Bernardini et al. 2007) that relates the expected mean damage ($0 < \mu_D < 5$), for a given macroseismic

Table 5 Weights associated with the selected parameters

	Parameter	Weight (W_i)
Structural system		
1.	Nature of vertical structures	0.0703
2.	Conventional strength	0.1295
3.	Topographic condition	0.0161
4.	Number of floors	0.0243
5.	Horizontal diaphragms	0.0909
Regularities		
6.	In-plane regularity	0.0615
7.	Vertical regularity	0.0633
8.	Wall façade openings and alignments	0.0569
Aggregate interaction		
9.	Presence of adjacent buildings with different height	0.0335
10.	Position of the building in the aggregate	0.1406
11.	Structural or typological heterogeneity among adjacent structural units	0.0449
12.	Percentage difference of opening areas among adjacent façades	0.0183
Conservation status		
13.	Conservation status	0.2230
Urban interaction among existing aggregates		
14.	Aggregate distance	0.0269

intensity level I , in terms of vulnerability index V , with a ductility factor Q (Kassem et al. 2020; Vicente et al. 2011).

As previously described, the GNDT and Macroseismic approaches use distinct intensity parameters (specifically PGA and EMS-98 macroseismic intensity), as well as different damage levels (namely d and μ_D), respectively. As a result, a comparison is possible, but a correlation between the two intensity parameters and the two distinct damage metrics must be established by some type of conversion (Kassem et al. 2020; Vicente et al. 2011). The approach used to compare the two alternative methods is fully documented in (Vicente et al. 2011). Once the correlation $PGA - I_{EMS-98}$ and $d_e - \mu_D$ have been carried out, it is then possible to compare the vulnerability curves of both methods in a $I_{EMS-98} - \mu_D$ graph (see Fig. 6), as explained in (Vicente et al. 2011). In magenta, the vulnerability curves are derived from the (GNDT 1993) approach, while in blue the vulnerability curves are obtained from (Milutinovic and Trendafiloski 2003).

Unlike the methodology proposed by (Vicente et al. 2011), by comparing the two vulnerability curves concerning the mean of each damage grade ($\mu_{D1} = 0.5$, $\mu_{D2} = 1.5$, $\mu_{D3} = 2.5$, $\mu_{D4} = 3.5$, $\mu_{D5} = 4.5$), see the red dashed line in Fig. 6, a linear regression was adopted to propose a new correlation:

$$V = 0.6125 + 0.008 I_V \quad (7)$$

The proposed relationship enables the vulnerability index I_V of the GNDT method to be converted into a vulnerability index V according to the Macroseismic method. The existing literature (Maio et al. 2015; Ortega et al. 2019b; Vicente et al. 2011, 2014), has provided a GNDT-Macroseismic correlation, and, for a clear understanding of the differences between

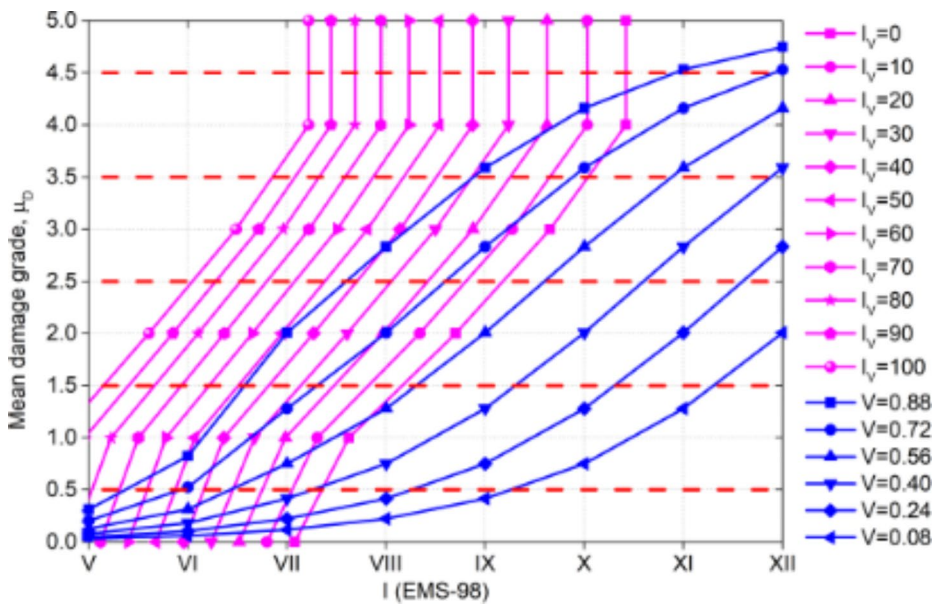


Fig. 6 Comparison of the vulnerability curves between GNDT (magenta) and macroseismic method (blue)

Table 6 Comparison between the proposed formulation and the literature

$V - I_V$ correlation	Sources	% difference for $I_V = 50$
$V = 0.6125 + 0.008 I_V$	Proposed	–
$V = 0.58 + 0.0064 I_V$	(Maio et al. 2015)	13%
$V = 0.46 + 0.012 I_V$	(Ortega et al. 2019b)	4%
$V = 0.56 + 0.0064 I_V$	(Vicente et al. 2011)	15%
$V = 0.592 + 0.0057 I_V$	(Vicente et al. 2014)	15%

the proposed formulation and existing ones, Table 6 illustrates the percentage variances among the formulations herein adopted, with an average I_V value set at 50.

As it is possible to observe from Fig. 7, the proposed correlation is adequate. It tends to overestimate the values of V respect to the (Maio et al. 2015; Vicente et al. 2011, 2014), especially for high values of I_V , with a difference between 13 and 15% for a $I_V = 50$. However, with respect to the formula provided by (Ortega et al. 2019b), the proposed formulation tends to underestimate V values for high I_V values and overestimate them for low I_V values. Specifically, for an I_V value of 50, the difference is approximately 4%. In contrast, (Ortega et al. 2019b) calibrated the expression based on post-earthquake damage data availability on the island of Faial in Azores, distinguishing it from the other approaches.

