Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 3151-3167

ECCOMAS
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COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

A MULTILEVEL APPROACH TO SEISMIC RISK ANALYSIS OF RESIDENTIAL BUILDINGS INCORPORATING TERRITORIAL EXPOSURE

Federica Del Carlo[1,2], Diego Altagini[3], Tiago Miguel Ferreira[4], and Silvia Caprili[1]

[1] Department of Civil and Industrial Engineering, University of Pisa, Largo L. Lazzarino 1, 56122 Pisa, Italy
[2] Technical University of Catalonia. Jordi Girona 1-3, 08034, Barcelona, Spain
e-mail: federica.delcarlo@phd.unipi.it, silvia.caprili@unipi.it
[3] Welsh School of Architecture, Cardiff University, Cardiff, UK
e-mail: altafinid@cardiff.ac.uk
[4] CERIS, Instituto Superior Técnico, University of Lisbon, Portugal
e-mail: tiago.ferreira@tecnico.ulisboa.pt

Abstract

Italy's high seismicity threatens a significant proportion of traditional building stock in Italy, particularly in small and medium-sized urban centers constructed before seismic codes were established. Many of these buildings, dating back to medieval or Renaissance periods, are masonry or stone structures with architectural and cultural value. Traditional seismic analysis primarily focuses on structural capacity, with little importance given to critical aspects such as accessibility during emergencies. This paper introduces a multilevel approach combining seismic susceptibility, evaluated through the Informed Vulnerability Index for Structures (In.V.I.S.), with territorial exposure analysis. The In.V.I.S. index, derived from the CARTIS methodology, offers a rapid and comprehensive structural resistance analysis. Coupling this with territorial exposure enables the evaluation of both physical susceptibility and accessibility during seismic events. The proposed methodology facilitates large-scale, multi-domain analysis, addressing the interplay between building susceptibility and access both pre- and post-event. By integrating these dimensions, the approach provides deeper insights into seismic risks and supports the development of more effective mitigation strategies, especially for small and medium-sized urban centers. As proof of concept, the approach is applied to a set of residential buildings located in two municipalities in northern Tuscany, demonstrating its ability to capture the interconnectedness of structural capacity and emergency accessibility.

Keywords: Seismic Risk Analysis, Informed Vulnerability Index (In.V.I.S.), Emergency Planning, Territorial Exposure, Network Analysis.

ISSN:2623-3347 © 2025 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.12642.25703

1 INTRODUCTION

Seismic vulnerability within urban aggregates often remains underestimated, yet it poses a substantial threat in seismically active regions. Recent earthquakes in Italy, such as those in L'Aquila (2009), Emilia-Romagna (2012), and Central Italy (2016 onward), have demonstrated the devastating consequences of seismic events, including loss of life, economic disruption, and irreversible damage to cultural heritage. These disasters underscore the need for more comprehensive risk analysis frameworks that go beyond assessing the physical vulnerability of the building environment by also accounting for the contribution of urban morphological characteristics to overall risk. Extensive research has refined seismic risk evaluation methodologies by incorporating structural, demographic, and territorial factors [1, 2]. Seismic risk is conventionally quantified using the widely adopted formulation [3–5]:

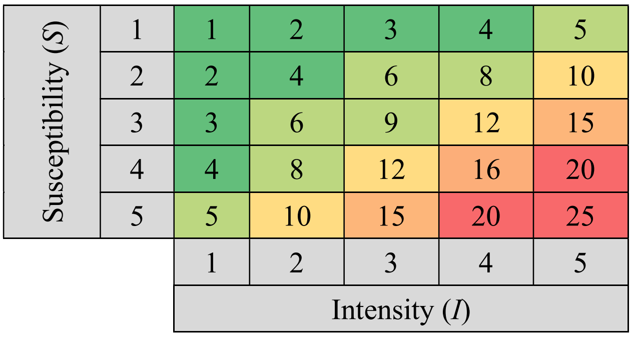
$$Risk = H \times V \times E \tag{1}$$

where hazard (H) represents the probability of one or more potentially damaging events of a given intensity occurring within a specific area over a defined period of time; vulnerability (V) denotes the expected degree of damage to exposed elements due to the hazardous event; and exposure (E) parameterizes the number, value, or significance of these elements. Since seismic hazard is an inherent geophysical phenomenon, mitigation efforts must primarily focus on reducing vulnerability and exposure. This aligns with modern disaster risk frameworks, such as the Sendai Framework for Disaster Risk Reduction 2015–2030 [6], which advocates for a holistic understanding of these components and emphasizes resilience-based approaches to urban planning and emergency management.

To address these challenges, this study introduces a multilevel methodology that integrates seismic susceptibility analysis with a configurational analysis of the urban road network. The urban road network is critical in post-earthquake response, ensuring access for rescue operations and providing evacuation routes for residents. Consequently, a comprehensive seismic risk evaluation should consider not only a building's seismic susceptibility but also its spatial interaction with the surrounding road network. To address this need, this study proposes a scenario-based risk matrix for assessing the seismic risk of urban aggregates, drawing inspiration from the methodology previously applied to religious buildings in [7]. The matrix captures two primary dimensions: (*a*) the hazard intensity and (*b*) the building susceptibility, defined as the ability of a structure to withstand seismic forces and its functional relevance within the urban road network. Both dimensions are expressed through indices, enabling a structured classification of seismic risk. Building susceptibility is evaluated using a linear parametric index, integrating three key factors: (*i*) *building exposure*, (*ii*) *territorial exposure*, and (*iii*) *physical susceptibility*. By combining these factors, the proposed methodology provides a comprehensive risk analysis tool that enhances urban resilience and informs decision-making processes for policymakers and engineers. Unlike conventional approaches that primarily emphasize structural retrofitting, this framework offers a cost-effective strategy for risk mitigation by optimizing territorial planning and resource allocation. As a proof of concept, the methodology is applied to quantify the seismic risk of a set of buildings located in two municipalities in northern Tuscany, Italy.

2 CONCEPTUAL FRAMEWORK

The proposed risk matrix adopts a quantitative approach to urban seismic risk analysis by combining building susceptibility (S) with classified seismic event intensities (I) in a structured matrix, illustrated in Figure 1. The matrix is formulated within a scenario-based approach, meaning that the seismic intensity refers to a fixed probability of occurrence. The details regarding the Intensity and Susceptibility parameters are provided below.



