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Multi-scale and multi-refinement framework for seismic risk assessment of urban areas

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Abstract

As a part of a wider research project, this paper aims to develop an innovative framework for seismic risk assessment of urban areas. The investigated procedure employs a multi-scale approach, from individual elements (e.g., single buildings, water pipelines), to various clusters and interconnected layers and, finally, the entire urban area. The last one is represented by a multi-layered model, including the "building stock" and the utilities layers (e.g. water distribution networks). Moreover, a key feature relies on a multi-refinement level framework, which allows for the evaluation of loss metrics even in the case of limited knowledge. Alternative refinement levels involve: i) typological-based vulnerability assessment; ii) analytical/mechanical procedures, and iii) numerical (software-based) simulations. The uncertainties for each refinement level are assessed and propagated. The paper also discusses preliminary results for the building stock and water utilities. Implementing such a framework in a City Digital Twin environment can enhance the awareness of stakeholders and the general population towards seismic risk prompting decision-makers in taking action.

Keywords: Seismic risk; Seismic vulnerability; Urban area; Urban networks; Risk management

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1. Introduction and motivations

In the last decade, significant advancements have been carried out in seismic risk assessment at the national scale in terms of expected damage and related impact. These studies typically rely on a statistical census-data-based characterization of the building stock. Nevertheless, the decision-making process for the selection of the most suitable risk mitigation policies would highly benefit from a more specific building-by-building vulnerability evaluation. Moreover, at the urban area scale, it is crucial to properly consider the most critical interconnections between different layers (e.g., building stock, utility networks).

Reducing the severe socio-economic impact of major earthquakes has been recognized as a fundamental objective in many seismic-prone countries worldwide. Focusing on the Italian scenario, past earthquakes from 1968 to 2016 have resulted in tragic human casualties and financial repercussions, with direct economic losses (mainly related to the reconstruction process) equal to almost €150 billion; this cost estimation becomes even more critical when accounting for indirect economic losses, public debt, and long-term interest rates (Pampanin, 2022). These unacceptable post-earthquake consequences further emphasize the crucial need to develop a medium-to-long-term national plan for seismic risk reduction towards a safer and more resilient community. However, the lack of a prioritization plan at a national scale - based on a Detailed Seismic Assessment (DSA) of the built environment - is often deemed as a primary obstacle to the implementation of such an ambitious plan (e.g., Pampanin, 2017).

In this context, significant research effort has been devoted to developing supporting tools for planning seismic risk reduction strategies at the national level. Among others, the Department of Civil Protection (DPC) carried out the last National Risk Assessment (NRA) for Italy in 2018 (Dolce et al., 2021), and further activities for its update are ongoing (Masi et al., 2021). Due to the evident complexity in the data acquisition of the building stock, large-scale seismic risk assessments (i.e., regional, and national scale) typically rely on a statistical census-data-based characterization of the construction environment. However, a more specific building-by-building seismic vulnerability evaluation, accounting for the uncertainties related to the building-knowledge level, would highly support the decision-making process for the selection and implementation of the most efficient risk reduction strategy (Pedone et al. 2022; Matteoni et al., 2024), as conceptually shown in Fig. 1. Moreover, recent research highlighted that the definition of the most suitable risk mitigation policies also requires a refined seismic risk assessment at urban level (e.g., De Risi et al., 2019); this evaluation should be based on a comprehensive model of urban environments, including both buildings and interconnected infrastructural systems (e.g., road network, utility networks such as water and gas pipelines; Cavalieri et al., 2012). Therefore, as a part of a wider PNRR (National Recovery and Resilience Plan) - National Research Centre (CN1) research project, this paper introduces an innovative framework for seismic risk assessment of urban areas. The proposed methodology allows for the evaluation of suitable loss metrics through a multi-scale and multi-refinement-level approach.

