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TOWARDS AN INTEGRATED INTERDISCIPLINARY APPROACH FOR LARGE-SCALE MODELLING, SIMULATION AND MANAGEMENT OF NATURAL DISASTERS: A VIRTUAL CASE STUDY URBAN AREA

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Abstract

The unacceptable consequences of recent natural hazard-related disasters such as earthquakes, landslides, floods, and intense rainfall have further highlighted the urgent need for a coordinated effort among researchers, practitioners, and governments to develop and implement effective disaster risk reduction policies in many countries worldwide. In Italy, several research studies in the last decades have been focusing on the analysis of natural hazards (single, chained or multiple) and the evaluation of the associated risks to the built environments, including the quantitative estimation of socio-economic impacts. Yet, a robust integrated approach capable of quantifying the interdependent impacts of multiple and multi-hazard scenarios and support, as a high-level decision-making operational "dashboard", the development of multi-risk reduction and resilience enhancement strategies at a national level, is still missing and urgently needed.

The primary challenges of such a topic involve the need for: (i) a multi-scale evaluation of both different hazards (e.g., from large-scale simulations to more detailed site-specific effects and in-situ observations) and exposure-vulnerability models (e.g., from territorial scale up to single structures/infrastructure and advanced Digital Twin model); (ii) properly considering inter- and intra-dependencies among infrastructural components (building stock, utility network, road network); (iii) accounting for uncertainties related to data availability and limited knowledge; (iv) huge computational resources to manage the required massive amounts of data.

In this context, as a part of a wider PNRR (National Recovery and Resilience Plan) – National Research Centre on High Performance Computing, Big Data and Quantum Computing (CN1) research project, this paper presents and discusses the ongoing activities carried out by an large interdisciplinary team of engineers, geologists, and geophysicists on large-scale modelling, simulation, evaluation and management strategies for natural disasters. Particularly, a major effort is devoted to the development of an integrated framework for scenario-based multi-risk assessment of urban areas, following an input-output data supply chain or "domino-like" sequential approach, primarily triggered by earthquake events. The workflow involves the following steps: (i) earthquake rupture simulations and seismic wave propagation; (ii) site-specific amplification analysis due to stratigraphic and topographic conditions; (iii) assessment of earthquake-induced natural events (such as earthquake-induced landslides); multi-scale and multi-refinement level risk assessment of the urban area considering different interconnected layers (building stock, water distribution system, road network); (iv) evaluation of risk metrics – Key Performance Indicators (KPIs) of primary interest for end-user and stakeholders, e.g., deaths, economic losses, downtime. The paper introduces the proposed methodology and discusses in more detail the development of a Proof-of-Concept (PoC) demonstrator, consisting of a Virtual Test Bed (VTB) ecosystem, based on an innovative approach where a virtual, i.e., realistic but not real, case study urban area, located in a multiple-hazard-prone zone, is populated by buildings of different use and material, and lifelines/infrastructures. The unique opportunity of implementing such an integrated digital twin-based framework within an HPC environment can represent a powerful decision-making tool supporting the management and planning of disaster risk reduction strategies and, ultimately, enhancing the resilience of our communities.

Keywords: Disaster Risk Management, Urban Areas, Multi-Hazard, Multi-Risk Assessment, High Performance Computing, Virtual Test Bed

1 INTRODUCTION AND MOTIVATIONS

Natural hazard-related disasters - including earthquakes, floods, landslides, storms, volcanic activity, and intense rainfalls - cause severe consequences worldwide, resulting in both casualties and socio-economic losses due to physical damage and downtime. According to the data collected in the Emergency Events Database (EM-DAT), disasters that occurred over the last twenty years (2000-2019) were responsible for approximately 1.23 million fatalities and approximately US$ 2.97 trillion economic losses ([1]). Therefore, there is an urgent and critical need for a coordinated effort among researchers, practitioners, and governments to understand, manage, and mitigate disaster risk worldwide.

Focusing on the Italian contest, among other natural hazard-related disasters, past earthquakes over the last 50 years have caused, in addition to an unacceptable number of human losses, huge direct economic losses (i.e., costs related to the reconstruction process) estimated to be in the order of €150-250 Billions. This cost estimation can be even more critical – with a Keynesian amplification factor of 5x or 10x - if indirect economic losses, thus including the cascade effects on economy and production chains, the impact on public debt, and the long-term interest rates were taken into account ([2]). A more realistic estimation of the economic impact in the past 50 years in Italy can thus be easily reach and go beyond an enormous amount of €1500 Billions, thus, in average, €40 Billion/year. Following a methodological procedure consisting of Diagnosis, Prognosis and Therapy, the reduction of seismic risk would require the deployment of a Detailed Seismic Assessment (DSA) of the entire built environment to support informed decision-making and the development of a, largely overdue, coordinated medium-to-long-term national plan for seismic risk reduction (e.g., [3]).

In the last decades, significant research efforts have been devoted to investigating and developing methodologies and tools for the assessment and management of earthquake-induced impacts. State-of-the-art procedures are based on probabilistic frameworks and involve: i) a probabilistic seismic hazard model, ii) an exposure dataset, and iii) a set of building-level fragility and/or vulnerability models. This method allows for the evaluation of decision variables of major interest for end-users and stakeholders (e.g., casualties, economic losses), which can be also visualized in the form of either municipal, regional, or national seismic risk maps (e.g., [4]). However, these maps typically rely on aggregated statistical data and significant assumptions to account for the soil amplification, mainly due to the limited availability of more detailed information at this scale of analysis. In the Italian national panorama, a tool of indisputable relevance is represented by seismic microzonation studies which, starting from the engineering-geological reconstruction of the near surface, aim at quantifying the modification of the expected seismic action, based on local seismic response effects of both topographic and stratigraphic origin ([5]). A fundamental complement to these studies consists in the analysis of quantitative scenarios of earthquake-induced ground instabilities (such as landslides) to identify areas of potential instability connected to the expected seismic action and, consequently, to provide a broader perspective of the damage caused on anthropic sites and infrastructures ([6]). Among others, landslides globally represent the most hazardous earthquake-induced effect ([7]) and they correspond to the most represented earthquake-induced ground-effect in Italy, according to the Italian Catalogue of Earthquake-inDuced ground failures (CEDIT) ([8-9]).