Susceptibility (S)	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25
		1	2	3	4	5
		Intensity (I)				

Figure 1 Proposed risk matrix.

A fundamental step in seismic risk analysis is estimating building susceptibility (S), which quantifies, in most general terms, the capacity of a vulnerable element to withstand seismic forces. The formulation adopted in this study follows [7], defining susceptibility as a linear parametric index that aggregates three key factors: Physical Susceptibility (S_p), Building Exposure (E_b), and Territorial Exposure (E_t), Equation (2).

$$S = (S_p + E_b) \cdot E_t \tag{2}$$

It is important to note that susceptibility is predominantly determined by physical and territorial features, and it is independent of any particular characteristic of the considered seismic event. Each factor is dimensionless, ranging from 0 (no susceptibility/exposure) to 1 (maximum susceptibility/exposure), ensuring that total susceptibility values range from 0 to 2. To align with the risk matrix, this continuous range is discretized into five susceptibility classes of equal amplitude (Table 1).

Susceptibility interval	**Susceptibility class**
$\mathbf{0 \leq S < 0.4}$	1
$\mathbf{0.4 \leq S < 0.8}$	2
$\mathbf{0.8 \leq S < 1.2}$	3
$\mathbf{1.2 \leq S < 1.6}$	4
$\mathbf{1.6 \leq S \leq 2}$	5

Table 1 Correlation between Susceptibility intervals and classes.

To ensure a comprehensive risk analysis, building susceptibility is broken into three components, each corresponding to a distinct factor:

- *Physical Susceptibility* (S_p) describes the inherent structural capacity of a building to maintain its physical integrity and functionality when subjected to seismic loads [3].
- *Building Exposure* (E_b) refers to people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses [8]. In this study, it is specifically measured based on resident population density.
- *Territorial Exposure* (E_t) Accounts for the road network configuration, evaluating a building's position within the road system, its centrality relative to key urban hubs, and its accessibility in an emergency. This factor is particularly relevant for ensuring post-earthquake resilience, which is defined as the ability to resist, absorb, accommodate, and recover from a hazardous event while preserving essential functions [8].

To ensure consistency between the two matrix dimensions, seismic intensity is categorized into five classes. These classes are designed to be flexible, allowing them to be associated with different seismic intensity measures, such as Peak Ground Acceleration (PGA), Modified Mercalli Intensity (MMI), or macroseismic intensity scales, depending on the available data and the purpose of the analysis. Importantly, the framework assumes a fixed-probability scenario (e.g., PGA with a 10% probability of exceedance in 50 years), so the five classes represent discrete levels of ground shaking intensity under a single hazard scenario. This enables the same risk matrix structure to be reused across different contexts by adjusting the thresholds of each class according to the chosen intensity parameter.

Finally, in order to facilitate interpretation, the risk values obtained from the matrix (ranging from 1 to 25) are categorized into five risk classes (Table 2).

Risk values	Risk class
Risk values < 5	1
5 ≤ Risk values < 10	2
10 ≤ Risk values < 15	3
15 ≤ Risk values < 20	4
20 ≤ Risk values ≤ 25	5

Table 2 Relationship between risk values obtained from the risk matrix and risk classes.

Building upon the approach in [7], each risk class is linked to a set of recommended actions aimed at reducing both structural vulnerabilities and territorial accessibility concerns, ensuring a comprehensive risk reduction strategy:

- Risk Level 5 (Highest Risk): Immediate priority should be given to both structural reinforcement and improvements to the surrounding infrastructure. Enhancing road networks or creating alternative access routes is essential to ensure reliable emergency response and evacuation pathways.
- Risk Level 4: Structural retrofitting should be prioritized, especially for buildings with higher susceptibility. If road accessibility is moderately adequate, efforts should focus on maintaining infrastructure quality. Improvements such as emergency signage and redundancy in access routes may be beneficial.
- Risk Level 3: The primary focus should be on maintaining accessibility through regular monitoring of roads and minor retrofitting where necessary. Community preparedness initiatives and public awareness programs could also be valuable.
- Risk Level 2: Regular inspections and basic accessibility maintenance should be carried out to ensure continued resilience. Routine evaluation of road conditions and minor preventive measures could help sustain the current risk level.
- Risk Level 1 (Lowest Risk): Buildings in this category require only routine maintenance and low-level monitoring. Limited interventions may be beneficial, but priority should be given to allocating resources toward higher-risk areas.

The following sections provide a detailed illustration of the factors comprising susceptibility and hazard indices, with specific reference to two municipalities in the northern part of the Tuscany region.

3 METHODOLOGICAL APPLICATION

This section presents the detailed formulation of the susceptibility and intensity indices introduced in the conceptual framework and applies them to a territorial-scale case study involving two municipalities in northern Tuscany: Gallicano and Piazza al Serchio. These municipalities were selected as representative examples of small size urban settlements characterized by historic centers with medieval origins and more recent 20th-century urban expansions. Both municipalities are predominantly residential in nature, with 3601 residents in Gallicano and 2051 in Piazza al Serchio [9], making them ideal case studies for evaluating seismic risk in typical Tuscan urban aggregates. The proposed methodology is applied to all masonry residential buildings within the municipalities, and each factor contributing to the susceptibility index, i.e., physical susceptibility, building exposure, and territorial exposure, is analyzed in relation to the specific characteristics of the selected urban areas. Similarly, the intensity index is contextualized based on the seismic classification of the area. The objective is to demonstrate the practical implementation of the proposed methodology and highlight its applicability in seismic risk analysis.

3.1 Physical Susceptibility

Physical susceptibility is quantified using the Informed Vulnerability Index for Structures (In.V.I.S.) [10], a rapid methodology specifically designed to evaluate the seismic performance of masonry buildings within urban aggregate. The index belongs to the category of rapid vulnerability analysis methods, and it's developed drawing from the GNDT II level approach while ensuring compatibility with the CARTIS form [11, 12]. Designed as a tool for large-scale building screening, the CARTIS methodology enables the identification and characterization of predominant building typologies through a structured form that can be quickly filled via in-site surveys or documentary sources. Seven selected fields of CARTIS form, each representing a critical factor influencing a masonry building's seismic response, were employed to construct the In.V.I.S. index. Specifically, fields were translated into seven key parameters (i), classified into four classes - A, B, C, and D – where class A reflects the most favorable configuration, typically corresponding to well-constructed, seismically resilient features. While class D represents the most critical conditions, such as poor construction quality, irregular geometry, lack of horizontal connections, or inadequate retrofitting. The transition between classes is based on the information required by the CARTIS form within the respective fields, for a detailed description of the field and the division into classes see reference [10].