5.2.3 Vulnerability assessment

The vulnerability evaluation was completed for all 324 URM “Pombalino” type buildings. After determining the class scores and weights of each of the 14 parameters (see Sect. 5.1.2), the vulnerability index I_V for each building was calculated by first assigning a class from A

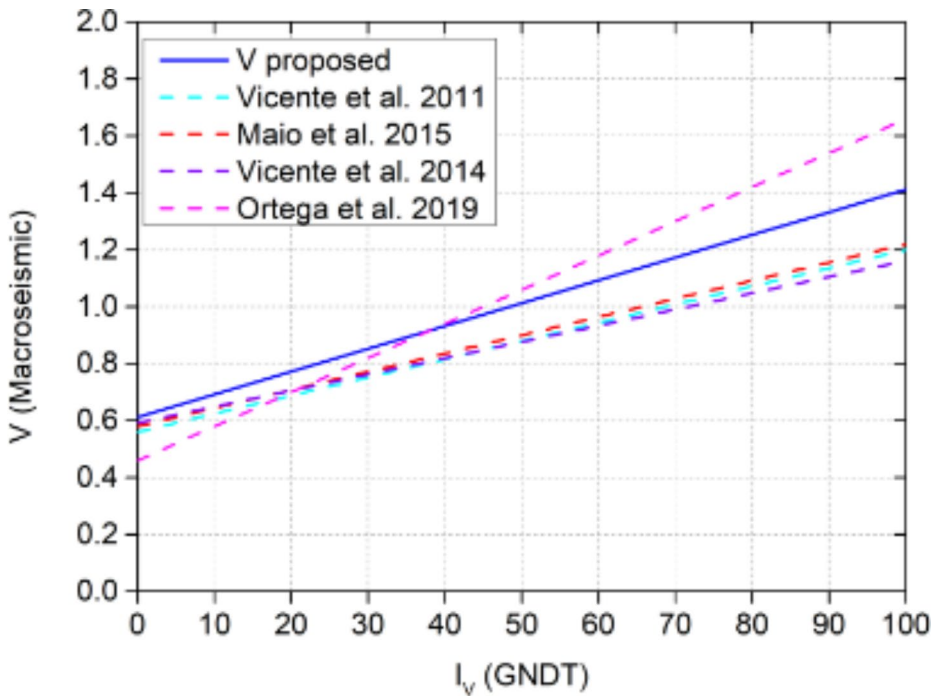


Fig. 7 Comparison of the proposed formulation with literature

to D to each of the 14 parameters and then applying the TOPSIS procedure (see Sect. 5.2.1). As a result, for each building, an I_V ranging from 0 to 1 has been calculated, which is subsequently reported on a scale of 0–100 to maintain the correspondence with the GNDT scale, as shown in Fig. 8a. Subsequently, the conversion into vulnerability index (V), according to the macroseismic method (Lagomarsino and Giovinazzi 2006; Milutinovic and Trendafiloski 2003) has been provided through Eq. (7), as depicted in Fig. 8b.

The normalized vulnerability index (V) may be associated with each macroseismic vulnerability class according to the EMS-98 scale (see Table 7), as defined by (Bernardini et al. 2007). Masonry structures, for example, are often classified as the most susceptible classes between A and C, whereas reinforced concrete buildings are typically classified as C, D, E, and, on rare occasions, F (Kassem et al. 2020). According to this subdivision, it is possible to conclude that, for this building sample (324 buildings), 35 buildings belong to vulnerability class A ($V_{mean, A} = 1.07$), while the majority of them (170) belong to class B ($V_{mean, B} = 0.77$), and 119 buildings belong to class C ($V_{mean, C} = 0.69$), see Fig. 8c. The average normalized index value, V_{mean} , is 0.77, corresponding to the most likely class B. These findings indicate that the Pombalino typology aligns with the M3.1 class (URM-wooden slabs) in the Risk-UE Building Typology Matrix (BTM) (Milutinovic and Trendafiloski 2003).

