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AUTHORS

F. Linda Perelli (UNINA)(Task Leader), F. Carotenuto (UNINA), S. Colombelli (UNINA), S. Nardone (UNINA), C. Scaini (OGS), D. Ertuncay (OGS), V. Poggi (OGS), S. Parolai (OGS), D. De Gregorio (UNINA), G. Zuccaro (UNINA) and A. Zollo (UNINA)

1. Technical references

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2. Abstract

This report presents the outcomes of research activities carried out within WP4 of the RETURN project, aimed at developing and testing innovative approaches for real-time earthquake risk mitigation and rapid response. The work focuses on the integration of monitoring technologies, modelling tools, and decision-support systems to enhance the operational capabilities of Early Warning and post-event response frameworks.

Four complementary research lines are presented. The first explores the use of wearable and adaptive devices, such as smart glasses and smartwatches, for the dissemination of earthquake early warning alerts and for supporting operators working in critical environments. The second concerns the development of the SismUp mobile application, a modular platform designed for the dissemination and monitoring of seismic alerts tailored to specific Early Warning System configurations. The third contribution introduces a probabilistic model to estimate the probability of interruption of evacuation routes due to building collapse during pre-eruptive seismic phases in volcanic areas. The methodology, tested in the Municipality of Pozzuoli within the Campi Flegrei volcanic red zone, provides spatial indicators of potential road network disruption to support evacuation planning and emergency management. Finally, the report presents a workflow for rapid first-order building damage estimation based on the integration of accelerometric recordings from the VenetONE network with simplified structural response modelling using the Thomson–Haskell method.

The combined results demonstrate the feasibility of integrating monitoring networks, modelling techniques, and digital tools into an end-to-end framework capable of supporting civil protection activities before, during, and after seismic events. The proposed approaches contribute to improving situational awareness, enhancing the reliability of rapid damage assessment, and strengthening the resilience of communities exposed to seismic and volcanic hazards.

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3. Table of contents

3.1.List of figures

4. Introduction

Earthquake risk mitigation increasingly relies on the integration of monitoring technologies, modelling tools, and digital communication systems capable of supporting rapid decision-making during emergency situations. In recent years, significant advances in seismic monitoring networks, Early Warning systems, and data processing techniques have opened new opportunities for the development of operational frameworks that can support civil protection authorities before, during, and immediately after seismic events. Within this context, the RETURN project aims to strengthen the resilience of communities exposed to natural hazards by developing integrated solutions for risk assessment, monitoring, and emergency management.

Work Package 4 (WP4) of the project focuses on the development of an integrated end-to-end system for earthquake monitoring, Early Warning, and rapid response. A key objective of this activity is to connect real-time seismic observations with tools capable of translating monitoring information into actionable knowledge for emergency management. This includes the development of innovative technologies for alert dissemination, the integration of infrastructure vulnerability indicators into Early Warning frameworks, and the implementation of simplified yet physically grounded models for rapid damage estimation.

This delivery presents a set of proof-of-concept applications developed within Task T3.4.4.1, aimed at exploring different components of an end-to-end risk reduction system. In particular, the report illustrates four complementary research activities addressing different stages of the earthquake risk management chain. The first investigates the potential use of wearable devices and artificial intelligence tools to support operators working in critical environments during seismic emergencies. The second presents the development of the SismUp mobile application, designed as a modular platform for the dissemination of seismic alerts. The third contribution introduces a probabilistic model for assessing the potential interruption of evacuation routes caused by building collapse during pre-eruptive seismic events in volcanic areas. Finally, the report describes a methodology for rapid first-order building damage estimation based on the integration of structural modelling techniques with real-time accelerometric data from regional monitoring networks.

Together, these activities demonstrate how monitoring infrastructures, modelling approaches, and digital tools can be integrated into a coherent framework aimed at improving situational awareness and supporting civil protection decision-making. The proposed approaches contribute to advancing the operational dimension of earthquake risk mitigation systems and represent a step toward the implementation of scalable and transferable solutions for multi-hazard risk management.

5. End-to-end real-time risk mitigation actions

5.1. Wearable, adaptive devices for EEW

5.1.1. State of the art and innovative elements introduced within the RETURN project

At the time of writing, there are no contributions related to EEWS applications related to wearable devices such as smart glasses and smartwatches for the protection of operators working in critical smart environments and of the equipment present in the critical environment itself. Consequently, the work conducted creates new food for thought on the applications in question.

