

A VULNERABILITY INDEX-BASED APPROACH FOR SEISMIC RISK ANALYSIS OF MASONRY STRUCTURES WITHIN THE HISTORICAL CENTRE OF META (NAPLES, SOUTHERN ITALY)

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Abstract

Over the past decades, seismic events occurred in Italy have revealed urban vulnerabilities, especially in historical centres, where the built environment's peculiarities can lead to extensive damage. Urban exposure assessments contribute to understanding the seismic susceptibility of structural types, offering crucial insights for mitigation strategies. However, comprehensive data on exposed buildings for large-scale seismic risk assessments remain limited.

This study focuses on characterizing, assessing, and predicting damage scenarios for masonry buildings in the historical sector of Meta, a small town in the Naples district of Italy's Campania region.

Data on building exposure were collected using the CARTIS form, developed within the DPC–ReLUIS Italian research project, and then statistically processed and integrated into QGIS. Approximately 400 buildings were analysed, and based on masonry types, three CARTIS typologies were identified.

The seismic vulnerability assessment was then conducted using a vulnerability index method, which utilizes a specialized form for aggregated buildings, that are the most common housing type found in historical centres.

Finally, expected damage scenarios were simulated using an intensity prediction equation, estimating the expected damage level for each building, according to the European Macro-seismic Scale (EMS-98), based on the vulnerability index.

Keywords: CARTIS Form, Unreinforced Masonry Buildings, Vulnerability Index Method, Damage Scenarios.

1 INTRODUCTION

Mitigating seismic risk in historical areas and preserving their cultural heritage are pressing needs in earthquake-prone regions. In Italy, the strongest recent seismic events (e.g. 2009 L'Aquila earthquake and 2016-2017 seismic sequence in Central Italy) have highlighted how the vulnerability of the building stock can link to the medium-high seismic hazard, resulting in severe damage scenarios that involve socio-economic, cultural and life losses [1,2].

Typically, seismic risk analysis at territorial scale combines -according to a probabilistic approach- three indicators: Hazard (H), Exposure (E) and Vulnerability (V). Although these indicators are interrelated, they can be studied independently. Hazard, as the propensity of the site to be hit by earthquakes that can cause losses, is an exogenous factor that can not be controlled. Vulnerability is the propensity of structures of interest to be damaged by earthquakes having a given intensity and, thus, it mainly depends on the characteristics of these structures. Exposure is a measure of the consequences of vulnerability, so it depends on the function the structure performs and the assets it contains.

In historical urban contexts, exposure is influenced by high population density and the value of cultural heritage. On the other hand, vulnerability is specifically the result of a huge variety of factors, including age of construction -and thus the presence of proper earthquake-resistant design- maintenance over time, material quality, construction details, geometric layouts and -above all- the presence of buildings in aggregated configuration (i.e. buildings built in continuity one to each other over different periods, which may interact under seismic actions). This configuration, in fact, involves additional vulnerability factors such as structural heterogeneity, different heights and inter-storey heights [3-6].

For these reasons, a comprehensive building inventory is a preliminary and crucial step to develop effective large-scale vulnerability assessment and risk predictions. The required data, such as the type of lateral load-bearing system, the structural regularity and the current damage state, is usually collected through a variety of methodologies, including surveys, the use of image processing techniques and interviews with experts.

In this context, the CARTIS survey form- developed in the framework of the Italian DPC-ReLUIS project- represents a useful tool to detect and analyse structural types in homogeneous urban sectors [7]. The resulting building inventory can be used to carry out large-scale seismic vulnerability assessment with various methods available in current literature, such as the well-known vulnerability- index based approaches proposed by [8-10].

In this paper, a vulnerability index-based procedure for the seismic risk analysis of the historical center of Meta (Naples, Campania region, Italy) was carried out based on the CARTIS building inventory. The main outcomes of the study are the typological vulnerability curves, the distribution of the vulnerability index on the urban plan and the expected damage scenarios, that were simulated selecting different earthquake scenarios by the INGV hazard map for Meta's municipality. These outcomes can be useful for a rapid identification of the most vulnerable building aggregates to be subjected to more accurate analyses and for decision-making for risk mitigation.

2 THE CASE STUDY AREA

The municipality of Meta is located 111 m above sea level on the Sorrento Peninsula, in the Naples district (Fig.1). It covers an area of 2.5 km² and has a population of 7,727 residents. Following the first-level CARTIS form, the municipal territory has been divided into six urban sectors, each characterised by distinct construction periods. In addition to the historic centre, three expansion zones, an urban fraction named Alberi and an area of scattered houses

have been identified (Fig.1). The three expansion zones consist mainly of buildings constructed after 1950, with the percentage of reinforced concrete buildings ranging from 23% to 40%.

For these reasons, the proposed study focuses on the urban sector C02 (historic centre) considering its highest population and architectural value.

