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1. Technical references

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2. ABSTRACT

Accurate modelling of earthquake ground motion and a deeper understanding of rupture processes are fundamental components of modern seismic hazard assessment. Within this context, the activities of WP5.2 addressed several complementary aspects of earthquake dynamics, combining numerical simulations, signal modelling, laboratory experiments, and data-driven analysis techniques to improve the characterization of ground-motion generation and variability.

A first line of investigation focused on physics-based numerical simulations of seismic wave propagation in complex geological environments. Three-dimensional spectral-element simulations were used to analyse the influence of basin geometry and velocity contrasts on the spatial distribution of ground motion, highlighting the role of geological heterogeneities in amplifying and redistributing seismic energy. These simulations provide valuable insights into the mechanisms controlling local ground-motion variability and represent an important tool for evaluating site-specific seismic response.

A second set of studies explored stochastic and non-stationary approaches for the generation of artificial earthquake accelerograms compatible with target response spectra. These methods allow the construction of synthetic ground-motion time histories suitable for engineering applications, while preserving key statistical and spectral characteristics of observed seismic signals.

Additional investigations addressed earthquake rupture dynamics and seismic signal properties through controlled laboratory experiments. Frictional tests performed on extended laboratory faults reproduced earthquake-like stick–slip instabilities, enabling the detailed observation of stress evolution, slip propagation, and acoustic emission activity during rupture cycles. The resulting datasets were analysed using machine learning and deep learning techniques aimed at identifying precursory patterns and exploring the potential predictability of failure processes.

Additional studies focused on large-scale physics-based earthquake simulations for scenario analysis and damage evaluation, providing further constraints on near-fault ground-motion variability, permanent deformation, and the generation of physically consistent input motions for seismic risk applications.

Taken together, these activities contribute to a more comprehensive understanding of the processes controlling earthquake rupture and ground-motion generation across different spatial and temporal scales. By integrating physics-based modelling, experimental observations, and advanced data-analysis approaches, WP5.2 provides new methodological tools and insights that support the development of improved models for seismic hazard and ground-motion characterization.

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4. Introduction

Accurate characterization of earthquake ground motion and of the physical processes controlling rupture propagation represents a fundamental component of modern seismological research and a key requirement for reliable seismic hazard assessment. While the identification and structural characterization of seismogenic faults provide essential information on where earthquakes may occur, understanding how seismic energy is generated, propagated, and recorded at the surface is equally important for evaluating the potential impact of earthquakes on the built environment. Ground motion results from the complex interaction between source processes, wave propagation through heterogeneous crustal structures, and local geological conditions, and its accurate modelling therefore requires the integration of multiple observational and theoretical approaches.

In recent decades, significant progress has been achieved in the numerical modelling of seismic wave propagation and in the simulation of earthquake ground motion. Advances in computational methods and high-performance computing now allow the simulation of wavefields in complex three-dimensional geological environments, enabling the investigation of how basin geometry, velocity contrasts, and structural heterogeneities influence the spatial distribution of ground motion. Physics-based simulations of seismic wave propagation provide an increasingly powerful tool for exploring the mechanisms responsible for ground-motion amplification and for evaluating the role of local geological structures in shaping the spatial variability of earthquake shaking. Such approaches complement traditional empirical and stochastic ground-motion models and contribute to a more physically grounded representation of earthquake effects.

At the same time, the generation of synthetic ground-motion time histories represents an essential component of engineering seismology and seismic risk assessment. Artificial accelerograms compatible with target response spectra are widely used in structural analyses and in performance-based earthquake engineering. The development of stochastic and non-stationary signal models capable of reproducing the main statistical and spectral characteristics of observed ground motion therefore constitutes an important methodological challenge. These approaches aim to combine physical realism with statistical consistency, allowing the construction of ground-motion scenarios that capture both the variability of seismic signals and the constraints imposed by seismic hazard models.

Another key aspect concerns the physical processes governing earthquake rupture and the nucleation of seismic slip. Earthquake initiation and rupture propagation depend on the frictional properties of fault materials, on stress conditions, and on the dynamic interaction between mechanical and physical processes occurring along fault surfaces. Laboratory experiments performed on frictional interfaces provide a valuable opportunity to investigate these processes under controlled conditions, enabling the direct observation of stress evolution, slip dynamics, and acoustic emission activity during earthquake-like instabilities. Such experiments allow researchers to reproduce stick–slip cycles analogous to small-scale earthquakes and to analyse the mechanical and seismic signals associated with rupture nucleation and propagation.

Recent developments in data analysis techniques further expand the possibilities for investigating earthquake processes. In particular, machine learning and deep learning methods have shown considerable potential for extracting patterns from large and complex datasets, including seismic waveforms and laboratory acoustic emission signals. These techniques can be used to explore the predictability of failure processes, to identify precursory signatures of rupture nucleation, and to analyse the statistical properties of seismic signals. The integration of data-driven approaches with experimental observations and physics-based models represents a promising direction for advancing the understanding of earthquake dynamics across different spatial scales.

Within this scientific context, the activities developed in WP5.2 aim to improve the characterization of earthquake ground motion and rupture processes through a multidisciplinary approach combining numerical modelling, stochastic signal generation, laboratory experiments, and advanced data analysis techniques. The work carried out within this task focuses on the investigation of ground-motion generation mechanisms, the development of methodologies for the simulation of realistic seismic signals, and the experimental and computational analysis of rupture dynamics.

Several complementary research activities contribute to these objectives. Physics-based numerical simulations are employed to investigate the propagation of seismic waves in complex geological environments and to analyse the role of basin structures and velocity contrasts in controlling the spatial distribution of ground motion. Stochastic modelling approaches are developed to generate artificial accelerograms compatible with target response spectra, enabling the construction of synthetic ground-motion scenarios suitable for engineering applications. In parallel, laboratory experiments on frictional faults are conducted to reproduce earthquake-like instabilities and to investigate the mechanical and seismic signals associated with rupture cycles. The resulting datasets are analysed using machine learning techniques to explore the potential identification of patterns associated with rupture nucleation and failure processes.

Together, these activities contribute to advancing the understanding of the mechanisms controlling earthquake ground motion and rupture dynamics. In particular, the activities presented in this deliverable combine large-scale numerical simulations of seismic wave propagation, stochastic modelling of synthetic ground motions, laboratory experiments on rock friction, damage evolution, and rupture processes, as well as the development of innovative approaches for analysing seismic signals, fault-zone effects, and structural response. This combination of complementary approaches allows the investigation of earthquake processes across a wide range of spatial and temporal scales, from laboratory faults to regional-scale ground-motion scenarios and engineering applications. By integrating physics-based simulations, signal modelling techniques, laboratory observations, and data-driven analysis methods, the work carried out within WP5.2 provides new insights into the processes governing seismic wave generation and propagation and supports the development of improved approaches for the characterization of earthquake ground motion and its implications for seismic hazard assessment.

5. Physics-based investigations of earthquake rupture processes and seismic response in complex geological and structural systems

5.1 Numerical simulations of site-city seismic interaction effects (OGS)

5.1.1 Scientific Context and Objectives

Seismic hazard in alpine valleys is often strongly influenced by complex geological structures and basin geometries that can significantly modify the propagation and amplification of seismic waves. In such environments, the interaction between topography, sedimentary deposits, and surrounding bedrock may produce strong site amplification effects within the frequency range of engineering interest. Recent investigations conducted in a valley located on the northern shore of Lake Garda have confirmed that earthquake ground motion in the frequency band between approximately 0.5 and 10 Hz can be amplified by up to an order of magnitude with respect to nearby rock reference sites. These observations indicate that local geological and morphological conditions play a critical role in controlling the seismic response of the valley.

Within this context, the objective of the present activity was to investigate the physical mechanisms responsible for these amplification patterns through three-dimensional physics-based numerical simulations of seismic wave propagation. The study aimed in particular to evaluate whether a realistic three-dimensional representation of the subsurface structure could reproduce the observed seismic response of the basin, and to identify the relative contribution of one-dimensional stratigraphic effects and three-dimensional basin geometry to the overall amplification pattern observed in the area.