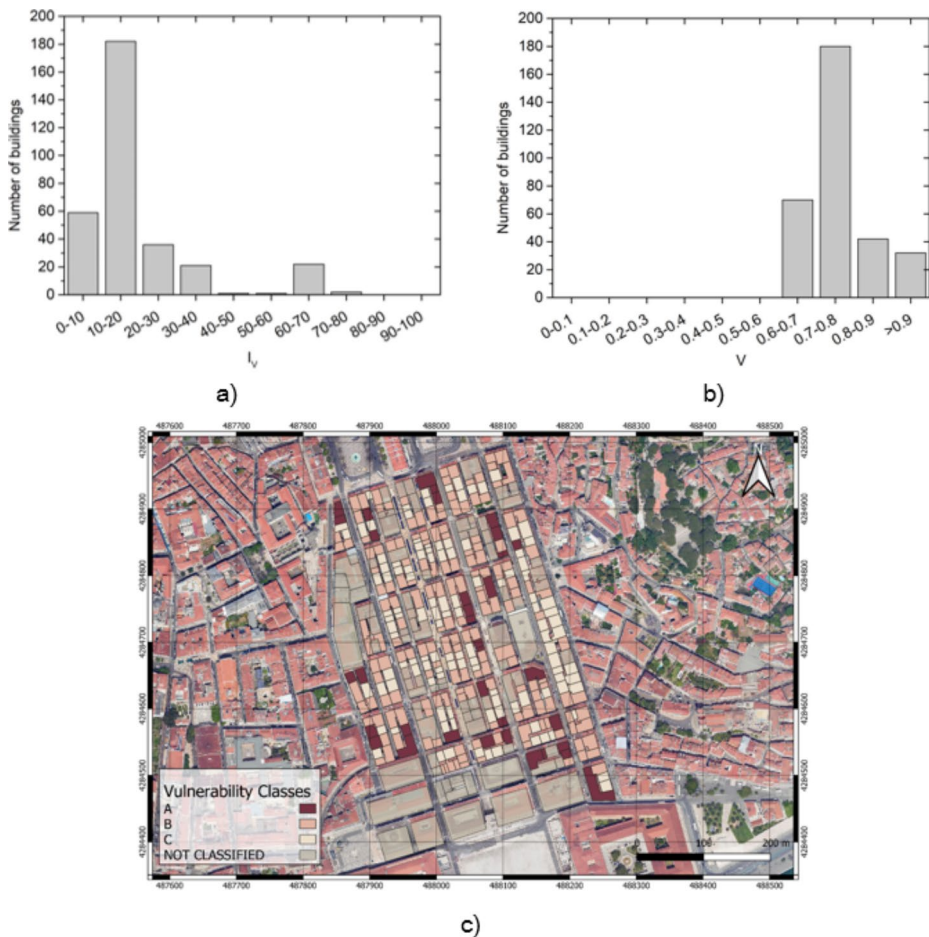


Fig. 8 Vulnerability distribution of Baixa Pombalina: **a** vulnerability index I_V ; **b** normalized vulnerability index V ; **c** spatial distribution of vulnerability classes within the case study area

Table 7 Vulnerability values (V) of the macro-seismic method for each corresponding vulnerability class from Risk-UE (Milutinovic and Trendafiloski 2003), as reported in (Kassem et al. 2020)

Vulnerability Class EMS-98	A	B	C	D	E	F
Vulnerability index (V)	0.88	0.72	0.56	0.40	0.24	0.08

5.2.4 Sensitivity analysis

The approach detailed here involves assessing different parameters to evaluate alternatives and is based on an essential decision-making process for assigning weights to the aforementioned parameters. In this study, it is deemed especially relevant to assess the sensitivity to the value of the parameters' weights provided by utilising the Saaty scale in the AHP approach (Saaty 1980). The sensitivity analysis, when applied to the values assigned to the weights of the criteria, gives a quantitative assessment of the real influence of the decision

Table 8 Sensitivity analysis

Parameter c_k	Current weight w_k	Minimum change $\delta_{k,i,j}$	Criticality criterion D'_k	Sensi- tivity criterion $sens(c_k)$
1.	0.0703	—	—	0
2.	0.1295	—	—	0
3.	0.0161	0.091	565%	0.002
4.	0.0243	—	—	0
5.	0.0909	—	—	0
6.	0.0615	0.086	139%	0.007
7.	0.0633	0.159	251%	0.004
8.	0.0569	—	—	0
9.	0.0335	—	—	0
10.	0.1406	0.140	99%	0.010
11.	0.0449	0.097	217%	0.005
12.	0.0183	—	—	0
13.	0.2230	0.222	100%	0.010
14.	0.0269	0.682	2531%	0.000

maker's judgements on the selection of the best alternative. In the current study, the sensitivity analysis serves to illustrate if the optimal solution changes with minor modifications in the weight values, i.e. if the selection of the best alternative is influenced by the decision maker's choices (Caterino et al. 2008; Gao and Hailu 2013). The sensitivity analysis is conducted for each criterion by calculating the weight of the parameter that causes the best alternative to change. In this investigation, the weight is set to move between 0 and 1 in small increments (in this study assumed equal to 0.001) until the first alternative A_1 changes (Caterino et al. 2008; Chakraborty and Banik 2006; Gao and Hailu 2013).

Two further measures can be defined. The first one is the so-called criticality degree of criterion, D'_k , which indicates the smallest percent change in the value of the criterion's weight, $\delta_{k,i,j}$, that would lead to a change in the best alternative, while the second term is the sensitivity of the solution, $sens(c_k)$, to each criterion and is determined by computing the reciprocal of the corresponding D'_k value (Chakraborty and Banik 2006; Gao and Hailu 2013):

$$sens(c_k) = \frac{1}{D'_k} \text{ for all } 1 \leq k \leq n \quad (8)$$

As $\delta_{k,i,j} D'_k$ values increase, the solution becomes more stable, resulting in reduced sensitivity levels for each criterion. Robust criteria are those that do not affect the identified optimal solution, regardless of their weight (ranging from 0 to 1). In this latter case, the $\delta_{k,i,j}$ and D'_k values cannot be defined, and the sensitivity equals zero. Identifying a consistent number of robust criteria gives appropriate stability to the decision-making process, which is less influenced by the decision-makers individual preferences (Caterino et al. 2008; Gao and Hailu 2013; Triantaphyllou and Sánchez 1997).

As reported in Table 8, criteria 10 and 13 are "critical" since they have the smallest D'_k (99% and 100% respectively), and consequently the highest sensitivity (0.010) of the solution. According to (Caterino et al. 2008), when weight changes are quantified in rela-

tive terms, the most sensitive criterion is frequently the one which has the highest value of weight.

Furthermore, seven of the fourteen criteria do not affect the best alternative when the criteria weight changes, hence they may be considered robust. As a result, the approach may be categorised as reasonably stable; nevertheless, sensitive criteria, i.e. 10 and 13 of the previously mentioned Table 8, must be carefully evaluated.

5.2.5 Damage and fragility evaluation

Once the vulnerability index (V) has been determined, DPMs and fragility curves can be evaluated. In the current study, the DPMs and fragility curves were estimated for each vulnerability class (A, B, C) by calculating the expected damage of each class through a macroseismic method. This utilises a well-known formulation that correlates the expected damage of a building μ_D , evaluated according to the EMS-98 scale (Grünthal 1998), with macroseismic intensity (I), (Chieffo et al. 2023):

$$\mu_D = 2.5 \left[1 + \tanh \left(\frac{I + 6.25 V - 13.1}{Q} \right) \right] \quad (9)$$

