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Adaptive regional seismic risk assessment under uncertainty: a case study in the Alto Garda area

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Abstract

A reliable national and regional risk assessment is essential for researchers, practitioners, and decision-makers. Seismic risk assessment is crucial for evaluating earthquake-induced damage to structures, infrastructure, and society. However, it cannot be effectively performed without properly managing uncertainty.
In this context, hazard models and vulnerability analysis are the two critical pillars that contribute most to improving risk management, infrastructure planning, and disaster response.
In this work, we present an adaptive risk assessment framework for the Alto Garda area, located in northern Italy. Leveraging newly available microzonation data and advanced hazard analysis within OpenQuake engine, the study achieves high spatial resolution at a local scale. Historical earthquake records, cadastral data, open-source maps, and satellite imagery are integrated to (i) compile a comprehensive building taxonomy and (ii) dynamically refine vulnerability models. Additionally, both aleatoric and epistemic uncertainties are carefully considered using a logic tree approach applied to both hazard and fragility analysis.
Moreover, an adaptive approach is implemented, meaning that as new information becomes available, updates are seamlessly integrated to enhance accuracy and refine models. By combining hazard and vulnerability maps, the study delivers a first semi-quantitative risk evaluation for the region. This approach highlights the potential of adaptive methodologies in improving seismic risk mitigation strategies and strengthening decision-making under uncertainty.

Keywords: Seismic regional risk assessment; uncertainty quantification; microzonation data; vulnerability maps; hazard analysis

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1. Background and motivation

The critical importance of seismic risk assessment is underscored by the frequent and devastating earthquakes that have impacted the Italian territory in recent decades, such as the L'Aquila earthquake in 2009 and the Central Italy sequence beginning in 2016. These events have caused severe human, social, and economic consequences, highlighting the urgent need for robust, site-specific risk mitigation strategies. While the scientific literature offers a wide array of seismic risk studies, these are predominantly conducted at broader spatial scales—global, continental, national, or regional—often at the expense of local detail. Notable examples include global-scale frameworks such as those in Silva et al. (2020) and comprehensive national efforts, such as the Swiss risk model Wiemer et al. (2023).

This study aims to take a first step toward the development of a flexible and adaptive seismic risk assessment framework, specifically tailored to operate at a local scale and capable of addressing uncertainties throughout the entire risk chain. Our focus is on the Alto Garda valley in northern Italy, an area with documented seismicity, including macroseismic intensities up to grade VII observed during the 1976 Northern Garda earthquake.

Working at this fine spatial resolution necessitates an equally detailed and high-quality knowledge base—particularly in key domains such as soil characterization, building typology classification, and the treatment of incomplete or uncertain data. To address these challenges, the methodology we propose is designed to quantify and manage both epistemic (stemming from limited knowledge) and aleatoric (stemming from inherent variability) uncertainties in hazard and vulnerability modeling.

Seismic hazard at the local scale is defined using advanced microzonation data, while the vulnerability component draws on a diverse integration of sources, including historical seismic records, cadastral databases, and remote sensing technologies.

A defining feature of the proposed framework is its adaptive architecture, which allows for the continuous incorporation of new data, model refinements, and improved analytical techniques over time. This ensures that risk estimates remain both current and increasingly reliable, supporting evidence-based decision-making in dynamic seismic contexts.

The remainder of the paper is structured as follows: Section 2 details the proposed framework, emphasizing the heuristic approach adopted to handle multi-level uncertainties and enable the assimilation of new data as it becomes available. Section 3 presents preliminary findings, illustrating how varying levels of input detail and the integration of refined microzonation influence hazard characterization in the Alto Garda case study. Lastly, Section 4 concludes with key takeaways and identifies promising directions for future research.

2. Heuristic of the framework

Risk quantification is built on the combined assessment of hazard, exposure, and vulnerability.

Concerning the hazard model, generally, region-specific or national datasets (e.g., Bindi et al. (2011)) are deployed to select suitable ground motion prediction equations (GMPEs), therefore incorporating epistemic uncertainties. In this study, local seismic effects from microzonation studies (SMZ) Laurenzano et al. (2022) are integrated into the model to refine ground motion estimates.

Instead, for the exposure and vulnerability components, a logic tree framework is adopted. This accounts for uncertainty at two Levels of Detail (LoD) in the exposure parameters and for the representativeness of fragility curves drawn from literature. These curves vary in relevance depending on how well they reflect the unknown characteristics and descriptive parameters of the built environment in the study area.