5.1.2 Methodological Development

The investigation was carried out through numerical simulations of seismic wave propagation using the spectral-element method implemented in the software package SPECFEM3D. A three-dimensional digital model of the study area was constructed in order to represent the main geological and structural features controlling the seismic response of the valley. The model covers an area of approximately 10 km in the east–west direction and 12 km in the north–south direction, with a vertical extent of about 1 km below the ground surface.

The subsurface structure was reconstructed by integrating results from recent non-invasive geophysical surveys with geological information available in the literature. The resulting model describes a basin structure characterized by strong vertical and lateral heterogeneities. The deepest portion of the model corresponds to the bedrock, mainly composed of limestones and sandstones, overlain by a relatively thin layer of weathered bedrock. Above this transition zone, the basin contains heterogeneous stiff deposits occupying the deeper portion of the sedimentary fill, while softer alluvial sediments characterize the upper basin layers. The spatial resolution of the model was selected to adequately capture the dynamic response of the valley within the frequency range of engineering interest.

Seismic wave propagation was simulated by considering vertically incident plane waves, allowing the analysis of the valley response under controlled input conditions and facilitating comparison with empirical amplification functions derived from observations. The numerical simulations reproduced a seismic response lasting approximately 24 seconds, and each simulation required about 5,000 core hours on the Leonardo high-performance computing system at CINECA.

To assess the reliability of the numerical model, the simulated amplification patterns were compared with observational constraints derived from earthquake ground-motion recordings collected at nineteen stations of a temporary seismic network deployed in the area between 2019 and 2021. These observations provided empirical amplification functions that could be used to evaluate the capability of the numerical simulations to reproduce the measured seismic response of the basin.

5.1.3 Discussion on Main Results

The comparison between simulated and observed amplification functions indicates that the seismic response of the valley is controlled by a combination of stratigraphic and three-dimensional basin effects. The numerical simulations reproduce the main amplification features observed in the empirical data within the frequency range between approximately 0.5 and 5 Hz, which corresponds to the dominant peaks identified in the observed site-response functions. These results highlight the important role played by the complex geometry of the basin and by the strong impedance contrasts between the sedimentary deposits and the surrounding bedrock in controlling the propagation and trapping of seismic waves.

The simulations show that both one-dimensional layering effects and three-dimensional wavefield interactions contribute to the observed amplification patterns. In particular, the lateral heterogeneity of the basin-filling deposits and the irregular geometry of the sediment–bedrock interface generate complex wave propagation phenomena that cannot be reproduced using simplified one-dimensional models.

An additional outcome of the study is the definition of a nine-component descriptor of site response, formulated as a site-to-site transfer function computed for vertically incident plane waves. This representation provides a more comprehensive description of the directional characteristics of site amplification and offers a practical framework for incorporating basin effects into the generation of realistic earthquake ground-motion scenarios in the region.

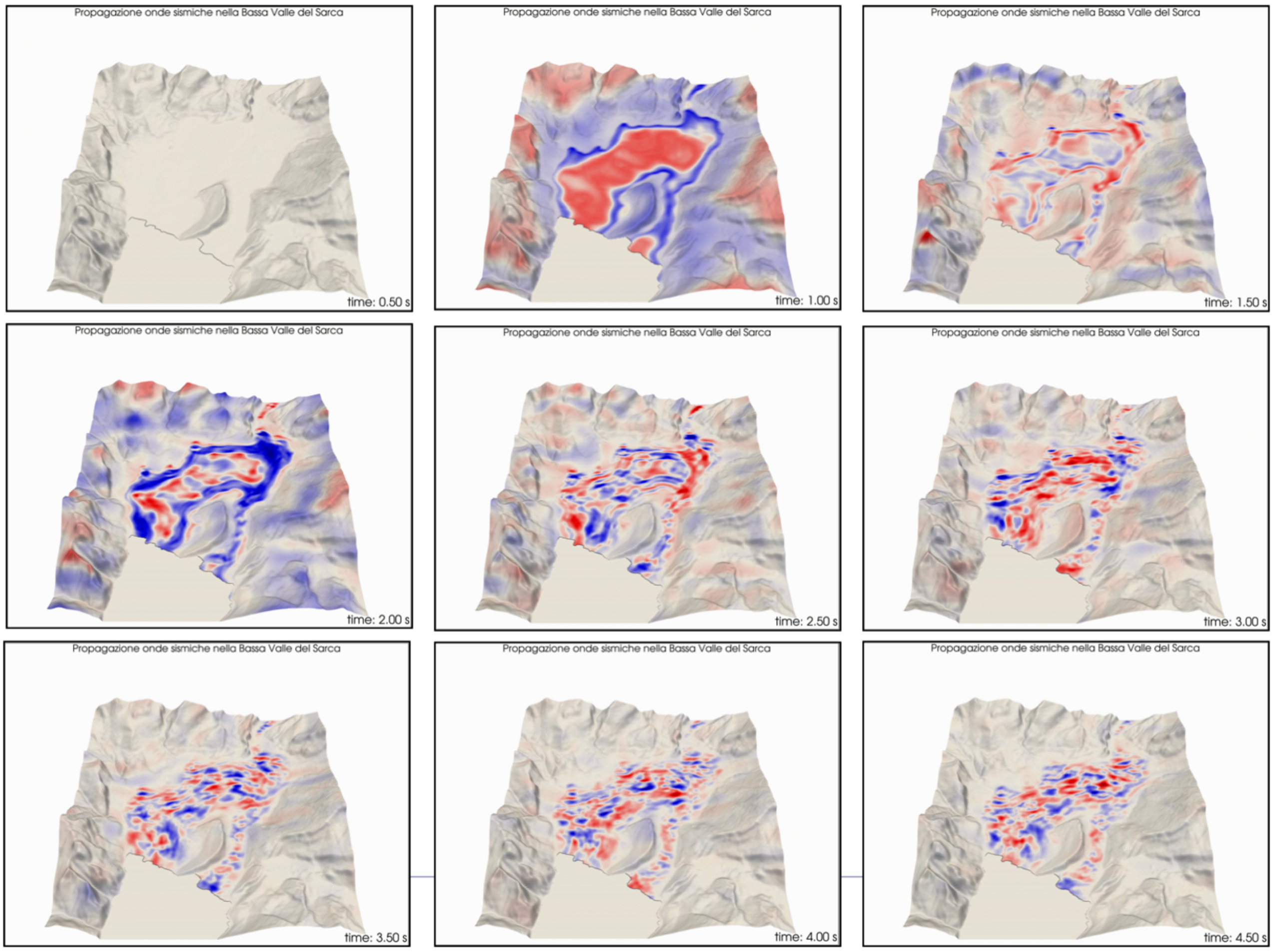


Figure 1. Snapshots of the simulated surface ground motion obtained from the three-dimensional spectral-element simulations of seismic wave propagation in the Alpine valley located on the northern shore of Lake Garda. The simulations consider a vertically incident plane wave polarized in the east–west direction. The snapshots illustrate the spatial distribution of ground motion amplification produced by the basin geometry and by the impedance contrast between sedimentary deposits and surrounding bedrock.

5.2 Laboratory experiments with rock samples, to investigate the mechanism controlling the nucleation and propagation of earthquake ruptures. Monitoring damage evolution in rock samples (in triaxial evolution) through accurate micro-crack location and high-resolution tomography. (UNINA-DipFis)

5.2.1 Scientific Context and Objectives

Understanding earthquake rupture nucleation requires investigating how progressive rock damage modifies elastic properties and controls the spatial distribution of microseismic activity. During deformation, the accumulation of microcracks produces measurable changes in seismic velocity, which in turn affect the localization and interpretation of acoustic emission (AE) or seismic events. However, most localization approaches assume a static velocity model, neglecting the mechanical evolution of the medium and potentially introducing systematic biases in the reconstruction of fracture processes.

The objective of this activity was to investigate the coupling between damage evolution, seismic velocity variations, and microseismic activity across scales. Laboratory rock physics experiments were used to study how stress-induced velocity changes influence AE localization during rock failure (De Landro et al., 2024) and to quantify the mechanical response of volcanic lithologies under stress and fluid pressurization conditions representative of the Campi Flegrei crust (De Landro et al., 2025). These investigations were complemented by field-scale analyses of seismicity migration and deformation during volcanic unrest (Iaccarino et al., 2025) and by interferometric monitoring of temporal seismic velocity variations associated with earthquake damage and recovery processes (Muzellec et al., 2025).