The lack of an integrated approach makes transitions across different scales a challenging goal, forcing a potential end-user to move to different (typically more detailed) models when a smaller scale such as urban areas is considered [10] (Figure 1). A rigorous and robust comprehensive methodology, able to consider the interdependent impacts of earthquakes and multiple hazard scenarios - while serving as a high-level decision-making “dashboard” to support the development of risk reduction and resilience enhancement strategies at the national level - is still missing and urgently needed.

A national risk map could be ideally carried out starting from the development of "digital twins" for urban areas. These digital models should include detailed data on the construction environment, geological features, and fault sources, while allowing for dynamic updates as new information becomes available. However, achieving this ambitious goal presents several key challenges: (i) developing a multi-scale assessment procedure for both different hazards and exposure-vulnerability models; (ii) properly accounting for inter- and intra-dependencies among critical infrastructural systems (e.g., building stock, utility network, road network); (iii) addressing uncertainties arising from the limited data availability and knowledge; (iv) managing the required huge computational resources and the massive amounts of data.

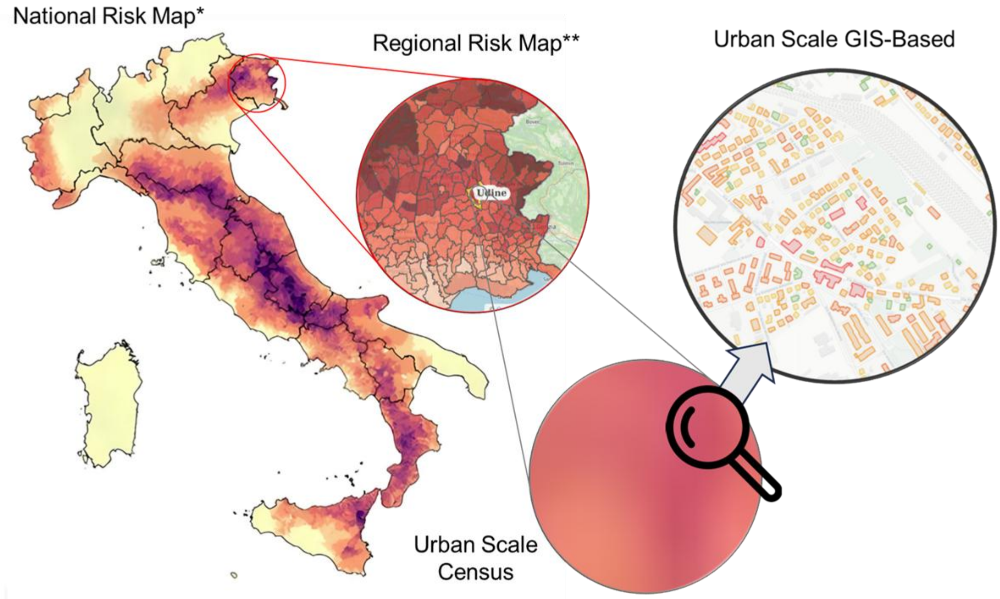

Figure 1: Conceptual representation of the challenges in moving from national to urban area scale when dealing with census data. (after Matteoni et al. [10]; *from Dolce et al. [4]; ** https://www.sicuropiu.it/index.xhtml).

To address these challenges (specifically concerning computational resources) the PNRR (National Recovery and Resilience Plan) – CN1 National Research Centre on High Performance Computing, Big Data and Quantum Computing project [11] aims to enhance the research potential and the efficiency of the scientific community in modelling and managing natural hazard-related disasters, as well as support the definition of suitable disaster-risk reduction policies. In this context, this paper presents and discusses the ongoing activities of an interdisciplinary team of engineers, geologists, and geophysicists focused on large-scale modelling, simulation, evaluation and management strategies for natural disasters. The paper introduces and discusses the methodology (Section 2) and details the innovative multidisciplinary approach adopted to develop a Proof-of-Concept (PoC) demonstrator (Section 3). Finally, conclusions are presented in Section 4.

2 METHODOLOGY

This research proposes a workflow which integrates frameworks for urban area multi-risk assessment, management, and mitigation. This workflow employs a "domino-like" sequence, as shown in Figure 2, composed of the main following steps: (i) earthquake source model, including finite-fault rupture simulations and seismic wave propagation; (ii) site response analysis for the evaluation of amplification factor due to stratigraphic and topographic conditions; (iii) assessment of earthquake-triggered natural hazards, such as earthquake-induced landslides; (iv) damage analysis of each urban area's component (single buildings, infrastructural systems); (v) evaluation of risk metrics (e.g., deaths, economic losses, downtime) for the whole urban area; (vi) evaluation of alternative risk management and mitigation strategies. Each step of the proposed workflow is discussed in the following sub-sections.