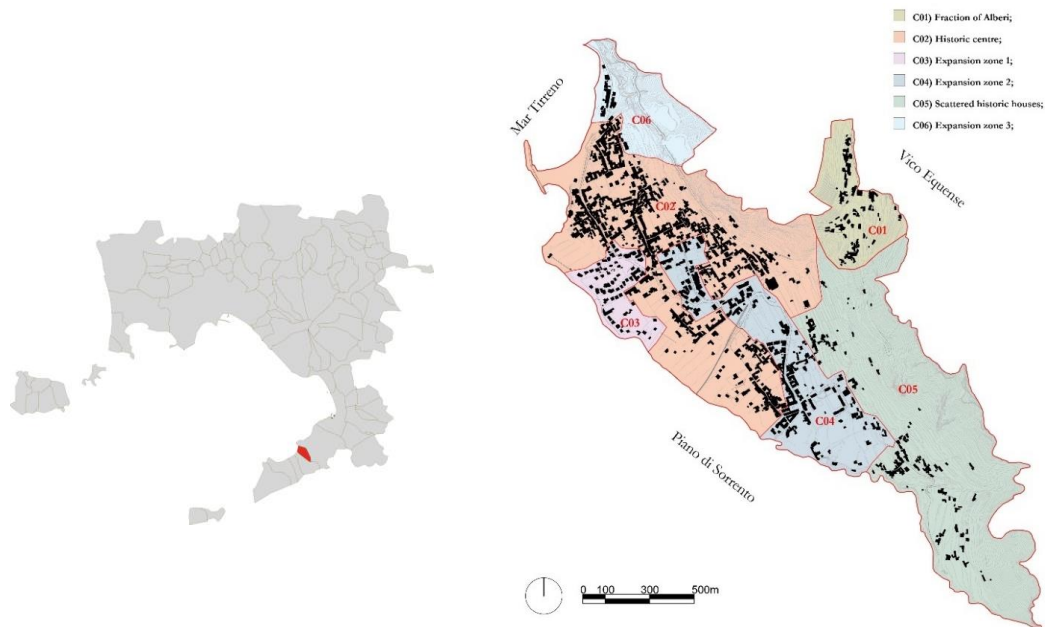


Figure 1: Location and urban sectors of the municipality of Meta (district of Naples).

According to the current national seismic classification, Meta belongs to the seismic zone 3 (low-medium seismicity), that may be subject to strong but rare earthquakes. Throughout its history, the area has been affected by significant seismic events, with the effects in terms of recorded macroseismic intensity values (I_s) shown in Table 1, where I_o represents the epicentral intensity according to the MCS scale.

I_s [MCS]	Year	Month	Day	Lat.	Long.	Epicentral area	I_o [MCS]	M_w
7-8	1930	07	23	41.07	15.32	Irpinia	10	6.67
7	1980	11	23	40.84	15.28	Irpinia-Basilicata	10	6.81
3	1996	04	3	40.66	15.45	Irpinia	6	4.9
2-3	1999	10	9	40.79	14.38	Area vesuviana	5	3.24

Table 1: The strongest earthquakes felt in Meta [11]

2.1 Inventory of the building stock

In the historic centre, data collection was based on Meta's 1998 Building Registry, as referenced in the municipality's General Plan (PRG), along with supplementary on-site inspections. Ordinary buildings, present in the number of about 450 (378 of which are masonry structures), are destined for residential use, to a lesser extent commercial.



(a) Figure 2: Some of the investigated buildings. (c)

The survey activities resulted in the typological and structural characterisation of the urban sector by identifying the prevailing building typologies. The distinguishing criterion for the building typologies was based on the type of masonry, referring to the AeDES (post-earthquake damage and safety assessment) manual [12] (Fig. 3).