The ductility factor normally indicated with Q , which can range from 1 to 4, was herein considered to be 2.3 (Lagomarsino and Giovinazzi 2006). Subsequently, six damage thresholds ($DS_k = 0, 1, 2, \dots, 5$) were defined according to the EMS-98 damage scale (Grünthal 1998), to which correspond certain μ_D thresholds: DS_0 , no damage ($\mu_D \leq 0.5$); DS_1 , negligible ($0.5 < \mu_D \leq 1.0$); DS_2 , moderate ($1.0 < \mu_D \leq 2.0$); DS_3 , substantial ($2.0 < \mu_D \leq 3.0$); DS_4 , near collapse ($3.0 < \mu_D \leq 4.0$) and DS_5 , collapse ($4.0 < \mu_D \leq 5.0$). The expected damage and relative DPMs for classes A, B and C have been evaluated for each scenario under consideration, refers from Figs. 9, 10, 11 and 12. However, lower return periods (2–50–100 years) exhibit less damage (D0–D1–D2) especially for classes B–C, for this reason only the

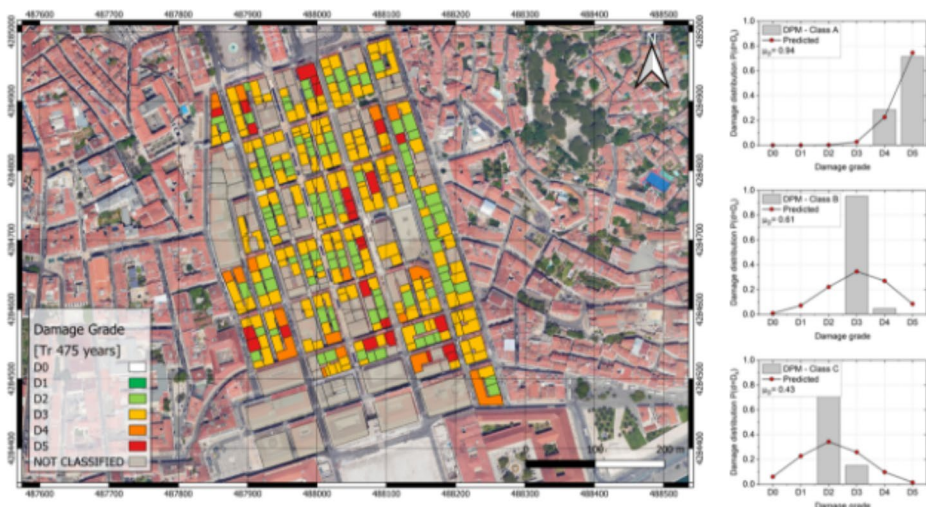


Fig. 9 Expected damage scenario for $T_R = 475$ years and related DPM for the examined building typologies

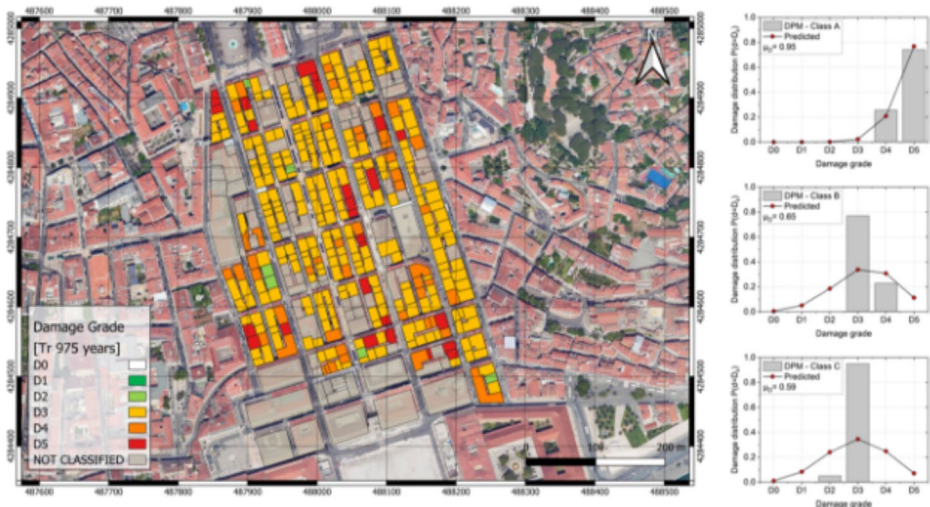


Fig. 10 Expected damage scenario for $T_R = 975$ years and related DPM for the examined building typologies

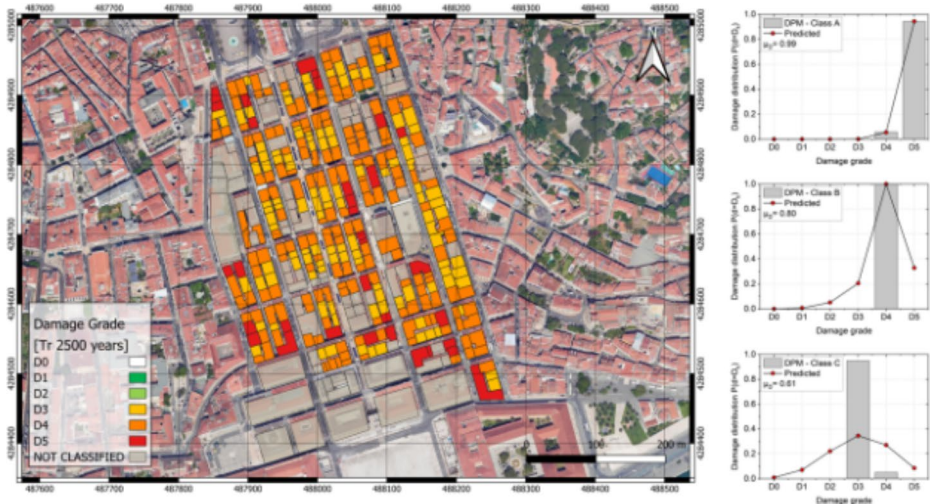


Fig. 11 Expected damage scenario for $T_R = 2500$ years and related DPM for the examined building typologies

most significant case scenario ($T_R = 475$, $T_R = 975$, $T_R = 2500$ and $T_R = 5000$) are reported below.