5.1.2. Research objectives

The goal of this research is to explore the potential applications of EEWS in smart critical environments where people interact with the environment through wearable devices, such as smartglasses for equipment maintenance or smartwatches for vital signs and stress analysis. Additionally, several AI-based applications have been developed to support operators in the event of physical damage sustained after the seismic event or at least facilitate monitoring by rescue teams.

5.1.3. Method and data

Augmented Reality paradigms were used to display seismic alerts on smartglasses, and AI technologies were applied to support operator safety, such as the design and implementation of Fuzzy controllers to analyze people's vital signs following a seismic event to establish a rescue priority level. An offline Large Language Model (LLM) was also used to support operators in the event of minor damage but unable to access rescuers.

5.1.4. Results

The results of this research have shown that a seismic alert is sufficient to:

1. Prepare the operator for their own protection while performing their work and guide them through each phase of the seismic alert (DROP, COVER, HOLD ON) with instructions tailored to the context of the environment in which they find themselves at the time of the seismic alert.

2. Capture the health status of operators at all times during the seismic event.

3. Offer support tools for rescuers and for self-rescue in the event of minor injuries.

Furthermore, a development platform has been designed that, through the creation of a digital twin of the smart critical environment subjected to a seismic event, allows the operator to evaluate the effectiveness of the proposed systems and improve the proposed workflow.

5.1.5. Impact of the research according to the objectives of RETURN and WP4 in particular

As illustrated above, this project aims to create new decision-making modules, control systems, and operational actions for real-time risk reduction in smart critical environments.

Figure 1: Summary diagram of wearable and AI-based systems interacting with EEWS and smart critical environments both in the real context and in the corresponding digital twin.

5.2.SismUp

5.2.1. State of the art and innovative elements introduced within the RETURN project

Smartphone apps for seismic warning, such as MyShake, have already been developed. SismUp's primary goal is to develop a highly modular smartphone app that can be configured by EEWS developers for use with various types and configurations of EEWS. Another goal of SismUp is to be the first seismic warning app specifically tailored to the EEWS installed or being tested in the Irpinia and Campi Flegrei areas

5.2.2. Research objectives

The research objectives in this area are to create an infrastructure that not only allows the dissemination of seismic alerts based on the architecture and structure proposed for ISNET EEWApp but also allows the analysis of alert sending to identify potential bottlenecks without excessive dependence on third-party infrastructure.

5.2.3. Results

The SismUp Android application for disseminating seismic alerts in the Irpinia area is currently in beta testing

5.2.4. Impact of the research according to the objectives of RETURN and WP4 in particular

The impact of this research is to create a flexible and modular infrastructure for the dissemination of alerts and a platform for monitoring.

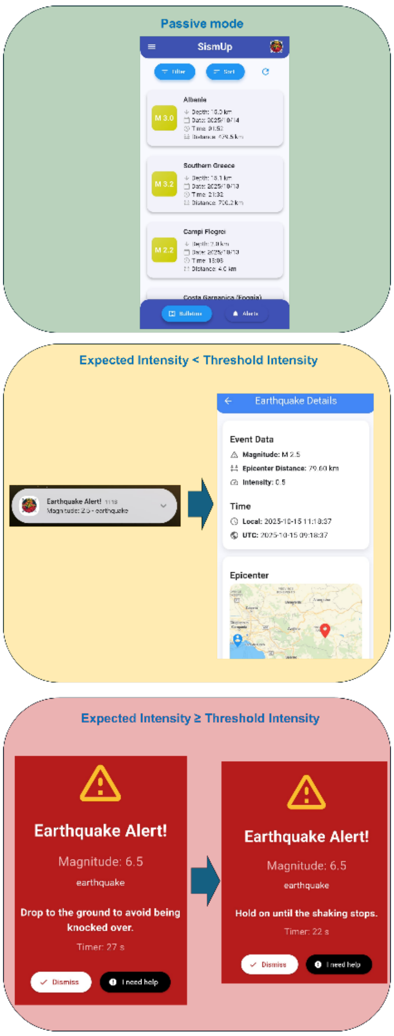

Figure 2: SismUp operating scenarios

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5.3. Integration in the EW system of a model to assess the probability of interruption of escape routes

5.3.1. State of the art and innovative elements introduced within the RETURN project

In volcanic areas exposed to unrest phenomena, the effectiveness of evacuation procedures is strongly influenced by the functionality of the road network during the early phases of a crisis. Pre-eruptive seismic activity may occur before the activation of large-scale evacuation measures and can cause structural damage or collapse of buildings located along evacuation routes. These processes may lead to the temporary or permanent obstruction of road sections due to debris accumulation, significantly reducing the efficiency of population outflow and emergency response operations.