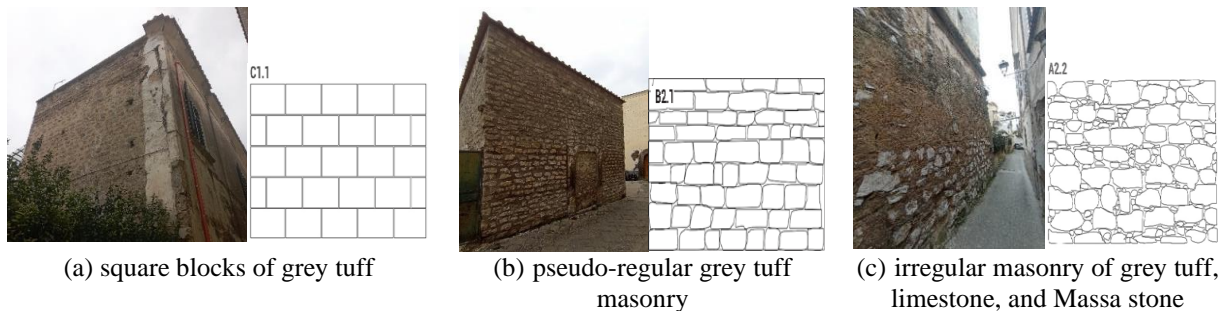
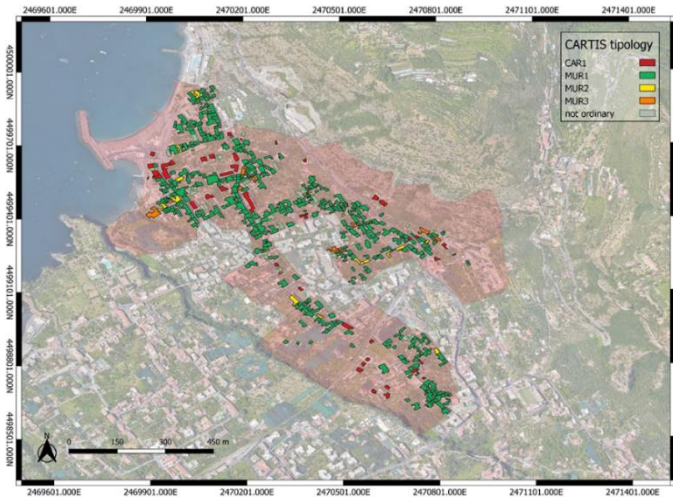


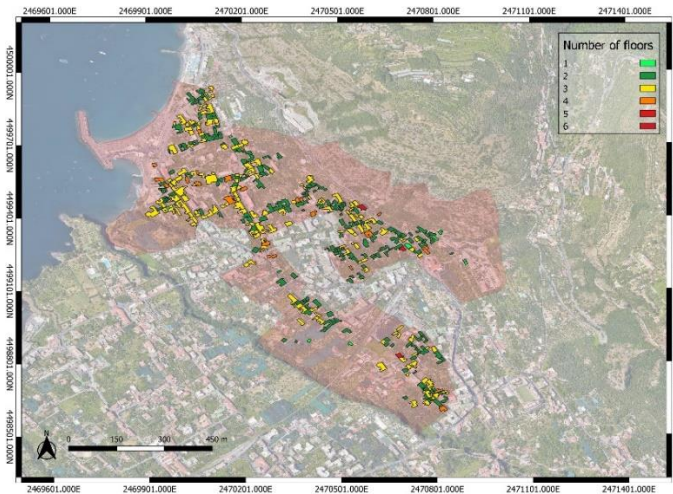
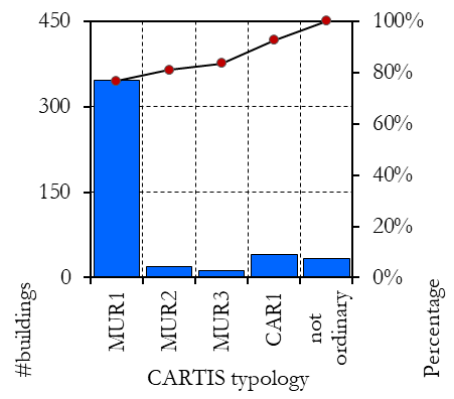
Figure 3: Identified masonry types, named MUR1(a), MUR2 (b) and MUR3 (c).

The second-level CARTIS form was used to collect more detailed data on individual buildings. This form, divided into four sections, includes information on the municipality and building location (Section 0), building identification (Section 1), general features such as geometric and structural characteristics (Section 2), and structural element characterisation (Section 3). The main outcomes are presented in Fig. 4 and can be summarised as follows:

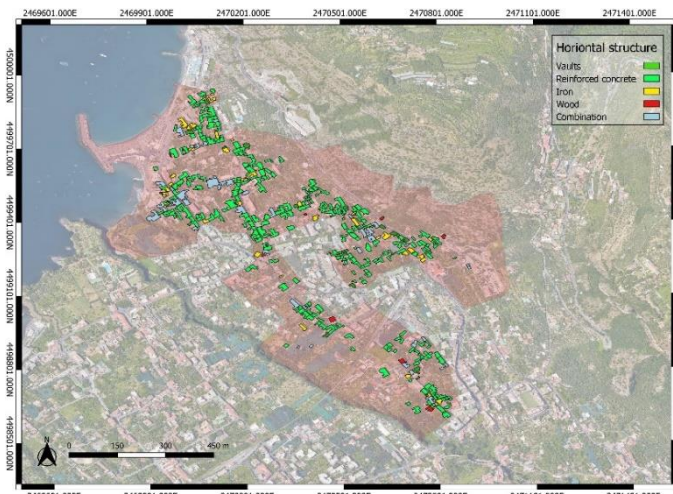
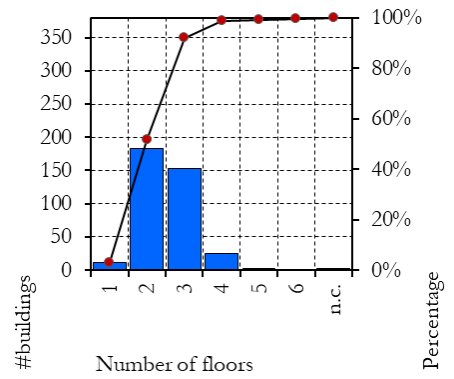
- MUR1 typology (347 buildings): primarily consists of two- to three-story buildings constructed in the 1700s (53.6%) and 1800s (39.5%), typically in an aggregate configuration. About 40% of these buildings are in mediocre to poor condition, and structural irregularities are common.
- MUR2 typology (20 buildings): consists of buildings dating back to the 1700s, featuring vaults in both the horizontal and roof structures, often combined with iron elements.
- MUR3 typology (12 buildings): these buildings date back to the 1800s and vary in height, with most having two floors and some reaching up to four. Vaults are predominant in both horizontal and roof structures. The roofing typically combines multiple materials.