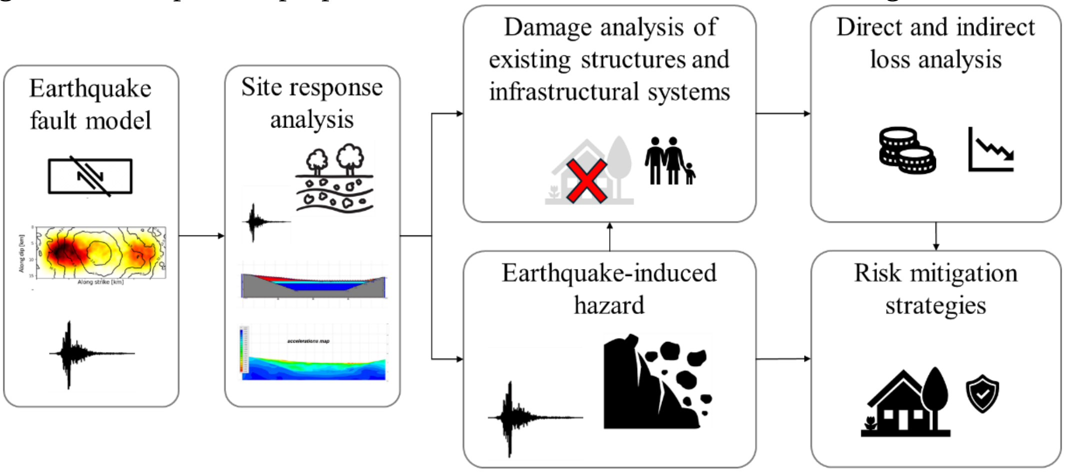

Figure 2: Multidisciplinary workflow: from earthquake source simulation to risk assessment and mitigation.

2.1 Earthquake source modeling

In this study, multiple kinematic fault rupture scenarios were generated by defining a fixed fault geometry and an earthquake magnitude of 6.2, while introducing variations in slip, nucleation point, and other kinematic parameters. Following Locchi et al. [12], the fault plane dimensions was set to 40 km × 16 km to maintain consistency with seismicity distribution on the Gorzano fault observed during recent seismic sequences of 2016 and 2009 in central Italy, as well as with previous modeling studies of fault activation. This plane was then discretized into square patches of 0.25 km × 0.25 km, over which a heterogeneous slip distribution was assigned. This distribution is constructed using a von Kármán spatial correlation function to reproduce realistic heterogeneities in the fault slip at different lengths. The nucleation (or hypocentral) point was chosen randomly on the fault plane, allowing for variability in rupture initiation and directivity. In the simulations both bidirectional and unidirectional rupture fronts were considered to explore different rupture propagation scenarios.

Once the slip distribution is established, the source time functions for each sub-fault patch is imposed using the Regularized-yoffe source time function (STF) ([13]). The rise time (i.e., the total duration of slip at each sub-fault) and the acceleration time (T_{acc}, the initial phase of the slip function where acceleration occurs) are determined as functions of slip. These two parameters are essential for constructing the STF, which governs the kinematic representation of the rupture process. Specifically, $T_{acc} \propto 1/slip$ was adopted, ensuring shorter rupture durations in regions of higher slip, which leads to a more physically plausible rupture evolution. Whilst such an assumption is reasonable, it should be noted that T_{acc} remains one of the least constrained parameters in kinematic models derived from real earthquakes. The rise time is imposed constant across the fault, given that in single-window scenarios it has limited influence on the resulting ground motion. Its value is selected as the average rise time extracted from a set of preliminary simulations with spatially heterogeneous rise time. Ongoing research showed that the parameters most influencing high-frequency ground motions are the rise time (which primarily affects PGV) and T_{acc} (which primarily affects the frequency content).

All kinematic parameters (slip, nucleation point, rise time and T_{acc}) are then combined to simulate ground-motion time histories with a frequency range of 0.02–10 Hz, suited for the engineering demands of a wide range of structural periods. This approach generates a comprehensive dataset of potential rupture scenarios, serving as the basis for subsequent local seismic response assessments and earthquake-induced hazard analyses. Simulations of forward models were performed using a deterministic code specifically designed for kinematic inversions based on a Non-Negative Least Squares (NNLS) approach ([14]). This methodology imposes physically meaningful spatial and temporal constraints on the model parameters, ensuring stable and interpretable results. The deterministic nature of the code enables reliable fault rupture simulations and allows to explore the impact of various parameters on secondary analyses (e.g., the seismic response). High-frequency content is generated stochastically at the source, rather than being added directly to the waveforms. For each subfault, the waveform is computed based on its slip pulse convolved with the STFe, and time-shifted according to the rupture time propagation. The final waveform results from summing these contributions, preserving the physical consistency of the rupture process. This approach captures the complex, heterogeneous slip history, while ensuring a realistic representation of both deterministic and stochastic aspects of the source model.

2.2 Site response analysis

For evaluating site response due to topographic conditions, land-surface quantitative analyses have been carried out. Analyses started from Digital Terrain Models (DTM) with different ground resolutions (i.e. 5 m, 10 m, 30 m). In particular, the topography of the area has been categorized by means of specific terrain morphology, known as Geomorphons [15]. These are object-based parameters which identify morphological types based on pattern recognition. Geomorphons, which usually considered 10 different landforms, have been simplified into five classes (Figure 3) considering the specific purpose of site response analysis.