Together, these activities aim to develop a multi-scale framework linking laboratory observations of rock damage with geophysical observations of seismic velocity variations and rupture processes in natural systems.

5.2.2 Methodological Development

The methodological approach combined laboratory rock physics experiments, seismic data analysis, and interferometric monitoring to investigate the relationship between damage evolution, elastic property variations, and rupture processes across scales.

Laboratory experiments were performed on rock samples subjected to controlled triaxial loading conditions. During deformation, stress–strain measurements, P-wave velocities, and acoustic emission (AE) activity were recorded simultaneously. To account for the evolution of elastic properties during progressive damage, an adaptive event relocation framework was developed. The method integrates laboratory measurements of velocity changes with a double-difference relocation algorithm that dynamically updates the velocity model during fracture propagation (De Landro et al., 2024).

Complementary rock physics experiments were conducted on volcanic lithologies representative of the Campi Flegrei crust under controlled stress and pore-pressure conditions. These experiments allowed the quantification of the relationships between fluid pressurization, elastic weakening, and deformation rate, providing constraints for interpreting geophysical observations at the caldera scale (De Landro et al., 2025).

At the field scale, high-resolution seismic catalogs and geodetic observations were analyzed to characterize the spatiotemporal evolution of seismicity and deformation during volcanic unrest (Iaccarino et al., 2025). In addition, ambient noise interferometry was applied to continuous seismic records to retrieve empirical Green's functions and monitor relative seismic velocity variations (dv/v) associated with earthquake damage and recovery processes (Muzellec et al., 2025).

5.2.3 Discussion on Main Results

The combined laboratory and field-scale analyses highlight the strong coupling between rock damage evolution, seismic velocity variations, and rupture processes. Laboratory experiments show that the progressive accumulation of microcracks produces measurable changes in elastic properties, which in turn influence the spatial distribution and localization of acoustic emission (AE) events. When these velocity variations are neglected, event locations may be artificially clustered, leading to a distorted reconstruction of fracture geometry. Incorporating time-dependent velocity models during deformation significantly improves the accuracy of event relocation and provides a more reliable description of fracture propagation and damage organization within the rock sample.

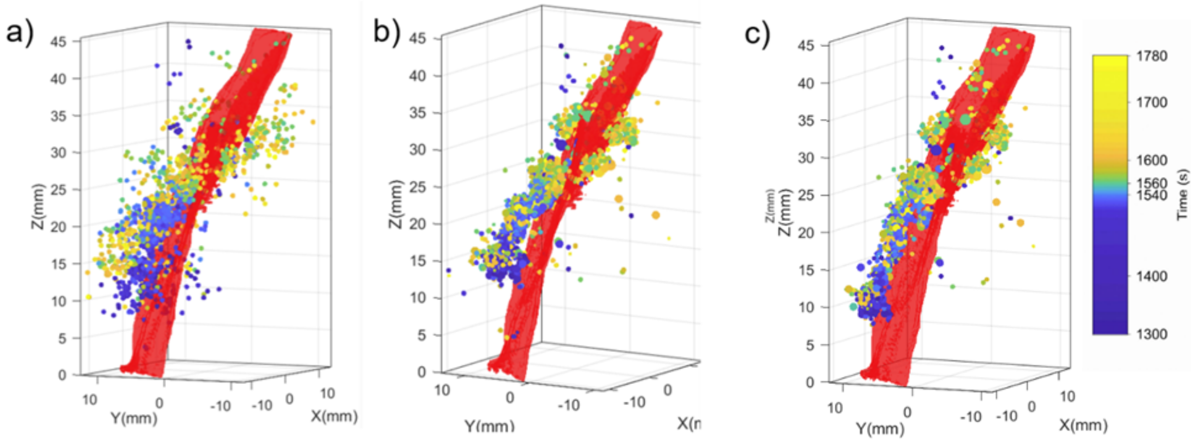


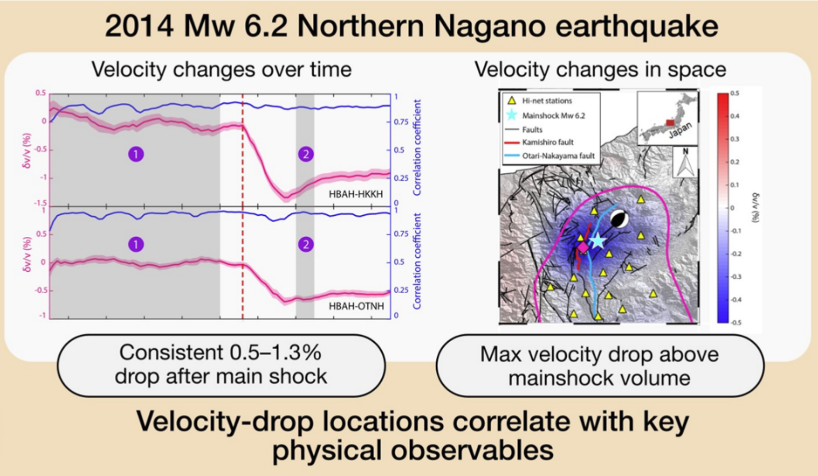
Figure 2. Comparison of AE event locations using three approaches: (a) standard absolute location; (b) traditional double-difference with constant velocity; (c) advanced double-difference with time-dependent velocity. The constant-velocity model (b) produces an unrealistically clustered AE pattern, while the adaptive approach (c) reproduces the actual fracture geometry observed in the sample. From De Landro et al. (2024)

Rock physics experiments on volcanic lithologies further indicate that fluid pressurization plays a key role in controlling the mechanical response of the crust. Increasing pore pressure promotes elastic stiffness reduction, accelerates strain accumulation, and favors the transition from distributed deformation to localized instability. These laboratory observations provide quantitative constraints for interpreting deformation and seismicity patterns observed in volcanic systems such as the Campi Flegrei caldera, where fluid-driven weakening and mechanical heterogeneity strongly influence crustal dynamics.

Field observations support this framework. High-resolution seismic and geodetic analyses indicate that earthquake occurrence in volcanic environments may be preceded by preparatory phases characterized by progressive stress accumulation and migration of seismicity within the fault system. Such spatiotemporal patterns suggest the gradual organization of damage and increasing mechanical coupling between crustal blocks prior to rupture initiation.

In addition, ambient noise interferometry reveals measurable seismic velocity reductions associated with coseismic damage within the rupture zone, followed by progressive recovery related to post-seismic healing processes. The spatial distribution of these velocity variations provides independent constraints on rupture extent and fault segmentation, highlighting the link between elastic property evolution and fracture processes at the seismological scale.

Overall, the results highlight the importance of accounting for elastic property evolution during rock damage and demonstrate how laboratory rock physics experiments and geophysical observations can be integrated into a coherent multi-scale framework for investigating earthquake rupture nucleation processes.


2014 Mw 6.2 Northern Nagano earthquake

Velocity changes over time

Velocity changes in space

Consistent 0.5–1.3% drop after main shock

Max velocity drop above mainshock volume

Velocity-drop locations correlate with key physical observables

Figure 3. Temporal evolution of seismic velocity variations and spatial distribution of velocity perturbations associated with earthquake damage processes. The left panel shows the time series of relative seismic velocity changes (dv/v), while the right panel illustrates the spatial distribution of velocity perturbations during the time interval 5–10 December 2014. Modified from Muzellec et al. (2025).

5.3 Deterministic and/or probabilistic models for seismic response of fault zones. (UNIBO)

5.3.1 Scientific Context and Objectives

Active and capable faults (ACFs) represent key structural elements controlling seismic hazard, not only because they host earthquake rupture but also because their internal architecture can significantly influence seismic wave propagation and ground deformation. Fault zones are typically characterized by a complex internal structure composed of a fault core surrounded by a damage zone with highly fractured rock. These structural domains exhibit mechanical and seismic properties that may differ substantially from those of the surrounding host rock, potentially affecting both rupture propagation and near-fault ground motion.

