102nd Journées Luxembourgeoises de Géodynamique (JLG) EFEHR Scientific Session 2024

November 27-29, 2024

Physics-based numerical simulations: recent advances and challenges of a new frontier for earthquake ground motion prediction

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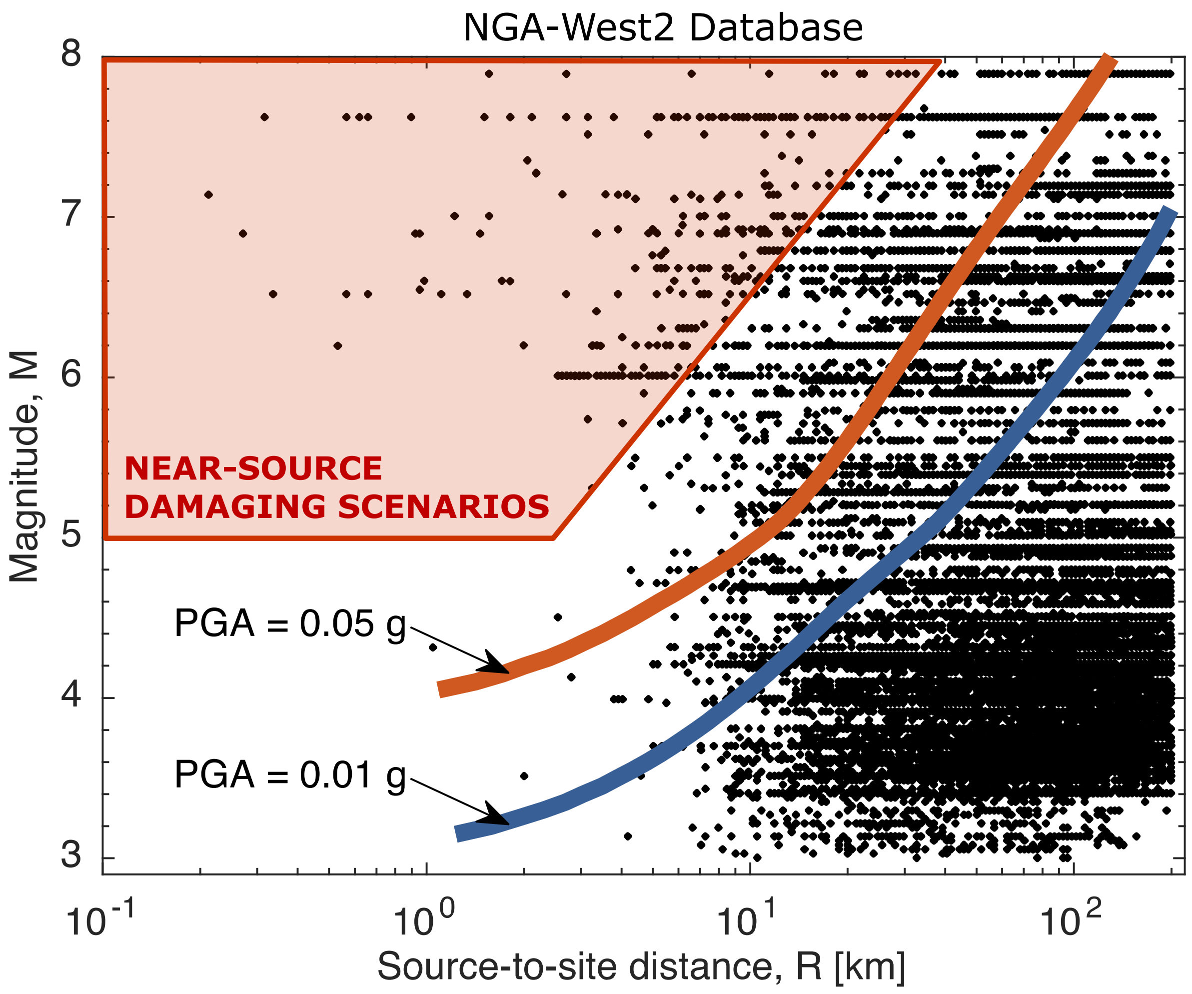
November 28th, 2024 – Luxembourg

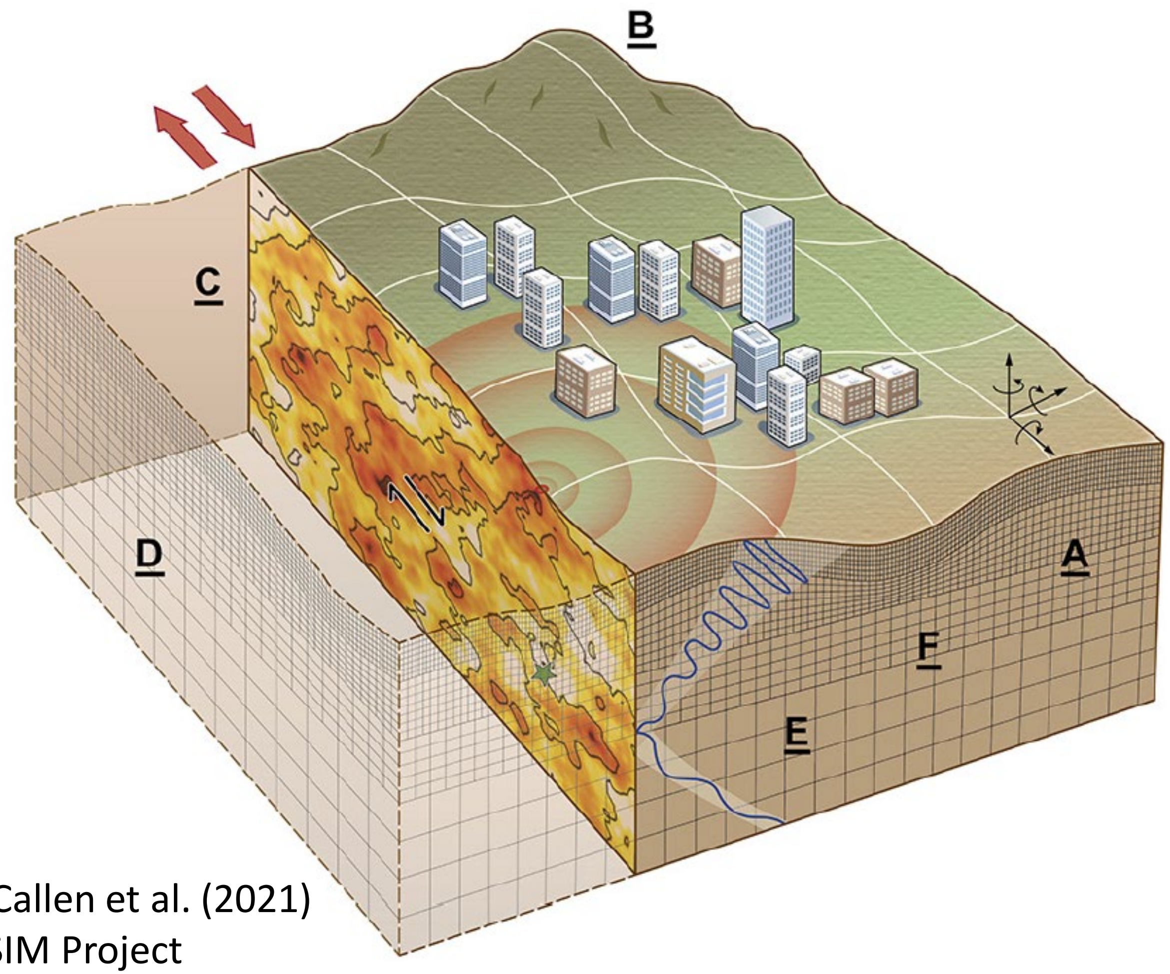
Knowledge gaps in ground motion observations and empirical modeling

- Sparsity of recordings in the near-source region, leading to high uncertainty for damaging earthquake scenarios
- Variability of ground motion with respect to the variety of source, path and site conditions (e.g. soft soils) is undersampled
- Spatial variability of ground motion is typically oversimplified
- Conventional peak intensity measures are provided (not time histories)



Baker, Bradley and Stafford (2021)