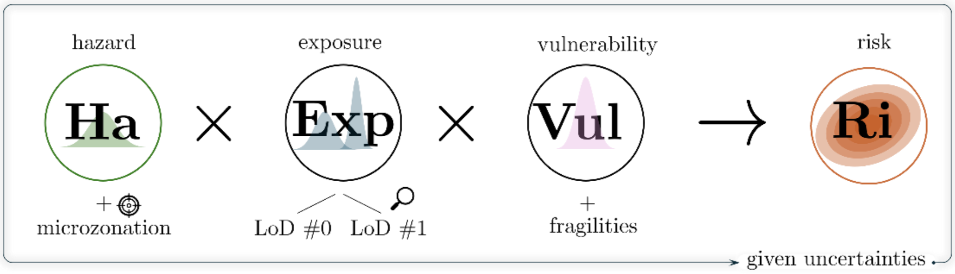

Fig. 1. Risk assessment's components.

In this study, first we calculate the ground motion intensities—both peak ground acceleration (PGA) and spectral acceleration ($Sa(T)$)— under reference conditions, i.e., considering stiff soil condition ($V_{S,30} = 800\ m/s$). These values are then modified deploying local amplification factors based on shear wave velocity and basin effects. The Alto Garda valley is subdivided into clusters, centered on recording stations, and amplification factors are empirically derived from real event records. Fig.2 reports the comparative results in terms of PGA distribution considering or neglecting SMZ effects. A stronger amplification pops out in the central valley due to deep sediment deposits, while weaker effects appear near the rocky valley edges.

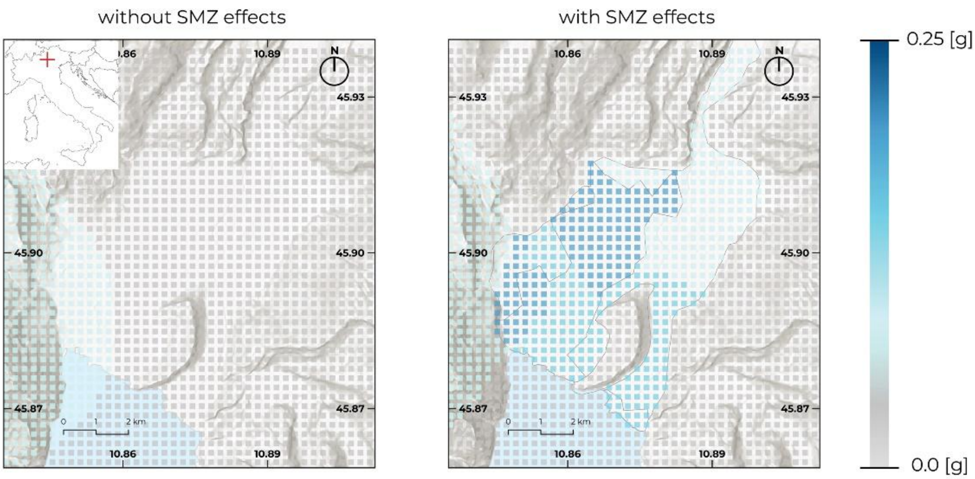

Fig. 2. Distribution of PGA without and with considering SMZ effects.

For the exposure model, a GIS-integrated system is developed to support the simultaneous management of both structural characteristics and exposure metrics (e.g., population or economic value). Buildings/assets are classified using a taxonomy string following Brzev et al. (2013) (see Fig.4), allowing each asset to be assigned a unique identifier and an appropriate fragility curve.

The exposure database is built through the integration of diverse data sources. The goal is to define the minimum parameters required to associate each building/asset with a fragility curve. However, due to the size of the study area, it is impractical to determine all attributes with precision. Moreover, uncertainty arises from both missing data and variability in curve applicability. Besides, fragility functions developed for other regions in Italy may not accurately reflect Alto Garda's building stock, due mostly to differences in typologies and building technologies.

To address this, the study introduces a two-level strategy for managing uncertainty. First, multiple fragility curves are used, each weighted by their similarity to the local building typologies. Second, a set of alternative exposure models is generated, where missing parameters are filled using probabilistic distributions derived from local data (e.g., ISTAT census information for the three municipalities in Alto Garda). The final outcome is a set of exposure–vulnerability combinations, from which a weighted average estimate is obtained to support risk evaluation under uncertainty.