Understanding how this structural complexity influences seismic hazard is particularly important when critical infrastructures intersect or run close to active faults. Linear infrastructures such as pipelines, transportation corridors, and lifelines are especially vulnerable to surface faulting and near-fault deformation processes. However, conventional seismic hazard assessments often simplify the structural complexity of fault zones and therefore may not fully capture the range of possible interactions between infrastructure and fault-related deformation.

The objective of this activity was to develop a structural geology–based framework for assessing the potential interaction between linear infrastructures and active and capable faults. The study focused on identifying the key structural configurations that control fault–infrastructure interaction and on defining methodological criteria for the characterization of fault-zone architecture during the early stages of infrastructure planning.

5.3.2 Methodological Development

The methodological approach consisted of a systematic analysis of fault-zone structure and rupture propagation mechanisms based on structural geology observations and published case studies. Particular attention was given to the internal architecture of active faults, including the geometry of fault cores, the spatial extent of damage zones, and the distribution of secondary fractures associated with fault growth.

Building on this geological framework, the study identified a set of representative geometrical configurations describing the possible spatial relationships between a linear infrastructure and an active fault system. These configurations include situations in which an infrastructure directly crosses the fault trace, runs parallel to the fault within the damage zone, approaches the tip of a propagating fault segment, or intersects structural transfer zones connecting different fault segments.

For each configuration, the analysis focused on identifying the structural parameters that most strongly influence the expected deformation patterns and therefore the associated seismic hazard. These parameters include the width and internal structure of the fault damage zone, the degree of fault segmentation, the geometry of fault tips, and the spatial distribution of secondary fault strands. Based on these considerations, the study also evaluated the investigation techniques most suitable for characterizing fault-zone structure during site assessment, emphasizing the importance of detailed geological and structural field observations supported by geomorphological and geophysical analyses.

5.3.3 Discussion on Main Results

The proposed framework highlights the importance of explicitly accounting for the internal architecture of active fault zones when evaluating seismic hazards affecting linear infrastructures. The analysis shows that different geometrical configurations between infrastructures and fault systems may lead to substantially different hazard scenarios.

In particular, infrastructures directly crossing a fault trace represent the most critical configuration, as they may experience significant surface displacement during seismic rupture. In contrast, infrastructures running parallel to a fault may be affected by distributed deformation occurring within the fault damage zone, where highly fractured rock and secondary fault strands may accommodate part of the coseismic displacement. Situations involving fault tips or structural transfer zones may also generate localized deformation patterns that require specific site investigations.

Our approach emphasizes that the structural complexity of fault zones plays a key role in controlling the spatial distribution of deformation associated with earthquake rupture. Incorporating structural geology constraints into hazard assessment can therefore improve the identification of critical segments along infrastructure routes and support more robust planning strategies during the early feasibility stages of engineering projects.

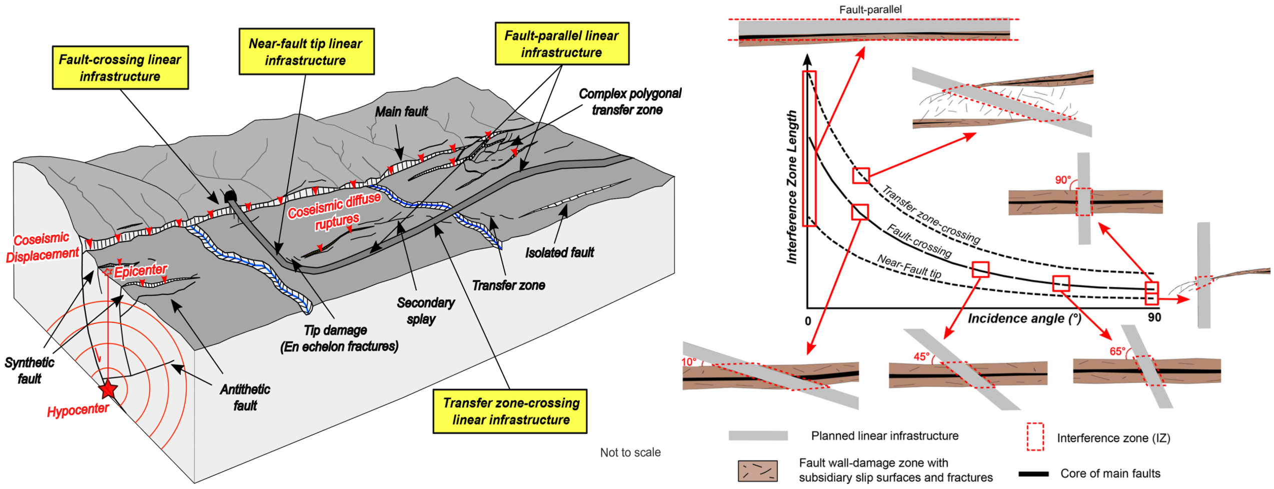


Figure 4. Conceptual diagram illustrating the main geometrical configurations describing the interaction between an active and capable fault and a linear infrastructure. The schematic highlights possible cases including fault crossing, near-fault tip interaction, fault-parallel configurations within the damage zone, and intersections with structural transfer zones (modified from Bonini et al., 2024).

5.4 Laboratory experiments to reproduce fault development and lubrication in dry natural rock systems. (UNIGE)

5.4.1 Scientific context and objectives

Stress accumulation at convergent plate margins and in subduction zones cyclically generates earthquakes. Our understanding of deep seismicity mainly derives from geophysical observations, laboratory experiments, numerical models, and the study of exhumed rocks preserving evidence of deep seismic processes. Many subducting slabs host double seismic zones, consisting of two distinct layers: one located within or just below the plate interface, associated with hydrated rocks and pressurized pore fluids, and another within the relatively dry mantle of the subducting plate (Hacker et al., 2003; Yamasaki and Seno, 2003). While hydrated plate-interface domains have been extensively studied, the dry portions of the slab remain poorly understood.

Here we investigate the brittle behaviour of dry faulted rocks by integrating natural observations with laboratory experiments. This work, carried out in collaboration with the University of Padova, focuses on pseudotachylytes in ophiolitic peridotite and gabbro from the Lanzo Massif (Western Alps), which record seismic rupture during Alpine subduction (Scambelluri et al., 2017). We aim to constrain the conditions leading to pseudotachylyte formation through structural and petrological analyses of natural samples, high-velocity deformation experiments simulating seismic slip, and chemical, microstructural, and Raman spectroscopic analyses of experimental products.

5.4.2 Methodological Development

Pseudotachylyte faults were experimentally reproduced in cylindrical samples (~60 mm length, 50 mm diameter) of natural Lanzo gabbro and peridotite using the Slow to High Velocity Apparatus (SHIVA) at the High Pressure–High Temperature laboratory at the INGV (Rome) (Di Toro et al., 2010). Samples were sheared at room humidity conditions, slip rates of ~3 m s^{-1}, with acceleration of 25 m s^{-2} and total slip of 0.3–3 m under an effective normal stress of 30 MPa, reproducing seismic slip conditions that promote frictional melting. Experimental products were analysed by Field Emission Scanning Electron Microscopy (FE-SEM; Tescan Clara FE-SEM, acquired with Return PNRR Grant), equipped with an Oxford Instruments Ultim Max 170 Energy Dispersive Spectroscopy (EDS) silicon detector and Oxford Instruments AZtecLive Advanced software. Raman spectroscopy has been employed to characterize mineral phases, glassy pseudotachylytes.

5.4.3 Discussion on Main Results

The experimental mechanical data for gabbro and peridotite shown in Fig. 5 display the trapezoidal velocity function (m s^{-1}), normal stress (MPa), shear stress (MPa), and shortening (mm) versus slip distance (m). The dashed red boxes indicate the data interval used to estimate the dynamic friction coefficient. As shown in Fig. 1B, the dynamic friction coefficient (μd) remains nearly constant for slip displacements of 1 and 3 m (≈0.06 for gabbro and ≈0.1 for peridotite), whereas it slightly increases to ~0.14 for the shorter 0.3 m displacement.