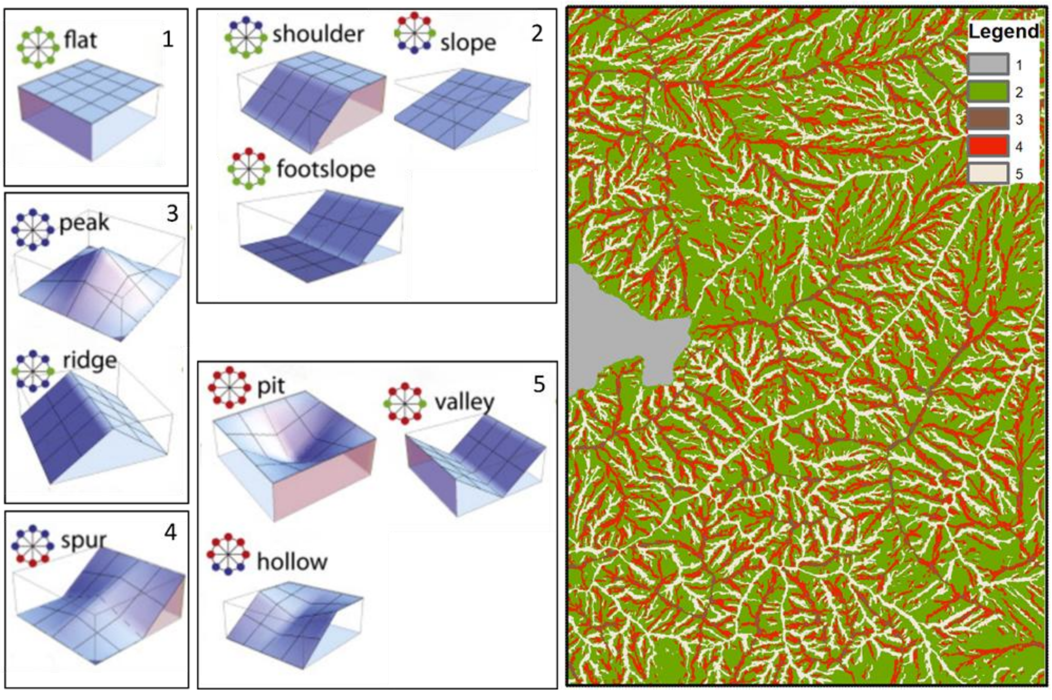

Figure 3: Classification of topographic amplification based on modified geomorphons classes (after [15]).

In order to evaluate the local seismic response within the project case study area in terms of seismic input modifications generated from different seismogenic sources, five engineering geological cross sections are reconstructed and a 2D numerical modelling is performed to simulate the propagation of seismic waves from the seismic bedrock to the surface, taking into account the latero-vertical variations of the physical and mechanical properties of soils (stratigraphic conditions), as well as the topography and buried geological bodies (e.g., [16-17]).

The simulation of the seismic motion propagation is performed by an equivalent linear analysis, through finite elements in the time domain, in total stresses, applying a viscoelastic rheological behavior of Kelvin–Voigt. To the different layers of the engineering geological cross sections, physical and geophysical parameters as well as decay parameters (i.e., shear stiffness and damping degradation curves) are assigned with a discretization of the model in quadrangular meshes (about 2-m resolution grid), free-field conditions (i.e., damping conditions in the X and Z direction) on the lateral borders and a kinematic constraint on the vertical motion at the base. At the base of the multilayer cross-sections (infinite half-space representative of the seismic bedrock) the seismic inputs with 7-time histories (X and Z components) for each generated rupture model, as representative of different seismogenic sources (Section 2.1), are applied.

From such a numerical analysis, it is possible to obtain for each control point fixed, at 10 m distance along the cross-sections, and for each rupture model: the time histories of the ground motion shaking (in terms of acceleration, velocity and displacement) and the elastic response spectra (with 5% damping) (for X and Z components) to be used as input for the subsequent damage analysis of the building structures and infrastructures designed in the area of the VTB crossed by the sections. To quantify the magnitude of the local seismic response, specific indexes, defined as normalized integral of the response spectra (namely Housner integral) within specific period intervals, can be computed.

2.3 Earthquake-induced hazard

Seismic action is largely recognized as a potential common trigger for landslides ([18]). In this project, the cascading effect of earthquakes on landslides has been evaluated following a multi-hazard approach, in order to assess a more comprehensive geo-hazard on site.

The approach applied for generating landslide scenarios is the PARSIFAL (Probabilistic Approach for Rating Seismically Induced slope FAiLures; [19, 20]), a toolchain that allows for the quantitative definition of seismically-induced slope failure scenarios in different contexts/environments and scales, and considering various soil saturation levels and seismic hazards. PARSIFAL includes a three-step procedure: 1) susceptibility analysis including a differentiated approach for rock and earth failure mechanisms; 2) slope stability analysis; 3) synthetic mapping of generated scenarios, based on a mix of grid and slope units. The result is a comprehensive representation of the slope stability conditions for defined seismic and hydraulic conditions, which aggregates the hazard related to first-time rock failures, first-time shallow earth slides, and reactivations of existing landslides in both rock and earth slopes.

In this project, the seismic actions derived from the possible fault rupture scenarios were used as a trigger for PARSIFAL application. Moreover, the spatial variability of the rupture scenarios' results has been taken into account, by considering seismic signals that are distinct by zones within the area of interest.

2.4 Damage and loss analysis of the urban area

The output from the previous steps is used to perform a seismic risk assessment of the urban area through an innovative multi-scale and multi-refinement approach ([21]). For the implementation of the procedure, urban areas are identified as "macro-systems" (e.g., [22]) composed of several clustered and interconnected layers, which are themselves composed of single elements/assets (e.g., buildings, water pipelines, roads; Figure 4).

Considering the complexity of the analyzed system, it is fundamental to account for the possible (negative) interaction between different interconnected layers for risk analyses (e.g., [22]). In the proposed method, a "master-slave" approach is employed: earthquake damage to one layer ("master") can lead to a loss of functionality of another layer ("slave"). For example, debris from earthquake-damaged buildings ("master") can lead to a loss of functionality of the road network ("slave") in terms of disruption of urban mobility, even if roads are undamaged.

Moving to a smaller scale of analysis, for each significant layer, direct and indirect losses need to be assessed. Direct losses can be directly related to damage to the layer's components (single assets). If direct economic losses are considered, they can be associated with the repair cost of damaged components and can be evaluated, at the layer level, as a simple sum of direct losses for each layer component. Differently, indirect losses are typically related to disruption and downtime, and can be either comparable or larger than the corresponding direct losses (e.g., [4, 23]). The evaluation of indirect economic losses for each layer requires accounting for possible cascading effects; the latter can be either "intra-layer" (i.e., negative interaction of assets of the same layer) or "inter-layer" (i.e., due to damage to components of another layer).