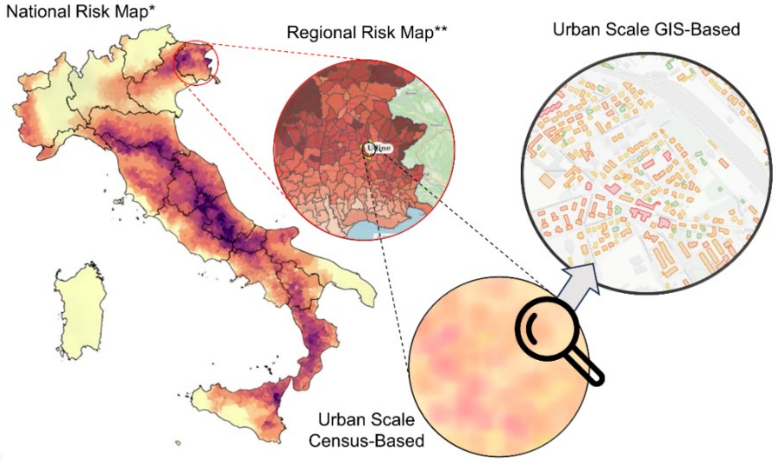


Fig. 1. Conceptual representation of the "scale issue" when dealing with census data. (after Matteoni et al., 2024; *Conceptual national risk map from Dolce et al., 2021; **Regional risk maps from "Sicuropiu", https://www.sicuropiu.it/index.xhtml).

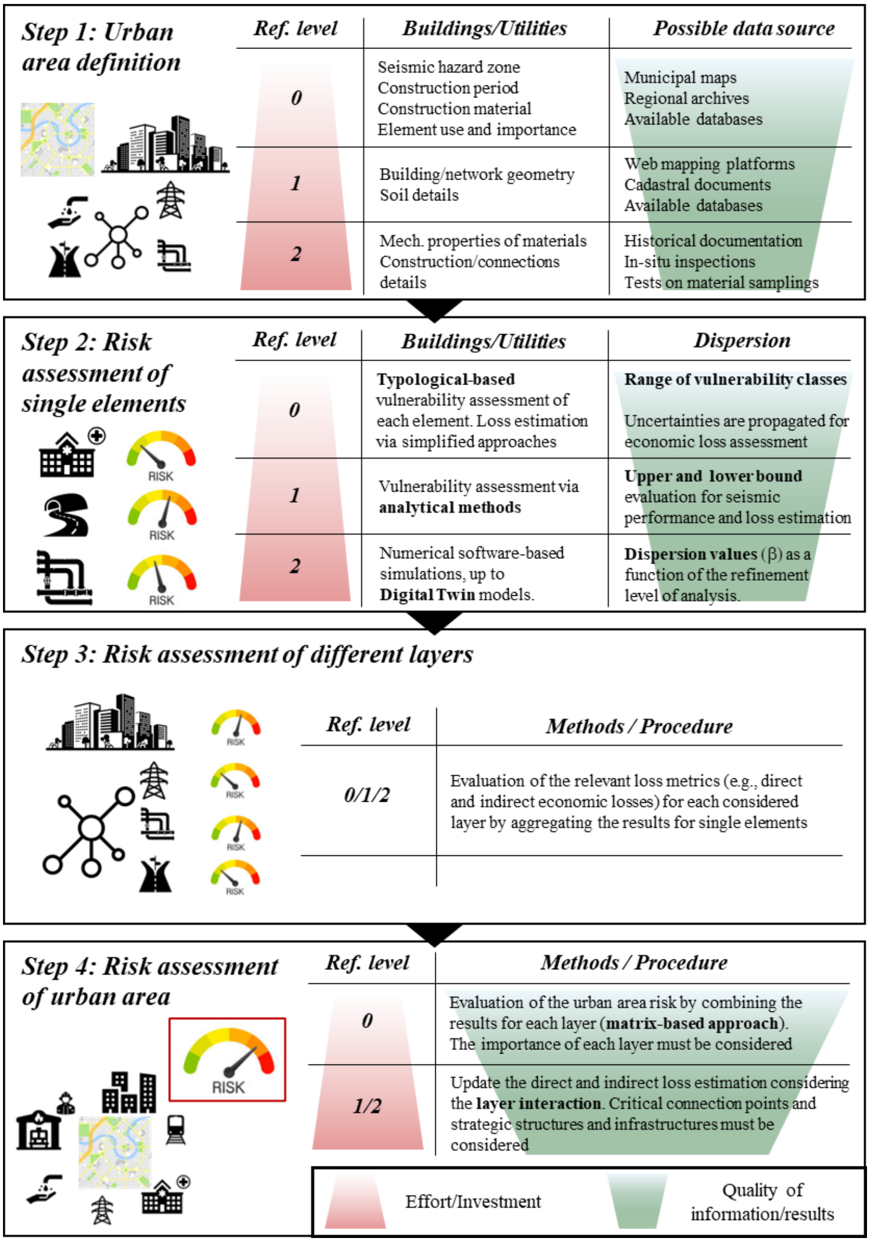
2. Seismic risk assessment of urban areas: methodology