Physics-based numerical simulation (PBS) of earthquake ground motion



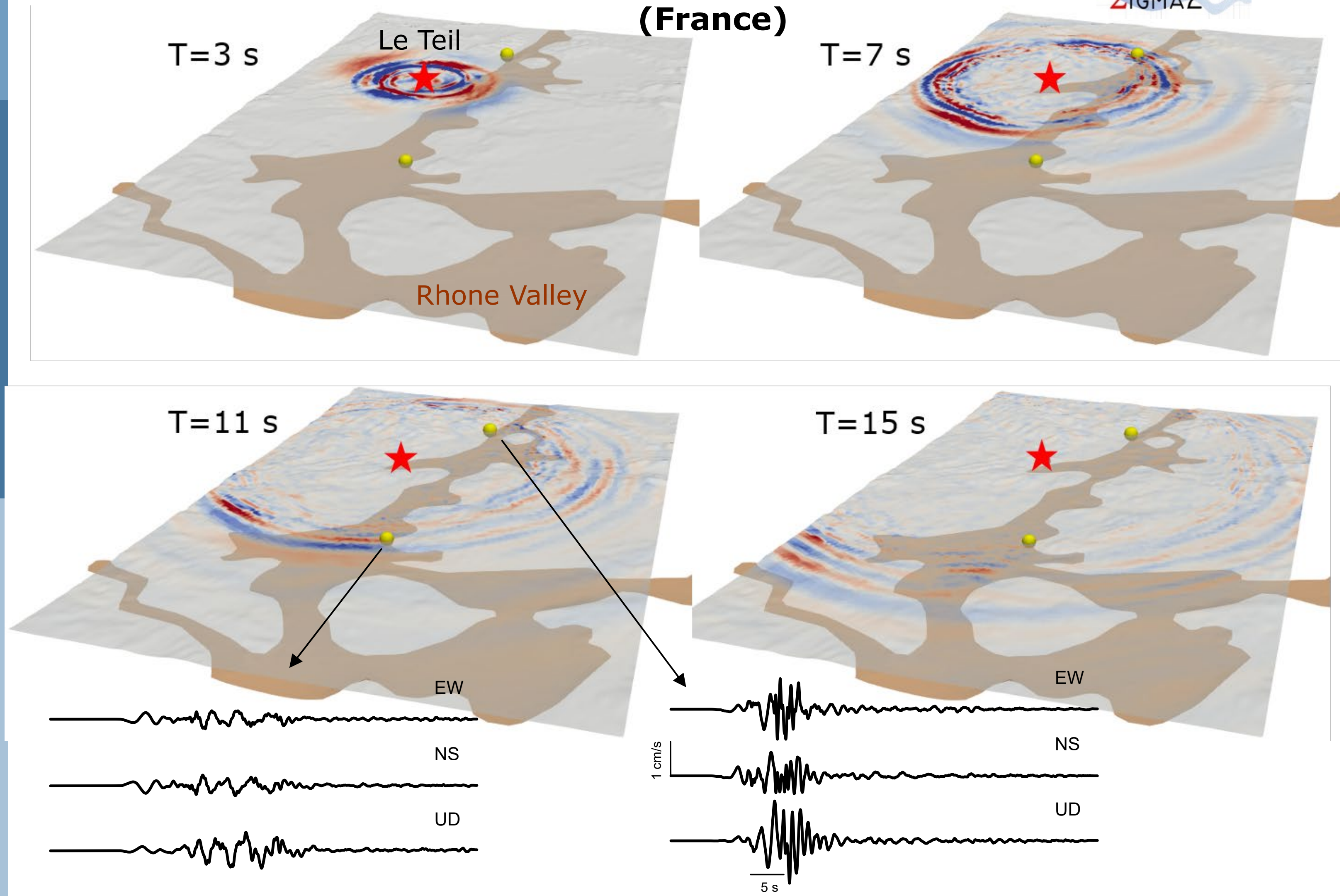
McCallen et al. (2021)
EQSIM Project

"Source-to-site(-to-structure)" numerical simulation of seismic wave propagation, including:

- seismic source
- source-to-site propagation path in heterogeneous Earth media
- local site effects due to 3D geological and topographical features
- …up to buildings in urbanized environments

High-performance numerical code for PBS: SPEED@PoliMI

Mw4.9 2019 Le Teil earthquake (France)



SPectral **E**lements in **E**lastodynamics with **D**iscontinuous Galerkin

http://speed.mox.polimi.it/

Antonietti et al. (2012), Mazzieri et al. (2013)

Main features

- ✓ 3D non-conforming grids
- ✓ kinematic and dynamic source models
- ✓ Soil modules: linear and non-linear visco-elastic, non-linear visco-plastic
- ✓ Parallel computing

Workflow to generate regional-scale PBS

Input data

SEISMOTECTONIC CONTEXT (FAULTS)