Existing studies on seismic impacts on transportation systems mainly focus on structural damage to infrastructures such as bridges and tunnels or on traffic congestion during evacuation. However, in densely urbanized volcanic areas such as the Campi Flegrei caldera, an additional mechanism of disruption is represented by the collapse of buildings facing road segments, which may obstruct the carriageway.

Within this context, the RETURN project introduces a methodological framework aimed at estimating the probability of interruption of evacuation routes due to building collapse induced by pre-eruptive seismicity. The proposed approach combines simplified seismic scenarios, building vulnerability assessment based on the SAVE methodology (Zuccaro & Cacace, 2015), and spatial analysis of building–road interactions in order to produce probabilistic indicators of road network reliability. The model is specifically designed to support integration within Early Warning (EW) systems and to provide rapid decision-support information for civil protection authorities.

5.3.2. Research objectives

The research activity aims to develop a simplified model for estimating the probability of interruption of evacuation routes under pre-eruptive seismic conditions and to evaluate its integration within an Early Warning framework. The main objectives are:

- to estimate the likelihood of road interruption caused by collapse of buildings located along evacuation routes;
- to integrate building vulnerability information and road network characteristics within a unified analytical framework;
- to produce spatially distributed indicators of road network reliability under different seismic intensity scenarios;
- to test the applicability of the proposed approach through a pilot application in the Municipality of Pozzuoli, located within the Campi Flegrei volcanic red zone.

5.3.3. Method and data

The proposed methodology assumes that the interruption of evacuation routes during pre-eruptive seismic phases is primarily caused by the collapse of buildings facing the road network. The road system is therefore represented as a graph composed of nodes and links, where each link corresponds to a road segment between two intersections. The probability of interruption is evaluated independently for each link.

The seismic input is defined in terms of macroseismic intensity according to the EMS-98 scale (Grünthal, 1998). For Early Warning applications, the intensity is assumed to be spatially uniform over the analyzed area. This assumption allows the definition of simplified and rapidly updatable scenarios that do not depend on the precise location of the seismic source, thus ensuring computational efficiency and operational applicability.

For each road segment, the expected number of buildings potentially collapsing and obstructing the road is estimated considering all buildings located along both sides of the road within a predefined distance from the road axis. This distance accounts for the combined influence of building height and road width.

Building vulnerability is assigned using two complementary approaches. For surveyed buildings, the vulnerability class is defined according to the SAVE methodology based on typological and structural characteristics. For buildings lacking survey information, vulnerability is estimated through statistical correlations with building height (expressed as number of floors), derived from previously validated datasets.

Once the expected number of collapsing buildings associated with each road segment is evaluated, the probability of interruption of the link is computed through an exponential relationship linking the disruption probability to the cumulative collapse potential along the road segment.

5.3.4. Results

The methodology was applied to the road network of the Municipality of Pozzuoli, selected as a pilot study area within the Campi Flegrei red zone. The road network was reconstructed from open-source cartographic data and processed to obtain a graph suitable for route-based analyses.

Building height information was derived from LiDAR surveys provided by the Metropolitan City of Naples. For each building footprint, representative height values were obtained from raster elevation data and used both to evaluate building–road interaction and to estimate vulnerability where survey data were not available.

The analysis was performed for two pre-eruptive seismic scenarios characterized by macroseismic intensities VII and VIII (EMS-98). For each scenario, the expected number of collapsing buildings affecting each road segment was calculated and the corresponding probability of interruption was derived.

The results consist of spatially distributed probability values associated with each road segment of the network, allowing the identification of potentially critical links that may act as bottlenecks for evacuation flows.