Moreover, the fragility curves, which represent the probability that the damage is equal to or higher than the given damage state DS_k , for a specific intensity, may also be used to assess the vulnerability of the area (Lagomarsino and Giovinazzi 2006). To create fragility curves for the different vulnerability classes, the mean vulnerability index (V) associated with each class (A, B, C) have been evaluated, see Table 9.

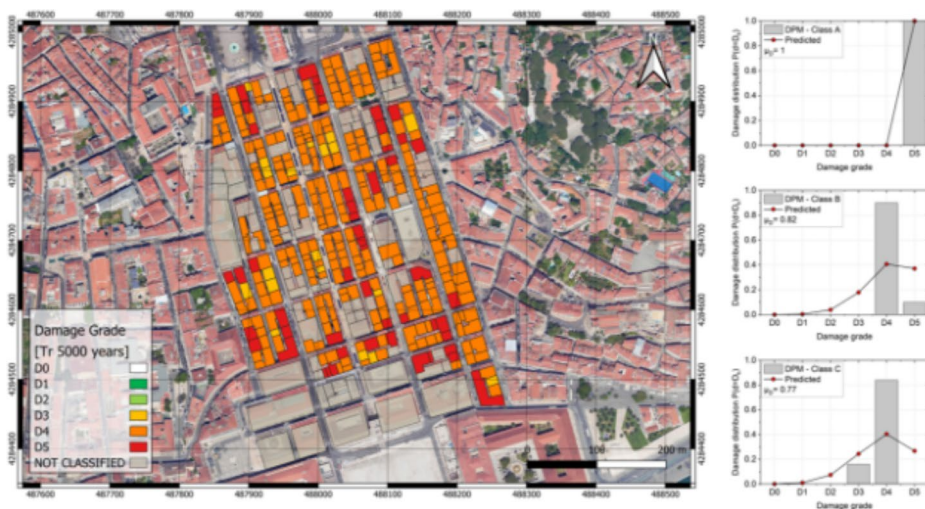


Fig. 12 Expected damage scenario for $T_R = 5000$ years and related DPM for the examined building typologies

Table 9 Mean vulnerability index (V) associated with each vulnerability class

Vulnerability class	Mean vulnerability index (V)
A	1.07
B	0.77
C	0.69

Starting from the above-introduced index values depicted in Table 9, the mean damage grade μ_D can be evaluated for each vulnerability class for a given intensity of an earthquake, see Eq. (9). The expected damage can be calculated through a probability distribution, with a binomial probability function (Lagomarsino and Podestà 2004):

$$p_k = \frac{5!}{k!(5-k)!} \left(\frac{\mu_D}{5} \right)^k \left(1 - \frac{\mu_D}{5} \right)^{5-k} \quad (10)$$

where μ_D is the mean damage grade ($0 < \mu_D < 5$) and p_k is the probability of having a damage of level k ($k=0, 1, 2, 3, 4, 5$). The fragility curves may then be developed for each vulnerability class using the binomial distribution, as described by (Chieffo et al. 2022; Lagomarsino and Podestà 2004). These curves describe the probability of the predicted damage grade D_i exceeding a predefined damage grade D_k at a given macroseismic intensity (I). They can be interpreted as the cumulative probability mass function of the expected probability (Chieffo et al. 2022):

$$P(D_i \geq D_k | I) = \sum_{k=0}^5 p_k \quad (11)$$

As pointed out by (Chieffo et al. 2022), the macroseismic method has limited application since it is computed in terms of macroseismic intensity, whereas the PGA is commonly used for scenario simulations. Thus, a correlation between macroseismic intensity and PGA may be utilised to evaluate fragility curves in terms of PGA. In this case study, the fragility curves were defined by accounting for the I-PGA relationship, as follows (Vicente et al. 2011):

$$\ln(y) = a \cdot I_{MCS} - b \quad (12)$$

However, it is worth noting that, since the derivation of the correlations involves different urban settings and earthquakes, there is an important estimated dispersion of the correlations available in the literature (Chieffo et al. 2022).

Subsequently, the obtained fragility functions were compared to those provided for the appropriate building type by the Building Typology Matrix (BTM), i.e. M3.1 typology (URM-wooden slabs), see (Milutinovic and Trendafiloski 2003), by applying the formulae provided in the above-introduced Eqs. (10)–(11). These steps allowed to comprehend the key differences in the expected damage probability, between the fragility curves of the proposed method (solid line) and the ones derived from BTM typology (dashed line), see Fig. 13. According to the BTM, the typology M3.1 has as most probable value of the vulner-