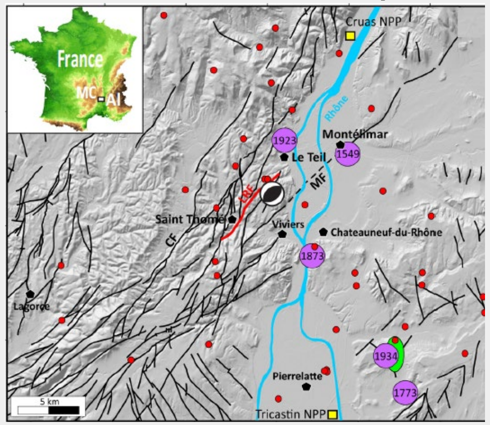
+

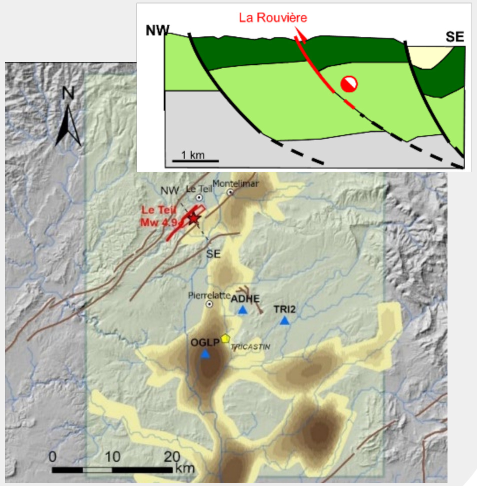
TOPOGRAPHY /BATHYMETRY

+

GEOLOGICAL-GEOTECHNICAL-GEOPHYSICAL MODEL

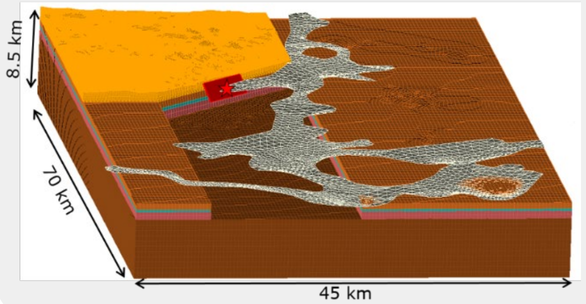
2019 Mw4.9 Le Teil earthquake



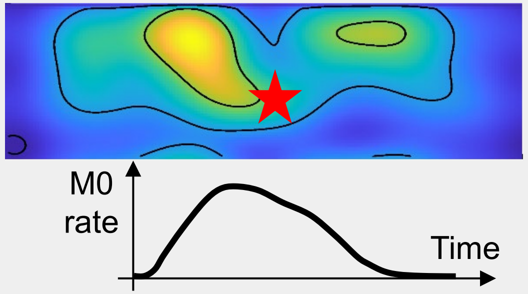


Smerzini et al. 2023 BEE

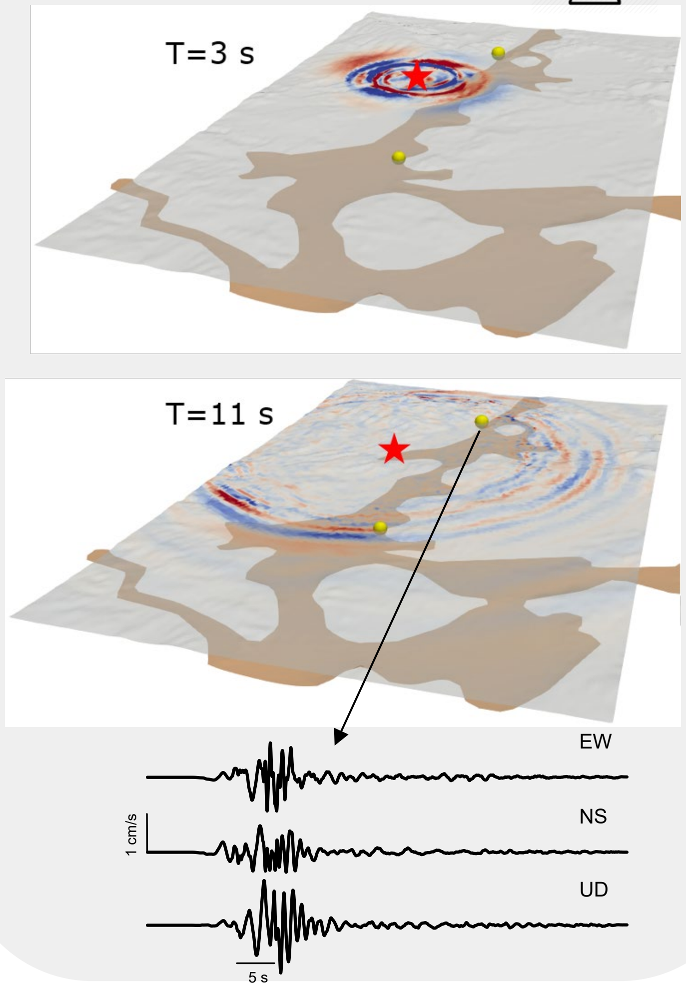
Set-up of the 3D numerical model



Fault rupture scenario



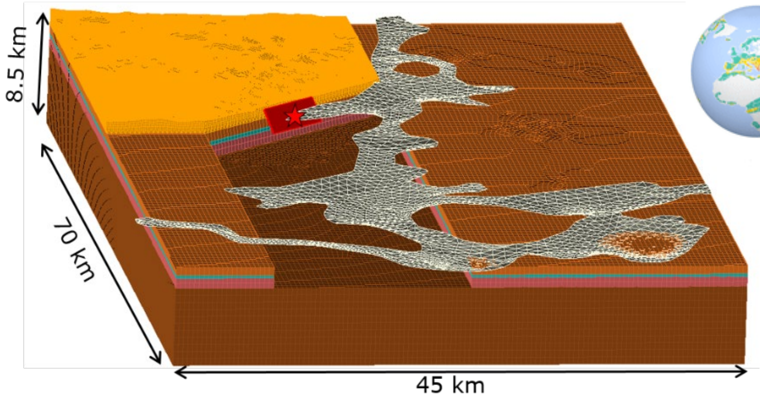
PBS - HPC



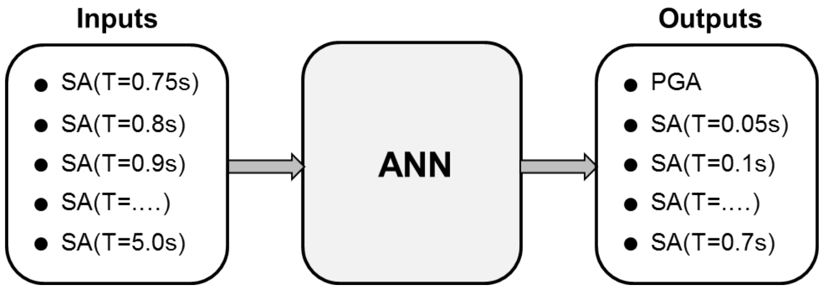
…and to compute broadband ground motions

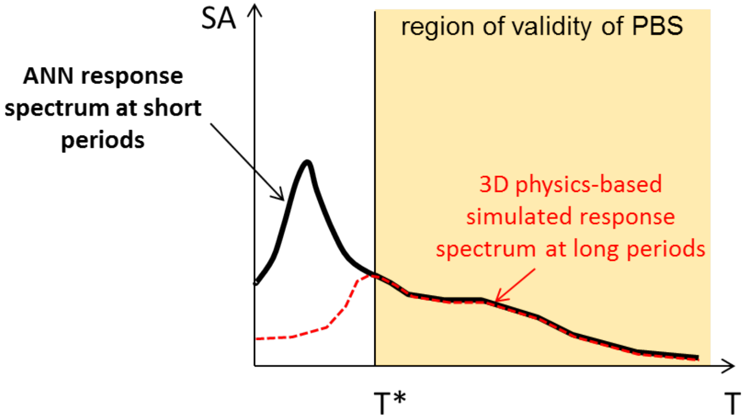
Regional-scale 3D PBS up to f_{max} (code: SPEED)

with f_{max} depending on spatial discretization and ability of velocity and source models to reproduce realistically high frequencies



Estimating Broadband (BB) Ground Motions through Artificial Neural Network (ANN2BB)





Paolucci et al. (2018) BSSA

Advances in engineering applications of PBS

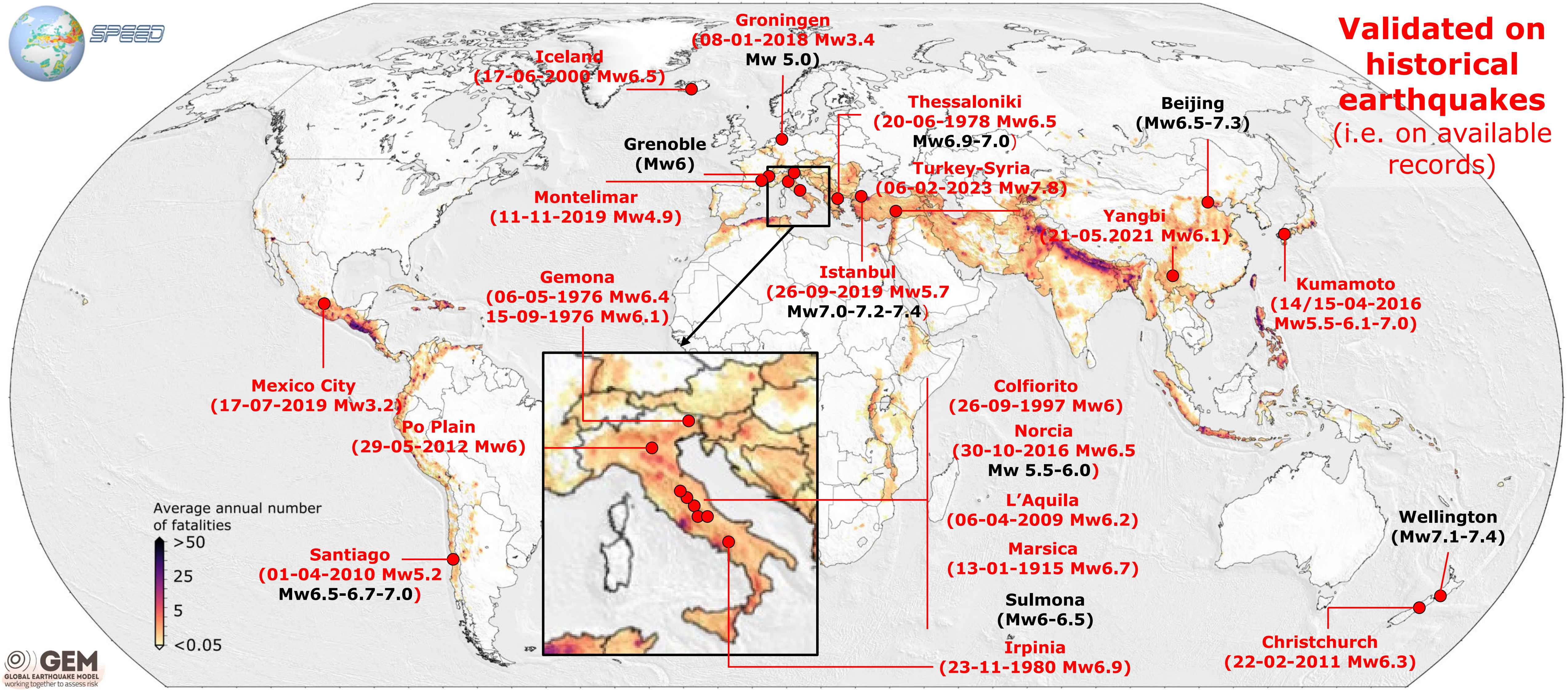
- Construction of *validated* datasets of simulated broadband ground motions for engineering aims

- Utilization of PBS in the domain of seismic hazard and risk assessments
  - Constraining region-specific GMMs within probabilistic seismic hazard assessment frameworks
  - Building empirical seismic fragility curves from physics-based ground shaking scenarios
  - Providing ground motion time histories for non-linear dynamic structural analyses and analytical seismic fragility studies
  - Physics-based seismic damage and loss assessments at urban and regional scale

International efforts towards the construction of datasets of simulated accelerograms

