Geo-INQUIRE Transnational Access Project Report

Geo-INQUIRE installation: CYBER@PSHA - Probabilistic Seismic Hazard Analysis (TA2-541-10)

Project title: **CyberShake physics-Based damage Evaluation for NorthEastern Italy CYBERNEI**

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Project acronym: CYBERNEI

Project report ID: TA2-541-10-C1-4 (1st call)

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Date of visit: March 2025 and remote sessions, also access to MN5 via RES project

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Introduction and objectives

Rapid estimation of earthquake impacts in near real time is a key requirement for effective seismic risk management and civil protection response. However, such estimates strongly depend on assumptions about earthquake source characteristics, which are often poorly constrained during an ongoing emergency. This uncertainty propagates through ground-motion modeling and can significantly affect impact and damage estimates.

Within this context, the Geo-INQUIRE Transnational Access aimed to explore how physics-based seismic simulations can be integrated into impact and damage assessment workflows currently used for civil protection purposes in northeastern Italy.

In this scientific collaboration between OGS and BSC, we aim at revisiting the 1976 Friuli earthquake (Mw 6.5) — a well-documented but sparsely recorded event — as a case study to explore the implications of source modeling uncertainties for impact estimation. In particular, we aim at improving physics-based simulations by accounting for multiple sources, and using their results to assess the potential seismic impact of the 1976 Friuli earthquake.

Main phases of this study

The foundation of this work is to identify the relevant fault sources and generate a set of plausible rupture scenarios through numerical modeling. The resulting ground motions are then analyzed to evaluate their variability across the region. Finally, the outcomes are planned to be used to assess potential damage distributions and support seismic risk management in NE Italy. The study is therefore organized in three consequent phases:

1) Physics-based ground-motion simulations
2) Comparison of the generated ground motions with the observed records
3) Damage assessment based on simulation results

In the first phase, we begin by identifying sources related to the Friuli 1976 earthquake, focusing on selecting 11 initial sources for simulations. The sources are chosen based on their proximity, fault characteristics, and relevance to the region's seismic activity. The ruptures generated through the simulation process are modeled using a set of well-established ground motion prediction equations and computational methods. Specifically, we use the finite difference method (FDM) to simulate the propagation of seismic waves across the region. This allows us to produce synthetic ground motion records, which can then be compared to actual observations from the Friuli 1976 event. One of the main challenges in this phase was defining accurate input parameters, such as fault geometry, stress drop, and material properties, which are essential for producing realistic simulations. The initial 11 source models provide a manageable starting point, though the aim is to scale this to over 200 sources in future work in order to better account for uncertainties in the source process resulting from the large uncertainty in the event location caused by highly sparse recordings.

In the second phase, we compare the generated ground motion to observed records to assess its variability and overall quality. This involves statistical analysis of the differences in terms of peak ground acceleration (PGA), spectral response, and other key intensity measures / parameters. The aim is to quantify the differences between synthetic and real-world data to better understand the variability of ground motion in the region.

In the third and final phase, the synthetic ground motion is used as input for damage assessment at various sites affected by the 1976 earthquake. Challenges in this phase include the difficulty of site-specific calibration and the variability in building codes and construction standards across sites. This activity is currently under development.

Activities carried out during the Transnational Access

The Transnational Access at the Barcelona Supercomputing Center (BSC) supported the implementation of the first two phases of this study by providing hand-on training and HPC resources. During the visiting at BSC, colleagues from OGS have received training to use Cybershake. Training materials were prepared by BSC and shared with the visiting people, and multiple Q&A virtual sessions were accommodated in the following months. The visit also facilitated in-person knowledge transfer, iterative problem solving, and scientific discussions.

The Geo-INQUIRE Transnational Access at the Barcelona Supercomputing Center allowed to define and test a methodological framework for integrating physics-based seismic simulations into damage assessment workflows currently used by OGS for civil protection purposes in northeastern Italy. In particular, the activities addressed all three phases of the work plan, even though they have not yet been completed:

1) Physics-based ground-motion simulations were performed for 11 potential seismic sources (Fig. 1) with their respective rupture variations associated with the 1976 Friuli earthquake, as documented in the literature (DISS3.3.1, Diss Working Group 2025; ITACA v4.0, Felicetta et al., 2023: Aoudia et al., 2000) were prepared and run using the Cybershake tools (e.g. Callaghan et al 2024).

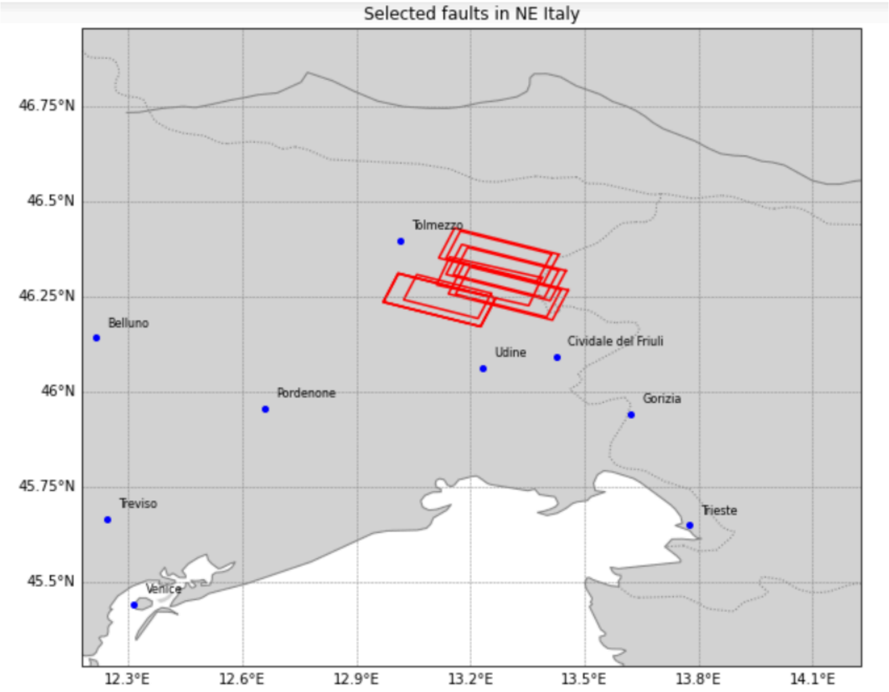


Fig. 1: Selected 11 rupture areas (DISS3.3.1, Diss Working Group 2025; ITACA v4.0, Felicetta et al., 2023: Aoudia et al., 2000) for the first version of this study, where a 1D velocity model is used to conduct numerical simulations with Cybershake platform.