Figure 6A shows a Lanzo metagabbro cut by a fault plane related to a subduction earthquake, producing a glassy pseudotachylyte fault and cataclasite–ultracataclasite in the damaged host rock (Scambelluri et al., 2017; Pennacchioni et al., 2020). The experimentally faulted gabbro (Fig. 6B, sample 2049) closely resembles the natural counterpart. The fault core (Fig. 6C) contains clasts of pyroxene, olivine, and plagioclase embedded in pseudotachylyte glass with abundant bubbles formed by volatile degassing during the experiment. Pores are particularly abundant along the upper side of the fault plane (Fig. 6C–D). The glass ejected during the rotary experiment (Fig. 6E) is highly vesiculated and contains fewer clasts.

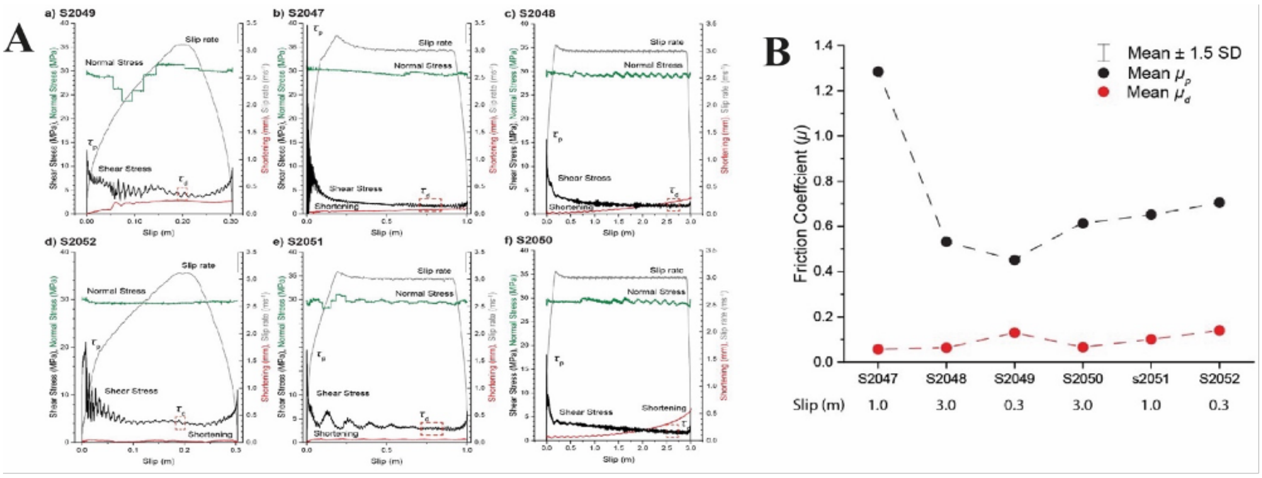


Figure 5. SHIVA experimental pseudotachylyte. (A) Mechanical data from six experiments on gabbro (a–c) and peridotite (d–f), showing velocity, normal stress, shear stress, and shortening versus slip distance; τp and τd indicate peak and dynamic shear stress. Red dashed boxes mark the data used to estimate the dynamic friction coefficient. (B) Peak and dynamic friction coefficients (μp, μd) at different slip distances.

Comparable features are observed in the experimentally faulted Lanzo peridotite (Fig. 6F–G), where ultramafic mineral clasts and idiomorphic microliths are embedded in bubble-rich pseudotachylyte melt. In Fig. 6G, irregular and corroded clasts derive from cataclastic host-rock fragments, whereas polygonal crystals likely represent microliths formed during melt quenching.

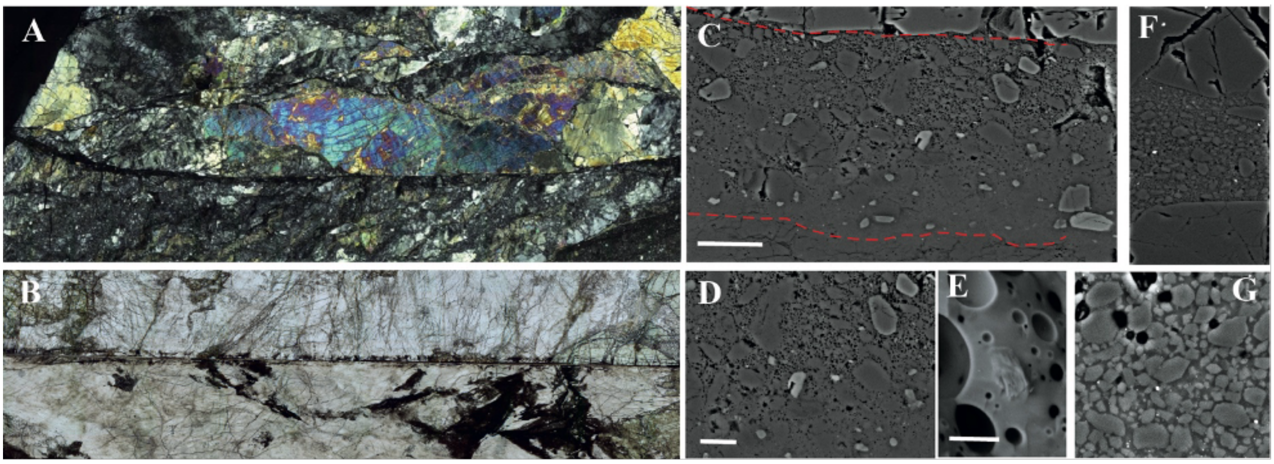


Figure 6. (A) Naturally faulted metagabbro from the Lanzo Massif. (B) Experimentally faulted gabbro sample 2049. (C) FESEM image of the fault zone in sample 2049 (scale bar 20 μm). (D) Enlargement of C showing a variably vesiculated glassy matrix (scale bar 10 μm). (E) Glass bleb expelled during the rotary experiment (scale bar 5 μm). (F) Experimental fault plane in peridotite. (G) Olivine clasts in ultramafic glassy pseudotachylyte.

The dataset presented here is based on a multidisciplinary and multiscale approach integrating structural geology, mineralogy, and petrology, and provides a starting point for understanding and modelling earthquake-related structures observed in natural rocks. Our results show that brittle seismic deformation preserved in exhumed rocks can be effectively reproduced through laboratory experiments constrain the frictional behaviour of dry lithospheric rocks, showing that dynamic weakening becomes more efficient as slip displacement increases, promoting stable low-friction conditions during sustained seismic slip. Experiments thus indicate that frictional melting and pseudotachylyte formation are key mechanisms governing the rock rheology during seismic activity at convergent plate margins.

5.5 Application of high-performance numerical codes for physically based earthquake ground motion simulations for multi-risk scenario analyses and damage evaluations, in cooperation with WP7 (POLIMI)

5.5.1 Scientific Context and Objectives

The 23 November 1980 Irpinia earthquake (Mw 6.8) represents the most destructive seismic event instrumentally recorded in Italy during the last century, causing approximately 3,000 fatalities and widespread damage across the regions of Campania and Basilicata. Despite its major societal impact, the limited number of near-source instrumental recordings available at the time still leaves several aspects of the ground-motion characteristics of the event insufficiently constrained, particularly in the immediate vicinity of the causative fault system.

In recent years, advances in high-performance computing and numerical modelling have made it possible to simulate earthquake ground motion using fully physics-based numerical approaches, allowing a more realistic representation of rupture processes, wave propagation, and the resulting spatial variability of ground shaking. These simulations can provide valuable insights into near-fault ground-motion features and support the development of realistic seismic scenarios for hazard and risk assessment.

Within this context, the objective of this activity was to perform large-scale three-dimensional physics-based simulations (PBS) of the 1980 Irpinia earthquake using a regional numerical model of Southern Italy. The simulations aimed to better characterize near-source ground-motion features associated with the multi-segment rupture of the event, including permanent ground deformation and pulse-like velocity signals typical of normal-faulting earthquakes. In addition, the modelling framework was designed to produce spatially distributed maps of ground-motion parameters that can be used for future regional seismic risk analyses and multi-risk scenario evaluations.