Database	Simulation Approach	Region	Mw-R range	References	Link
CyberShake Subset	PBS: Graves and Pitarka (2008; 2015)	California - Los Angeles	6.3-8.0 0-45 km	Baker et al. (2021)	https://zenodo.org/records/3875541
SIGMOID-TR	Stochastic Finite-Fault: EXSIM	Turkey	6.5-7.8 0-100 km	Altindal & Askan (2023)	https://zenodo.org/records/7007918
PEER-SGD	PBS: Finite Difference SW4 – EQSIM	California - San Francisco	*Under development*	McCallen et al. (2024)	
BB-SPEEDset v2.3	PBS: Spectral Element SPEED	Worldwide	4.9-7.4 0-110 km	Paolucci et al. (2021), Smerzini et al. (2024)	https://speed.mox.polimi.it/bb-speedset/

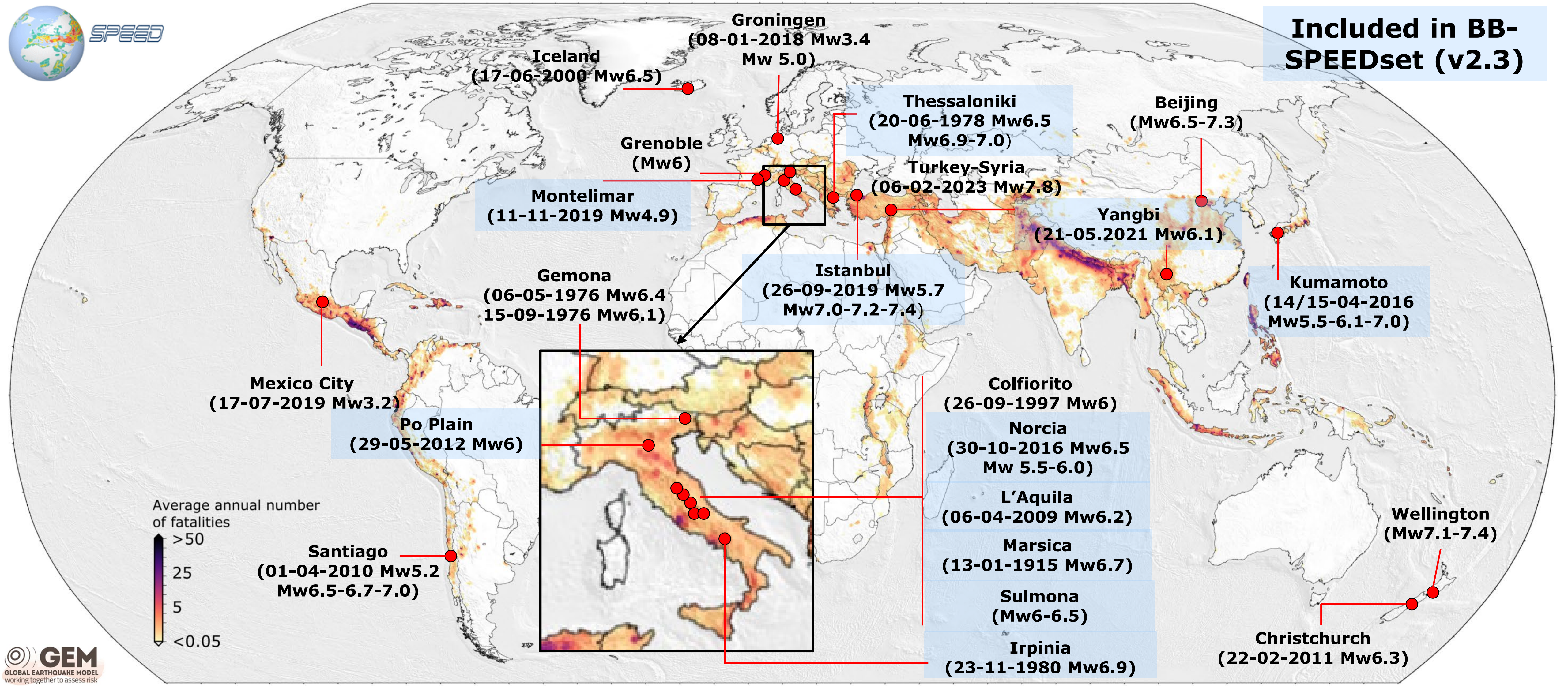
Overview of case studies simulated by SPEED



Validated on historical earthquakes
(i.e. on available records)

GEM
GLOBAL EARTHQUAKE MODEL
working together to assess risk

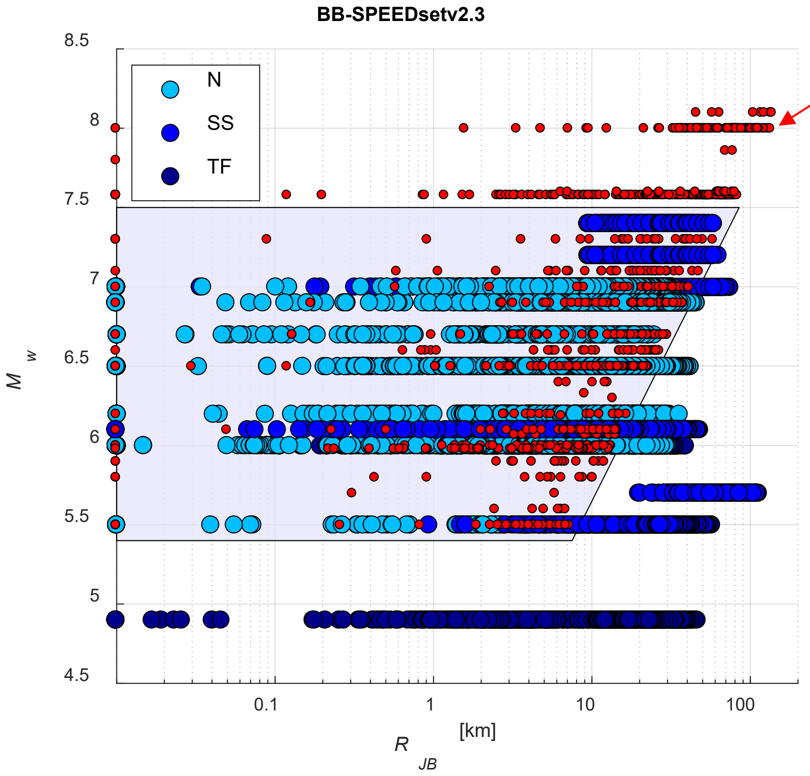
Construction of BB-SPEEDset (v2.3)



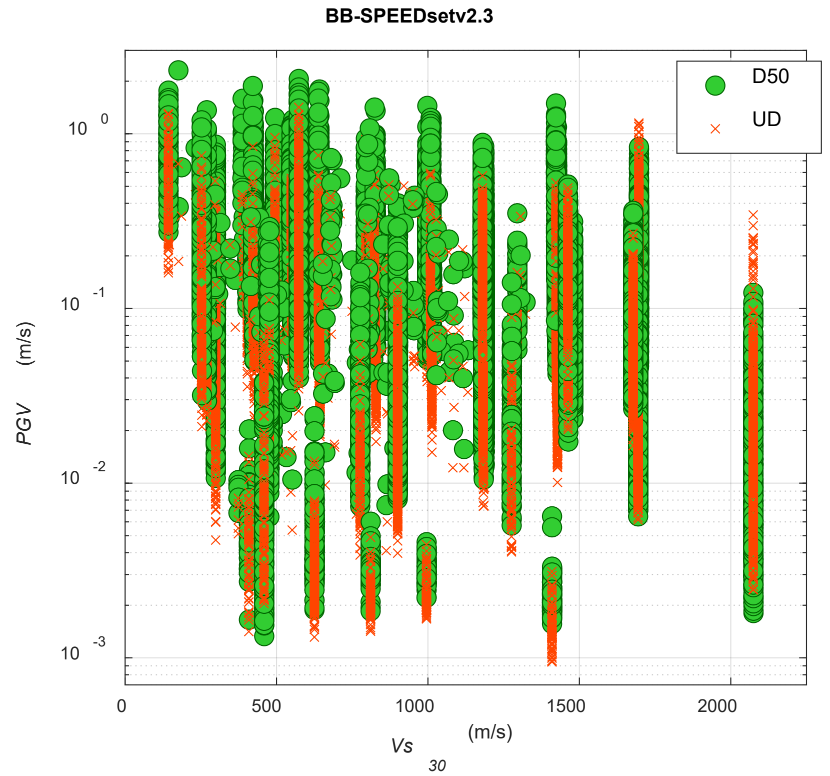
GEM
GLOBAL EARTHQUAKE MODEL
working together to assess risk

BB-SPEEDset (v2.3): a dataset of near-source accelerograms from PBS

M_w- R_{jb} and V_{S30} distribution of BB-SPEEDset



NESS2.0
(Sgobba et al. 2021)