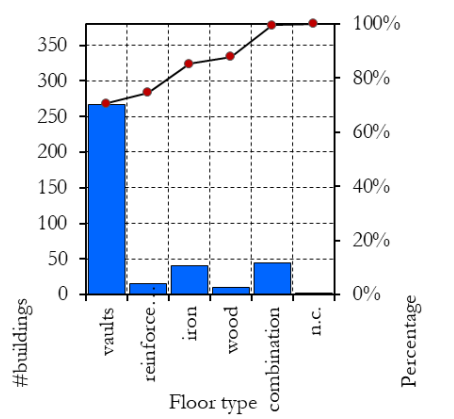
(a)



(b)



(c)



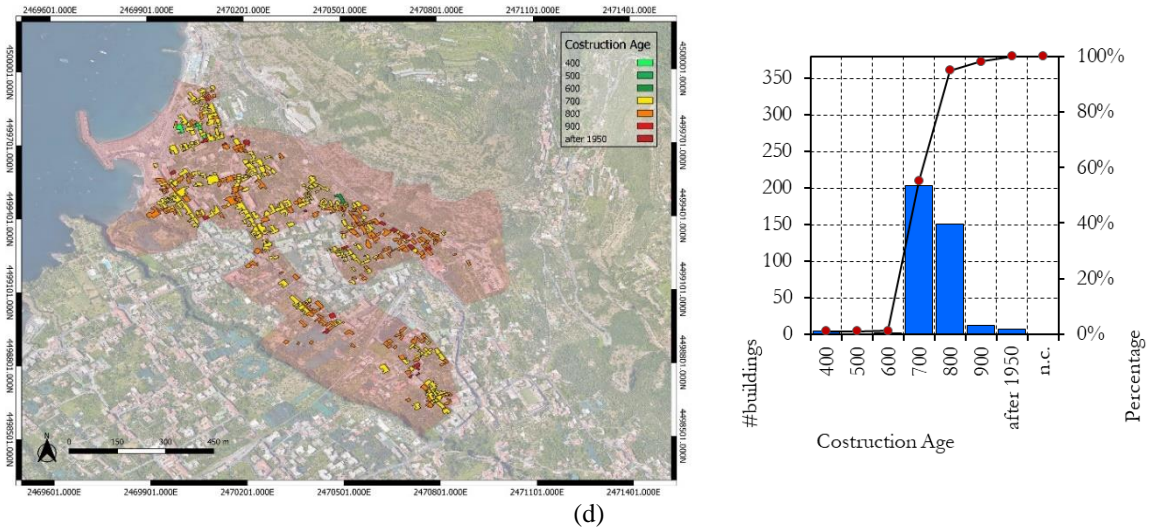


Figure 4: GIS mapping and statistical elaboration of the main collected structural features of masonry buildings within Sector 2: (a) masonry type, (b) no. of floors, (c) floor type, (d) construction age.

3 SEISMIC VULNERABILITY ASSESSMENT

The previously collected data were analysed using the vulnerability index method initially developed by Benedetti and Petrini [8] and later refined by incorporating five additional parameters proposed by Formisano et al. [13]. These additional parameters specifically address interactions between adjacent buildings, enhancing the accuracy and of the assessment method. To support this process, a specialized form for aggregated buildings is used (Table 2), allowing experts to conduct visual evaluations through weighted scores. The weights assigned to parameters 11-15 derive from numerical analyses carried out on many structural models that simulate the effect of each parameter on buildings belonging to a given class and standing in aggregate configuration [13].