5.5.2 Methodological Development

The numerical simulations were carried out using SPEED (SPectral Elements in Elastodynamics with Discontinuous Galerkin, https://speed.mox.polimi.it), a three-dimensional spectral-element code developed at Politecnico di Milano (Mazzieri et al., 2013). The simulations were executed on the CINECA high-performance computing infrastructure, enabling the modelling of seismic wave propagation over a large regional domain. The computational model covers an area of approximately 147 km × 110 km, extending from the ground surface down to a depth of 22 km. The domain was discretized using a high-resolution spectral-element mesh consisting of approximately 67 million spectral nodes, allowing accurate simulation of wave propagation within the frequency range resolved by the model.

The numerical simulations were performed with a frequency resolution up to 2 Hz, and the resulting synthetic ground motions were subsequently extended to broadband frequency content using the ANN2BB artificial neural network approach (Paolucci et al., 2018). This hybrid strategy allows the generation of broadband ground motions suitable for engineering applications while maintaining the physical realism of the numerical simulations.

The crustal velocity structure adopted in the model is based on published geophysical data for the Southern Apennines, incorporating realistic distributions of P-wave velocity (Vp), S-wave velocity (Vs), and frequency-dependent anelastic attenuation. The simulations assume a reference engineering bedrock condition characterized by $V_{s30} = 800$ m/s at the ground surface; consequently, local site amplification effects are not explicitly included in the model.

The seismic source model used to reproduce the Mw 6.8 Irpinia earthquake accounts for the well-documented multi-segment rupture of the event. The earthquake rupture is represented by three normal-fault segments that are sequentially activated at $t = 0$ s, 20 s, and 40 s, respectively. The kinematic parameters of the rupture, including the slip distribution along the fault planes, were derived from previously published source inversion models. The geometry and spatial distribution of the fault segments, together with the configuration of the computational mesh and the location of accelerometric stations used for validation, are illustrated in Figure 7.

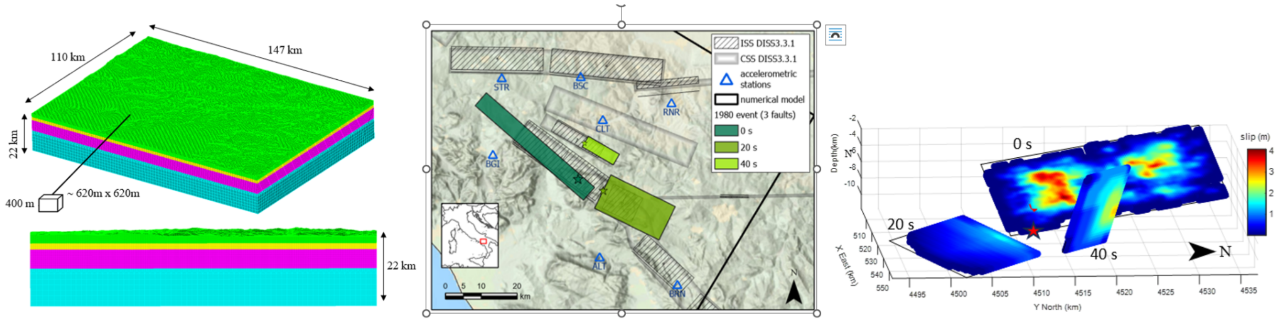


Figure 7. Computational mesh used for the three-dimensional simulations of the 1980 Mw 6.8 Irpinia earthquake. The central panel shows the geometry of the multi-segment fault model adopted in the simulations, together with the distribution of accelerometric stations and the regional tectonic setting. The right panel illustrates the slip distribution on the rupture fault planes.

5.5.3 Discussion on Main Results

The simulated ground motions were validated through comparison with the available analog recordings collected at eight accelerometric stations, located at epicentral distances ranging between 19 km and 78 km. Despite the inherent uncertainties associated with modelling a historical earthquake recorded more than forty years ago, the numerical simulations reproduce the main temporal and spectral characteristics of the observed waveforms on both horizontal and vertical components.

A quantitative comparison based on the logarithmic residuals of response spectral ordinates confirms a generally good agreement between simulated and recorded ground motions across most vibration periods. This result supports the capability of the numerical model to reproduce the main features of the seismic wavefield generated by the multi-segment rupture. The spatial distribution of simulated peak ground velocity (PGV) and peak ground acceleration (PGA) across the computational domain highlights the directional influence of the three fault segments and the progressive attenuation of shaking with distance from the source. The simulated ground-motion patterns are broadly consistent with the observed distribution of damage associated with the 1980 earthquake.

The simulations also reveal several near-fault ground-motion features of direct engineering relevance. The computed coseismic deformation field shows extensional motion affecting both the hanging-wall and footwall regions of the fault system. Vertical displacements along the main fault scarp are consistent with field observations, while maximum horizontal permanent displacements reach several tens of centimetres in the immediate source region, with potential implications for extended infrastructures such as pipelines, tunnels, and transportation corridors.

Another important feature emerging from the simulations is the presence of velocity pulses associated with rupture directivity. Up-dip directivity produces short-period pulses polarized in the fault-normal direction, characterized by dominant periods between 0.5 s and 1.5 s and PGV values exceeding 1.5 m/s close to the upper edge of the main fault segment. Longer-period pulses, with dominant periods between 4 s and 6 s, are observed further north and are predominantly polarized in the fault-parallel direction, with lower amplitudes.

Overall, the results highlight the strong spatial variability of ground motion in the near-fault region, particularly above the fault rupture area. Such variability has direct implications for structural demand and cannot be adequately captured by conventional isotropic ground-motion models.

These findings demonstrate that physics-based simulations of historical earthquakes, even when observational constraints are limited, can provide realistic ground-motion scenarios suitable for applications in seismic risk assessment, fragility-curve calibration, and the design or evaluation of critical infrastructures.

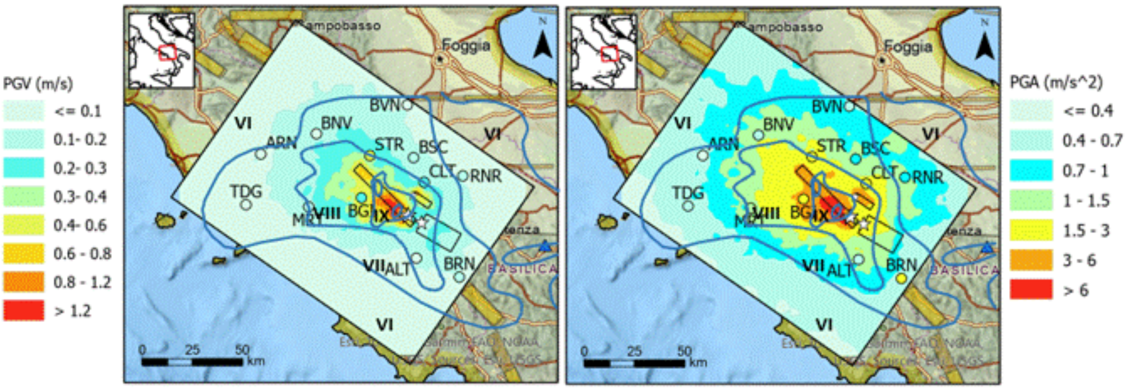


Figure 8. Spatial distribution of simulated peak ground velocity (PGV, left) and peak ground acceleration (PGA, right), computed as the horizontal geometric mean. Coloured dots indicate the recorded values at accelerometric stations, using the same colour scale. Isoseismal lines from Postpischl et al. (1985) are superimposed for comparison.

5.6 Perform lab experiments of earthquake-like failure to study the mechanisms of rupture nucleation. Use lab seismic data to develop ML and DL models of time to failure and changes in frequency magnitude relations prior to and after failure. (UNIROMA1)

5.6.1 Scientific Context and Objectives

Understanding the mechanisms controlling the nucleation of earthquake rupture remains a central challenge in earthquake physics. Laboratory experiments provide a unique opportunity to reproduce earthquake-like instabilities under controlled mechanical conditions, allowing the investigation of the physical processes governing fault slip and rupture initiation at high spatial and temporal resolution.