BB-SPEEDset v2.3:
- **37 scenarios** (12 validations + 25 scenarios)
- 55% N; 38% SS; 6% TF
- 75% V_{S30} > 600 m/s; 1% V_{S30} < 200 m/s

BB-SPEEDset: A Validated Dataset of Broadband Near-Source Earthquake Ground Motions from 3D Physics-Based Numerical Simulations

Roberto Paolucci; Chiara Smerzini; Manuela Vanini

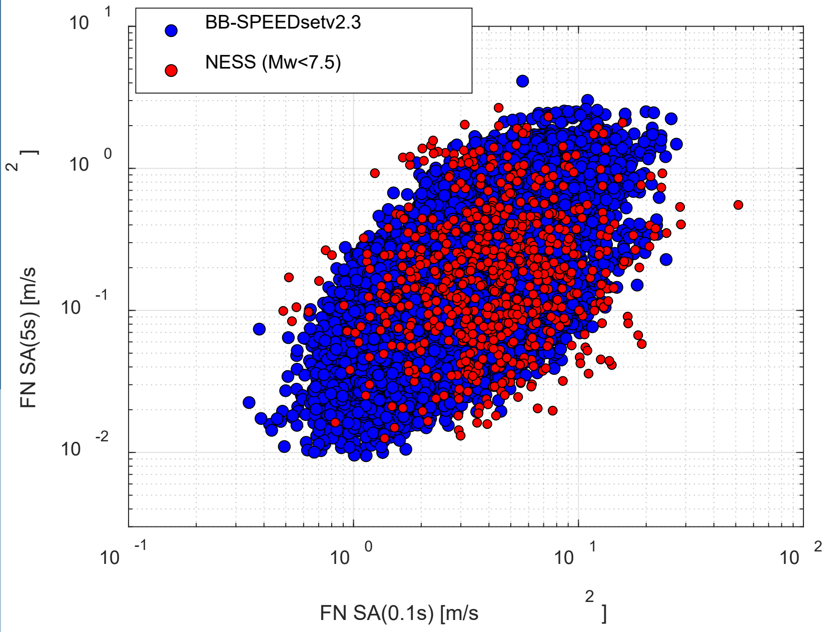
Bulletin of the Seismological Society of America (2021) 111 (5): 2527–2545.

Open-source: **http://speed.mox.polimi.it/bb-speedset/**
- Flatfile
- 3-component broadband accelerograms (~20’000)

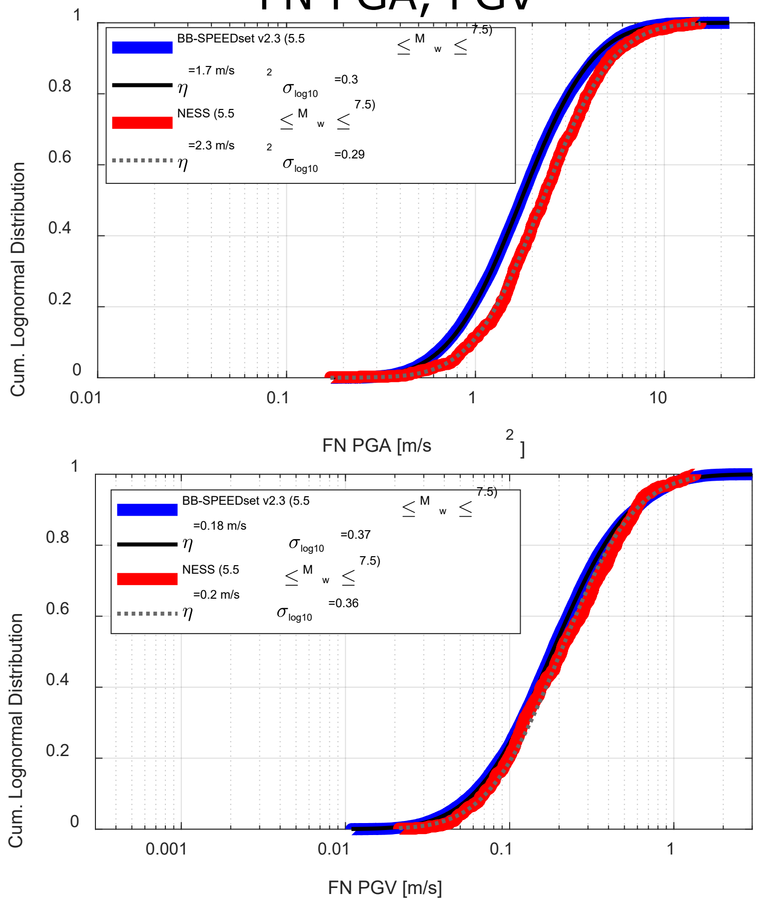
Seismological validation of BB-SPEEDset on several ground motion features

Comparison, in the same (Mw,R) range, with the NESS2.0 dataset of near-source records

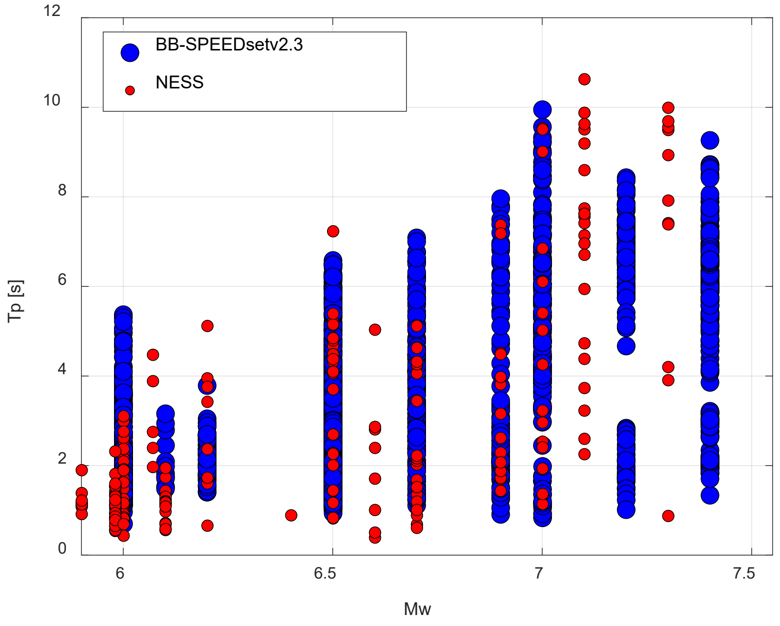
Fault Normal (FN) SA(0.1s)-SA(5s) correlation



Cumulative Distribution Function FN PGA, PGV

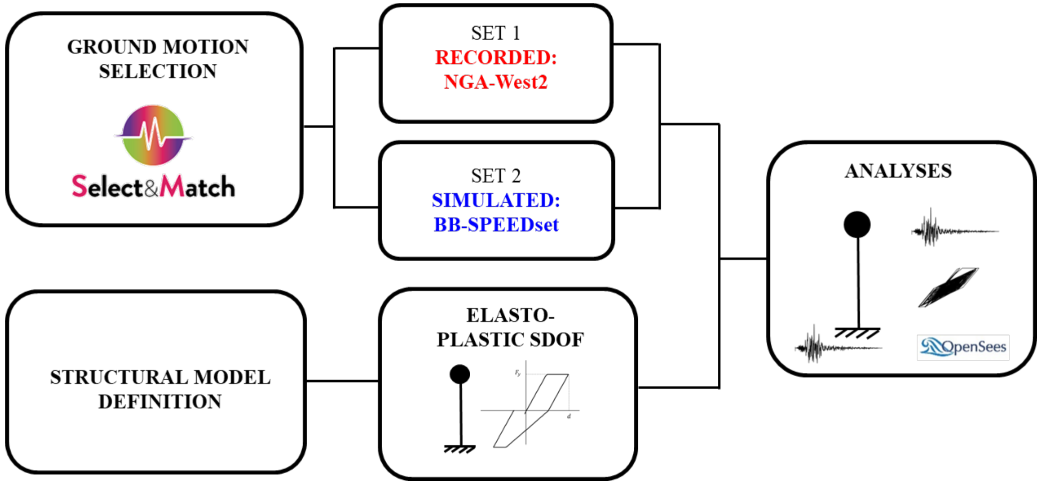


Pulse-like waveforms: Pulse Period T_P Vs M_W (Shahi and Baker, 2014)