The original GNDT scoring logic was adopted to enhance rapid, semi-quantitative screening, therefore each class is associated with a score (v_i) assigned according to their relative contribution to seismic resistance (5, 10, 20, and 50, respectively). To ensure that the index accurately reflects structural resistance, a weight factor (w_i) is assigned to each parameter, accounting for their varying influence on overall seismic performance. The methodology was calibrated using a dataset of 5000 simulated buildings, and its effectiveness was validated through statistical correlation measures.

Table 3 presents the seven In.V.I.S. parameters, their respective class scores, and weight factors used in the index computation.

In.V.I.S. form		**Class Score v_i**				**Weight**
	Parameter i	A	B	C	D	w_i
P1*	Construction period	5	10	20	50	2.50
P2*	Masonry characteristics	5	10	20	50	1.00
P3*	Total number of floors	5	10	20	50	0.50
P4*	Mixed RC-masonry structures	5	10	20	50	0.50
P5*	Slabs and vaults characteristics	5	10	20	50	0.75
P6*	Roofing system	5	10	20	50	2.00
P7*	Structural interventions	5	10	20	50	1.00

Table 3 In.V.I.S. parameters, class scores, and parameter weights.

The In.V.I.S. index computation follows the formulation in Equation (3).

$$I_{V,InVIS} = \sum_{i=1}^{7} v_i \times w_i \tag{3}$$

where v_i represents the class score assigned to parameter i, and w_i is the corresponding weight factor. The summation provides an aggregate measure of the building's physical susceptibility, allowing for comparative analysis across different structures. To ensure consistency and comparability with the other index estimating seismic susceptibility, the final values were normalized to fall into the range 0 to 1, where 0 corresponds to 'no susceptibility' and 1 to 'maximum susceptibility'.

The In.V.I.S. methodology is applied to all masonry residential buildings within the municipalities of Gallicano and Piazza al Serchio. For the purpose of visualization and clarity, selected sectors, representing distinct urban morphologies, are highlighted in the results to illustrate how the index performs across different contexts. These sectors were defined through a morpho-historical analysis, based on historical records, bibliographic sources, cadastral data, and municipal planning documents, enabling the identification of homogeneous urban areas characterized by similar construction periods and development patterns, as detailed in [10]. Each sector represents a distinct construction phase or urban expansion stage, typically delineated by factors such as building age, materials, construction techniques, and spatial layout.

Within each sector, representative building typologies were selected based on their typological and structural features, extracted from a simplified reading of the CARTIS form. These typologies reflect the most recurring characteristics of the building stock in that sector. The In.V.I.S. index was then computed for each typology using the weighted scoring system previously described, yielding an estimation of physical susceptibility representative of the buildings within each urban sector. This typology-based approach allowed for a rapid yet robust estimation of seismic susceptibility across the entire residential building stock, providing an initial estimate aimed at directing subsequent in-depth analyses.

Figure 2 illustrates the spatial distribution of physical susceptibility values for selected urban sectors in the municipalities of Piazza al Serchio and Gallicano, as estimated using the In.V.I.S. index. The In.V.I.S. value shown for each sector corresponds to the index computed for the identified representative typologies. As visible, most sectors present one representative building typology, based on common structural characteristics and construction period. As expected, higher In.V.I.S. values (indicating greater physical susceptibility) are concentrated in the historic centers (e.g., Sector S01 in both municipalities), where masonry structures are older and generally more susceptible to seismic load. Conversely, lower values are associated with more recent residential areas, reflecting improved structural performance and construction standards. It is important to note that these values are not averages of building-level analysis, but rather typology-based estimates representing the dominant building typologies' physical susceptibility in each sector.

Figure 2 Physical susceptibility values based on In.V.I.S. index.

3.2 Building Exposure

Building exposure is quantified based on population density, representing the concentration of people within a given area who may be affected by a seismic event. To quantify this parameter, data from the 2011 Italian Population and Housing Census (*Censimento generale della popolazione e abitazioni* – 2011) [9] was utilized. The Census dataset, originally structured in tabular form with demographic subdivisions (e.g., age, gender), was spatialized using a census zone mosaic, where each record is linked to a specific geographic area via a section code. This spatial representation enables data aggregation or averaging at broader urban scales, allowing for an accurate territorial estimation of population distribution.

For the risk index computation, population density was derived by dividing the total number of residents within each census zone by its respective area (in km²), as expressed in Equation (4):

$$Pop. Density = \frac{Population}{Census\ Area} \tag{4}$$

To maintain a high-resolution representation of population distribution, density values were not averaged or aggregated at the municipal scale. Instead, the population density value of the census zone was assigned to each residential building based on its location. While a more detailed exposure analysis could involve normalizing density values by individual building areas, this study prioritizes a territorial-scale approach. Therefore, exposure remains defined at the census zone level, ensuring consistency with urban and regional analysis.

Population density values were normalized with respect to the maximum value within the municipality, allowing for a relative comparison of building exposure across different municipalities and for consistency with the other two susceptibility factors (Figure 3).