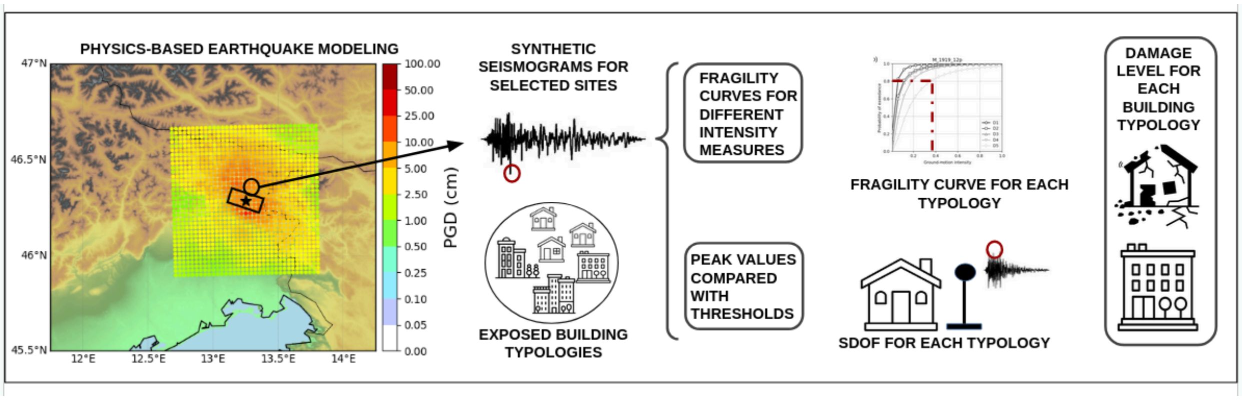
The Cybershake model was run for each of the 11 identified sources. Since CyberShake simulations are limited to a maximum frequency of 1-2 Hz due to the computational burden, it was necessary to complement our results with high-frequency simulations in order to extract PGA and other spectral ordinates required for damage assessment. To this end, the implementation of modifications to the RAPIDS code (Zuccolo et al., 2024; Zuccolo et al., 2025) has been initiated to allow the rupture models defined by CyberShake to be used as input for the synthetic seismogram generation code developed at the University of California [Santa Barbara (Crempien and Archuleta, 2014).

The UCSB code enables the computation of broadband synthetic seismograms. Accordingly, the development of a processing pipeline has been initiated to stitch together the seismograms generated by CyberShake and those computed using the UCSB method, exploiting each signal in the frequency band where it performs best: UCSB at high frequencies and CyberShake at low frequencies.

CyberShake was selected for the low-frequency range also in view of future developments, as it allows the use of a three-dimensional velocity model, which is expected to replace the current 1D model. This capability distinguishes CyberShake from the UCSB approach, which does not support 3D subsurface models.Once this work is completed, it will be possible to proceed with the second phase of the study, namely the comparison of the generated ground motions with the observed records.

2) Preliminary comparisons were made between the ground motions generated by CyberShake and the observed records (at 0.5 and 1 Hz). Also, preliminary comparisons were made between the damage probability for damage level 3,4, and 5 of the EMS98 scale using fragility curves from literature and the PGAs obtained from the seismograms generated by the Cybershake simulations at 0.5 and 1 Hz.

3) A pipeline was defined together in order to assess expected damages for different building typologies. The pipeline uses the output produced for the selected scenario (synthetic seismograms and intensity measures) to assess the expected damage for each building typology in the study area using fragility curves or other methods (Fig. 2).



<u>Fig. 2:</u> Pipeline for the use of physics-based simulations outputs for damage assessment based on fragility curves for each exposed typology.

The relevant information for applying the pipeline were identified and prepared. The main building typologies in the 1976 building stock were unreinforced masonry constituted by either stone, pebbles or bricks and blocks, and pre- or low-code reinforced concrete. The current building stock was derived from the last comprehensive building census in Italy (Istat, 2011) and is mostly constituted by unreinforced or mixed masonry and reinforced concrete. Data sources related to damages suffered by buildings during the 1976 event were also gathered from past work (e.g. Grimaz, 2009). Each building typology in the old and new exposure layer is then associated with fragility curves from literature. Alternatively, for the building typologies for which thresholds are available (e.g. from Lagomarsino and Giovinazzi, 2006 or from ad-hoc building modeling), damage state can be assessed by comparing the relative displacement or average interstory drift in the building with the thresholds for different damage levels (e.g. Petrovic et al., 2023).

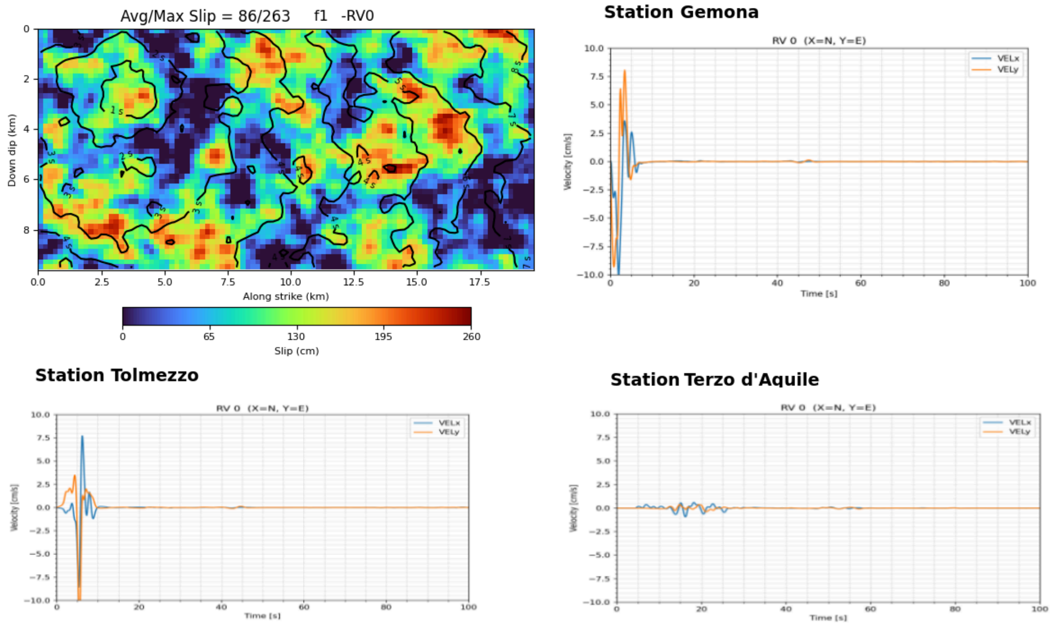
The modeling outputs produced during the transnational access support the subsequent work, which will be focused on applying and testing the damage assessment method for the same event, using historical exposure data from 1976 as well as current exposure data.

Main outcomes from the transnational access:

1. Definition and implementation of the modeling strategy for physics-based simulations in northeastern Italy

The first outcome is that the visiting researchers (Chiara Scaini and Elisa Zuccolo) were able to understand the wide range of potential applications of Cybershake and adapt the modeling strategy to their specific use case. In particular, the working group identified a simplified modeling strategy with selected sources and with 1D velocity profile, and a more sophisticated approach using more than 200 sources and a 3D velocity model.