Parameters	Vulnerability classes				Weight
	A	B	C	D	
1. Organisation of vertical structures	0	5	20	45	1
2. Nature of vertical structures	0	5	25	45	0.25
3. Location of the building and type of foundation	0	5	25	45	0.75
4. Distribution of plan resisting elements	0	5	25	45	1.5
5. In-plane regularity	0	5	25	45	0.5
6. Vertical regularity	0	5	25	45	0.8
7. Type of floor	0	5	25	45	0.8
8. Roofing	0	15	25	45	1
9. Details	0	0	25	45	0.25
10. Physical conditions	0	5	25	45	1
11. Presence of adjacent building with different height	-20	0	15	45	1
12. Position of the building in the aggregate	-45	-25	-15	0	1.5
13. Number of staggered floors	0	15	25	45	0.5
14. Structural or typological heterogeneity among adj. SUs	-15	-10	0	45	1.2
15. Percentage difference of opening areas among adj. facades	-20	0	25	45	1

Table 2: Vulnerability form adopted. [8,13]

The vulnerability index, which represent a measure of a building's susceptibility to damage, was calculated for each building within the investigated urban sector as follows:

$$I_V = \sum_{i=1}^{15} S_i \cdot W_i \quad (1)$$

Subsequently, it was normalized in the range [0-1] as follows:

$$V_I = \left[\frac{I_V - (\sum_{i=1}^{15} S_{min} \cdot W_i)}{|\sum_{i=1}^{15} [(S_{max} \cdot W_i) - (S_{min} \cdot W_i)]|} \right] \quad (2)$$

where values closer to 1 reflect the most vulnerable buildings, while values near 0 imply the presence of structures designed in conformity with recent seismic codes or subjected to retrofit interventions.

To represent the statistical and spatial distribution of the vulnerability within the urban sector, six distinct ranges of the vulnerability index were identified. The results of the analysis are reported in Fig.5, where it appears that 79.16% of the buildings exhibit medium vulnerability, accounting for 300 units, while the remaining buildings exhibit medium-low vulnerability (15.57%) and medium-high vulnerability (4.75%).

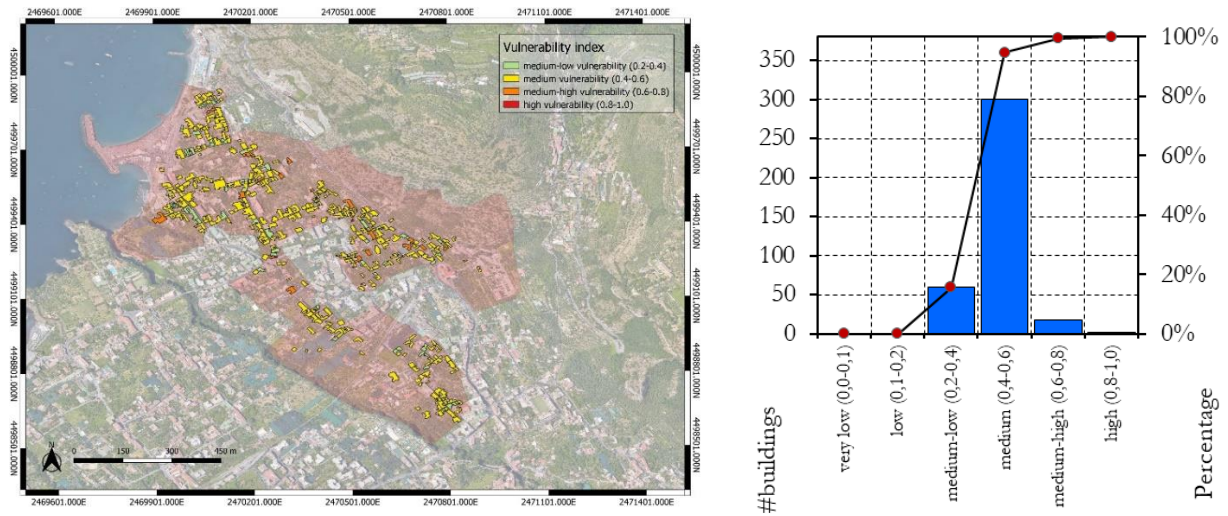


Figure 5: Distribution of the vulnerability index within the investigated area.

3.1 Typological vulnerability curves

A macroseismic approach was then adopted to include vulnerability curves to quantify the expected damage of the three identified building typologies. These curves use a synthetic factor, the mean damage grade μ_D , -which ranges from 0 to 5- to evaluate the expected damage, according to the MCS scale, by the following analytical relationship [14]:

$$\mu_D = 2.5 \cdot \left[1 + \tanh \left(\frac{I + 6.25 \cdot V_I - 13.1}{Q} \right) \right] \quad (3)$$

The expected damage depends on three key variables, i.e. the normalised vulnerability index (V_I), the macroseismic intensity (I) and a ductility factor Q , which describes the ductility of the building typological classes, and it is herein assumed equal to 2.3. In Fig.6, y represents the standard deviation of the values of each class.