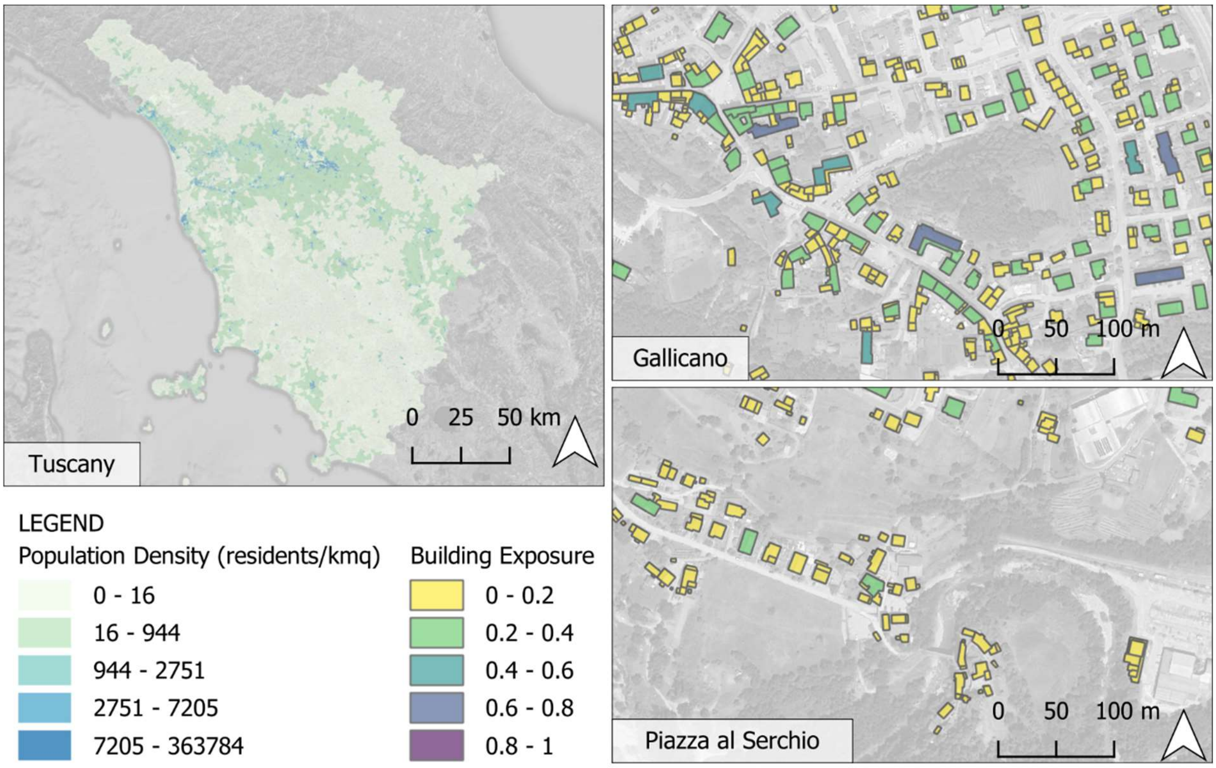


Figure 3 Population density for Tuscany and its normalization into the exposure index for Gallicano and Piazza al Serchio buildings.

3.3 Territorial exposure

Three network-based analysis models are employed to describe different centrality patterns in urban-regional road networks. These models evaluate the hierarchical role of each road segment within the network, revealing distinct properties that influence the exposure of buildings in terms of accessibility and connectivity.

The first two models, derived from Space Syntax's Angular Segment Analysis (ASA) [13–17], include Normalized Angular Integration (NAIN) and Normalized Angular Choice (NACH), as defined in [18]. These configurational analysis metrics capture the potential movement and flow dynamics within the road network based on its overall morphology and configuration. Both NAIN and NACH are calculated based on the shortest topological paths from each road element to all others in the system. NAIN reflects the *relative accessibility* (to-movement), indicating the degree to which each road element contributes to local cohesiveness, in terms of guaranteeing accessibility and reach. NACH measures the *probability of choice as a preferential route* (through-movement) of each road element, reflecting how much a road element contributes to local traversal capability and direct access, i.e. identifying roads that fall within the most direct paths used by emergency services or that provide direct access to shelters. To capture local pedestrian-scale dynamics, both NAIN and NACH were computed within a 400 m metric radius, representing an average pedestrian escape distance in urban settings.

In addition to these widely used centrality metrics, the analysis includes a third, less conventional indicator: Kemeny-Based Centrality (KBC). Introduced in [23] and further refined in [24], KBC measures the contribution of individual road segments to the robustness and redundancy of the entire road network. It identifies key connections whose removal would significantly compromise the overall system, offering insights into the network's resilience to localized disruption. To assign territorial exposure values at the building scale, the mean centrality of the surrounding road segments was calculated within a 50 m buffer from each building's centroid. This buffer-based approach was implemented in a GIS environment, where the centrality values of all road segments intersecting the buffer were aggregated and assigned to the corresponding building. Figure 4 illustrates the spatial distribution of the three road centrality indicators (NAIN, NACH, and KBC) for the municipalities of Gallicano and Piazza al Serchio. Each centrality measure captures distinct characteristics of the road network.