An example of the results obtained during the first and second phase of the study are shown in Fig. 3, which presents the synthetic seismograms obtained by Cybershake at three selected stations from the simulation of two ruptures, using a 1D velocity model.



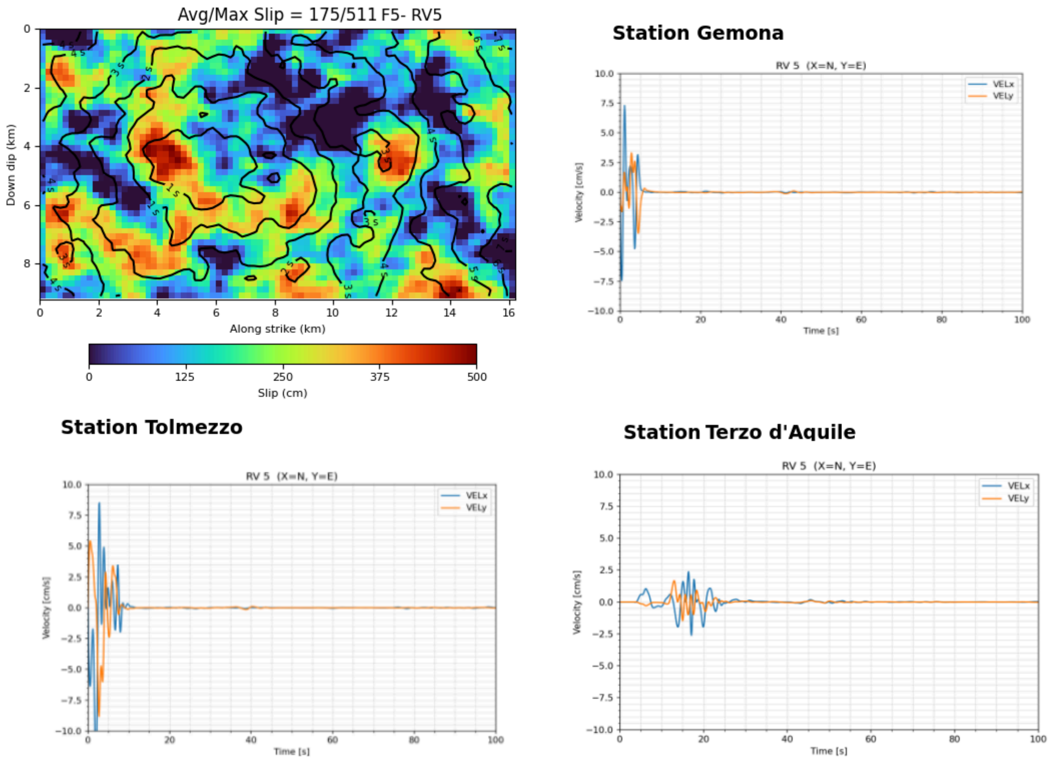


Fig. 3. Examples of outcomes of the simulations for two selected faults and saved at three stations (Tolmezzo, Gemona and Terzo d'Aquileia).

Similar results were obtained for the simulations at 1 Hz considering 11 sources and 150 ruptures. The main effect is amplitude and energy content as expected, and this will be reflected in the damage analysis below.

2. Damage assessment for selected sources and ruptures in two test sites

Regarding the damage assessment, the working team identified the building typologies present in the study area, and the fragility curves to be used for each intensity measure to test the damage assessment pipeline. The first phase is to check if the results that we obtain are consistent with the observed damages in 1976. Preliminary tests have been run to check if the expected damages vary using different sources as input for the computation. For this, we assess expected damages for selected building typologies using as input:

- Simulations produced at 0.5 Hz with Cybershake, in terms of PGA computed for 4 faults and their respective ruptures variations, for a total 58 ruptures.

- Simulations produced at 1 Hz with Cybershake, in terms of PGA computed for 11 faults and their respective ruptures variations, for a total 150 ruptures.

To assess the expected damages, we used fragility curves for different unreinforced masonry building typologies, including historical masonry which is one of the typologies largely present in the study area in 1976. Curves are obtained from Rosti et al., (2020).

Results of the first test are shown below for two points located in the proximity of the villages of Gemona and Tolmezzo (see fig. 1). The maximum PGAS obtained in Gemona and Tolmezzo are 0.119g and 0.045g, respectively. The probability of having a damage greater than damage level 3 (corresponding to the occurrence of first structural damages), 4 (heavy structural damages) and 5 (collapse) following the EMS98 scale were computed using the PGA computed with the different ruptures. Results for Gemona (Site 17) showing that, depending on the rupture, there is a large variability of the probability of occurrence of damage level 3 or greater. Results for Tolmezzo (Site 19) show a lower variability of the probability of occurrence of damage level 3 or greater.