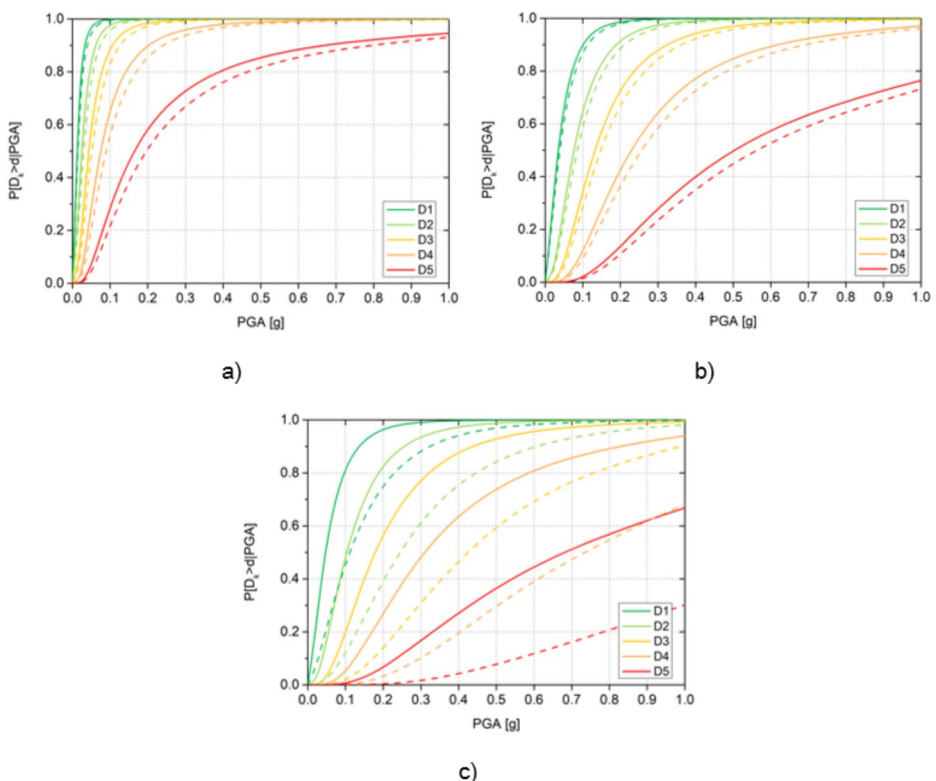


Fig. 13 Fragility curves for different vulnerability classes: **a** class A; **b** class B; **c** class C

ability index (V_I^*) a value equal to 0.74, and upper (V_I^{max}) and lower (V_I^{min}) bounds of the possible values equal to 1.02 and 0.46, respectively.

Calculating the fragility curves for these three distinct values reveals that the curves for classes A and B practically overlap, however, the suggested approach for vulnerability class C typically overestimates the damage probability. Thus, the proposed method may be regarded as trustworthy even if it produces higher damage probability estimates for class C, resulting in a safety condition for the predicted scenario analysis. This discrepancy might be explained by the fact that the vulnerability index (Milutinovic and Trendafiloski 2003) has been statistically calibrated based on a larger number of data (Chieffo et al. 2022).

6 Loss assessment model

The impact of the earthquake on Baixa Pombalina was assessed for individual buildings and the whole building stock in terms of direct economic losses.

According to (Nassirpour 2018), monetary losses may be assessed using the obtained fragility functions, through the Mean Damage Ratio (MDR). The Mean Damage Ratio (MDR) is the expected value of the damage ratio (DR) for a given seismic intensity (I) and is obtained by multiplying the probability of each damage state $P(DS_k|I)$ by the associated damage ratio DR_{DS_k} (Nassirpour 2018):

$$MDR_{DS|I} = \sum_{DS=1}^k P(DS_k|I) \cdot DR_{DS_k} \quad (13)$$

As explained in (Nassirpour 2018), the damage ratio (DR) measures the cost of damage by relating structural damage to economic losses and may be broadly defined as the ratio of the repair cost of a building to its replacement value. Indeed, in seismic loss assessment, a damage ratio DR_{DS_k} is assigned to each of the considered damage states DS_k , and is obtained by either expert judgement or empirical post-earthquake loss data analysis (Damage-to-Loss model).

In the current study, the Damage-to-Loss model adopted is the one provided by (Roca et al. 2006), which evaluated the damage ratios DR_{DS_k} , 0–0.01–0.2–0.4–0.8–1, according to the respective damage state DS_k experienced by the building, 0–1–2–3–4–5 respectively.

Thus, the MDR curves have been derived for each vulnerability class (A, B, C) starting from the associated probabilities calculated according to Eq. (10) and using this Damage-to-Loss model. In Fig. 14 the MDR curves for each vulnerability class are shown.

According to (Nassirpour 2018), by multiplying the MDR by the building's replacement value, the estimated total damage can be expressed in terms of monetary value. It is important to note that generally, damage ratios are multiplied by replacement value (Babić et al. 2021; Nassirpour 2018). However, due to a lack of data, the latter was not considered in this study, and instead the market value was used (E_i), see Eq. (1) in Sect. 3. As a result, losses are calculated as a percentage of the market value, which indicates the reduction in a building's market value caused by an earthquake.

Based on the MDR calculated for each vulnerability class (A, B, C), the losses of i -th building in the simulated scenario l -th, have been calculated by multiplying the $MDR_{i,l}$ of the respective vulnerability class by the monetary exposure E_i :

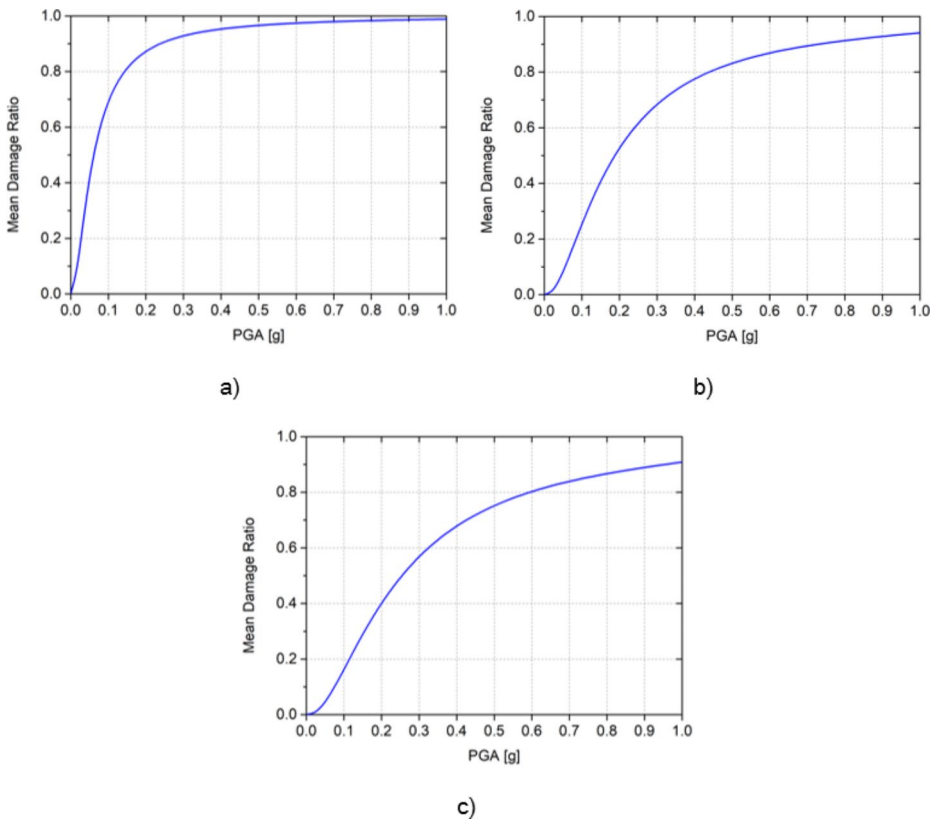


Fig. 14 MDR curves for different vulnerability classes: **a** class A; **b** class B; **c** class C