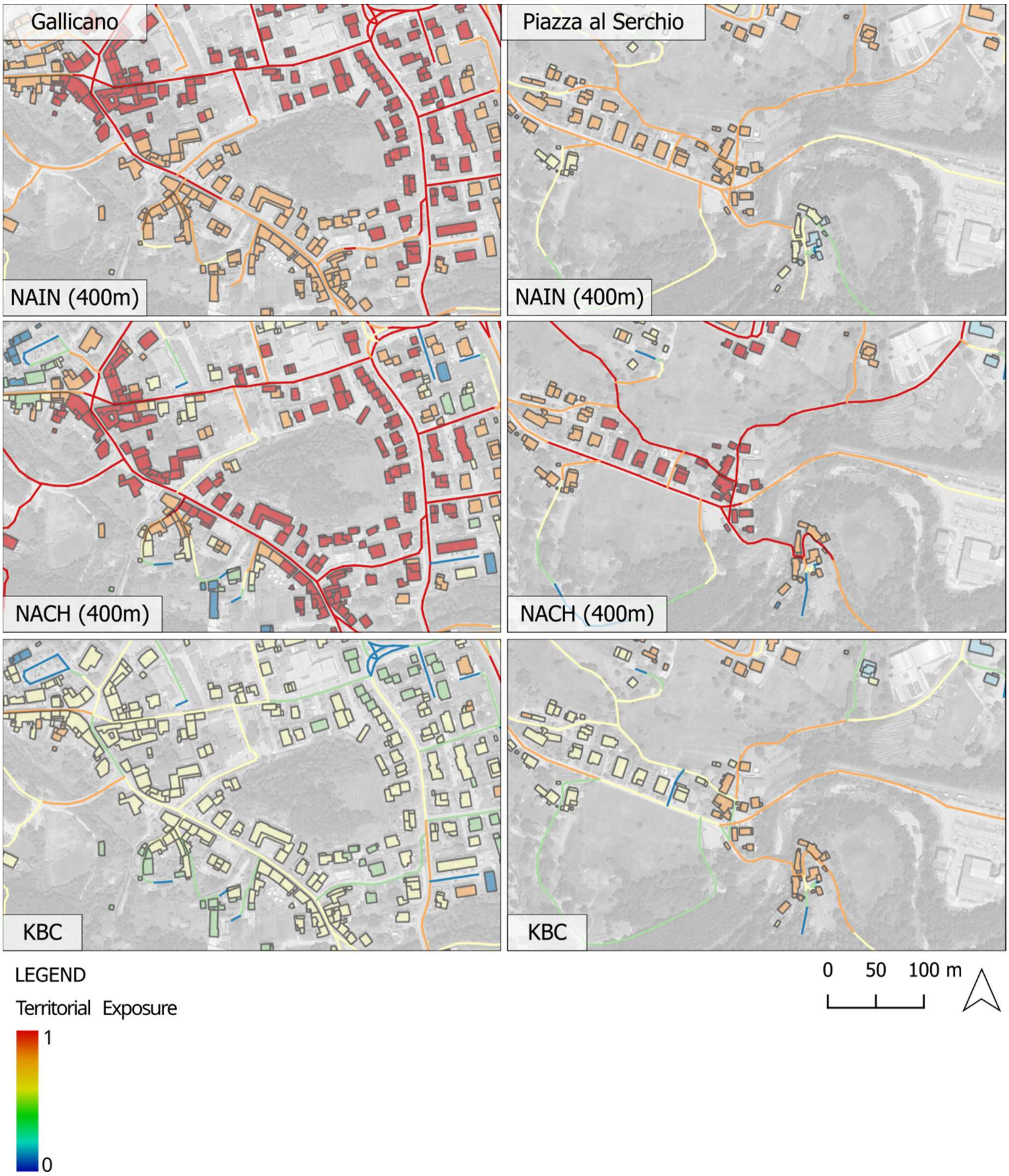


Figure 4 NAIN, NACH, and KBC measures for the municipalities considered.

While the three centrality metrics are standardized to range between 0 and 1, their interpretation differs depending on the indicator used. Table 4 summarizes the meaning associated with the extreme values of each metric.

Metric	Values closer to 0	Values closer to 1
Integration (metric)	Low relative accessibility compared to other road elements in the system (or within the metric boundary).	High relative accessibility compared to other road elements in the system (or within the metric boundary).
Choice (metric)	Low probability of being traversed as part to reach other elements in the system – or its metric boundary.	High probability of being traversed to reach other elements in the system – or its metric boundary.
Kemeny-Based Centrality	High structural redundancy: alternative paths are available and nearby.	Low structural redundancy, as fewer or no close alternatives exist.

Table 4 Interpretation of network centrality values for defining territorial exposure.

To ensure methodological consistency, each metric was rescaled or transformed so that 0 represents the most favorable condition (lower exposure) and 1 the most critical (higher exposure). For NAIN and NACH, this was done by reversing the scale using the transformation:

$$Adjusted_{NAIN,NACH} = 1 - Original_{NAIN,NACH} \tag{5}$$

For the Kemeny-Based Centrality, which originally produced values with a highly skewed distribution, a custom categorical scale was implemented to bring its range into a more comparable and interpretable format. The values were classified into five discrete intervals, as shown in Table 5.

Kemeny-Based Centrality range	Associated value
0-0.000013	0.20
0.000013-0.000085	0.40
0.000085-0.000482	0.60
0.000482-0.003212	0.80
0.003212-1	1

Table 5 Adjustment of Kemeny-Based Centrality to standardized territorial exposure scale.

By harmonizing all three indicators onto a 0-to-1 scale, three comparable susceptibility indices could be computed. In this form, territorial exposure acts as a reduction factor in the final susceptibility, according to Equation (2). In the worst-case scenario, where $E_t = 1$, the final susceptibility is equal to the sum of $S_b + E_b$. In all other cases, the final susceptibility is proportionally reduced, reflecting the positive role of network accessibility and redundancy.

3.4 Susceptibility

Results are illustrated in terms of susceptibility values distribution for the municipalities of Piazza al Serchio (Figure 5) and Gallicano (Figure 6), computed using the three distinct territorial exposure metrics: NAIN, NACH, and KBC. For each building, the physical susceptibility and building exposure components ($S_p + E_b$) are held constant, while territorial exposure varies depending on the chosen centrality measure. This methodology results in three different susceptibility maps per municipality, each reflecting how a specific aspect of network configuration influences the overall seismic susceptibility of the built environment. Buildings are categorized into five susceptibility classes, ranging from Class 1 (lowest) to Class 5 (highest), based on the final value of the susceptibility index.

Notably, the maps reveal how the incorporation of different territorial exposure indicators affects the spatial distribution of seismic susceptibility compared to baseline conditions, which consider solely $S_p + E_b$. In the baseline maps, higher susceptibility values are concentrated in the historic centers (higher physical susceptibility) and in dense urban fabric (higher population density, i.e., building exposure).

Incorporating territorial exposure led to a generalized decrease in susceptibility values, though with distinctions depending on the specific territorial indicator. NAIN-based susceptibility shows a consistent downgrading of approximately one class from the baseline in both municipalities. However, it preserves the contrast between historic centers and newer urban expansions, reflecting the influence of local integration and accessibility on seismic susceptibility. NACH-based susceptibility results in a more generalized downgrading across the entire urban area. The distinction between historic centers and peripheral areas becomes less pronounced, and the overall susceptibility field appears more uniform. This could relate to the fact that NACH captures the through-movement potential, emphasizing street segments likely to be used in the shortest paths across the system. In small and medium-sized towns like Gallicano and Piazza al Serchio, many streets may participate in short traversal paths, leading to less differentiation in NACH values (Figure 4, NACH (400m)). Consequently, buildings throughout the municipalities benefit from relatively uniform territorial exposure, resulting in broadly reduced susceptibility. KBC-based susceptibility exhibits a similar pattern of NAIN-based susceptibility, with a downgrading of one class from the baseline. However, it is important to note that buildings situated along critical links with low redundancy retain higher susceptibility values. This is especially evident in the historic center of Gallicano, where several buildings fall in Class 4 due to the absence of alternative routes (Figure 6, Susceptibility-KBC).