Figure 3: Probability of interruption of road sections in the center of Pozzuoli relative to a risk scenario with an intensity of VII (blue: ≤20%, green:]20%-40%], yellow:]40%-60%], red ≥ 60%)

The map highlights several road segments characterized by relatively high interruption probabilities, mainly located in densely built urban areas where buildings are close to the road network.

5.3.5. Impact of the research according to the objectives of RETURN and WP4 in particular

The proposed model contributes to the objectives of the RETURN project by providing an operational approach for evaluating the reliability of evacuation networks under pre-eruptive seismic conditions.

In particular, the methodology supports WP4 activities by enabling the integration of infrastructure vulnerability indicators within Early Warning systems aimed at improving preparedness and emergency response capabilities. By identifying road segments that are more likely to become obstructed following seismic events, the model provides useful information for evacuation planning, route prioritization, and traffic management strategies.

The pilot application to the Municipality of Pozzuoli demonstrates the capability of the approach to identify critical elements of the evacuation network and to provide a transferable framework that can be replicated in other volcanic areas exposed to combined seismic and volcanic hazards.

5.4. Assessing the Potential of Two Methods for Rapid First-Order Damage Estimation Using Structural Monitoring Data

5.4.1. State of the art and innovative elements introduced within the RETURN project

Modern seismic monitoring has improved rapidly through the deployment of accelerometric stations, both in free-field conditions and inside buildings. Despite this progress, only a small fraction of the built environment is instrumented, especially in highly urbanized and earthquake-prone regions. Because of this limitation, methodologies capable of estimating the seismic behaviour of buildings using only ground-level recordings remain essential.
One such framework is the Thomson–Haskell method, a physics-based analytical approach traditionally used to model wave propagation through layered media. When adapted to structural systems, it allows a building to be represented as a series of vertically stacked shear layers, enabling the estimation of its frequency-dependent response and the prediction of displacement and drift at upper stories.
There are multiple contributions of the RETURN project on the topic from modelling to decision making. Adapting the Thomson–Haskell wave propagation method to simulate building response using only ground accelerometric data recorded on the structures. Integrating this approach into a dense regional accelerometric network (VenetONE, Bragato et al., 2025) for rapid first-order damage estimation for Northeast Italy is an important outcome of the project to improve the earthquake resilience subject. Creating a homogenized workflow that links seismic monitoring, building inventory data, transfer-function modelling, and damage classification. Designing the system to be scalable and transferable to other regions (e.g., Friuli Venezia Giulia). This integration of structural modelling into a regional rapid-response framework represents a key advancement aligned with WP4 objectives.

5.4.2. Research objectives

The main objectives of this contribution are to evaluate the feasibility of applying the Thomson–Haskell method for rapid first-order damage estimation at the regional scale, and to investigate its potential integration with real-time accelerometric data provided by the VenetONE network. In this framework, the study also aims to estimate building-level drift and to classify the corresponding expected damage states through simplified, yet physically grounded, modelling approaches. Ultimately, the work seeks to assess the potential of this workflow as a support tool for civil protection authorities, contributing to emergency response activities through the rapid assessment of potential structural damage following seismic events.

5.4.3. Methods, Algorithms, and Data Analysis

5.4.3.1. Study area and data

To illustrate how the methodology works, real earthquake data recorded by the VenetONE network are used. ML 4.2 occurred in Castelmassa on 25/10/2023 and was detected by the dense network (Figure 1).
The methodology is tested in the Veneto region (NE Italy), characterized by heterogeneous building stock and moderate seismic hazard. Although hazard levels are lower than in central and southern Italy, historical earthquakes (e.g., 1695 Asolo, 1936 Cansiglio, 1976 Friuli, 2012 Emilia) demonstrated the region's vulnerability.

5.4.3.2. Damage estimation pipeline

The acquired seismic data are managed and processed through dedicated software platforms. The earthquake magnitude is calculated, and when a magnitude greater than 4 is detected, the event is suitable for damage distribution analysis. The output of this stage is a set of standardized, quality-controlled earthquake signals suitable for subsequent analysis.

The processed earthquake signal is then combined with a database of building characteristics to evaluate structural vulnerability. This building dataset includes attributes such as construction material, number of stories / total height, age, and the soil type, all of which influence a structure's seismic response. By integrating these parameters, the system can estimate how different buildings may amplify the recorded ground shaking at the bottom (red triangle) and predict the motions at the top (blue triangle). This procedure is explained in the Thomson-Haskell Method section.