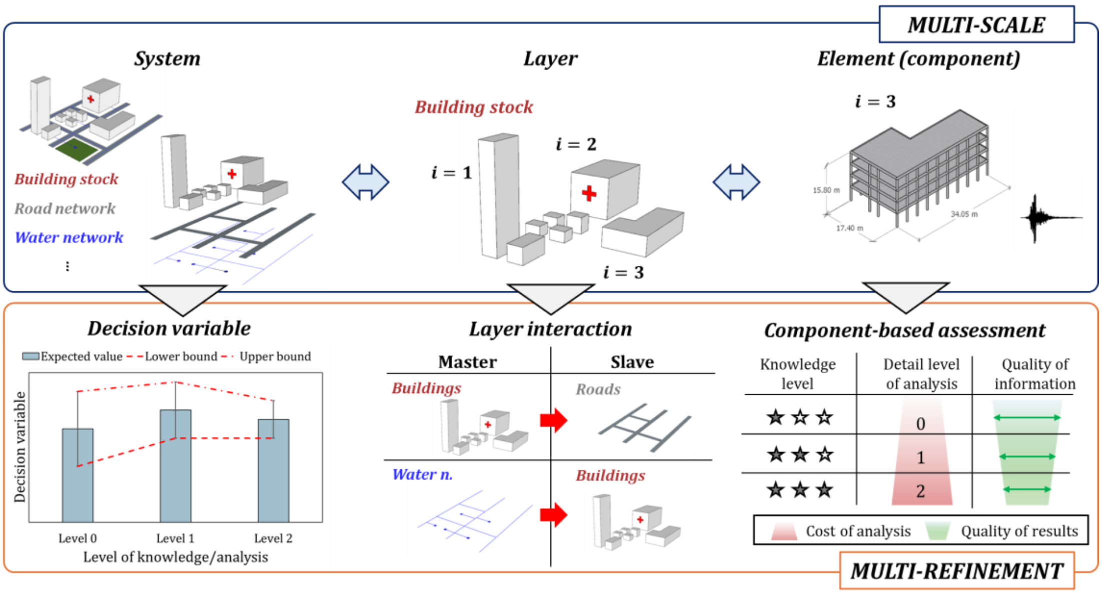

Figure 4: Multi-scale and multi-refinement framework for seismic risk assessment of urban areas.

Finally, at the scale of single components, the framework employs alternative refinement levels of analysis (from rapid and simplified procedures to more advanced software-based simulations, possibly up to "Digital Twin" models) to perform both damage and loss evaluation. The level of analysis can be selected based on the available documentation for the specific components and the specific needs of end-users and stakeholders. Alternative refinement levels involve: i) typological-based vulnerability assessment; ii) analytical/mechanical procedures, and iii) numerical (software-based) simulations. The output from the previous steps is thus used to define the demand in seismic response analysis (acceleration, velocity, displacement/rotations/drifts, internal moment/shear/axial actions), which may be performed either according to simplified spectrum-based approaches or Non-Linear dynamic (Time History) Analyses (NLTHA). To account for the related uncertainties of each refinement level, results are always provided in terms of expected and dispersion values (e.g., [10, 21, 24]). Moving from a lower refinement level to a more refined one must return more reliable (i.e., less uncertain) results; yet, it would also require an increasing effort for data collection and higher computational costs. A key feature of the framework relies on the possibility of "mixing" the knowledge levels, thus adopting, for instance, refined simulations only for strategic buildings and critical infrastructural systems. More details on the procedure are discussed in Matteoni et al. [21].

2.5 Refinement and mitigation of risk

Within the multidisciplinary, integrated framework outlined so far, the actions detailed in this Section represent both the culmination of acquired knowledge and a potential catalyst for fundamental improvements in urban multi-risk assessments. These advancements are achieved through: (i) the incorporation of refined digital models and (ii) the implementation of targeted risk mitigation strategies. While operating on different aspects, both these actions contribute to improving urban-scale risk assessment estimates: the former by decreasing prediction dispersions, the latter by reducing expected values of risk metrics.

Under these circumstances, automating structural damage identification and classification is a valuable tool for improving both emergency response efficiency (e.g., timely interventions, optimized resource allocation, and informed reoccupation decisions) and the understanding of pre- and post-event building behavior. A dedicated Machine Learning (ML) algorithm is developed to automate and standardize this process, traditionally reliant on visual inspections. Specifically, the methodology combines expert-based labeling of an RGB image dataset and AeDES-scale damage classification ([25]) with Convolutional Neural Networks (CNNs), transfer learning and data augmentation. Alignment with AeDES criteria ensures adherence to established Italian standards, guaranteeing precise, region-specific assessments.

At the structural component level, improved knowledge derived from exhaustive building-specific data availability (including original drawings, on-site inspections, and updated structural damage information), is reflected in a more refined modeling approach, attempting digital twin fidelity through advanced numerical simulations. Specifically, highly refined 3D numerical models, consistent with current state-of-the-art modeling strategies, are developed. Such models can ultimately be converted into digital twins when real-time monitoring data from their physical counterparts are accessible. Increased computational investment and analytical complexity are accepted trade-offs for progressively reducing epistemic uncertainties and refining expected risk estimates.

Notably, a key distinction is drawn: a detailed representation of the building conditions minimally affects the expected risk level while it significantly enhances the accuracy of consequence prediction (e.g., casualties, direct and indirect economic losses, downtime). However, increased precision in the as-built evaluation of specific buildings, with a preference for strategic ones, also translates into more informed decision-making for risk mitigation actions. In this context, local and global retrofitting strategies are considered to enhance the structural capacity of existing buildings.