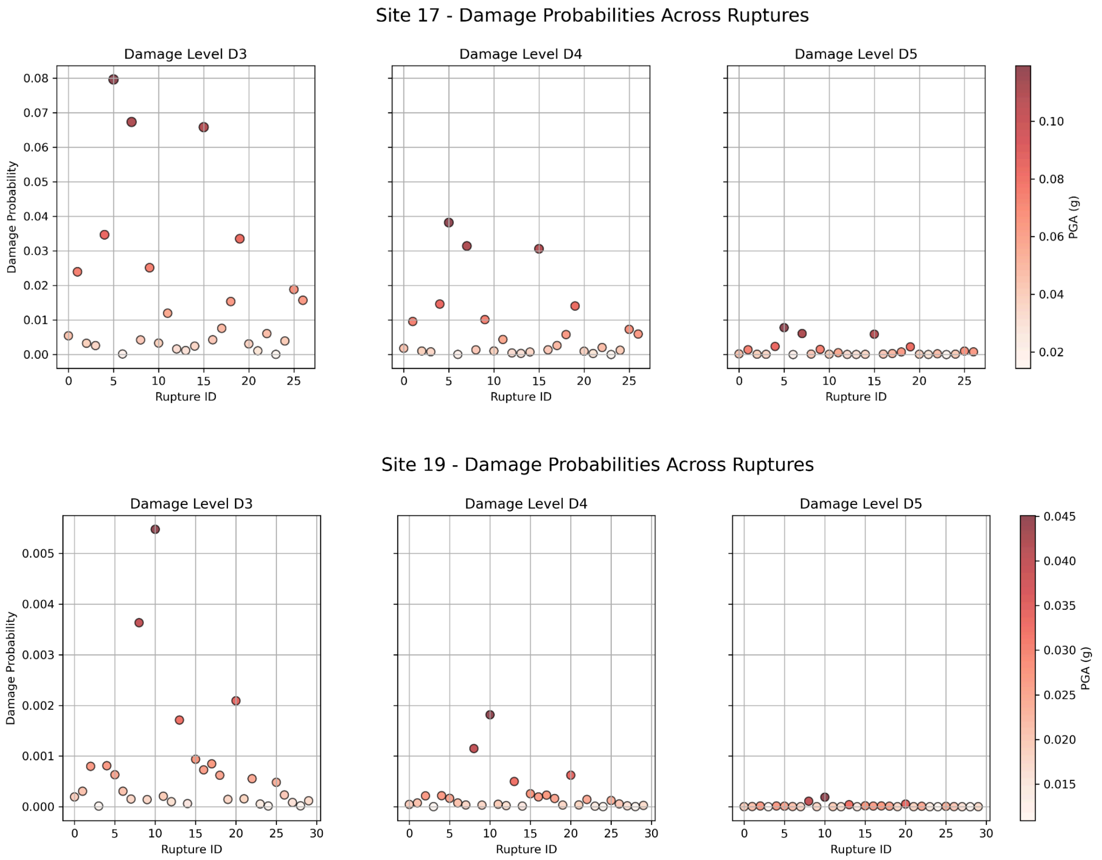


Fig. 4: Probability of reaching a damage state greater than 3, 4 and 5 (from left to right) for historical URM, low-rise in Gemona and Tolmezzo (site 17 and 19 respectively).

Results for historical masonry of medium to high height are very similar to the ones for low-rise masonry for Gemona and Tolmezzo.

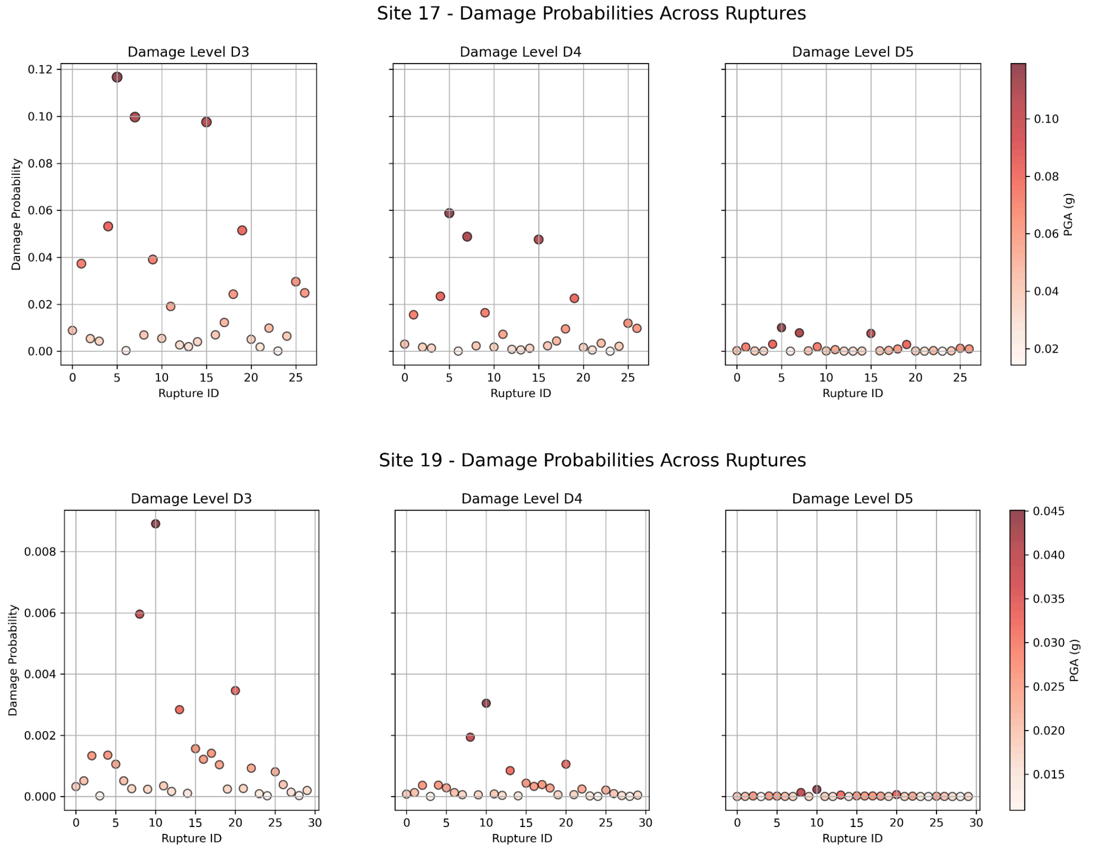


Fig. 5: Probability of reaching a damage state greater than 3, 4 and 5 (from left to right) for historical URM, mid-rise in Gemona and Tolmezzo (site 17 and 19 respectively).

Finally, we ran a test with a typology that was not present in Friuli in 1976, but is very present now (unreinforced modern masonry constructed after 1980). The results are shown for low-rise buildings and allow making two preliminary observations: the probability of structural damage is much lower due to the higher resistance to seismic loads associated with this building typology.