Engineering validation of BB-SPEEDset for structural non-linear dynamic analyses

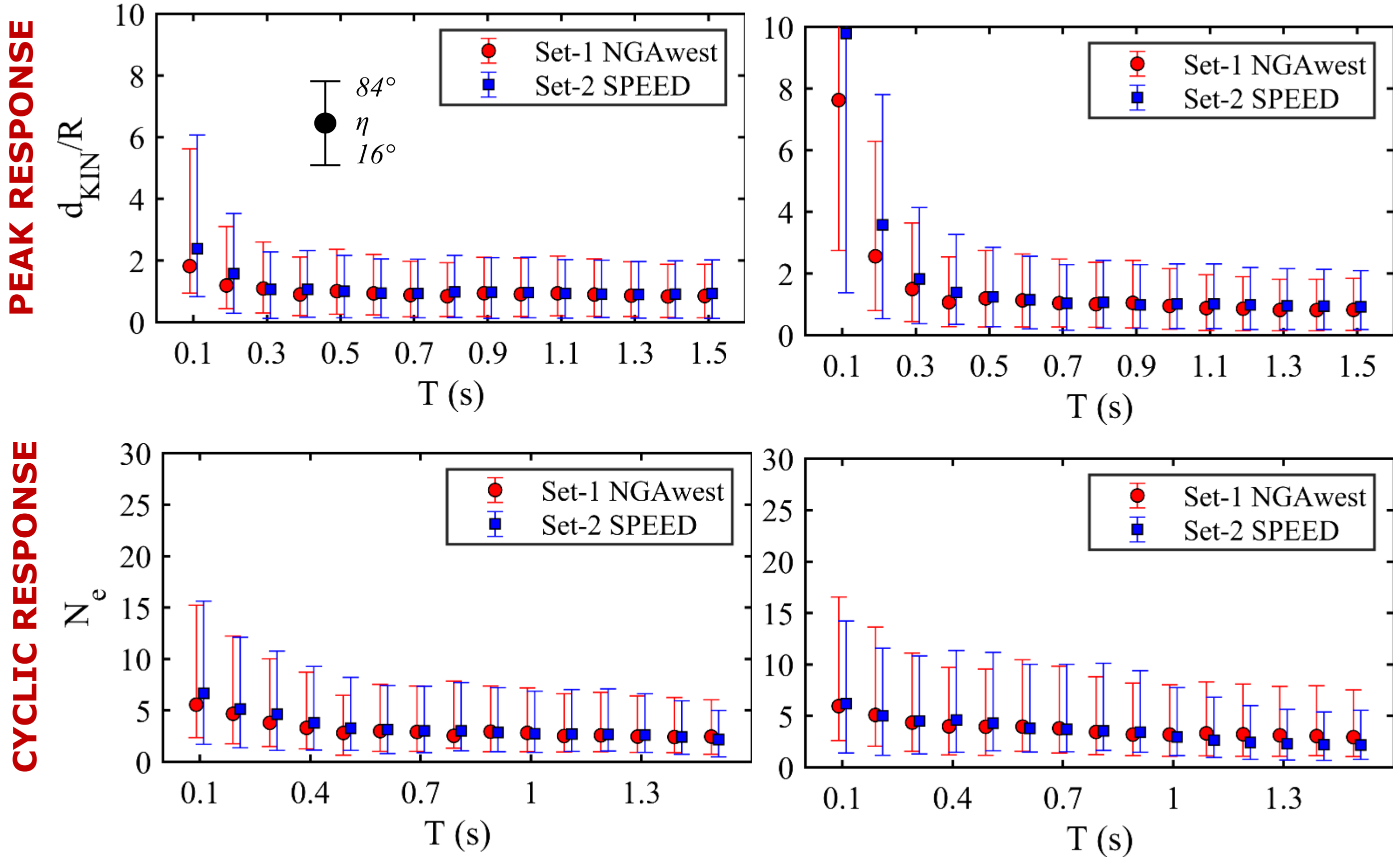
Response of inelastic SDOF under compatible sets of recorded and simulated accelerograms



increasing non-linearities

R=2

R=4



Engineering validation of BB-SPEEDset, a data set of near-source physics-based simulated accelerograms

Earthquake Spectra
1–26

DOI: 10.1177/87552930231206766
journals.sagepub.com/home/eqs
Sage

Chiara Smerzini[1], Chiara Amendola[2], Roberto Paolucci[1], and Arsalan Bazrafshan[3]

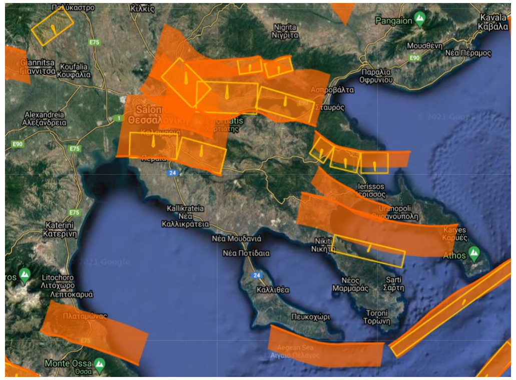
Advances in engineering applications of PBS

- Construction of *validated* datasets of simulated broadband ground motions for engineering aims

- Utilization of PBS in the domain of seismic hazard and risk assessments
  - Constraining region-specific GMMs within probabilistic seismic hazard assessment frameworks → **Istanbul case study: Infantino et al. (2020) BSSA, Stupazzini et al. (2021) EESD**
  - Building empirical seismic fragility curves from physics-based ground shaking scenarios → **L’Aquila case study: Rosti et al. (2023) BEE, Monsalvo et al. (2024) BEE**
  - Providing ground motion time histories for non-linear dynamic structural analyses and analytical seismic fragility studies → **Manfredi et al. (2024) WCEE**
  - Physics-based seismic damage and loss assessments at urban and regional scale

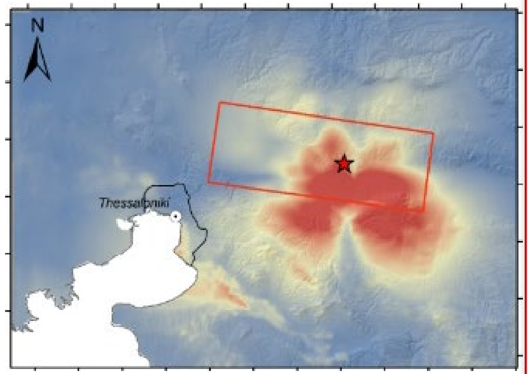
Seismic damage and loss assessments using PBS ground shaking scenarios

TARGET AREA: FAULT RUPTURE REALIZATIONS



PBS BY SPEED

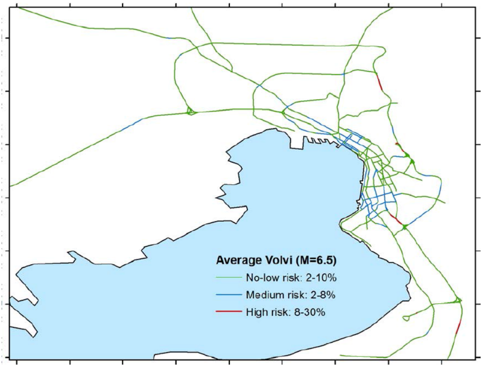
GROUND SHAKING SCENARIO



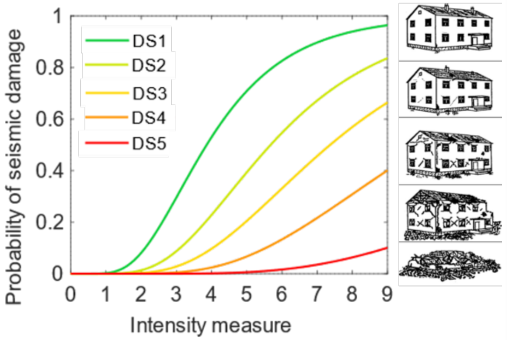
Typically, given by:

- ShakeMaps
- GMMs

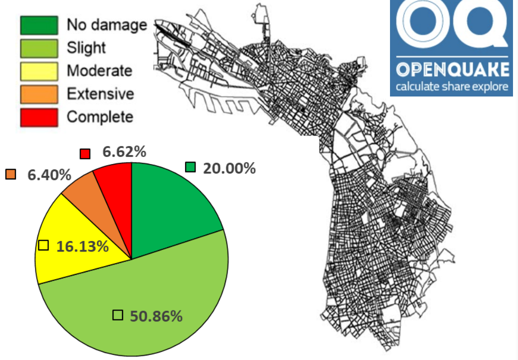
EXPOSURE (ASSETS AT RISK)