Focusing on an urban area, whose individual elements (e.g., single building, utility or infrastructure) are identified, seismic risk assessment is performed starting from these components. The proposed framework employs alternative refinement levels of analysis, which can be selected based on the available information and/or the importance of the considered elements (e.g., strategic structures and infrastructures); the latter involves: i) typological-based vulnerability assessment; ii) simplified analytical/mechanical procedures, and iii) numerical (software-based) simulations. A key feature of the procedure relies on the estimation of uncertainties related to the adopted refinement level, as well as their propagation among the various scales (i.e., from single elements to layer and urban area).

The proposed framework is schematically illustrated in Fig. 2. For the sake of brevity, the methodology in Fig. 2 refers to only the building stock and the utility networks, but the same approach can be conceptually extended also to other relevant layers (e.g., road network). Each step of the procedure is discussed in more detail below.

The first fundamental step of the procedure consists of the definition of the urban area (*Step 1*). This task requires a data acquisition process for each single element of the relevant layers, e.g. the building stock and the infrastructure systems. In line with the adopted multi-refinement approach, the achievable knowledge level depends on the quality and quantity of the available documentation. More specifically, in Fig. 2 the needed information for each alternative refinement level is listed, together with the possible data source. Moreover, listed data are highlighted by two pyramid shapes to qualitatively indicate, on one hand, the dispersion of uncertainty of the data (inversely proportional to the quality of information, in green) and, on the other hand, the increasing effort/investment to move from a lower refinement level to a higher one (in red). It is worth noting that “Level 0” only employs a basic knowledge (i.e., seismic hazard zone, construction period, construction material, and element use and importance), achievable through documentation typically available to stakeholders. Yet, moving to a higher refinement level (“Level 1”) requires additional information, such as building geometry (e.g., height, footprint, number of stories), utility network geometry (e.g., graph, pipe diameters), and soil details. These data can be collected through a “desktop study” using web mapping platforms (e.g., OpenStreetMap; https://www.openstreetmap.org), cadastral documents, and/or available databases. Consequently, the effort/investment increases due to the required scientific background and technical skills. Finally, the last knowledge level employs more advanced data, such as the mechanical properties of the materials (both for buildings and utilities) and construction details. This information typically requires in-situ inspection and tests on material samplings, notably increasing the investment cost. A key feature of the framework relies on its possible implementation by “mixing” the knowledge levels of various elements. In other words, for instance, the framework can be implemented by considering a lower refinement level for non-strategic structures (e.g., residential buildings) – thus accepting higher uncertainties in the results - and achieving a higher knowledge only for strategic structures (e.g., hospitals). Then, results can be dynamically updated once more information becomes available.