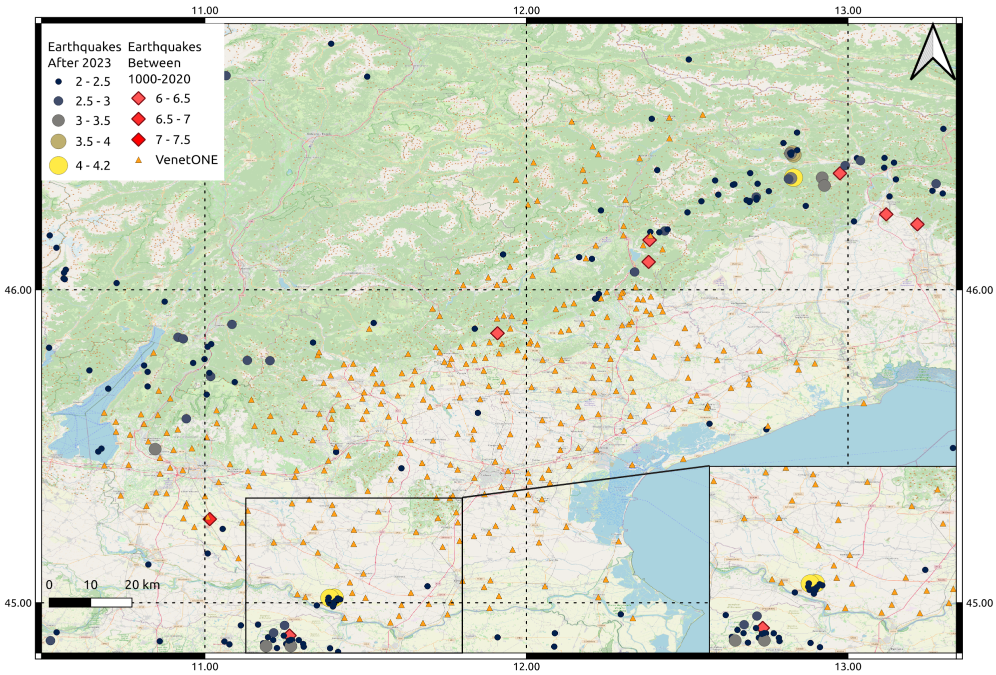

Figure 4: VenetONE network and the earthquakes between 2023 and 2025.

Finally, the damage assessment module synthesizes the shaking intensity and the building vulnerability information to estimate the expected damage state for each structure. The results are classified into discrete damage categories ranging from no damage to extensive or complete damage (see the Damage assessment section). This spatial representation enables rapid identification of the most affected areas and supports emergency response planning and post-event decision-making.

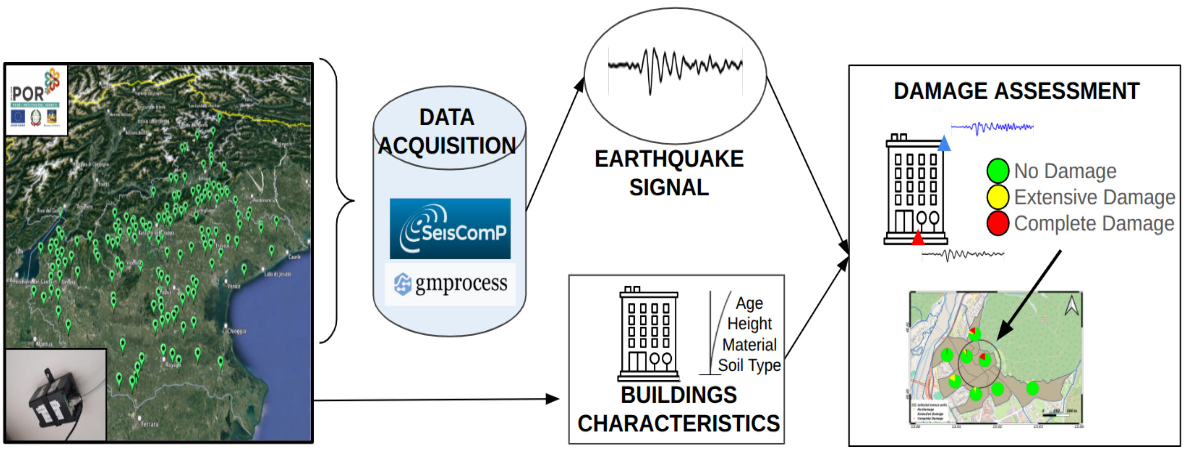

Figure 5: Flowchart of the procedure.