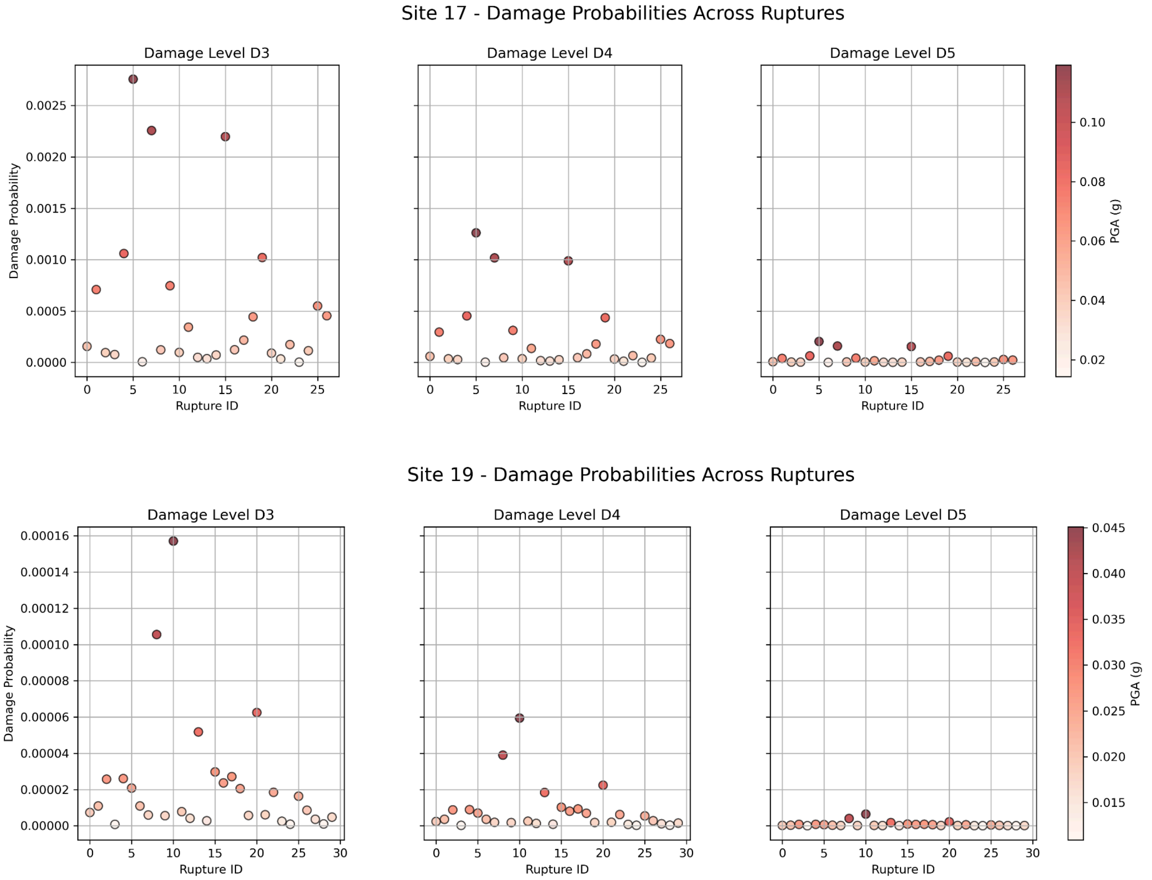


Fig. 6: Probability of reaching a damage state greater than 3, 4 and 5 (from left to right) for modern URM, low-rise in Gemona and Tolmezzo (site 17 and 19 respectively).

The second test was done using simulations produced at 1 Hz with Cybershake, in terms of PGA computed for 11 faults and their respective ruptures variations, for a total 150 ruptures. The maximum PGAS obtained in Gemona and Tolmezzo (sites 107 and 19) are of 0.210g and 0.113g, respectively. Results for historical URM, low- and mid-rise and for modern URM are shown below for Gemona and Tolmezzo:

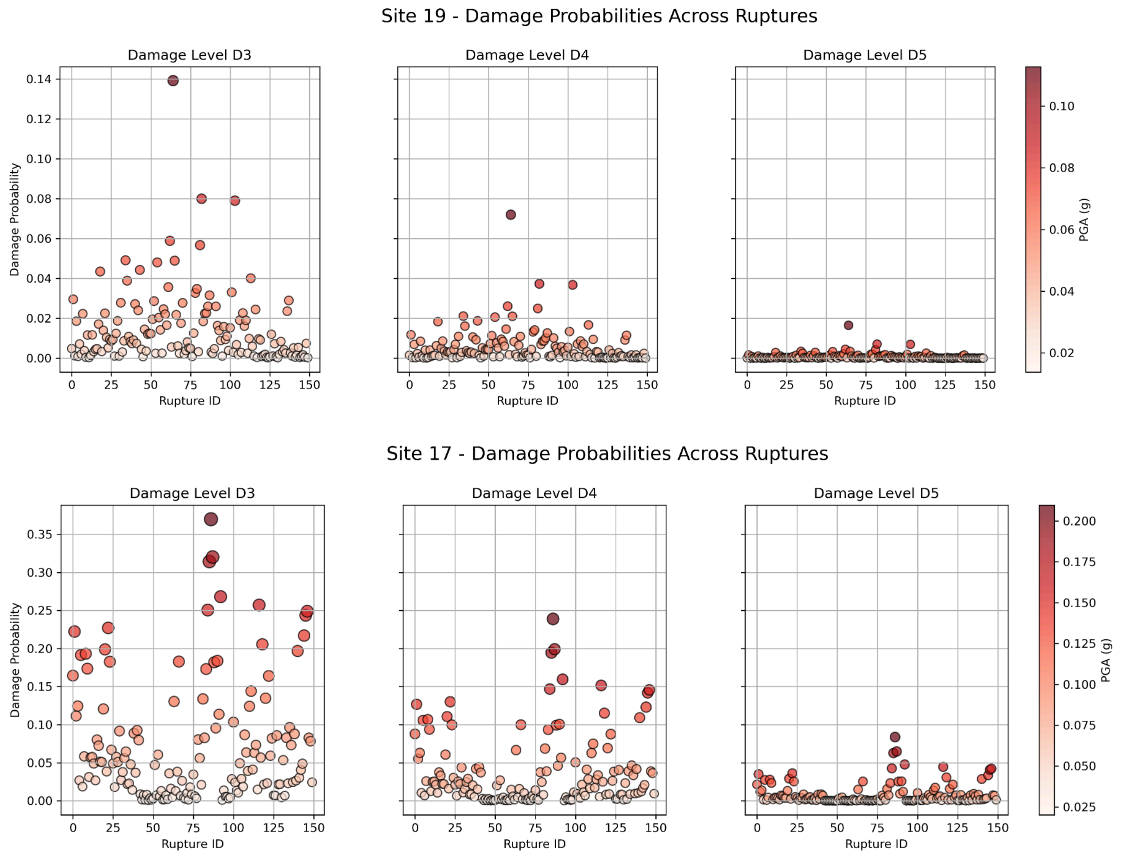
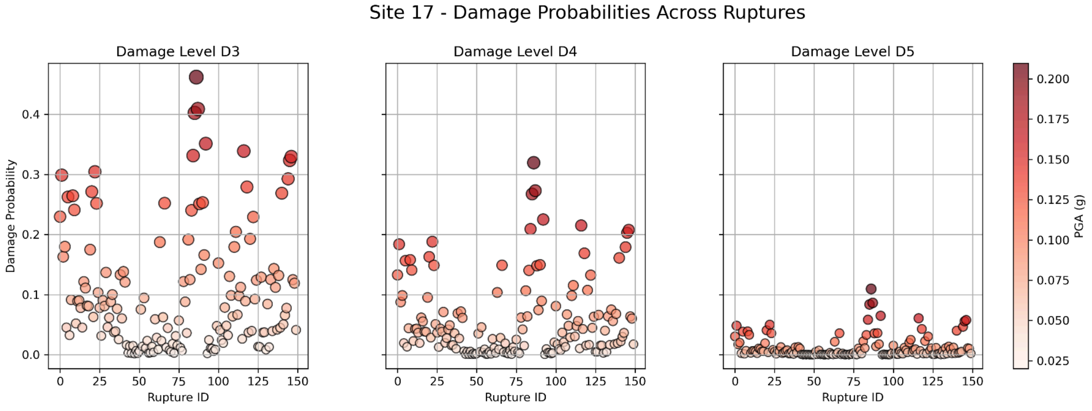


Fig. 7: Probability of reaching a damage state greater than 3, 4 and 5 (from left to right) for historical URM, low-rise in Gemona and Tolmezzo (site 17 and 19 respectively)