In the second step, a seismic risk assessment of each single element is carried out (*Step 2*). The refinement level of the analysis depends on the collected data in *Step 1*. More specifically, if only a basic knowledge level is available (Level 0), vulnerability assessment is performed considering typological-based approaches, in line with other procedures available in the literature (e.g., EMS-98; Grunthal, 1998). Seismic risk assessment is thus performed by combining the expected vulnerability with the seismic hazard zone. The adopted seismic risk metric is the Expected Annual Loss (EAL), similarly to the “simplified approach” for masonry buildings described in the Italian “Sismabonus” guidelines (DM 65, 2017). Yet, higher dispersion in the results is expected due to the uncertainty affecting the unknown data in *Step 1*. The same procedure is applied for buildings and utility networks (more details are given in the following Section 3). If more information is collected (Level 1), seismic risk assessment is carried out through simplified analytical/mechanical procedures or mathematical implementations. It is worth noting that Level 1 does not involve a complete knowledge of the building or utility, and assumptions are needed to account for the related uncertainties. For this refinement level, dispersion is typically assessed considering an upper and lower bound for the expected seismic performance of the analyzed element; both deterministic/semi-probabilistic (parametric) or probabilistic (mathematical distributions) approaches can be adopted. Finally, the last refinement level (Level 3) involves a complete knowledge of the analyzed urban area component. Therefore, seismic risk assessment can be performed through more advanced numerical (software-based) simulations and according to state-of-the-art procedures available in the literature. Nevertheless, for the correct implementation of the framework, the seismic risk metric must be the same for each refinement level (i.e., economic losses).



Step 1: Urban area definition

Ref. level	*Buildings/Utilities*	*Possible data source*
0	Seismic hazard zone Construction period Construction material Element use and importance	Municipal maps Regional archives Available databases
1	Building/network geometry Soil details	Web mapping platforms Cadastral documents Available databases
2	Mech. properties of materials Construction/connections details	Historical documentation In-situ inspections Tests on material samplings

Step 2: Risk assessment of single elements

Ref. level	*Buildings/Utilities*	*Dispersion*
0	**Typological-based** vulnerability assessment of each element. Loss estimation via simplified approaches	**Range of vulnerability classes** Uncertainties are propagated for economic loss assessment
1	Vulnerability assessment via **analytical methods**	**Upper and lower bound** evaluation for seismic performance and loss estimation
2	Numerical software-based simulations, up to **Digital Twin** models.	**Dispersion values** (β) as a function of the refinement level of analysis.

Step 3: Risk assessment of different layers

Ref. level	*Methods / Procedure*
0/1/2	Evaluation of the relevant loss metrics (e.g., direct and indirect economic losses) for each considered layer by aggregating the results for single elements

Step 4: Risk assessment of urban area

Ref. level	*Methods / Procedure*
0	Evaluation of the urban area risk by combining the results for each layer (**matrix-based approach**). The importance of each layer must be considered
1/2	Update the direct and indirect loss estimation considering the **layer interaction**. Critical connection points and strategic structures and infrastructures must be considered

Fig. 2. Proposed framework for multi-scale and multi-refinement risk assessment of urban areas (note: Ref. level = Refinement level).

Then, the results of single elements are used to perform a seismic risk assessment of each relevant layer (*Step 3*). In this step, no distinction between different refinement levels is considered since the loss metric is evaluated by a simple aggregation of the results obtained in *Step 2*; yet, dispersion values are dependent on the refinement of the analysis in previous steps. This means that uncertainties in the results can be reduced by increasing the knowledge level in *Step 1* and, consequently, the refinement of analysis in *Step 2*. In other words, a higher investment directly returns a reduction in the result dispersions (or, in a complementary way, a more reliable risk assessment).

Finally, seismic risk assessment of the whole urban area is performed by combining the results of each layer (*Step 4*). In the case of basic knowledge (Level 0) for utility networks, the information on the graph is typically not available, thus the layer interaction is only addressed through a “matrix-based” approach. More specifically, for instance, poor seismic performance of the water utilities can affect the results in terms of expected indirect losses and recovery time for the urban area, even for a not-seismic-vulnerable building stock. Differently, for higher refinement levels (i.e., Level 1 and Level 2), layer interactions can be addressed through a more refined approach. Therefore, critical connection points and strategic structures/infrastructures must be correctly identified. As an example, a critical structural weakness of the water utility network at the hospital connection point could significantly increase the seismic risk of the urban area, and the results of the previous *Step 3* need to be updated to account for indirect losses related to the reduced serviceability of the hospital, whilst remaining structurally integer, due to the lack of water.

3. Illustrative application and preliminary results

This section provides some preliminary results for the development of the framework previously discussed in Section 2. Specifically, illustrative applications for the building stock and water utilities are reported, with a specific focus on “Level 0” and “Level 1” of the proposed methodology.