5.4.3.3. *Thomson-Haskell Structural Modelling*

The Thomson-Haskell method is used to compute the impulse response spectrum of the system, in our case, the transfer function of the building. In this method, a structure is modelled as a stack of one or more elastic layers. The layers are introduced by defining their shear wave velocity, density, quality factor, and height. Estimation of those parameters can be challenging; hence, each structure has its own characteristics.

Shear wave velocity (β) is estimated via a two-step process. Fundamental frequencies of structures are determined via the period-height relationship developed by Gallipoli et al. (2023). Then, by using a 1D shear-wave resonance formula, shear wave velocities are determined. The effect of density (ρ) is negligible for the analysis; however, we estimated an average building density, assuming that the RC elements fill around 15% (0.1*2400kg/m3=240kg/m3) and masonry walls 20% of the total volume (0.2*1500kg/m3=300kg/m3) of a given structure which led to have 540kg/m3 of density. The quality factor (Q) is fixed at 25, corresponding to a 2% damping ratio which is a value that is reasonable and is observed by previous studies (eg. Snieder & Safak, 2006). The floor height is fixed at 3 meters, and the total height of the buildings is calculated accordingly. In Figure 6, an example of the TFs calculated for a 4-story building for each floor.

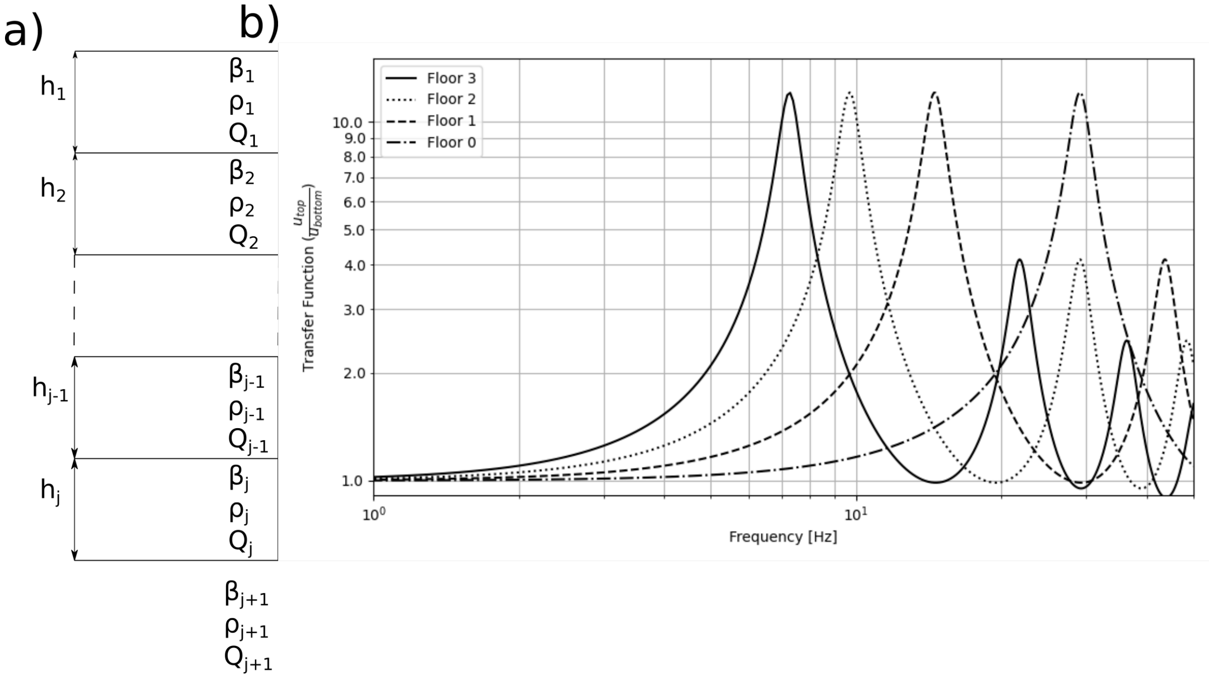

Figure 6: a) Visualization of an example building for the Thomson-Haskell Method, and b) response of each layer for a hypothetical 4-story building.