FRAGILITY CURVES



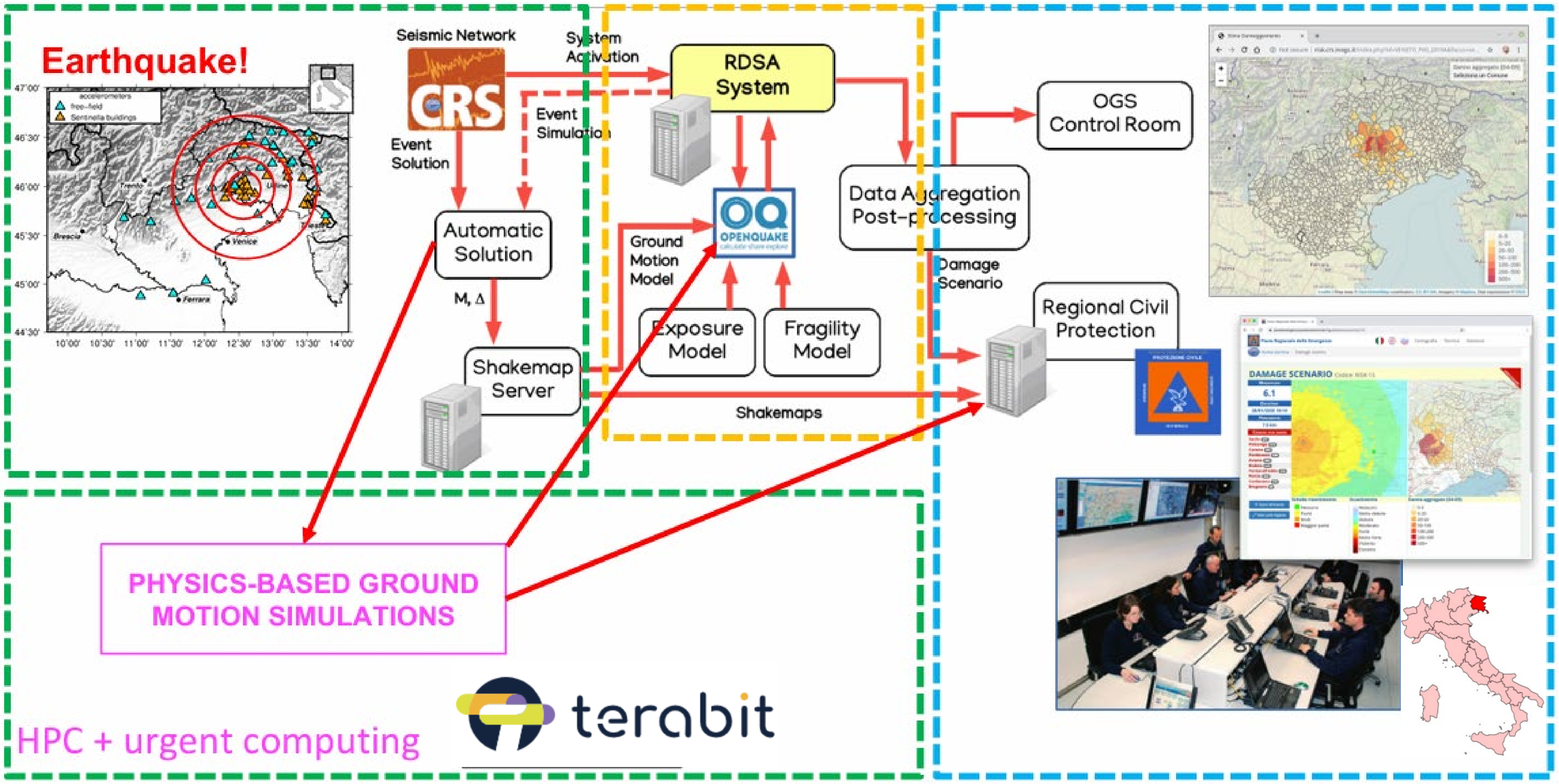
DAMAGE AND LOSS AT URBAN SCALE



URBASIS-EU

Smerzini and Pitilakis (2018)
Lin and Smerzini (2023)
Jiayue Lin PhD Thesis (2023)

Urgent seismic damage and loss assessments using PBS



From Zuccolo & Scaini (TeRABIT Conference, 25 June 2024)

OGS Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

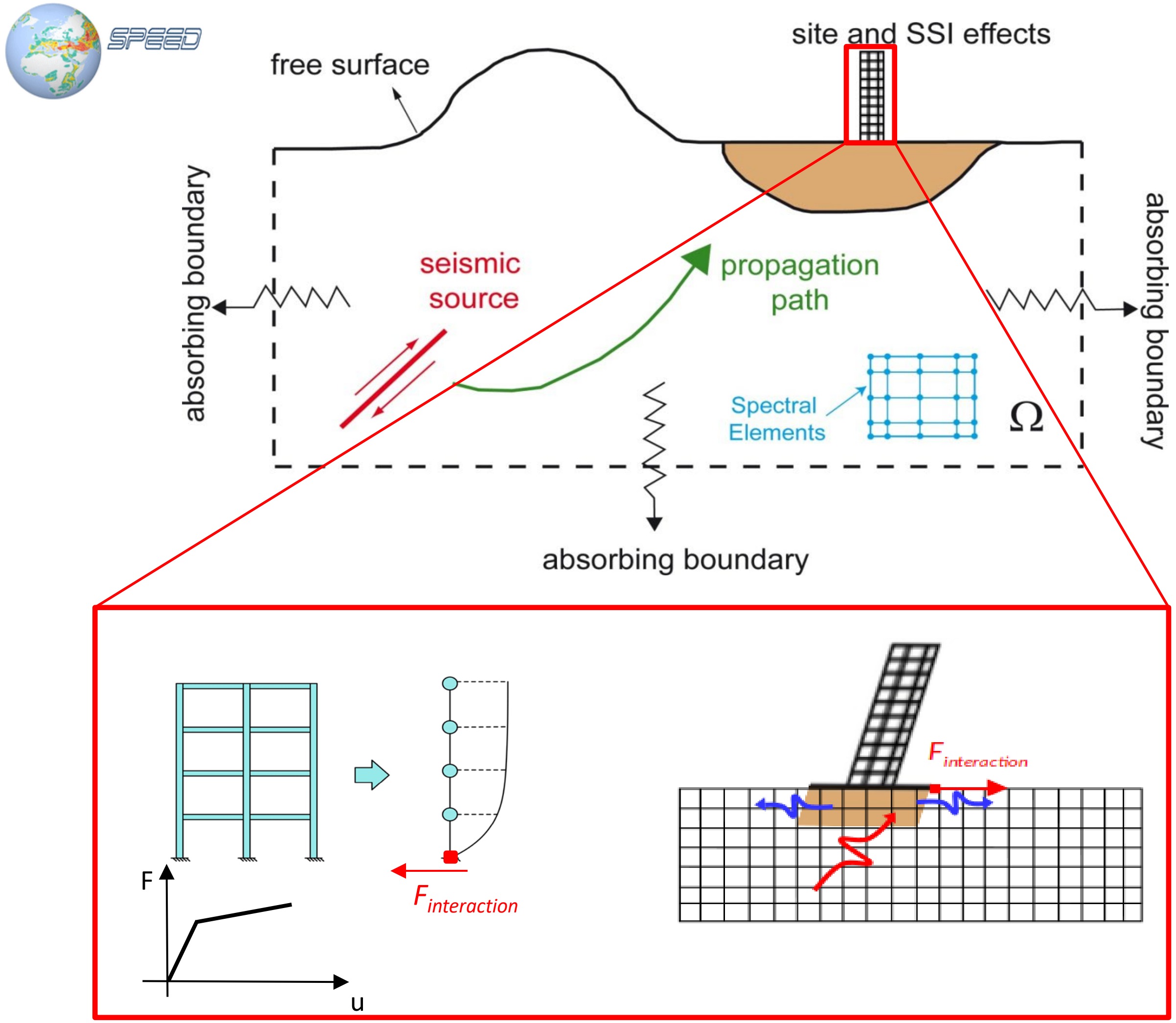
Development of an Urgent HPC framework for the near real-time physics-based simulation of earthquake impact at regional scale

support Regional Civil Protection activities in emergency planning and response (Friuli-Venezia Giulia)

Zuccolo et al. (2024) – submitted

Ileana Monsalvo PhD Thesis (in progress)