$$L_{i,l} = E_i \cdot MDR_{i,l} \quad (14)$$

The current study evaluates losses using risk curves that, for the selected hazard, correlate the annual frequency of exceedance to the chosen loss metric. So, considering all possible hazard occurrences the Loss Exceedance Curve may be built, Fig. 15a, see (Mascheri et al. 2024). Another type of curve analysed is the Probable Maximum Loss curve (PML), which relates losses to the return period, Fig. 15b, (Mascheri et al. 2024).

The above-introduced figure indicates that, for longer return periods, building losses are higher, see Table 10: for a 2-year return period, earthquake losses are 41 M€, for a 475-year scenario, losses are 595 M€ while for a 5000-year return period, losses are 1108 M€.

7 Conclusions

The present research proposed a seismic loss assessment method for a subsector of Lisbon's city centre, known as Baixa Pombalina. The study employed an index-based method to analyse the vulnerability of ordinary unreinforced masonry (URM) structures, highlighting

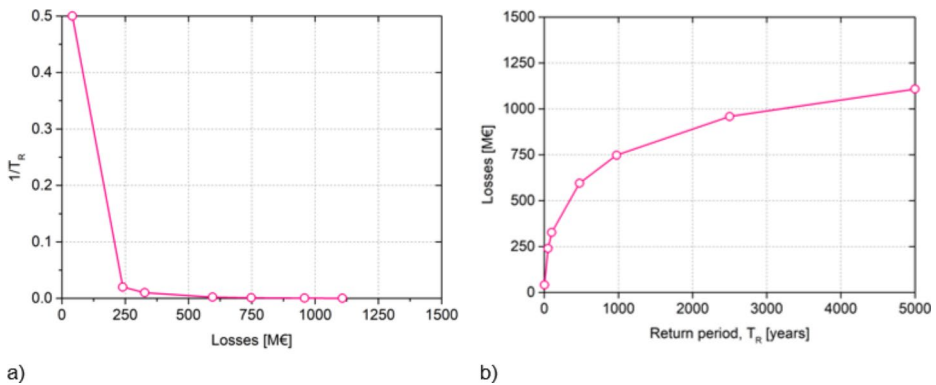


Fig. 15 Loss assessment: **a** LEC, **b** PML

Table 10 Evaluated seismic losses in millions of euros (M€)

Return period T_R (years)	Total earthquake losses - MDR (M€)	Earthquake losses for class A MDR (M€)	Earthquake losses for class B MDR (M€)	Earthquake losses for class C MDR (M€)
2	41	28	10	3
50	240	118	92	31
100	327	141	138	48
475	595	185	295	116
975	748	199	387	162
2500	959	212	513	234
5000	1108	219	599	290

the significance of historical urban areas in risk assessment and mitigation (Arrighi et al. 2023).

The method required a thorough examination of exposure, hazard, and vulnerability. The first step was to assess an exposure model to better understand the primary features and monetary exposure of the structures being investigated. Data were gathered via remote resources such as Google Maps, Census data, and literature. According to the statistics, 82% of the buildings examined are of the “Pombalino” type, while the other 18% are RC. The monetary exposure was calculated by multiplying the market value by the total building floor area, which simplified the loss assessment process.

The seismic hazard was analysed using empirical formulae to obtain the PGA for the considered return periods, which was then transformed into EMS-98 macroseismic intensity. It has been shown that the empirical formulation used by (Lantada et al. 2018) slightly overestimates the PGA when compared to the PGA provided by the hazard map of the “2020 European Seismic Hazard Model (ESHM20)” hazard model (Danciu et al. 2021), resulting in safe conditions. The seismic vulnerability was studied using an index-based method that thoroughly investigated the potentialities of Multi-Criteria Approaches. The procedure began with the selection of the most significant criteria available in the literature (based on the features of the area and data availability), followed by the use of the AHP technique to evaluate the class scores (from A to D) and weights of the parameters. The

vulnerability index I_V was then calculated through TOPSIS approach, and a correlation between the GNDT and the macroseismic method was proposed in order to derive a macroseismic vulnerability index (V) and determine the mean damage grade of each structure. The main outcomes showed that the mean vulnerability index (V_{mean}) is 0.77 and, and that 35 buildings belong to vulnerability class A ($V_{mean, A} = 1.07$), while the majority of them (170) belong to class B ($V_{mean, B} = 0.77$), and 119 to class C ($V_{mean, C} = 0.69$), according to the EMS-98 vulnerability classes described by (Bernardini et al. 2007). Subsequently, the evaluation of the mean damage grade μ_D for each vulnerability class, enabled the evaluation of fragility curves and Mean Damage Ratio (MDR) curves. The final phase involves assessing earthquake consequences in terms of economic losses using the MDR calculated through the probability of each damage state for a specific earthquake intensity.

The results show that earthquake losses are roughly 41 M€ for a 2-year return period, 595 M€ for a 475-year scenario, and 1108 M€ for a 5000-year return period.