Transfer functions (TFs) are estimated for each building type (masonry, reinforced concrete, and mixed), soil type (soft site and rock site), and number of floors (2-10 stories). The transfer functions are stored for use with a given seismic record. For a given earthquake, the following steps are applied:

- Waveform cut from 5s before the P wave arrival to 85s after the P wave arrival, and gain is applied to convert the data to physical units.
- The trend is removed, tapered, and filtered between 0.5Hz and 40Hz.
- The acceleration record is converted to displacement by applying the trapezoidal integration twice.
- Fourier amplitude spectra (FASs) are calculated, and the TFs are applied separately to FASs. Then, the inverse Fourier transform is used to convert the computed displacement FAS back to the time domain.
- The relative displacement (total drift) is then estimated by simply subtracting the computed displacement at the top from the observed displacement at the base.

5.4.3.4. Damage Classification

Total drift values are converted into three damage levels: No–Slight Damage, Moderate Damage, Extensive/Complete Damage. Damage thresholds follow Ertuncay et al. (under preparation), based on drift limits from Lagomarsino & Giovinazzi (2006) and validated in pilot areas (Friuli Venezia Giulia, Central Italy, Petrovic et al., 2022, 2023).

Once the amplitude of the simulated waveform exceeds the damage threshold, the damage level is assigned regardless of the maximum drift value. In the case of large-magnitude earthquakes, buildings will most likely behave nonlinearly, which is not accounted for by the Thomson-Haskell method. This may lead to a mismatch between the real shaking and the predicted ones. However, the thresholds will almost certainly be exceeded, leading to a realistic damage distribution for the earthquakes.

5.4.4. Results, Validation and Application

5.4.4.1. Test Case: Castelmassa Earthquake (ML 4.2)

The methodology was applied to the 25 October 2023 Castelmassa earthquake (Ml 4.2). The built environment in the Veneto region is highly heterogeneous, encompassing densely urbanized areas, medium-size towns, peri-urban expansion zones, and rural settlements. A significant portion of the building stock was constructed after 1950, primarily using brick masonry or concrete blocks, often combined with reinforced concrete elements and stiff floor and roof diaphragms (Scaini et al., 2021). This structural diversity, together with the occurrence of damaging historical earthquakes such as the 1695 Asolo, 1873 and 1936 Alpago-Cansiglio, and 1891 Valle d'Illasi events, highlights the seismic relevance of the region in terms of both hazard and risk.

For the Castelmassa earthquake, damage states were computed for the exposed building stock. Owing to the relatively small magnitude of the event, no significant damage was predicted. This result is consistent with expectations, as moderate ground-motion levels associated with small-magnitude earthquakes are generally insufficient to induce structural damage in ordinary buildings. Moreover, no observed damage was reported in the investigated area, further supporting the consistency of the model predictions.

To evaluate the performance of the methodology under more demanding conditions, additional simulations were conducted using a set of independent records from larger-magnitude earthquakes extracted from the European Strong-Motion Database (ESM; Luzi et al., 2020). Under these scenarios, the first occurrence of non-negligible damage was predicted for events with a magnitude exceeding approximately 5.0. These results confirm the physical consistency and practical applicability of the proposed workflow, demonstrating its capability to discriminate between non-damaging and potentially damaging seismic scenarios.

5.4.5. Impact of the research according to the objectives of RETURN and WP4 in particular

The activities carried out in Task 4.4 of the WP4 lead several improvements on integration of end-to-end earthquake rapid response systems. Integrating local structural response modelling into a regional earthquake monitoring system expanded the arsenal of methodologies for damage estimation. Moreover, the developed Thomson-Haskell method improved the representation of the physical processes affecting the structures. Supporting civil protection decision-making with spatially distributed damage maps generated by the developed model enhanced local authorities' capabilities to respond to earthquake-related disasters.