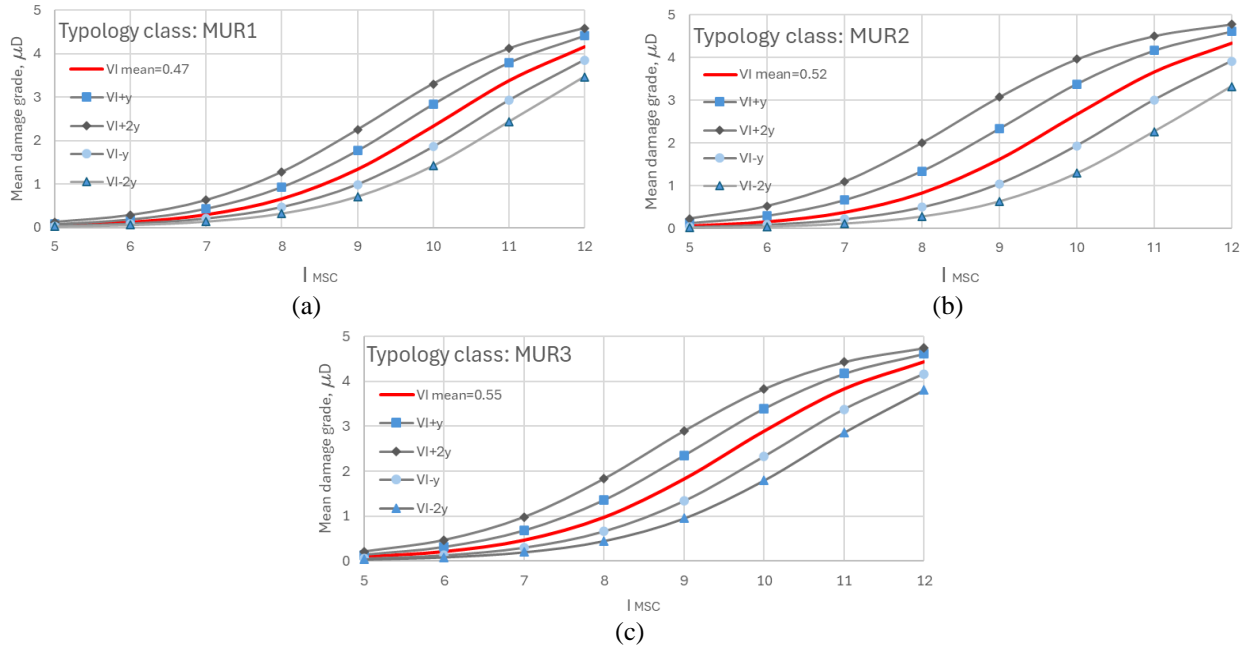


Figure 6: Vulnerability curves derived from (a) MUR1, (b) MUR2 and (c) MU3 building types.

4 DAMAGE SCENARIOS

The adopted damage model prediction uses data from the seismic hazard model MPS04-S1 [15], provided by the National Institute of Geophysics and Volcanology (INGV), particularly the disaggregation of Peak Ground Acceleration (PGA) with a 10% probability of exceedance over 50 years, as reported in Fig. 7.

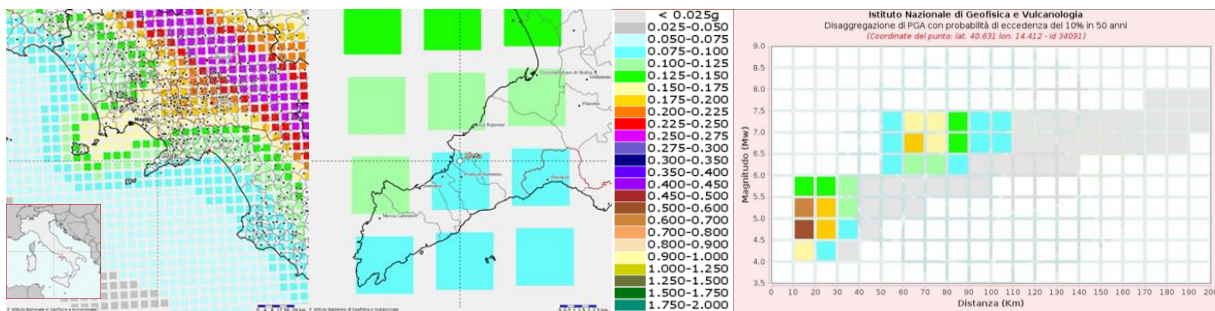


Figure 7: INGV's MPS04-S1 model for Meta [15].

Consequently, six earthquake scenarios, in terms of magnitude (M_w) and epicentral distance (D), were selected (Table 3) and then the corresponding expected macroseismic intensity (I) was calculated according to the following simplified intensity prediction equation provided by Crespellani et al. [16]:

$$I = 6.39 + 1.756 \cdot M_w - 2.747 \cdot \log(D+7) \quad (4)$$

The results obtained by applying Eq. (4) to various combinations of magnitudes and macroseismic intensities are presented in Table 3.

Magnitude, M_w	Macroseismic Intensity, I	
	D = 10 km	D = 20 km
4.0	VI	–
5.0	VII	VI
6.0	IX	VIII

Table 3: Expected macroseismic intensities for the simulated earthquake scenarios.