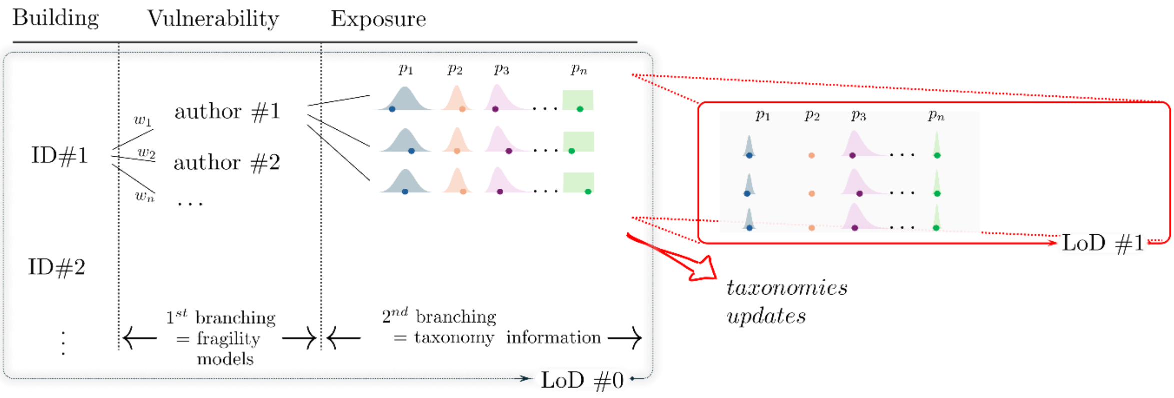

Fig. 3. Logic tree graph and LoD's levels for the vulnerability and exposure models.

This procedure is applied to two Levels of Detail (LoD) for the exposure model. The first model (LoD 0) covers the whole study area. The second model (LoD 1) is limited to the historic center of Riva del Garda. It is derived entirely from an extensive urban survey conducted in the area. The increased knowledge level significantly reduced uncertainties for most parameters (pertaining to both vulnerability and exposure). This directly affects the logic tree used for handling uncertainty, reducing the number of required exposure simulations. As a result, risk estimates become more precise.

Moreover, all vulnerability models were obtained by assembling fragility functions with consequence models, also sourced from the literature (expressed in terms of structural, non-structural, and injury mean loss ratios) and divided into classes (unreinforced masonry, reinforced concrete, etc.) – see Appendix A. Ideally, these should be calibrated at the regional (not national) scale. Thus, local data were gathered from different sources, such as, just to mention a few, cadastral databases, satellite imagery, LiDAR surveys (exclusive to Trentino), visual inspections, historical maps (Austrian cadastre for Trentino) and municipal statistics (ISTAT), as depicted in Fig.4.

Moreover, parameters strictly related to exposure include reconstruction costs ($€/m^2$) for structural and non-structural components, assigned also based on thorough calibration of historical-cultural value of the assets, as proposed in recent literature (Di Ludovico et al. (2023), Dolce and Manfredi (2015)). The number of occupants is assigned parametrically ($people/m^2$) and can be estimated probabilistically based on a hierarchy of building use, footprint area, and seasonal/time-of-day population variations across Alto Garda.

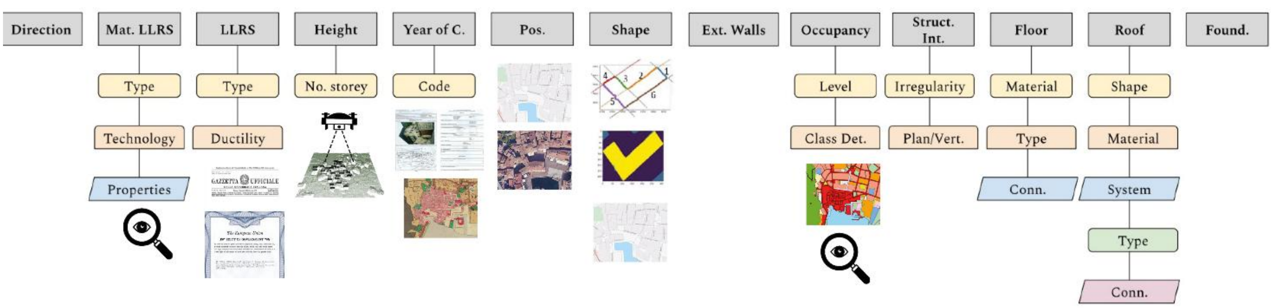

Fig. 4. Multi-level taxonomy and data's sources.