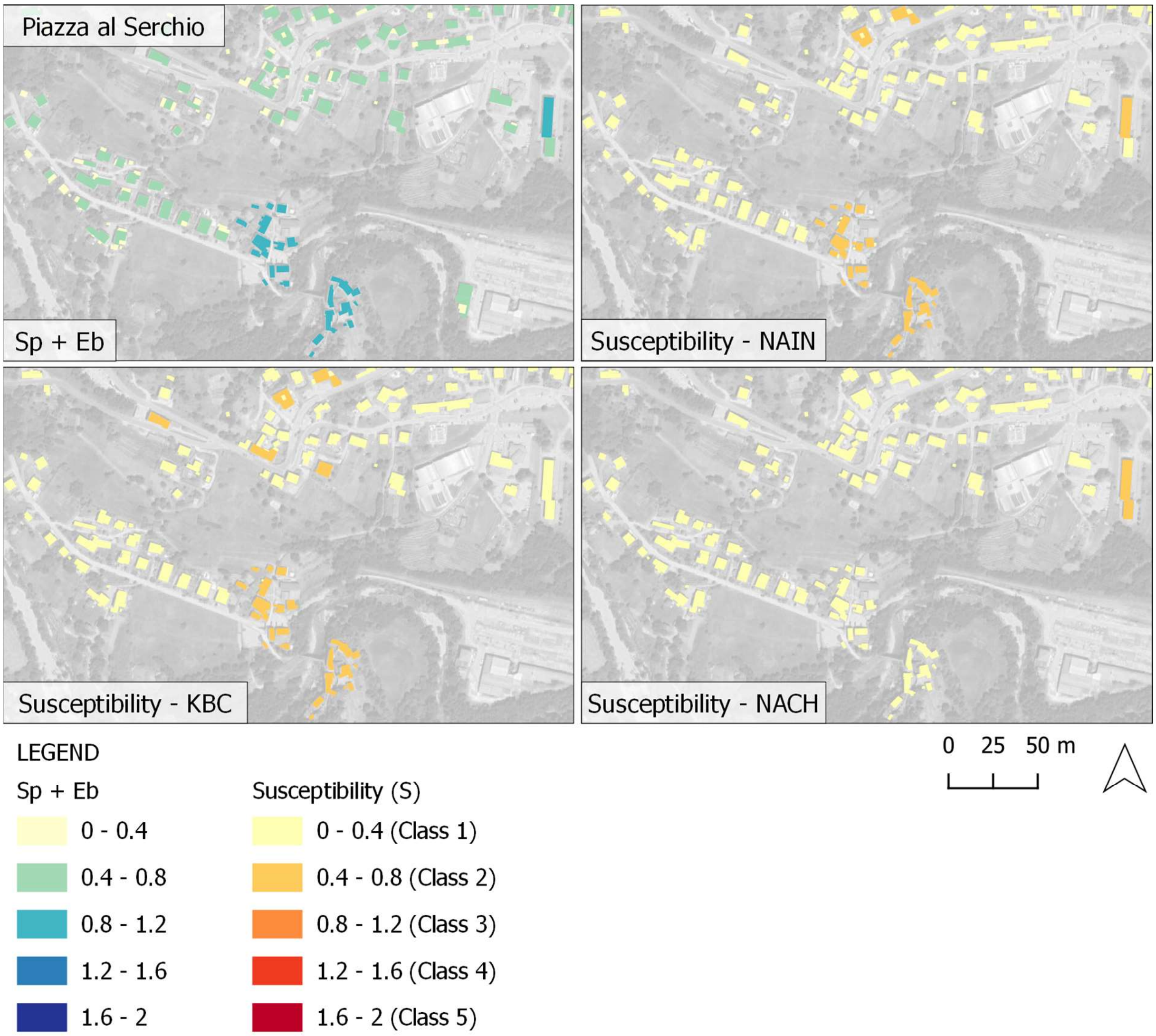


Figure 5 Spatial distribution of the susceptibility values for Piazza al Serchio municipality.

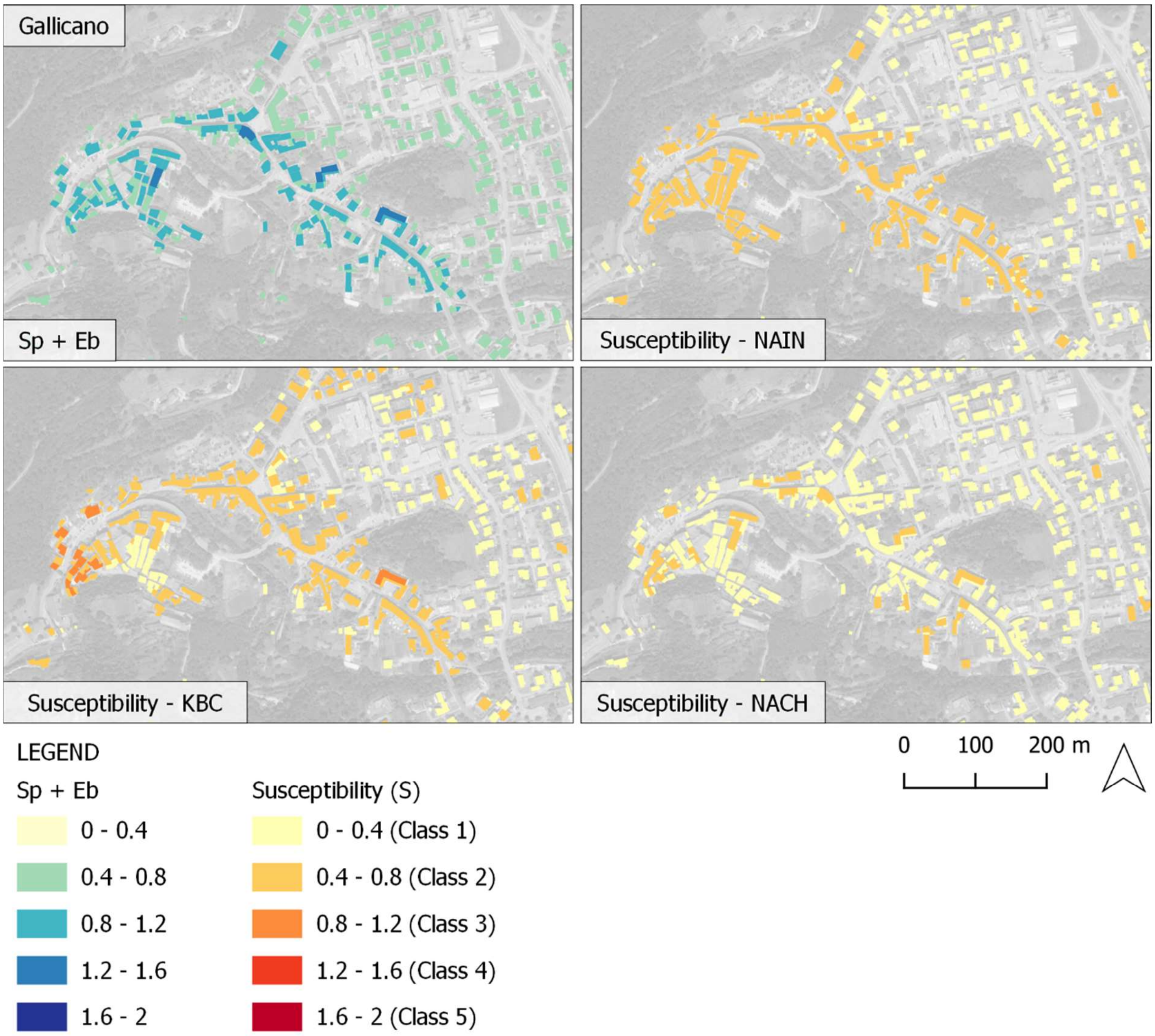


Figure 6 Spatial distribution of the susceptibility values for Gallicano municipality