The study provided a novel strategy for assessing Baixa Pombalina's seismic vulnerability and losses by giving a simplified method for forecasting the probability of damage and loss scenarios. Furthermore, the index-based vulnerability model proposed was adapted to the research location by utilising existing literature and data. The use of MCDM approaches strengthens the methodology and allows it to be readily adopted and replicated in many settings. The sensitivity analysis and comparison to the fragility curves derived from the BTM typology demonstrated the effectiveness of the approach. However, further advances might be included in future works. One of the most significant disadvantages is the data's reliability. However, the data collection process might be improved by conducting building surveys, on-site inspections, or utilising a more accurate dataset. This assessment marks the initial phase of a 4-year project funded by the Fundação para a Ciência e a Tecnologia (FCT), developed in collaboration with the Municipality of Lisbon. Consequently, a more comprehensive inspection and analysis of data acquisition will be conducted shortly. Furthermore, the approach might be enhanced by including out-of-plane mechanisms or other relevant characteristics, resulting in a new calibration and vulnerability assessment. Finally, this method adds new perspectives to seismic risk analysis for metropolitan areas, setting the way for future, more detailed risk evaluations in Lisbon. This technique gives valuable information for informed decision-making in disaster management and urban planning, ultimately leading to better resilience and risk reduction measures in the examined region. Indeed, the methodology can help decision-makers prioritise future risk reduction efforts and tailor urban risk mitigation strategies.

Appendix

The innovative parameters used in the proposed study are described in the following [Appendix](#), with emphasis on the description, class, and associated main sources. For an explanation of the other well-known parameters, please see the references in Table 2.

Conventional strength

(Formisano et al. 2015; GNDT 1993).

This parameter provides an estimate of the in-plane resistance of a masonry wall, through the use of a simplified procedure adopted in the absence of detailed information regarding the wall arrangement. The evaluation is carried out through the characteristic value of the tangential strength of the masonry τ_0 , based on the classification proposed by the Italian Code NTC 2018 (Ministero delle Infrastrutture e dei Trasporti 2018) and CNTC 2019 (Ministero delle Infrastrutture e dei Trasporti 2019) in the table C8.5.I, see Table 11.

Table 11 Strength values of different types of masonry (Ministero delle infrastrutture e dei Trasporti 2019)

Masonry typology	f_c [MPa] min-max	τ_0 [MPa] min-max	f_{v0} [MPa] min-max	E [MPa] min-max	G [MPa] min-max	ρ [kN·m ⁻³] min-max
Irregular stone masonry (pebbles, erratic, irregular stones)	1.0–2.0	0.018–0.032	–	690–1050	230–350	19
Uncut stone masonry with inhomogeneous thickness of leaves	2.0	0.035–0.051	–	1020–1440	340–480	20
Regular stone masonry with good bonding	2.6–3.8	0.056–0.074	–	1500–1980	500–660	21
Soft stone masonry (tuff, limestone, etc.)	1.4–2.2	0.028–0.042	–	900–1260	300–420	13–16
Regular soft stone masonry (tuff, limestone, etc.)	2.0–3.2	0.04–0.08	0.10–0.19	1200–1620	400–500	
Dressed rectangular (ashlar) stone masonry	5.8–8.2	0.09–0.12	0.18–0.28	2400–3300	800–1100	22
Solid brick masonry with lime mortar	2.6–4.3	0.05–0.13	0.13–0.27	1200–1800	400–600	18
Hollow bricks (voids < 40%) with cement mortar	5.0–8.0	0.08–0.17	0.20–0.36	3500–5600	875–1400	15

The identified shear strength τ_0 , divided in range values (min-max), is selected based on the Knowledge Level (KL) as proposed by the Italian regulation:

- KL1: - Resistances: the minimum values of the intervals reported in Table 11.
- KL2: - Resistances: the average values of the intervals reported in Table 11.
- KL3: - Resistances calculated according to the methodology explained in CNTC 2019 (Ministero delle Infrastrutture e dei Trasporti 2019), which requires an in situ test.

Once the value of τ_0 is identified, the α factor is normalized according to the following formula:

$$\alpha = \tau_0^{norm} = \frac{\tau_0 - \tau_0^{min}}{\tau_0^{max} - \tau_0^{min}}$$

where τ_0 is the tangential strength value depicted in table C8.5.I. chosen according to both, the type of masonry and the Knowledge Level (KL), respectively; τ_0^{min} is the minimum tangential tension value among all the types of masonry, based on KL; τ_0^{max} is the minimum tangential tension value among all the types of masonry, based in KL.

These two latter values are taken from the respective range according to the KL. As an example, if the Knowledge Level is LC1 the τ_0^{min} and the τ_0^{max} have to be taken among the minimum values of all the masonry typologies. If the Knowledge Level is LC2 or LC3 the τ_0^{min} and the τ_0^{max} have to be taken among the medium values of all the masonry typologies.

The normalized tangential strength corresponds to α value, which allows to identification of the appropriate vulnerability class (Table 12).

Table 12 Parameter 2: conventional strength

Buildings with $\alpha \geq 1.0$	A
Buildings with $0.6 \leq \alpha < 1.0$	B
Buildings with $0.4 \leq \alpha < 0.6$	C
Buildings with $\alpha < 0.4$	D

Aggregate distance

(Brando et al. 2017).

This parameter considers the potential interaction among aggregates, which might be critical in the case of an earthquake in an urban setting. Specifically, the influence of the overturning mechanisms of the aggregate’s façade (or a portion of it) on the prospicient aggregate one is considered. To do this, the orthogonal distance, d , between two aggregates is considered to evaluate the minimum safety condition. In this context, if the evaluated aggregate’s façade is located at a distance d from the frontal aggregate, the vulnerability class is selected based on the following range (Table 13).

Table 13 Parameter 14: aggregate distance

Aggregates with a distance $d \geq 20$ m	A
Aggregate with a distance $10 \text{ m} \leq d < 20$ m	B
Aggregate with a distance $5 \text{ m} \leq d < 10$ m	C
Aggregate with a distance $d < 5$ m	D

Vulnerability class A is attributed to buildings with higher distances from other aggregates ($d \geq 20$ m), and vulnerability class D to buildings which are very close to other aggregates ($d < 5$ m).

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Data availability The data are made available only upon private request to the first author.

Declarations

Conflict of interest The authors have no competing interests to declare.

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