3 PROOF-OF-CONCEPT DEMONSTRATOR

For the implementation of the proposed workflow, a proof-of-concept (PoC) demonstrator is defined by adopting a Virtual Test Bed (VTB) ecosystem. This task is addressed through an innovative multidisciplinary approach, which allows for the creation of a virtual – i.e., realistic but not real – case-study urban area located in a multiple-hazard-prone zone. The following sub-sections present and discuss the adopted procedure to define the geological features of the site and the construction environment, including the building stock, strategic buildings, road networks, and water distribution networks.

3.1 Geological features transposed from the site to the VTB

The VTB has been deduced from the Lake Campotosto area, within the Central Apennines in the L'Aquila province, bordered by the Gran Sasso d'Italia Massif to the south and the Laga Mountains to the north. This choice was motivated by the representativeness offered by this site to model a characteristic seismogenesis of chain sectors in the national context, with heterogeneous outcropping rocks and recent debris and alluvial covers. The area also guarantees a good representation of contexts ranging from mountainous to hilly to valleys, the latter interposed on rocky slopes. These situations are suitable for emphasizing the local seismic response as well as predisposing to the triggering of landslides due to earthquakes. The Campotosto basin lies in a seismically active region, with an estimated peak ground acceleration of 0.250–0.275 g at the seismic bedrock for a 475-year return period, according to the Italian seismic hazard map ([26]). Due to its tectonic setting, the basin is vulnerable to multiple earthquake-induced hazards, including seismic shaking, surface faulting, and various types of landslides.

The Campotosto Basin (CB) is an intramontane basin in the Central Apennines, formed after the tectonic impulse in the Upper Tortonian, which led to the fragmentation of the carbonate platform and the creation of small turbiditic basins. These basins are bordered by normal faults that existed prior to thrusts. The faults resulted in the foreland being dislocated from the Tortonian to the Messinian and are currently visible at the margins of the basin ([27]).

The turbiditic succession that fills the basin lies on the pelagic and hemipelagic deposits of the Lower Tortonian-Messinian. Originally interpreted as a deep-sea fan succession, it was subdivided into three members: pre-evaporitic, evaporitic, and post-evaporitic ([28]).

Recent cartography has considered the subdivision of the Laga Formation, but the three geological bodies have been renamed Campotosto Lake Member, Gessarenitic Member, and Teramo Member. The entire basin of Lake Campotosto is outcropped by the Lake Campotosto Member (Messinian). With a thickness of approximately 1100 m, it was distinguished into four different associations and a guide layer (Figure 5). The arenaceous association has an S/A (sand/clay) ratio greater than one, characterized by thick arenaceous layers in tabular and lenticular forms. These layers are typically massive, with no internal grading, and occasionally feature lamination at the upper boundary. The pelitic-arenaceous association has an S/A ratio below one, predominantly consisting of tabular layers with fully laminated arenaceous portions. The arenaceous-pelitic association II exhibits an S/A ratio between 1 and 3, with medium to thick tabular layers. The arenaceous-pelitic association I show an S/A ratio of 3 to 10, consisting of alternating thick and very thick arenaceous layers, interbedded with medium to parallel arenaceous-pelitic layers.

A notable feature of the sequence is the arenaceous-pelitic turbiditic guiding layer, approximately 10–15 m thick, marking the transition between lower arenaceous facies and upper arenaceous-pelitic and pelitic-arenaceous facies ([29, 30]).

The CB has been shaped by intense normal faulting since the Quaternary. Initially, the depression was filled with alternating coarse gravel and silty-sandy fluvial deposits, later overlain by lacustrine silt-clay sediments. The basin evolved from a peat bog, leaving behind a 10-m-thick peat layer, to its current state with thin, recent deposits. The surrounding Laga Fm. reliefs are frequently mantled by debris at their base. While gravitational forces are moderate, the region exhibits gravitational deformations and shallow landslides, often linked to extensional tectonics. Normal faulting strongly influences the landscape, particularly in shaping the western Laga Mountains, where morphological scarps are evident. At the transition zones between ridge slopes and valley edges, alluvial fans overlay older alluvial accumulations from the Lower-Middle Pleistocene, further shaping the geomorphology. These alluvial deposits behave as soft soils during seismic events, in contrast to the more competent seismic bedrock of the Laga Fm [15].

The main tectonic element of the area is the Mt. Gorzano fault, with extensional kinematics, that extends for a total of 28 km, subdivided into the Amatrice (8 km) and Campotosto (18 km) faults (Figure 5). It connects the Cerrogna Formation at the footwall and the Laga Formation at the hanging wall. Quaternary activity is evident, with slip rates along the Campotosto fault ranging from over 1 mm/yr to 0.7–0.9 mm/yr ([31-33]). The majority of vertical slip occurred during the Pliocene-Quaternary period, with potential for Holocene activity. In literature, it has been classified as a seismic gap, with the capacity to generate an earthquake measuring M6.6–6.7, although this classification remains contentious ([32]).