The mean damage degree, μ_D , was adopted as the indicator of damage. For each building it was calculated using equation (3), where I represents the intensity derived from the previous calculation and V_I is the vulnerability index from the previous vulnerability assessment.

The actual damage level was then classified as reported in Table 4, corresponding to the type of structural damage provided by the EMS-98 scale [17].

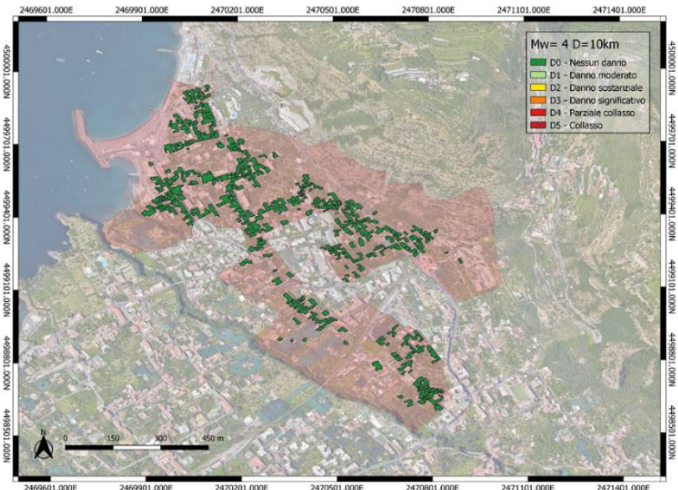
Mean damage grade (μ_D) range	Damage state (EMS-98)	Description
0-0.5	D0	No damage
0.5-1.0	D1	Negligible
1.0-2.0	D2	Moderate
2.0-3.0	D3	Substantial
3.0-4.0	D4	Partial collapse
4.0-5.0	D5	Collapse

Table 4: Identified damage levels.

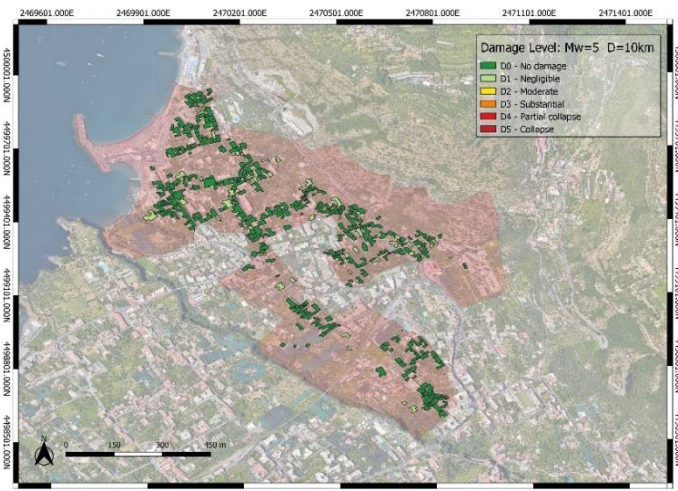
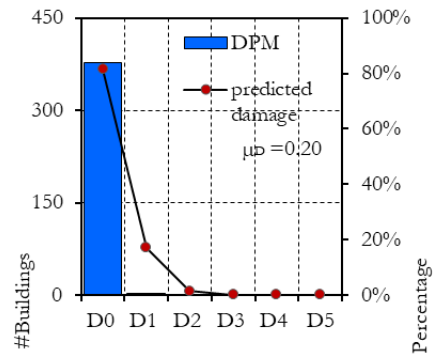
In addition, Damage Probability Matrices (DPMs) of the simulated events were evaluated based on the weighted average of damage, μ_D , according to the following equation [18]:

$$\begin{cases} p_k = \frac{5!}{k!(5-k)!} \cdot \left(\frac{\mu_D}{5}\right)^k \cdot \left(1 - \frac{\mu_D}{5}\right)^{5-k} \\ \mu_D = \sum_{k=1}^5 p_k \cdot k \end{cases} \quad (5)$$