3.5 Intensity

Among the various seismic intensity measures that can be integrated into the methodology, this study adopts PGA as the selected parameter for representing seismic hazard. PGA provides a probabilistic measure of ground motion intensity and is widely used in seismic risk analysis. Intensity classes are obtained through the discretization into five ranges of the four seismic zones proposed within the probabilistic seismic hazard map for Italy, created in 2004 and published under the name Mappa di Pericolosità Sismica 04 (MPS04) [19, 20], ensuring consistency with Italy's probabilistic seismic hazard framework. Table 6 illustrates the relationship among the horizontal PGA values, the four existing seismic zones, and the intensity classes identified. PGA values refer to the reference stiff soil computed with a 10% probability of exceedance (P_{vr}) in 50 years.

PGA with a 10% Pvr in 50 years	Seismic zone	Intensity class
≤ 0.05g	4	1
$0.05 < \text{PGA} \leq 0.12$g	3	2
$0.12 < \text{PGA} \leq 0.18$g	2-3	3
$0.18 < \text{PGA} \leq 0.25$g	2	4

0.25< PGA ≤ 0.35g	1	5

Table 6 Relationship between: PGA with 10% probability of exceedance in 50 years – Seismic zone – Intensity class.

To maintain a generalized and large-scale applicability, the methodology utilizes PGA values on stiff soil while neglecting site-specific lithostratigraphic amplification effects. This approach is in line with methodologies designed for territorial-scale risk analysis [21, 22], allowing for further refinement in localized studies where soil effects may be significant. Moreover, since the probability of exceedance is fixed (10% in 50 years), the proposed risk matrix follows a scenario-based rather than fully probabilistic approach. By anchoring the analysis to a seismic scenario, this method prioritizes understanding the variation in risk due to different susceptibility levels rather than focusing on seismic intensity.

The intensity classes derived from the seismic zoning framework were spatially assigned to individual buildings based on their geographic location within the study area, ensuring the integration of seismic intensity into the building-scale risk analysis. Each building was mapped to the corresponding seismic zone, thereby inheriting the associated intensity class, ranging from 1 (lowest intensity) to 5 (highest intensity). Figure 7 illustrates the resulting intensity classes across the Tuscany region and their spatial distribution among the studied buildings.

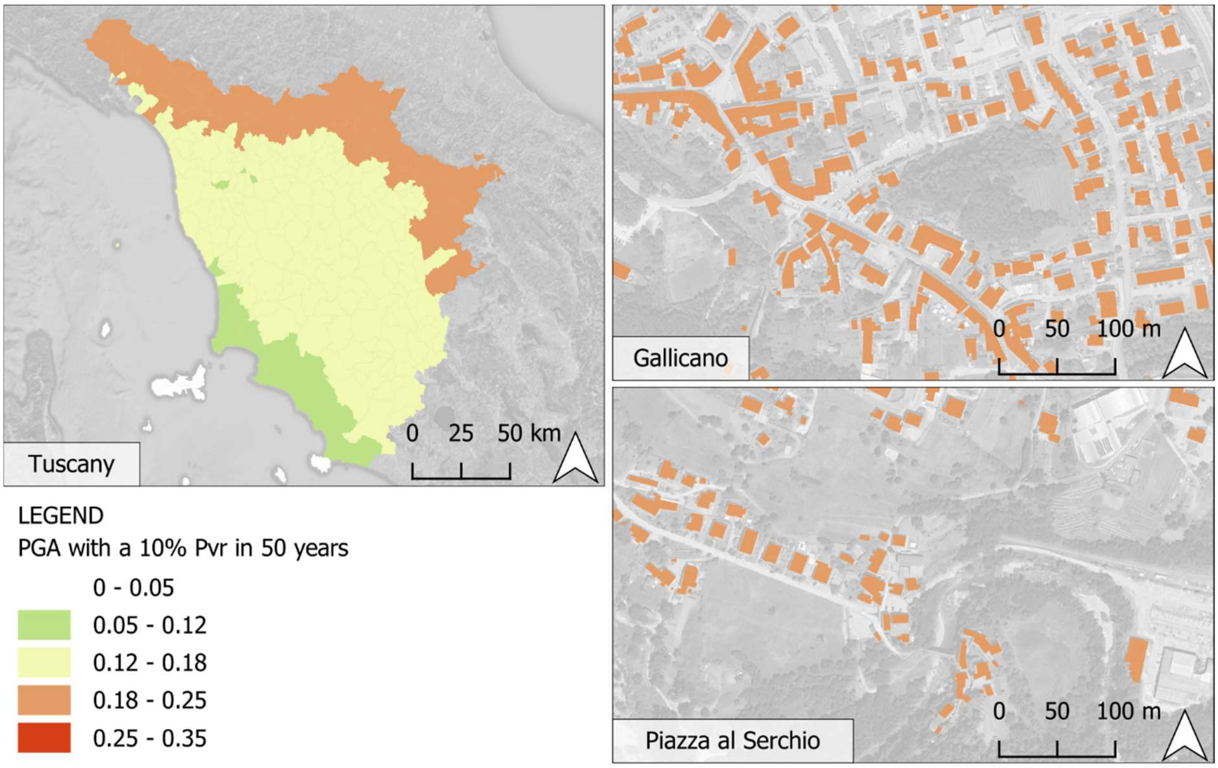


Figure 7 Seismic intensity classes for Tuscany and their association with the studied buildings.