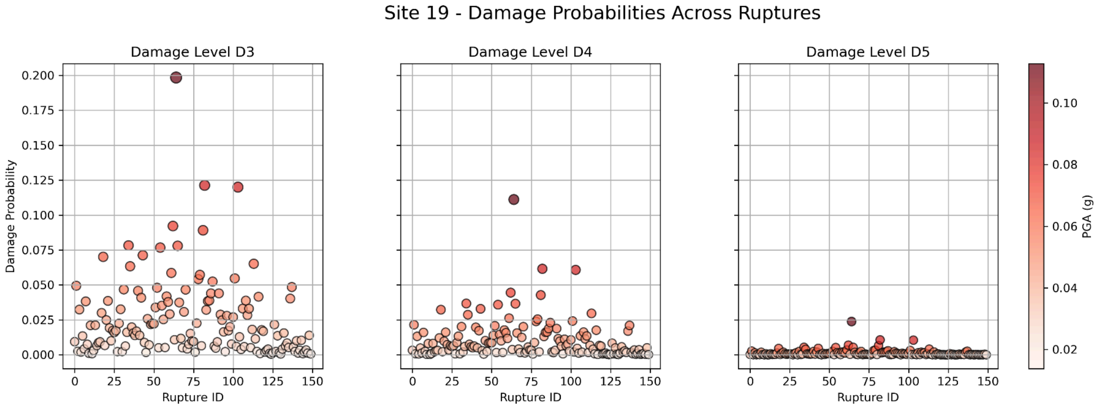


Fig. 8: Probability of reaching a damage state greater than 3, 4 and 5 (from left to right) for historical URM, mid-rise in Gemona and Tolmezzo (site 17 and 19 respectively)

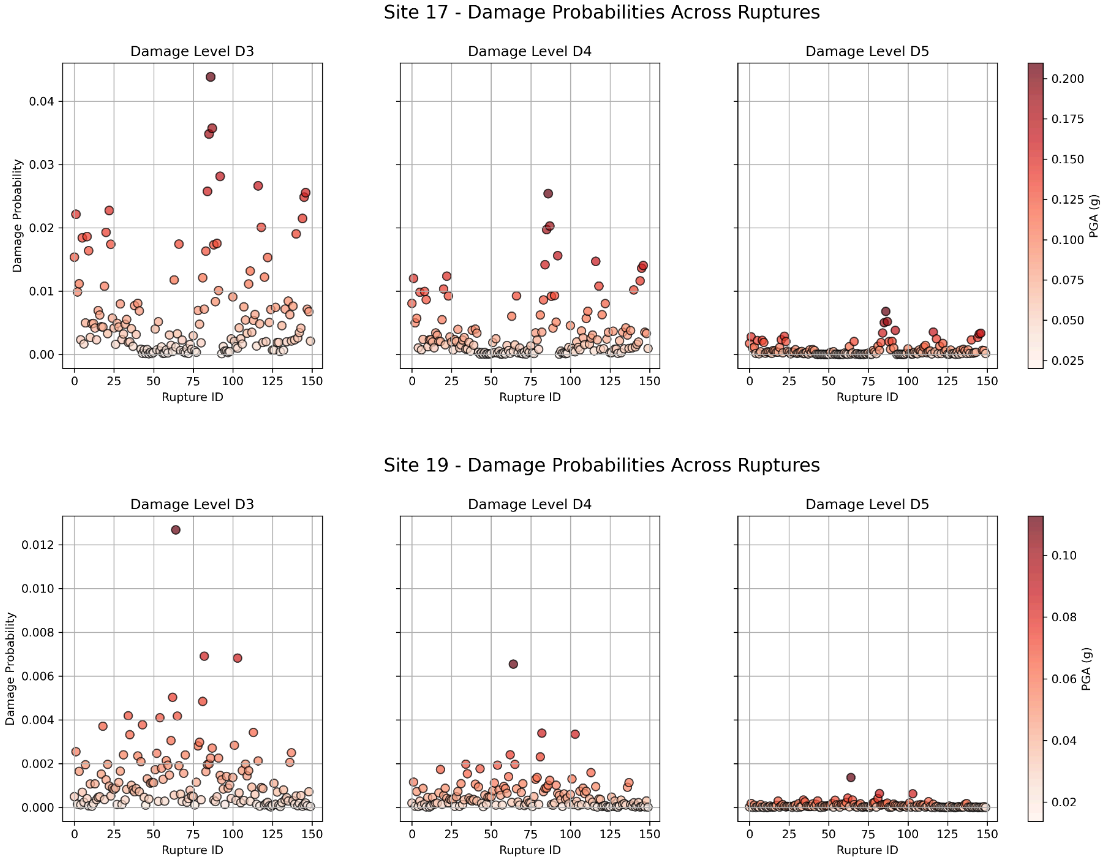


Fig. 9: Probability of reaching a damage state greater than 3, 4 and 5 (from left to right) for modern URM, low-rise in Gemona and Tolmezzo (site 17 and 19 respectively)

The maximum damage probability obtained for each building typology to suffer a damage level 3 or greater using the simulations at 0.5 and 1Hz is summarized below:

Building typology	Maximum damage probability of D3 or greater					
	Gemona (site 17)			Tolmezzo (site 19)		
	0.5 Hz	1 Hz	Difference (points %)	0.5 Hz	1 Hz	Difference (points %)
Historical URM low-rise	0.08	0.32	24	0.006	0.15	14
Historical URM mid-rise	0.12	0.48	36	0.009	0.2	19
Modern URM low-rise	0.003	0.045	4	< 0.001	0.013	1

Table 1: Maximum probability of occurrence of damage level D3 or greater for each building typology, site and simulation. The difference between the probability for the 1Hz and the 0.5Hz simulation, in points percentage, is also shown, with values approximated to integer.

Results obtained with the simulation at 1Hz associated with an increased number of considered sources (11) and ruptures (150) generate larger damage probabilities in both sites. Differences between the two simulations are very large, reaching the 24 and 36 percentage points for Gemona historical URM low and mid rise, respectively. Differences are also large in Tolmezzo (14 and 19% for historical URM low- and mid-rise), where the maximum PGA increases substantially with respect to the simulation at 0.5 Hz.

These results are preliminary, and no direct conclusion can be done from these tests. In particular, table 1 refers to the maximum value of probability, which is often associated with single or very few ruptures, while many of the considered sources and ruptures produce much lower damage probabilities. A statistical treatment of the results is therefore necessary. Further tests are also needed and will be carried out for different sources, intensity measures, building typologies and fragility curves, and running the simulations including also the high-frequency part. Also, the expected PGA and other IMs might vary once the site effects are implemented. Despite all the limitations, however, preliminary results suggest that there might be a strong influence of the source on the expected damage, in particular for some building typologies such as historical masonry.

3. Demonstration of the damage assessment pipeline

For demonstration purposes, a final test was carried out in order to show what kind of results can be obtained using the proposed pipeline (Fig. 2) can be implemented. To do that, we identified all the unreinforced masonry residential buildings in the municipalities located in the proximity of the two considered points (17 and 19, Gemona and Tolmezzo), which sum a total of 1450 buildings.