3. Preliminary results for the Alto Garda area

All the components described so far (hazard, exposure, vulnerability) are then combined to simulate the Northern Garda (1976) risk scenario, in terms of structural and non-structural losses, as well as injured occupants.

The results confirm a loss distribution pattern influenced by valley zonation (greater losses in areas with poorer soil), and also highlight significant site effects, with values up to five times higher than those estimated for rock soil conditions ($V_{S,30} = 800\ m/s$). In the first case, nearly all buildings register losses of around €5'000, while in the second case, many reach €30'000.

Furthermore, considering only the historic center of Riva del Garda—where a LoD 1 exposure model was also developed—results show a 40% difference compared to the same area extracted from the LoD 0 model (applied to the entire Alto Garda). This underscores the importance and relevance of extracting accurate parameters, such as in the case of extensive field surveys for urban mapping. Indeed, the results obtained appear to be closer to the estimates compiled in 1976 following the actual event, as reported in Molin (1979).

Furthermore, given the same hazard level, localized losses and damage are observed in correspondence with historic centers (both major and minor), where buildings are more vulnerable due to their geometric configuration and the construction techniques employed. Being the largest and closest to the epicenter, the historic center of Riva del Garda records the highest number of losses.

In terms of hazard, however, the expected results are similar even when using other GMPEs specifically developed for active shallow crust.

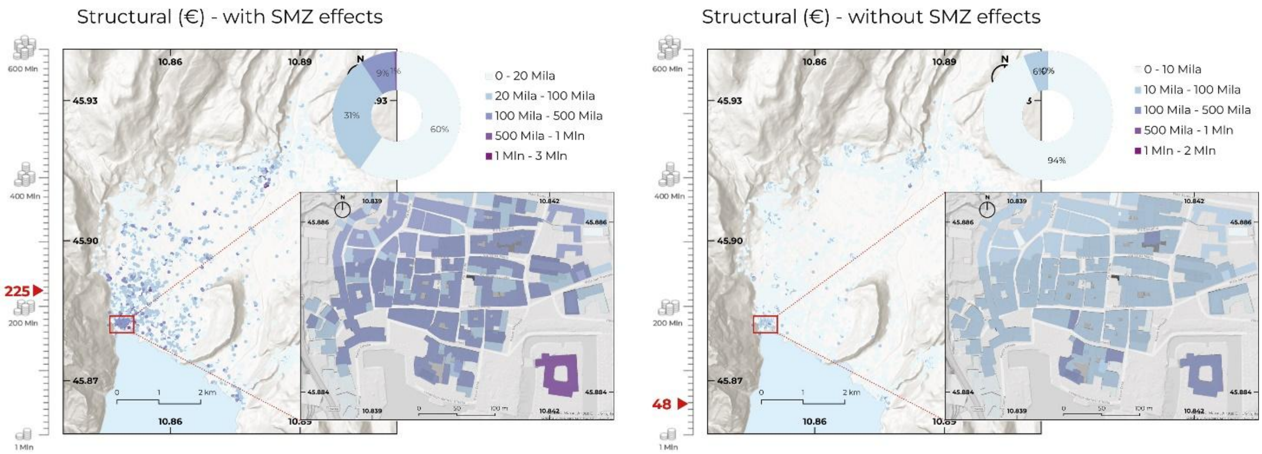

Fig. 5. Distribution of structural losses with and without considering SMZ effects, and local zoom on the Riva historic centre enriched with LoD 1 information.

4. Final remarks and future perspectives

This study presents an adaptive seismic risk assessment framework applied to the Alto Garda area, combining detailed microzonation data, a comprehensive exposure model, and refined vulnerability classification. By integrating heterogeneous data sources and adopting a logic tree approach, the framework explicitly addresses both epistemic and aleatoric uncertainties, enabling a first quantitative risk estimate at high spatial resolution. The adaptive nature of the framework allows it to evolve as new information becomes available, offering a scalable tool for seismic risk mitigation and emergency planning.

To advance toward a more robust and operational model, future work should thoroughly investigate the hazard and vulnerability components. Specifically, on the hazard side, calibrating GMPEs tailored to low-magnitude events and embedding site-specific effects at an early stage will improve accuracy. In parallel, vulnerability modeling should include detailed evaluations of strategic and critical structures to better represent local building performance. These improvements will support more reliable loss scenarios and form the basis for applications such as road occupancy analysis and better emergency response planning for civil protection.

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Appendix A. Fragility curves used in this study

A.1. Fragility curves for masonry buildings

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