Within this framework, the objective of this activity was to reproduce earthquake-like failures in laboratory faults and to analyse the associated seismic and mechanical signals in order to identify diagnostic patterns preceding failure. The generated datasets were used to develop machine learning (ML) and deep learning (DL) models aimed at predicting the time to failure and characterizing changes in frequency–magnitude relations before and after slip events (Laurenti et al., 2022; Borat et al., 2023, 2024, Bolton et al., 2023; Magrini et al., 2025; and Wang et al., 2025).

By combining controlled laboratory observations with data-driven modelling approaches, the study aims to bridge laboratory-scale seismicity with the behaviour of natural faults, contributing to the development of predictive frameworks for rupture nucleation and fault slip evolution (Laurenti et al., 2024; Magrini et al., 2025).

5.6.2 Methodological Development

A series of frictional experiments was performed on extended laboratory faults measuring 760 × 80 mm using the Big-Biax apparatus at the Earthquake Physics and Rock Mechanics Laboratory of Sapienza University of Rome. The experimental configuration allows the reproduction of stick–slip instabilities analogous to small-scale earthquake ruptures (Laurenti et al., 2024; Magrini et al., 2025).

Experiments were carried out on both bare granite surfaces and quartz gouge layers, enabling the investigation of fault slip behaviour under different frictional and mechanical conditions. A multi-sensor monitoring system was used to record the mechanical and seismic signals associated with the slip cycles.

The instrumentation included load cells to measure stress, LVDTs to monitor displacement, eddy current sensors to track local slip along the fault, piezoelectric transducers to record acoustic emissions, and a high-speed camera to observe rupture propagation. This integrated setup allowed the simultaneous acquisition of mechanical, acoustic, and optical observations during repeated stick–slip cycles.

The resulting datasets provide a detailed description of the temporal evolution of stress, slip, and acoustic activity during the preparation, nucleation, and propagation phases of laboratory earthquakes.

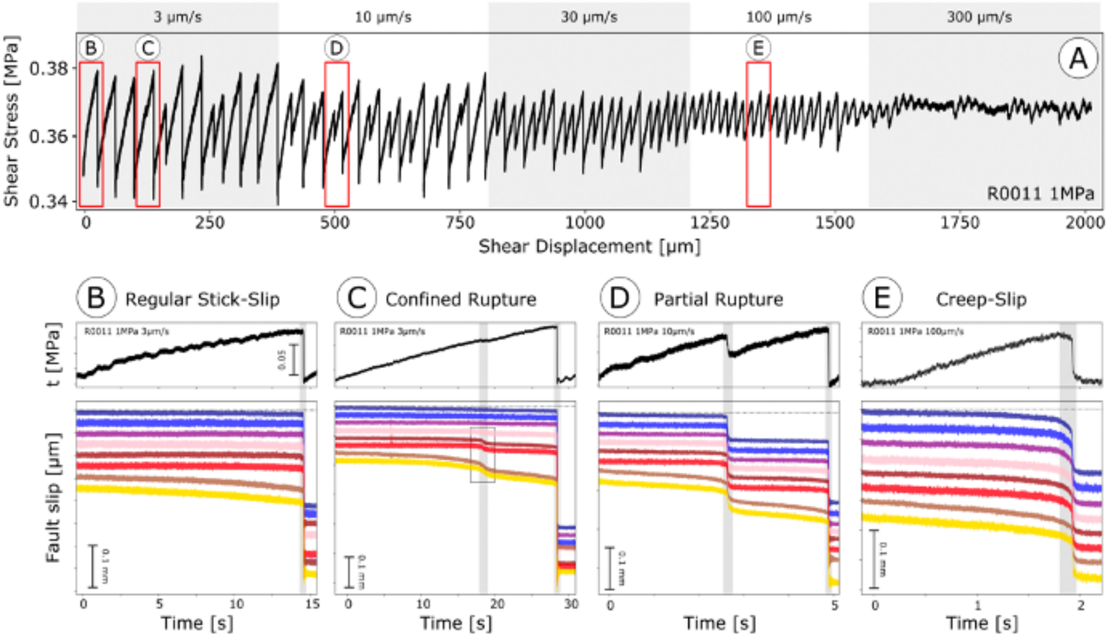


Figure 9. Detailed analysis of slip events within one sequence of laboratory earthquakes. Panel (A) shows the shear stress history for slip events recorded at a normal stress of 1 MPa and shear loading velocities ranging from 3 to 300 μm/s. Red boxes indicate the time intervals analysed in detail in panels B–E. These panels illustrate the mechanical data and rupture dynamics of stick–slip cycles observed during velocity steps at 1 MPa in the R0011 experiments.

5.6.3 Discussion on Main Results

The experiments (Laurenti et al., 2024; Magrini et al., 2025) show that the observed slip behaviour conforms to the rate-and-state friction framework, which describes the dependence of frictional resistance on slip velocity and state variables controlling fault surface properties. Under conditions of high normal stress and low sliding velocity, the experiments produce unstable slip events interpreted as laboratory earthquakes, whereas more stable slip behaviour occurs at lower stress levels.

In addition to this primary behaviour, the experiments reveal the spontaneous emergence of second-order complexities during the stick–slip cycles. These include partial ruptures, off-fault fracturing, and the development of confined slip zones, which produce variable stress drops and heterogeneous rupture histories. These observations highlight that even under controlled laboratory conditions, rupture processes may exhibit significant variability and complexity.

By coupling these experimental observations with ML and DL modelling, the datasets allow the training of predictive algorithms capable of identifying patterns preceding failure and characterizing the evolution of acoustic emission activity during the preparation phase of rupture. Such approaches provide a promising framework for integrating laboratory observations with data-driven techniques aimed at improving our understanding of rupture nucleation processes.

When integrated with complementary observations from natural systems, including geochemical and hydrological monitoring of active faults, these results may contribute to the development of digital twin representations of fault zones, capable of simulating and forecasting rupture nucleation and fault slip evolution. Data and code are available here:

https://github.com/AuroraBassani/LLM-for-Earthquake-Characterization

5.7 Development of novel models for non-linear response of structure using synthetic seismograms. Validation on selected target buildings. (UNIPA)

5.7.1 Scientific Context and Objectives

The assessment of the Local Seismic Response (LSR) to the expected seismic motion in a territory is the subject of seismic microzonation studies. For the estimation of the seismic action, it is necessary to define some fundamental elements: the input representative of the seismic action at the bedrock and an adequate geotechnical model. Generally, at least seven accelerograms compatible with the site target response spectrum must be identified. Typically, such accelerograms are selected from available databases in order to provide the best approximation of the target spectrum. However, this selection is made regardless of the time-dependent characteristics that describe the real seismic signals of the area subject to microzonation (e.g., duration, evolution of amplitude and energy frequency content, total energy and its distribution over time, strong motion duration, etc.).

With the aim of obtaining accelerograms suitable for seismic microzonation studies and capable of reproducing the specific characteristics of the construction site, it is worth noting that, in a recent paper (Colajanni, Pagnotta, et al., 2020), four methods (Cacciola, 2010; Preumont, 1985; Rofooei et al., 2001; Spanos & Solomos, 1983) for generating fully non-stationary artificial accelerograms, based on a target spectrum and on a set of accelerograms recorded in the neighborhood of the construction site that provide a mean response spectrum different from the target one, were compared. Among these, one of them, namely the method (CA), proposed by Cacciola (2010) proved to be particularly efficient in reproducing the characteristics of the seismic events expected at the site. More precisely, the CA method provides reliable results; however, its efficiency is strongly influenced by the selection criterion adopted for the group of real records used to define the non-stationary counterpart.

5.7.2 Methodological Development

Within this context, in the proposed methodology the set of accelerograms obtained using the Cacciola method is adopted as input for an LSR analysis, performed through the one-dimensional equivalent linear method implemented in the AlgoShake2D software (Algoritmiqa, 2023). The results are then compared with those obtained from LSR analyses performed through the natural accelerogram selection procedure currently used in professional practice mentioned above (SMEE), hereafter referred to as “representative accelerograms”, and with the results obtained by assuming as bedrock input motion a set of accelerograms actually recorded at the site (target accelerograms), which constitute the benchmark, in analogy with the procedure adopted in (Colajanni, Pagnotta, et al., 2020).