4 RESULT AND DISCUSSION

The susceptibility and intensity classes obtained were used as input data for the risk matrix in Figure 1. Figure 8 shows the final seismic risk maps for Gallicano and Piazza al Serchio. Risk patterns closely reflect the previously discussed susceptibility distributions, highlighting differences depending on the territorial exposure metric used. As observed in the susceptibility analysis, KBC proves particularly effective in highlighting areas where limited redundancy in the road network may lead to the isolation of entire building clusters, as can be seen within the historic center of Gallicano. In contrast, NAIN consistently identifies higher risk concentrations in the historic centers of both municipalities, attributable to lower local accessibility, which may affect rapid evacuation and emergency response.

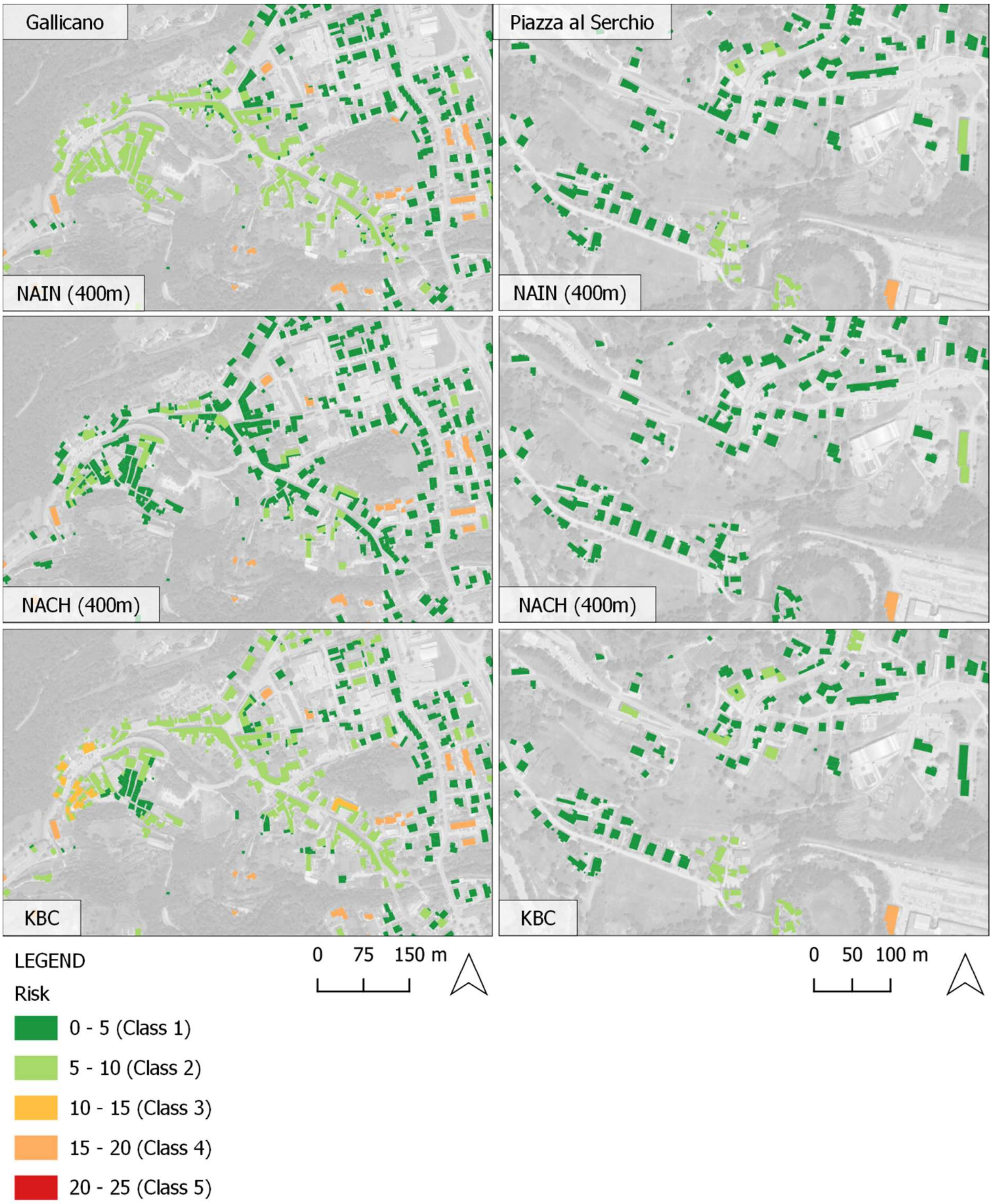


Figure 8 Seismic risk maps for Gallicano and Piazza al Serchio.

These differences emphasize that the choice of territorial exposure indicator should align with the specific goals of the risk analysis. For instance, KBC may be more appropriate in the context of resilience planning, where the focus is on maintaining access routes and ensuring connectivity in the event of disruptions. On the other hand, NAIN may be more relevant for preparedness and emergency management, especially in pedestrian-dominated urban aggregates, where local integration plays a critical role in evacuation efficiency and access for rescue services. The ability to compute and compare alternative risk maps supports a flexible and context-sensitive approach to seismic risk analysis.

5 CONCLUSIONS

This paper proposes a multilevel methodology for seismic risk analysis of residential buildings that integrates physical susceptibility, population exposure, and territorial exposure based on road network analysis. The approach expands upon traditional building-level analysis by incorporating the spatial role of the road network in the emergency response and disaster recovery planning.

The methodology was applied to two small municipalities in northern Tuscany—Gallicano and Piazza al Serchio—using three distinct centrality-based indicators to define territorial exposure: Normalized Angular Integration (NAIN), Normalized Angular Choice (NACH), and Kemeny-Based Centrality (KBC). For each of these, a different susceptibility map was computed, and the final risk was assessed using a scenario-based matrix combining susceptibility with seismic intensity classes.

Susceptibility is constructed on the premise that territorial exposure can act as a modulating factor on overall building physical susceptibility and exposure. Results highlight that NAIN and KBC are particularly useful in emphasizing local accessibility and potential isolation of historic cores due to limited redundancy, respectively. While NACH provided a more generalized result, diminishing the contrast between urban areas, thus providing less meaningful information. These findings suggest that the choice of centrality metric can be adapted to serve different risk management goals. For example, NAIN is well-suited to preparedness strategies in pedestrian-oriented environments, while KBC supports the identification of areas with limited connectivity, useful for planning alternative routes and enhancing system redundancy.

By enabling comparison between alternative configurations of territorial exposure, this methodology provides a flexible tool for informed decision-making for seismic risk mitigation, urban planning, and emergency preparedness, especially in small to medium-sized historic towns.

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