The methodology enables a transition from purely intensity-based rapid mapping to structure-informed impact assessment, improving the reliability of first-order damage estimation, and provides an end-to-end pipeline for deploying the system to support civil defense and local authorities in decision-making.

Furthermore, the framework is transferable to other regions and is currently being extended to Friuli Venezia Giulia through the development of a cost-effective accelerometric network. This will significantly improve the earthquake resilience of Northeast Italy, an area suffered many damaging earthquakes throughout history. Currently, the technical aspects of the integration process are being investigated, while improving the monitoring capabilities of the already existing structural monitoring systems with more capable equipment and increasing the number of structures being seismically monitored.

6. Conclusions

The activities presented in this report demonstrate the potential of integrating monitoring technologies, modelling approaches, and digital communication tools within an end-to-end framework for earthquake risk mitigation and emergency response. The research developed within WP4 contributes to advancing the operational capabilities of Early Warning systems and rapid response methodologies by bridging the gap between seismic monitoring, infrastructure vulnerability assessment, and decision-support tools for civil protection.

The development of wearable-based solutions shows how emerging technologies such as smart glasses, smartwatches, and artificial intelligence can support operators working in critical environments, improving both individual safety and situational awareness during seismic events. In parallel, the SismUp application represents a flexible platform for the dissemination of seismic alerts and the monitoring of alert delivery processes, providing a scalable infrastructure that can be adapted to different Early Warning System architectures.

The probabilistic model developed for assessing the interruption of evacuation routes highlights the importance of considering indirect effects of seismic activity on critical infrastructures. The application to the Municipality of Pozzuoli demonstrates the capability of the methodology to identify potentially critical road segments and to provide useful information for evacuation planning and emergency management in volcanic areas characterized by dense urbanization.

Finally, the integration of structural response modelling with accelerometric recordings from the VenetONE network shows promising results for rapid first-order damage estimation at the regional scale. The Thomson–Haskell-based workflow provides a physically grounded yet computationally efficient approach for estimating building drift and classifying expected damage states, enabling the generation of spatial damage indicators shortly after a seismic event.

Overall, the research outcomes presented in this deliverable contribute to strengthening the operational dimension of earthquake monitoring and response systems. By integrating technological innovation, simplified physical modelling, and real-time data, the proposed approaches support the development of more resilient territorial systems and enhance the ability of civil protection authorities to manage seismic emergencies in complex multi-hazard environments.

The research activities presented in this delivery also generate relevant scientific, technological and socio-economic impacts in line with the objectives of the RETURN project and, in particular, with WP4, which focuses on the development of advanced monitoring systems and operational tools for multi-risk management. From a scientific and methodological perspective, the work contributes to expanding the current state of knowledge on the integration of real-time seismic monitoring with infrastructure vulnerability modelling and rapid impact assessment. The proposed approaches combine simplified physical models, probabilistic methods and digital communication technologies to support the transition from hazard detection to actionable risk information. The development of novel modelling strategies for infrastructure reliability, structural response estimation and damage indicators represents an important step toward more integrated and operational earthquake response frameworks. From a technological standpoint, the project introduces innovative tools that enhance the operational chain of earthquake early warning and rapid response systems. These include wearable-based solutions for operators in critical environments, modular mobile applications for alert dissemination and monitoring, and scalable workflows for regional damage estimation based on accelerometric data. Such developments strengthen the capacity of monitoring networks and decision-support systems to provide timely and reliable information during seismic emergencies. The socio-economic relevance of the research lies in its potential to improve preparedness, situational awareness and emergency management in densely populated and multi-hazard environments. By supporting the identification of vulnerable infrastructures, improving the reliability of evacuation planning, and enabling rapid first-order damage estimation, the proposed methodologies contribute to more effective response strategies and to the reduction of potential human and economic losses. Overall, the outcomes of this work reinforce the role of integrated monitoring, modelling and communication technologies in enhancing territorial resilience and supporting civil protection authorities in managing complex seismic risk scenarios.

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7.1. Software

Ertuncay, D., Petrovic, B., Scaini, C., Parolai, S., Poggi, V.

Assessing the potential of two methods for rapid first-order damage estimation using structural monitoring data

Soil Dynamics and Earthquake Engineering (under preparation)

Modelling codes: https://github.com/dertuncay/Structural-Modeling