3.1. Building stock

The assessment of the building stock is usually regarded as the most important step given that structures account for much of the socio-economic impact of earthquakes. So far, two levels have been tackled in the scope of the proposed framework: Level 0 and Level 1.

Level 0 approach is based on existing and readily available data, regarding hazard, vulnerability, and exposure models. Therefore, a common building-level approach for seismic risk assessment - which relies on the performance-based earthquake engineering (PBEE) framework – is adopted (e.g., D’Ayala et al. 2004). Yet, to develop a rapid and easy-to-apply tool for seismic risk assessment at this refinement level, the seismic hazard classification in Italy is considered (i.e., “Zone 1-4”, where a lower number corresponds to higher seismicity; OPCM 3519, 2006); the latter is based on peak ground acceleration (PGA) values corresponding to a seismic event with 10% probability of exceedance in 50 years according to the MPS04 hazard model (Stucchi et al., 2011). The fragility and vulnerability models are the same employed for the definition of national seismic risk maps developed over the years based on either empirical, analytical, or heuristic approaches (Dolce et al., 2021). Vulnerability-Exposure models are thus developed for different categories of buildings based on synthetic data such as construction material and construction period. Vulnerability relationships are evaluated by adopting the damage-to-loss model provided by DM 65 (2017). Thus, for each combination of Vulnerability-Exposure and Hazard, values of EAL are evaluated to be assigned to every building in the urban area. Severe dispersion in the results is typically obtained due to the different fragility/vulnerability models employed in the procedure and the high uncertainties on the seismic hazard.

Differently from Level 0, Level 1 leverages more information to refine the evaluation of seismic risk on a building-by-building level. As reported in Fig. 3, additional building information, such as height and building footprint, is queried to continue with the next step in the procedure. Such data is available for some urban areas thanks to open-source projects (e.g., OpenStreetMaps). Construction year can be inferred by census data, given that usually, buildings belonging to the same block tend to be developed in similar time frames. The same is valid for construction materials; however, a fast desktop study can be useful to validate such data. From the regularized building footprints, it is possible to assume a structural skeleton, as well as the material proprieties, based on the year of construction (e.g. Verderame et al., 2001). Consequently, a “simulated design” procedure can be conducted to define the complete structural system based on code provisions of the construction period. Then, the building’s capacity curve can be evaluated using an analytical procedure such as SLaMA (Simple Lateral Mechanism Analysis, NZSEE 2017; Pampanin, 2017). Finally, the capacity curve can be used to estimate the performance of the building both in terms of safety and economic losses. The probable range of performance is obtained by evaluating different possible inelastic mechanisms of the structure. It is worth noting that an analytical procedure is well suited for this refinement level since it allows for reducing both time and computational cost when compared to numerical simulations making the procedure scalable.

To prove this concept, a neighborhood in Udine has been analyzed according to the Level 1 procedure; the application is discussed in detail in Matteoni et al. (2024). As expected, the procedure was able to yield a risk class both in terms of Safety Index (IS-V) and Expected Annual Losses (EAL/PAM), according to DM 65 (2017). Together with the expected value, a probable range, as well as an exceptional range, were computed; results are shown in Fig.

3. Even if the procedure yields highly uncertain results, insights are already gained since the results highlight a possible high seismic vulnerability of the analyzed building portfolio, suggesting the need for retrofitting interventions.