The effectiveness of the proposed procedure is evaluated in two ways. First, response spectra of ductility demand are derived for different values of the behavior factor, considering SDOF cyclic behavior typical of: steel Moment Resisting Frames (SMRF), Reinforced Concrete (RC) Moment Resisting Frames designed without anti-seismic details, i.e., with cyclic behavior characterized by stiffness and strength deterioration (pinching effect), and Concentric Braced Frames (CBF) with very slender braces, i.e., with zero buckling strength. Second, the results are compared with the response obtained from nonlinear time-history analyses (NLTHAs) of two reinforced concrete (RC) multi-story spatial buildings. The first building is regular in elevation and has a regular plan geometry, but it is characterized by irregular in-plane mass distribution. The second building exhibits structural irregularities both in elevation and in plan.

5.7.3 Discussion on Main Results

The analyses confirmed that the proposed procedure, when applied with an appropriate selection of representative accelerograms from which the characteristics of the accelerograms related to the seismogenic zone governing the site hazard are derived, is able to reproduce the shaking of the site with excellent reliability, and proves to be particularly effective for the evaluation of local seismic response. Conversely, the scaling of accelerograms with large scale factors, which is often required to ensure the compatibility of the representative accelerogram spectra with the spectrum representing the seismicity of the site, cannot guarantee a reliable representation of the seismic demand.

Furthermore, it has been highlighted that the use of accelerograms that are, on average, compatible with the target response spectrum but are characterized by large scattering of the elastic spectra in certain frequency ranges may lead to an overestimation of the seismic demand, especially for systems characterized by high pinching in the hysteretic cyclic behavior, even in the case of structures with long vibration periods. This effect becomes even more pronounced when local seismic response analyses are performed.

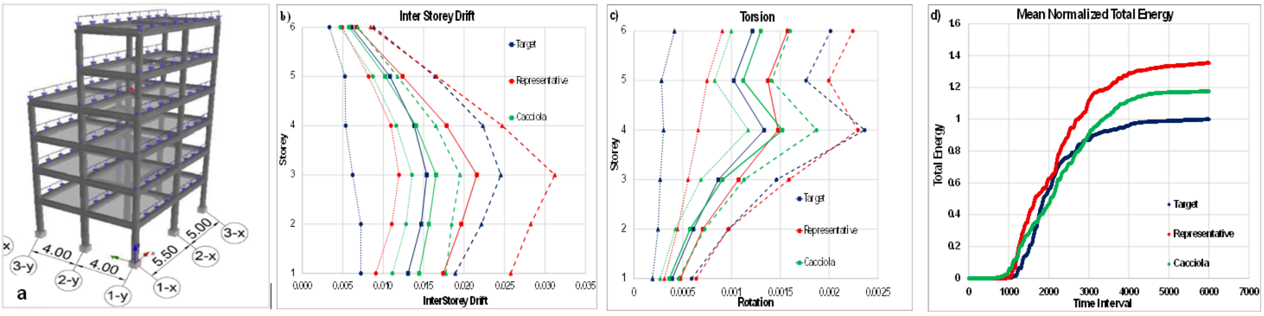


Figure 10. Detailed a): geometry of the structure; b) to d): response on NLTHA for the three datasets of accelerograms: mean and mean ± standard deviation of interstory drift (b) and of interstory rotation (c); d) ratio of dissipated energy and total energy dissipation predicted with target accelerograms

6. Conclusions

The activities carried out within WP5.2 contribute to improving the understanding of the processes controlling earthquake ground motion and rupture dynamics through a combination of numerical simulations, stochastic signal modelling, laboratory experiments, and advanced data-analysis techniques. The different studies presented in this chapter address complementary aspects of earthquake physics, ranging from the simulation of seismic wave propagation in complex geological environments to the experimental investigation of rupture processes and the statistical characterization of seismic signals. Together, these approaches provide new insights into the mechanisms governing the generation, propagation, and variability of earthquake ground motion.

The studies presented in this deliverable also emphasize the importance of integrating different methodological approaches to investigate earthquake processes and their impact on the built environment. In particular, the combination of numerical simulations, laboratory observations, structural geology analyses, and engineering-oriented modelling provides a more complete framework for understanding how rupture processes, geological structures, and local site conditions jointly influence seismic ground motion and structural response.

A first important outcome of this work concerns the investigation of ground-motion variability through physics-based numerical simulations of seismic wave propagation. Three-dimensional spectral-element models allow the simulation of wavefields in realistic geological environments, making it possible to analyse how basin geometry, velocity contrasts, and structural heterogeneities influence the spatial distribution of seismic shaking. The results highlight the strong control exerted by local geological structures on the amplification and redistribution of seismic energy. These findings confirm that ground-motion patterns cannot be fully understood without explicitly accounting for the structural complexity of the crust and the interaction between seismic waves and geological boundaries. Physics-based simulations therefore represent an essential tool for exploring the mechanisms responsible for local amplification effects and for improving the physical realism of ground-motion modelling.

Complementary insights are provided by the development of stochastic and non-stationary approaches for the generation of artificial earthquake accelerograms. The generation of synthetic time histories compatible with target response spectra represents a key component of engineering seismology and seismic risk assessment. The methodologies explored in WP5.2 contribute to improving the capability to reproduce realistic seismic signals while preserving their statistical and spectral characteristics. In particular, the adoption of non-stationary signal models allows a more realistic representation of the temporal evolution of ground motion, capturing important features such as amplitude modulation and frequency content variations during the shaking process. These approaches provide flexible tools for the construction of ground-motion scenarios that are consistent with seismic hazard models while retaining a physically meaningful description of seismic signals.

Another important contribution of WP5.2 concerns the investigation of rupture processes through controlled laboratory experiments. Frictional tests performed on extended laboratory faults reproduce stick–slip instabilities analogous to small-scale earthquakes, allowing the direct observation of stress evolution, slip propagation, and acoustic emission activity during rupture cycles. These experiments reveal the complexity of rupture behaviour even under controlled conditions, including the occurrence of partial ruptures, variable stress drops, and heterogeneous slip patterns along the fault interface. Such observations highlight the strongly nonlinear nature of fault slip processes and the importance of frictional properties and stress conditions in controlling rupture dynamics.

Additional results highlight the importance of damage evolution and time-dependent changes in elastic properties for understanding rupture nucleation, showing how laboratory observations of rock failure can be linked with field-scale seismic velocity variations and deformation processes in natural systems.

The integration of laboratory observations with machine learning and deep learning techniques represents a further innovative aspect of the work carried out within this task. By analysing large datasets of acoustic emissions and mechanical signals produced during laboratory stick–slip cycles, data-driven approaches can be used to identify patterns associated with the preparation phase of rupture and to explore the potential predictability of failure processes. Although the extrapolation of laboratory observations to natural fault systems must be treated with caution, these approaches offer promising perspectives for improving the identification of precursory signals and for developing new methodologies for the analysis of seismic signals.

Taken together, the results obtained within WP5.2 underline the importance of combining physics-based modelling, experimental observations, and advanced data-analysis techniques to investigate earthquake ground motion and rupture dynamics. The integration of numerical simulations, stochastic signal modelling, and laboratory experiments provides a more comprehensive framework for analysing the processes that control seismic wave generation and propagation. Such multidisciplinary approaches help bridge the gap between theoretical models, experimental observations, and the statistical characterization of seismic signals.

Looking forward, several research directions emerge from the results presented in this deliverable. Future work will benefit from the continued development of large-scale numerical simulations capable of incorporating increasingly realistic geological models and source representations. Further progress is also expected from the integration of experimental datasets with high-resolution observational records, enabling more detailed comparisons between laboratory-scale rupture processes and natural seismicity. At the same time, advances in machine learning and data-driven analysis techniques may provide new opportunities for extracting information from complex seismic datasets and for identifying subtle patterns associated with rupture nucleation and ground-motion generation.

In this perspective, the results obtained within WP5.2 contribute to advancing the physical understanding of earthquake processes across multiple spatial scales. By improving the modelling of seismic wave propagation, the generation of realistic ground-motion signals, and the experimental investigation of rupture dynamics, these studies provide important methodological developments and new insights that support the ongoing effort to improve seismic hazard assessment and the characterization of earthquake effects.

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