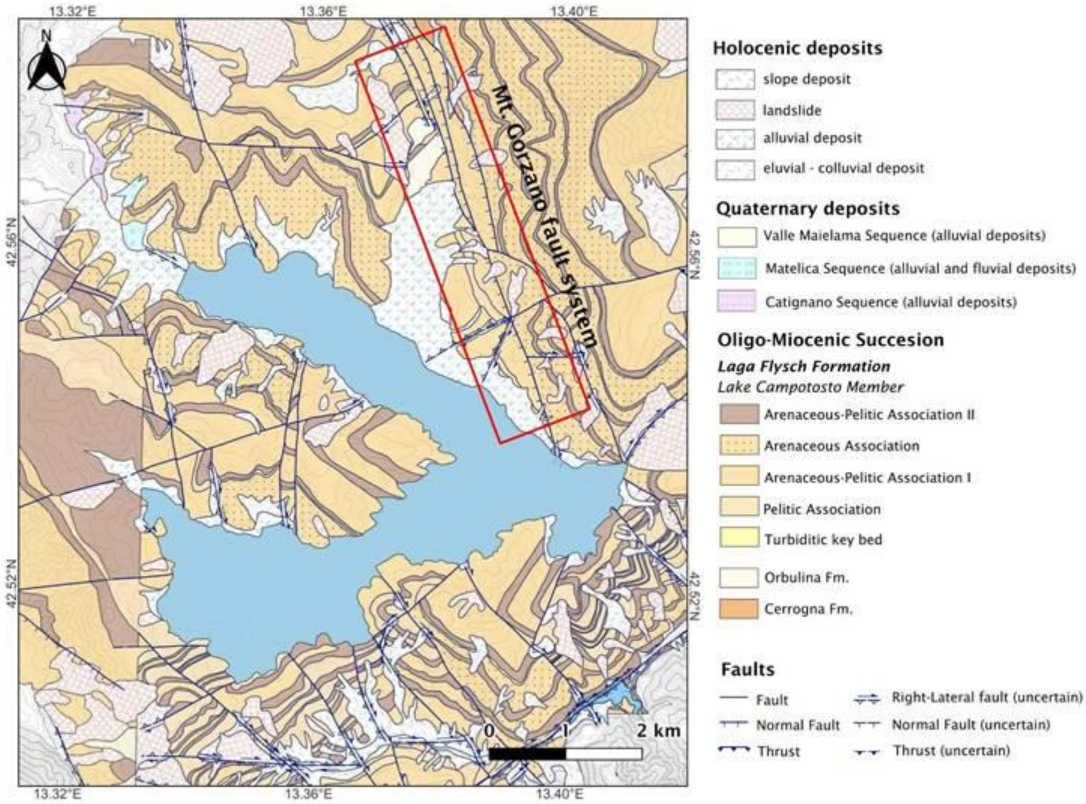

Figure 5: Geological Map of the POC area, based on geological map "Gran Sasso" n°349, scale 1:50.000 ([29])

3.2 Construction environment

The construction environment is defined to reproduce a realistic (but not real) urban area in Italy, composed of different interconnected layers. Urban areas can be classified into four categories (e.g., [34]): (i) compact monocentric, (ii) predominantly monocentric tending towards dispersion, (iii) dispersed cities, and (iv) polycentric. In this demonstrator, it has been decided to "build" a virtual polycentric urban area, in analogy within the real construction environment of the site; moreover, a polycentric structure allows for a better estimation of the effects of both stratigraphic and topographic amplification of the seismic demand, as well as the possibility of structures and infrastructures also in multiple-hazard-prone zones. At this stage of the research, three main layers are considered for the case-study urban area: the building stock, the water distribution network, and the road network.

Cornering the building stock, different urban blocks are identified to include different building classes (i.e., structures with different materials, construction periods, geometry, and construction details): pre-1970s residential areas, historical town, central business district, and community service facilities. Each urban block is defined in analogy with GIS data (e.g., OpenStreetMap) of the real construction environment in Italy to reproduce a suitable distance between buildings and adopt realistic dimensions of strategic buildings and historical constructions. Then, operatively, the urban area is populated with structures (real or archetypes) whose main information/documentation is available. The PoC demonstrator is shown in Figure 6. Each urban block is briefly discussed below.

The residential building stock in the case study area is predominantly composed of reinforced concrete (RC) structures, chosen as representative of the Italian building stock. In particular, seven residential building archetypes were defined. Six of these represent the Italian building stock constructed before 1970, characterized by gravity-load-designed structures. Five of the pre-1970 building archetypes were developed considering variations in building height (3 to 5 stories) and floor plan configurations (more details available in [35]). Additional six-story RC archetypes were developed considering two different configurations. One simulates a pre-code design according to the obsolete seismic code in force at that time (R.D. 2229 [36]), while the other follows a modern code-based seismic design according to the Italian building code [37]. The design simulations adopted herein adhere to methodologies established in De Risi et al. [38] and Ricci et al. [39], respectively, within the framework of the ReLuis RINTC (Implicit Risk of structures designed according to NTC) research program.