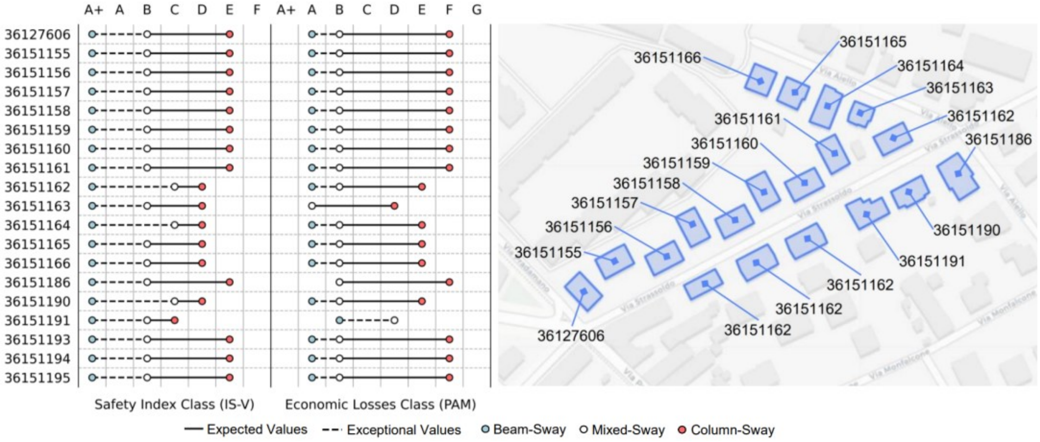


Fig. 3. Results of the “Level 1” procedure in terms of safety and expected annual losses for the analyzed buildings.

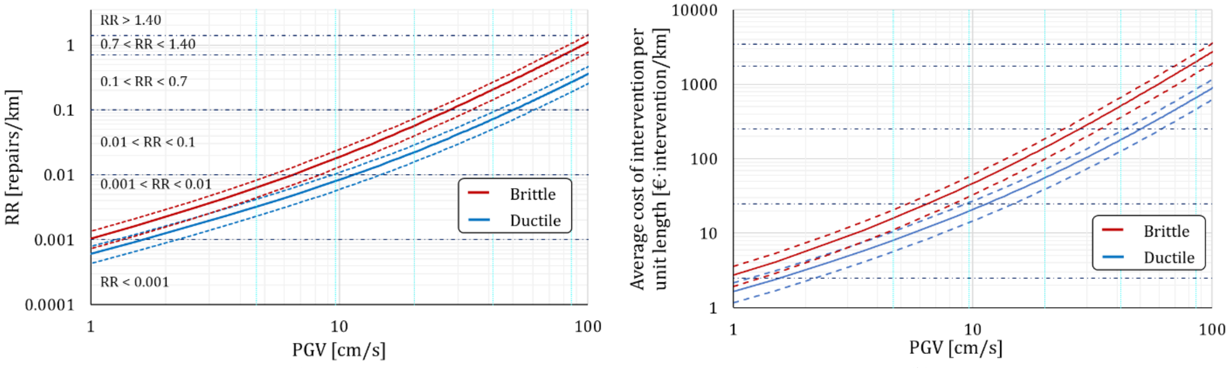
3.2. Utility network

Regarding network utilities, a specific focus has been given to water distribution systems (WDSs), whose pipelines belong to complex systems that regularly distribute water to consumers. Water pipelines are, generally, buried underground and designed to withstand all the hazards that could occur during their nominal life (Fragiadakis and Christodoulou, 2014; Mazumder et al., 2020). Among possible hazards, both natural and man-induced, earthquakes are those that provoke more damage to WDS, causing serious consequences, such as reduced water supply for several days (Nair et al., 2018); these events can even compromise the quality and potability of the water itself, thus complicating the activities of recovering the full functionality of the urban area and introducing important problems, such as the spread of diseases and infections. Performance of WDSs during an earthquake is highly interdependent with other layers which constitute the urban area, such as other networks or building components (e.g., medical facilities and shelters, firefighting system and power system) and often attention is paid to the global system rather than to the individual element. Usually, when the seismic damage of pipelines and WDS is assessed, the most commonly used parameter is the Repair Rate (RR), which represents the number of repairs needed per one unit of length of pipe ([repairs]/[L]) (O'Rourke and Ayala, 1993; ALA, 2001); many different parameters should be considered, such as pipe's material, pipe's diameter, soil in which pipes are buried, etc.