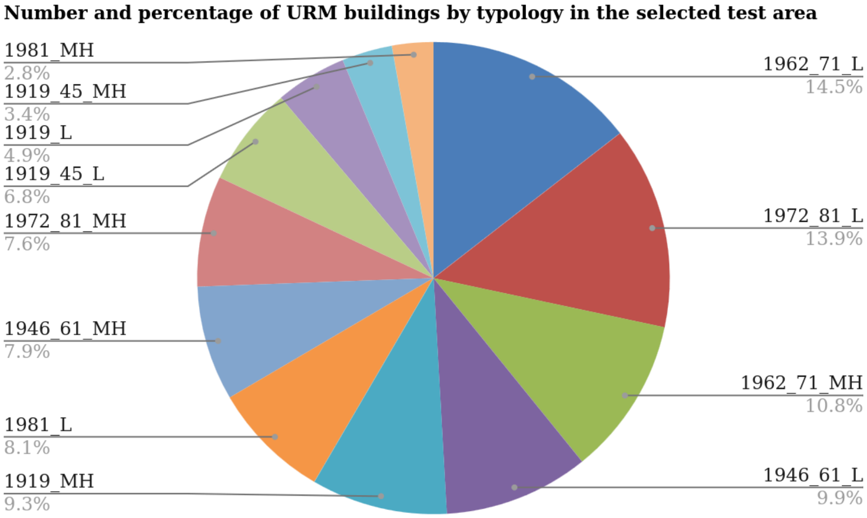


Fig. 10: Composition of the building stock in the area considered for the demonstration, which includes buildings constructed in the following age classes: prior to 1919, in the range 1919-1945, 1946-1961, 1962-1971, 1972-1981 and after 1981. The strings 'L' and 'MH' refer to the typology height range (low and medium-high, respectively).

The pie chart (Fig. 10) shows the composition of the building stock considered, which includes buildings constructed in the following age classes: prior to 1919, in the range 1919-1945, 1946-1961, 1962-1971, 1972-1981 and after 1981. The strings 'L' and 'MH' refer to the typology height range (low and medium-high, respectively).

Then, using the corresponding fragility curves from Rosti (2020) and matching them with each typology in the exposure dataset, the damage was computed. Results are provided below in two ways: the total number of unreinforced masonry residential buildings damaged, and the corresponding percentage of the total unreinforced masonry buildings considered in this test area (1450), for damage level 3, 4 and 5 of the EMS98 scale (corresponding to substantial, very heavy or total damage).

Results of the damage assessment using as input the PGA computed, for 2 sources and 27 ruptures, in the point located in Gemona are shown below. A total of 11.5%

percent of the residential building stock (corresponding to 167 buildings) is expected to suffer a damage equal or greater than level D3.

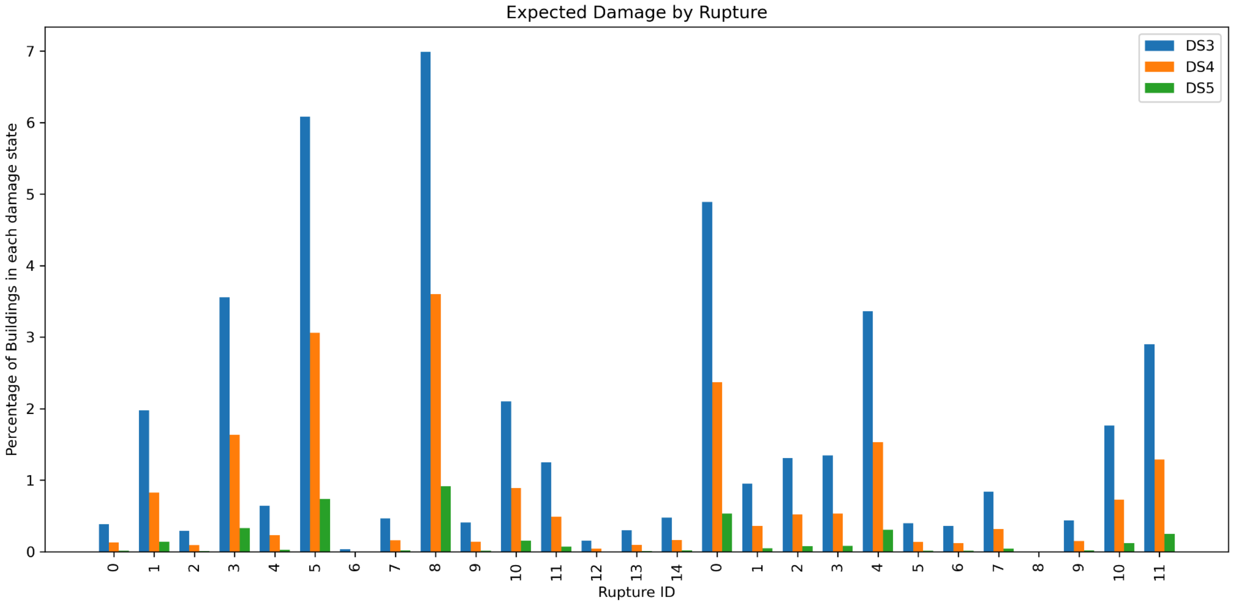


Fig. 11: Percentage of buildings in damage state 3, 4, and 5 for each considered rupture

Results of the damage assessment using as input the PGA computed in the point located in Tolmezzo for 2 sources and 30 ruptures are shown below. A total of 1.5% percent of the residential building stock (corresponding to 21 buildings) is expected to suffer a damage equal or greater than level D3.