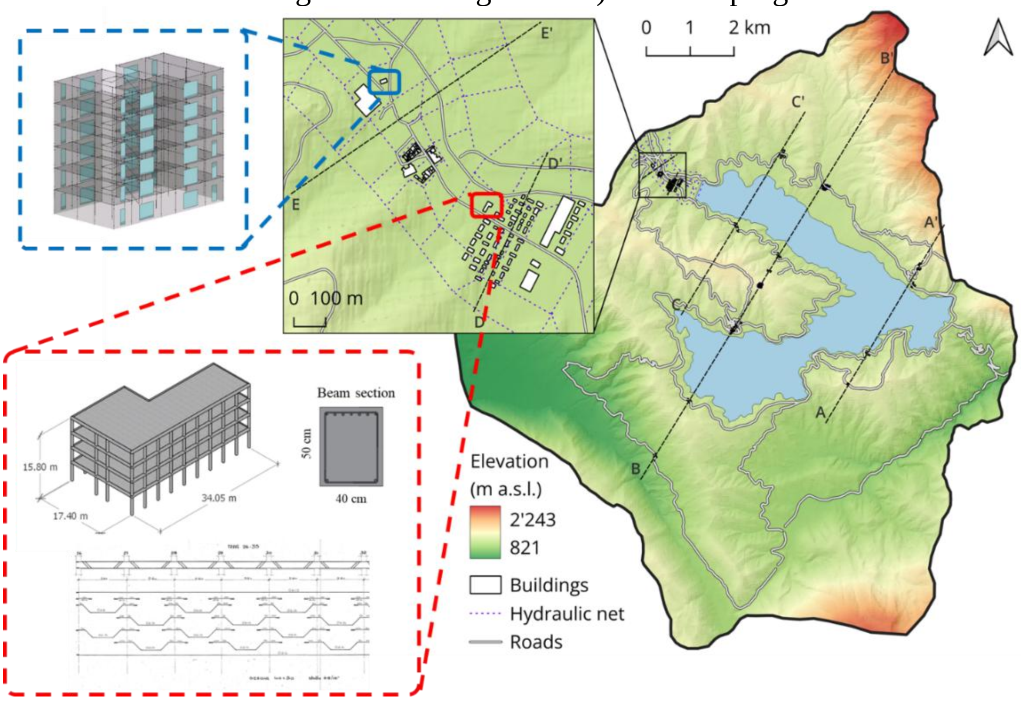

Figure 6: Schematic illustration of the PoC demonstrator, including geological features, the construction environment (building stock, road network, water distribution system), and examples of building numerical modelling.

A historical center is also included in the PoC demonstrator. The latter is composed of masonry structures with residential use, as well as a Church and a Town Hall. Differently from the residential area, these buildings are deemed to have historical value. Moreover, a central business district is also considered, involving an industrial warehouse and a high-rise building, both constructed with steel. Additionally, a contemporary low-damage timber-based building based on the Pres-Lam technology [40] is included, which serves as an office/commercial building. The latter is selected from the five-story structure analyzed by Matteoni et al. [41].

Finally, the case-study urban area also includes some strategic structures, such as a Hospital, a Police precinct, and a School. Specifically, as depicted in Figure 6, the Police precinct is a pre-1970 six-story RC structure (upper left) and the school is a four-story RC building constructed in the early 1970s (lower left). The school is part of a comprehensive data collection conducted on school buildings in the Foggia province, Southern Italy [42, 43].

The archetypal buildings were positioned within the case study area to reflect the influence of spatially varying ground motions. By strategically placing the structures in different locations within the valley and considering various orientations, the study accounts for the impact of site-specific seismic waveforms on structural response. In total, 177 buildings were considered.

Refined numerical models, aligned with current state-of-the-art strategies, were developed for strategic buildings and structures of significant cultural importance to enhance urban-scale risk assessment estimates. These digital models demonstrate the framework’s comprehensive modeling flexibility and software interoperability within the proposed multi-scale approach. Moreover, they are designed for efficient updating, facilitating the integration of strengthening effects for post-retrofit structural capacity evaluation and quantification. Specifically, RC structures were modeled using a lumped plasticity approach implemented in OpenSees software [44], while masonry structures were modeled via a macro-element approach within 3Muri software [45]. A code-based safety assessment of the as-built structures was performed to prioritize and select appropriate strengthening techniques. For RC buildings, local strategies considered include steel and reinforce concrete jacketing, externally bonded fiber-reinforced polymers (FRP) wrapping and pre-stressed steel strips application. Global strategies encompass the addition of RC walls, isolation systems, bracing systems, external exoskeletons and tuned mass dampers (TMDs). Strengthening techniques for masonry structures include tie rod systems, as well as global strategies employing compatible binding mixture injections, fiber-reinforced cementitious matrix (FRCM) systems, steel framing, and pre-stressed steel strips. Further details of the retrofitted masonry case studies can be found in Pompili et al. [46, 47].

Concerning the water distribution network, due to the absence of detailed data on the actual underground water network, a plausible representation was reconstructed based on information from analogous sites in the literature, with necessary adjustments to align with the specific topography of the study area. Assumptions regarding pipe diameters, materials, and installation depths were incorporated. Additional site-specific data, including terrain characteristics, were integrated to enhance the reliability of the representation. Given the extensive study area, only selected portions of the hypothesized network are presented, particularly those corresponding to the built environment considered in the examined PoC.

Differently, the existing road network in the selected site is considered for the case-study demonstrator. It is worth highlighting that this network has low redundancy and is exposed to landslides in several areas. Consequently, a major seismic event and associated earthquake-triggered hazards are expected to cause significant disruptions to urban mobility.

4 CONCLUSIONS

This paper has provided an overview of the ongoing extensive research performed by a multidisciplinary team of engineers, geologists, and geophysicists, on large-scale modeling, simulation, assessment, and management of natural-hazard-related disasters. A key aspect relies on the development of a comprehensive Framework for scenario-based multi-risk analysis of urban areas, adopting an input-output data chain or "domino-like" workflow composed of: (i) simulations of earthquake rupture and seismic wave propagation; (ii) site-response analysis to account for both stratigraphic and topographic amplification; (iii) evaluation of earthquake-triggered hazards, such as earthquake-induced landslides; (iv) multi-scale risk assessments of various urban system layers, (e.g., building stock, water and road networks); and (v) evaluation of risk indicators relevant to stakeholders and suitable risk mitigation strategies. Moreover, the paper details the innovative multidisciplinary methodology adopted to define a Proof-of-Concept (PoC) demonstrator, consisting of a "virtual test bed" ecosystem (i.e., realistic but not real contest) urban environment designed to replicate the complexity of a real urban area exposed to multiple hazards. The procedure for the selection of the geological area of the demonstrator, the fault model, and the definition of the construction environment has been presented and discussed together with the relevant assumptions and the expected outcomes.

The integration of this methodology within a High-Performance Computing (HPC) environment such as the one of the PNRR-CN1 - ICSC – national research project underscores its potential as a valuable tool for disaster risk assessment, management, and mitigation at the national level. This integrated approach, able to capture the interdependent impacts of multi-hazard scenarios, can operate as a high-level decision-making "dashboard", supporting the development of risk reduction and resilience enhancement strategies at a national level. As the work is in progress, research effort is still needed for the full implementation of the framework on both the PoC demonstrator by adopting a VTB solution and, as future development, on real case-study urban areas.

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