Similarly to the building stock, when little information is achievable (“Level 0”), the identification of the utility network typology could be made by the relevant material of the pipelines, identified referring to the urbanization year in order to get an approximate value of the RR. Typically, two types of material can be considered to model WDS under the aforementioned assumptions: “brittle material” and “ductile material”. It follows that the two typologies of WDS are characterized by a predominance of one specific material in one case and equally distributed material in the other. Consistently with what is reported by Alexouidi et al. (2004), it was decided to assume a possible risk-based classification of the utilities on the RR value (Table 1). At the same time, a correspondence was sought between the expected acceleration value (ag) in the Italian seismic areas and the peak ground velocity (PGV) in areas with comparable ag values (Earthquake Hazards Program. U. S. Geological Survey). Thus, having assumed this correspondence and considering the average trend and a constant dispersion of the RR parameter, it is finally possible to anticipate what the vulnerability/risk class of the network will be. By varying the PGV (cm/s) and intersecting the graph with the thresholds of Table 1, it is possible to obtain a synthetic representation of the WDS's seismic risk, as is reported in Table 1 and Fig. 4; additionally, by assuming an average value of intervention (2500 euros as medium value for the replacement of the pipe and/or its repair), the cost associated to a generic intervention in the WDS can be estimated.

Table 1. Proposed vulnerability classification for utilities according to “Level 0” procedure (note: bold = expected vulnerability class).

Risk-based classification for utilities (*Alexouidi et al. 2004*)		Italian seismic classification (OPCM 3519, 2006)		Acceleration and PGV relationship (United States Geological Survey)		Vulnerability classes of the network	
Risk	Repair Rate (RR) [Repairs/km]	Zone	Acceleration (P_{vr} 10% in 50 y)	Acceleration [g]	Corresponding PGV [cm/s]	Ductile material	Brittle material
(High) F	RR > 1.40	1	0.25 < ag ≤ 0.35g	≥ 0.747	PGV ≥ 85.8	**D** – E	D – **E** – F
				0.401 – 0.747	41.4 ≤ PGV < 85.8	C – **D**	**D** – E
(Moderate-High) E	0.7 ≤ RR < 1.40			0.401 – 0.215	20 ≤ PGV < 41.4	**C**	**C** – D
(Moderate) D	0.1 ≤ RR < 0.70	2	0.15 < ag ≤ 0.25g	0.115 – 0.215	9.64 ≤ PGV < 20	B – **C**	B – **C**
(Low-Moderate) C	0.01 ≤ RR < 0.1	3	0.05 < ag ≤ 0.15g	0.0276 – 0.115	4.65 ≤ PGV < 9.64	A – **B** – C	**B** – C
(Low) B	0.001 ≤ RR < 0.01	4	ag ≤ 0.05g	0.00297 – 0.0276	PGV < 4.65	A – **B**	**B**
(No damage) A	RR < 0.001						



(a) (b)

Fig. 4. Vulnerability relationships of water distribution systems in terms of (a) Repair Rate (RR) and (b) expected repair/replacement cost.

4. Conclusions

In this research work, an innovative framework for seismic risk assessment of urban areas has been introduced. The proposed methodology relies on a multi-scale and multi-refinement approach. Risk assessment is thus performed firstly considering single components (e.g., individual buildings, water pipelines), then moving to different layers (e.g., building stock, utility networks), and, finally, analyzing the whole urban area as well as the interaction between the building portfolio and different infrastructural systems. Moreover, alternative refinement levels of analysis are employed in the procedure, depending on the achievable knowledge level or, in a complementary way, on the investment of potential stakeholders to implement the framework. The latter involve: i) typological-based vulnerability assessment; ii) analytical/mechanical procedures, and iii) numerical (software-based) simulations. Dispersion values for the results of each refinement level are assessed and propagated. The framework can be also implemented by “mixing” the knowledge levels, for instance reducing uncertainties only for specific strategic structures and infrastructural systems. Illustrative applications and preliminary results for the building stock and water distribution systems have been also presented and discussed. Results preliminarily confirm the feasibility of the proposed methodology, which can serve as an effective supporting tool for decision-making in seismic risk reduction policies at the urban scale. However, more research effort is still needed to fully implement the proposed framework for a case-study urban area. Moreover, further improvements to this approach would involve a micro-zonation of the hazard for higher refinement levels of analysis, in order to properly perform a seismic risk assessment of both the building portfolio and the utility network at the urban area scale. Finally, the framework will be extended to manage the risk assessment in multi-hazard scenarios (Francioli et al., 2023).

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