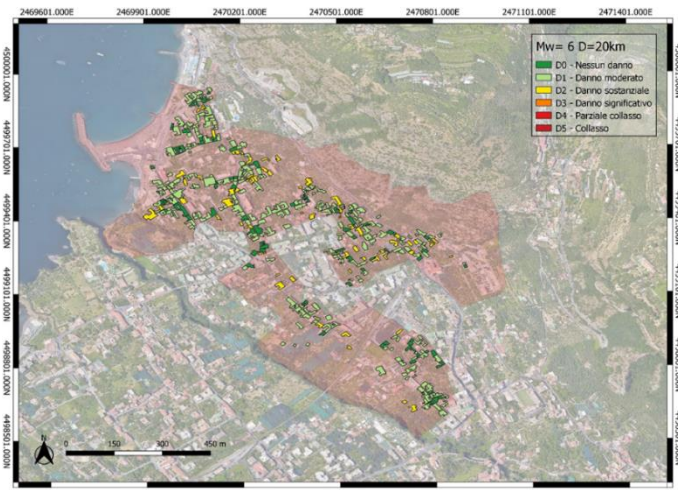
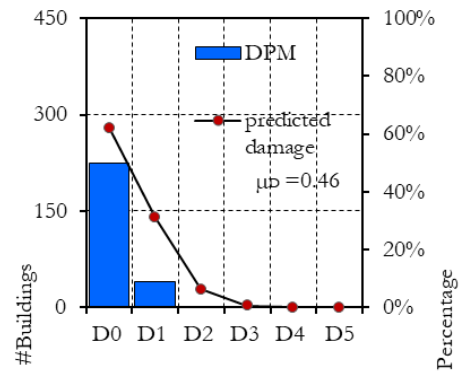
where k, representing the numerical parameter associated with different levels of damage, ranges from 0 to 5 and it indicates the potential severity of damage as defined in a classification system [17], while p_k is the probability (binomial distribution) or the statistical frequency of experiencing a damage level k. The most relevant results are reported in Fig.8.



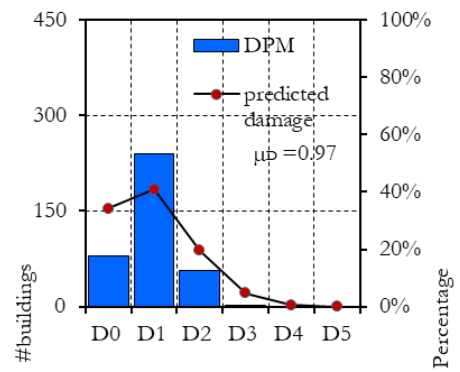
(a)



(b)



(c)



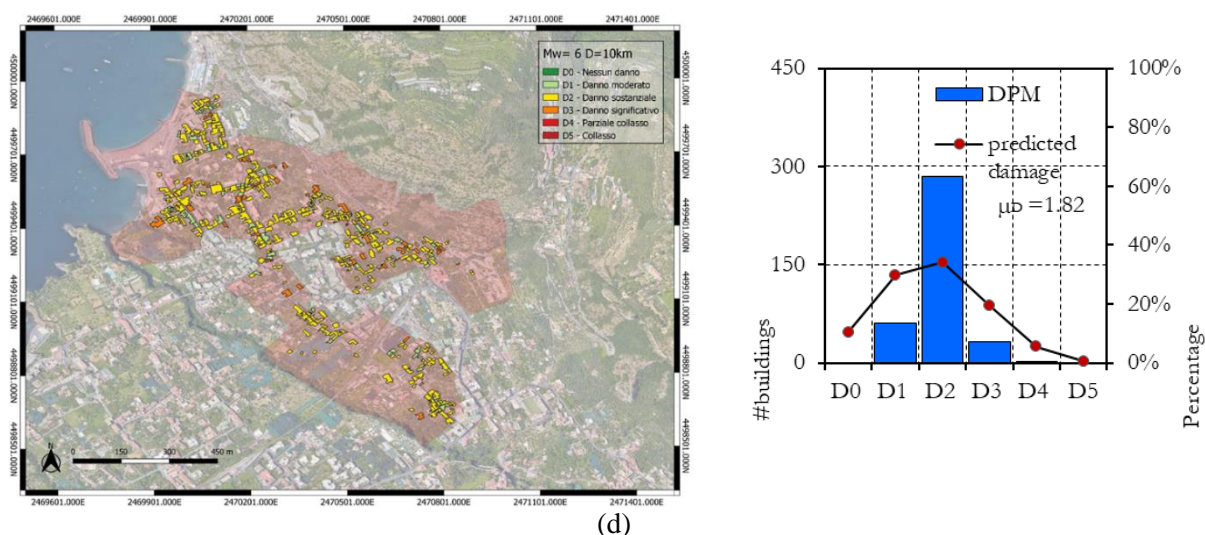


Figure 8: GIS mapping and statistical elaboration of the simulated damage scenarios: (a) M_w :4; D:10km, (b) M_w :5; D:10km, (c) M_w :6; D:20km, (d) M_w :6; D:10km.

5 CONCLUSIONS

This study provides a comprehensive evaluation of the seismic vulnerability of masonry buildings in Meta's historic centre, demonstrating how various masonry types react to seismic events with different magnitudes and epicentral distances. The findings revealed that structures with regular masonry (MUR1) show the highest resilience, particularly during moderate earthquakes. In contrast, MUR2 and MUR3 typologies, characterised by structural irregularities and inconsistent material quality, exhibit increased susceptibility at damage.

The study underscored the crucial link between building's structural properties, earthquake magnitude, and epicentral distance in influencing the extent of structural damage. The study, finally, emphasised the need for detailed seismic vulnerability assessments to support informed urban planning and enhance disaster preparedness strategies.

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