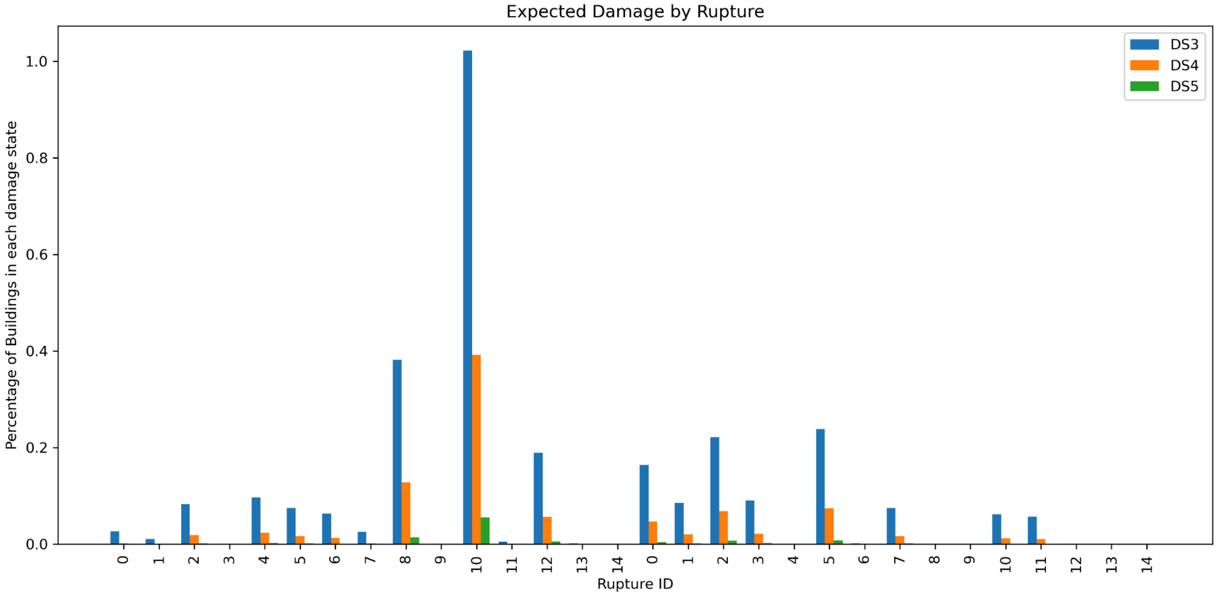


Fig. 12: Percentage of buildings in damage state 3, 4, and 5 for each considered rupture

The maximum number of buildings and corresponding percentage in each damage state (from 1 to 5) are reported below for the two points 17 and 19 (Gemona and Tolmezzo, top and button row respectively) for the rupture that generates the higher number of damaged buildings in damage level D5.

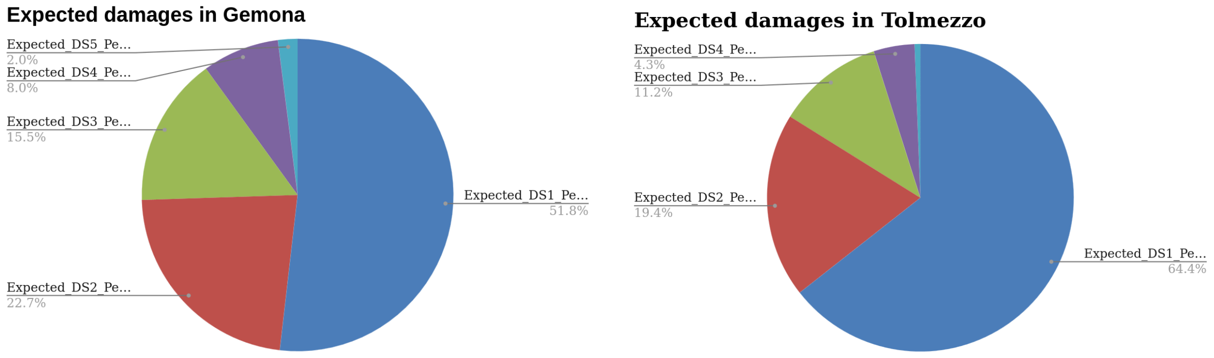


Fig. 13: Percentage of buildings in each damage state (DS1 to DS5 of the EMS98 scale) in Gemona and Tolmezzo corresponding to the rupture that generates the highest number of D5 damages.

In general, the expected damages in Tolmezzo are lower than in Gemona, similarly to what was observed using the fragility curves to compute the damage probability.

The results presented here are demonstration of the use of the pipeline, but they are not intended to provide a final damage assessment result. Further analyses have to be conducted in order to select the sources that are compatible with observed damages, and to include site effects. However, they already show how the physics-based simulations carried out for multiple sources can inform the damage assessment procedure.

Part of these results are shared in the Simulation Data Lake. The data lake will be updated with the datasets generated during the TA, and additional results when the 3D velocity model will be available and the pipeline is applied to a broader area.

Future work: from ground shaking to damage

The work carried out so far allowed the team to prepare the inputs needed to systematically apply the pipeline in fig. 2 and to test it for a selected simulation set.

Regarding the physics-based modeling, additional work is ongoing in order to calibrate the high-frequency physics-based modeling and run different end-to-end simulations. The results of the simulations with 1D velocity model will be compared to simulations with a 3D velocity model. To handle the large number of simulations required for the

UCSB calculation code and for the seismogram stitching, the HPC system UrgentShake (Zuccolo al., 2025), currently used at OGS, will be appropriately modified and utilized.

As for the damage assessment phase, the simulation results obtained with the Cybershake coupled with UCSB tools will be used for physics-based damage assessment using the updated simulations and the existing information on exposure and fragility, and following the pipeline in Fig. 2. Information on exposed building typologies and their corresponding fragility curves were already gathered. Additional work will be devoted to comparing the results obtained with different sources with historical data from the 1976 Friuli earthquake damages (e.g. Grimaz et al., 2009). Building on an existing damage assessment approach based on intensity measures derived from shakemaps (Bragato et al., 2021; Poggi et al., 2021) and on the current efforts for developing higher-resolution exposure data for the region (Badreldin et al., 2025; Scaini et al., 2025), future activities will be focused on adapting this method to ingest outputs from physics-based simulations and carry out damage assessment for different building typologies in the study area using the pipeline (Fig. 2).

Conclusive remarks

The Geo-INQUIRE Transnational Access enabled the methodological setup and proof-of-concept needed to integrate physics-based seismic simulations into damage assessment workflows relevant for civil protection. Using the 1976 Friuli earthquake as a test case, the study supported the implementation of a simplified Cybershake modeling strategy based on selected sources and a 1D velocity model, allowing effective testing of model functionalities and generation of ready-to-use simulation outputs. At the same time, it laid the groundwork for future developments based on more advanced configurations, including larger source ensembles, 3D velocity models and integration with other computational codes for the high-frequency ground motion generation.

Preliminary simulation results enabled testing of the full workflow for selected building typologies and allowed initial observations on the variability of expected damage as a function of seismic source and rupture selection. These findings highlight how the variability in rupture modeling can influence ground motion intensity (e.g., PGA) and, consequently, damage probability estimates. This can have direct implications for impact estimates and near real-time seismic risk assessment and will therefore be investigated further.

Although this study adopts a single historical scenario as a demonstrative case, the proposed pipeline is general and transferable. It accommodates the use of one or multiple damage assessment approaches, either independently or in combination. Future developments include the integration of methods that exploit the full seismogram (e.g., Scaini et al., 2021; Petrović et al., 2022, 2023), as well as the incorporation of updated building-by-building exposure datasets currently under development (Badreldin et al., 2025).

Results produced so far, together with the ones under development are subject of an abstract submitted to EGU 2026 and a publication in preparation. The in-person visit and direct interaction with BSC experts proved essential not only for rapid knowledge transfer and iterative problem solving, but also for fostering scientific exchange beyond technological implementation, creating opportunities for new joint research activities and projects.

Overall, this activity represents a foundational step toward the operational use of physics-based simulations for seismic risk assessment, strengthening the capacity of OGS to exploit HPC tools and bridging advanced modeling, decision support, and societal impact.

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