A *fault-to-structure* approach for physics-based earthquake damage scenarios



3D FULLY COUPLED APPROACH OF EARTHQUAKE GROUND MOTION AND STRUCTURAL RESPONSE AT CITY SCALE

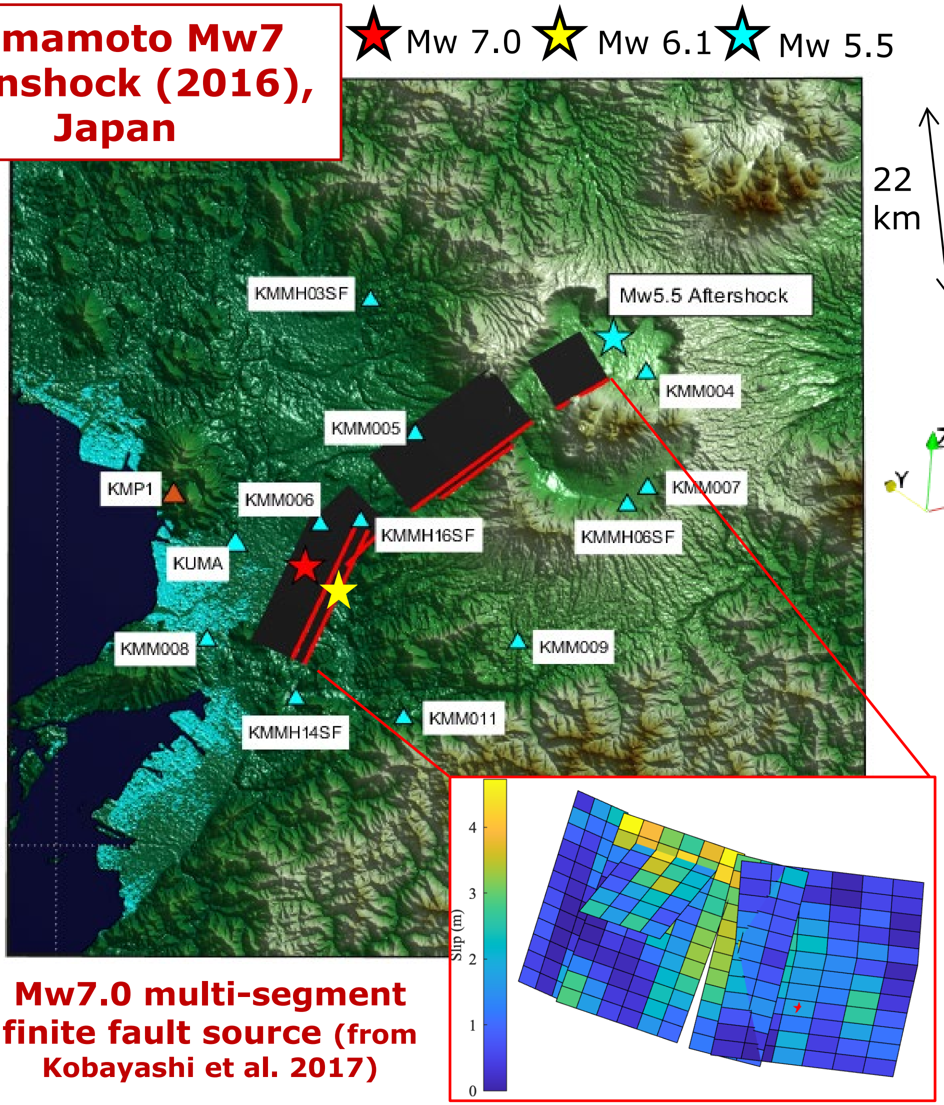
- ✓ SPEED-SCI module: coupling algorithm embedded in SPEED kernel at each time step
- ✓ Buildings are modelled as linear or non-linear SDOF or MDOF systems (not included in the mesh)
- ✓ Building clusters for urbanized environments
- ✓ Effects of soil-structure interaction (SSI) and site-city interaction (SCI) accounted for

Srihari Sangaraju, PhD thesis (2024)

URBASIS-EU

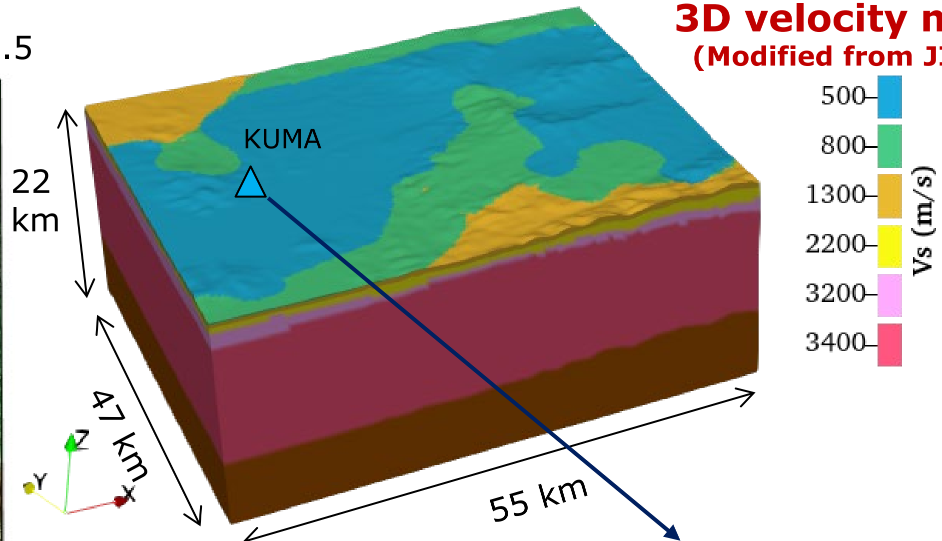
A *fault-to-structure* approach for physics-based earthquake damage scenarios

Kumamoto Mw7 mainshock (2016), Japan



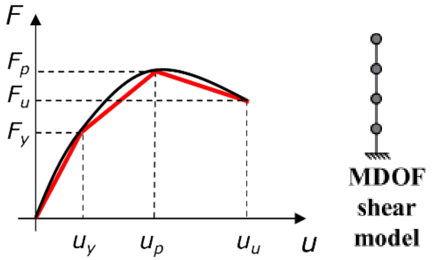
Mw7.0 multi-segment finite fault source (from Kobayashi et al. 2017)

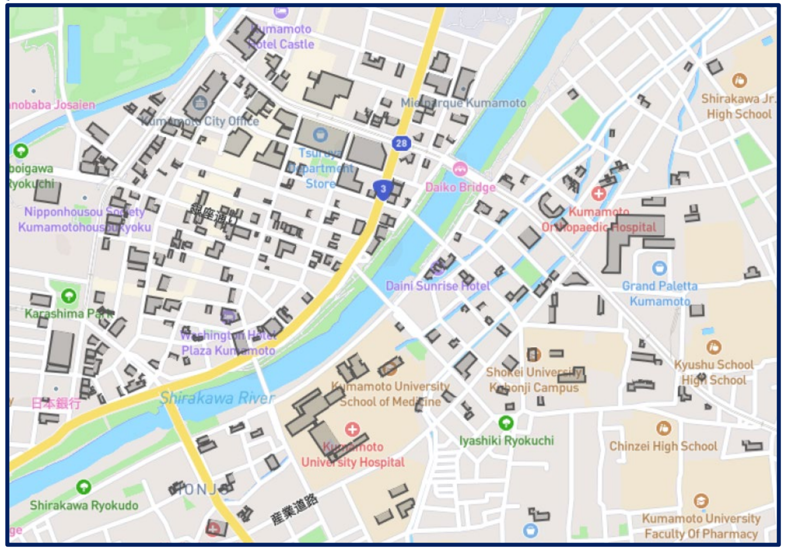
3D velocity model
(Modified from JIVSM)



- Domain size : 55 km x 47 km x 22 km. Smallest size 100m.
- 1.4 Million Elements (**36M nodes**) with SD=3.
- Simulation Time : 4 Hours on 380 compute cores.

Modeling of Kumamoto urban district (~ 300 buildings) as clustered MDOF systems with prescribed capacity curves
(buildings taller than 25 m)





A *fault-to-structure* approach for physics-based earthquake damage scenarios

Movie of city response under the Mw7 scenario with indication of building damage levels

Srihari Sangaraju, PhD thesis (2024)

Concluding remarks

- PBS is recognized as one of the most promising tools to face the knowledge gaps due to the sparsity of recordings (near-source conditions, complex geology and spatial variability studies).
- Recent research has shown that simulation methodologies and tools are mature enough to boost the use of PBS in a variety of engineering seismology and earthquake engineering studies (e.g. ground motion modeling, seismic hazard and risk assessments)
- Key steps to strengthen such utilization of PBS are:
  - Validation and dissemination of simulated motions according to standards recognized by the international community (ground motion data centers and platforms)
  - Enhancement of approaches for broadband ground motion simulation
  - Networking and coordination among international research groups to establish best practices and guidelines (dataset, validation, utilization, etc.)

Questions for the interactive discussion

- In spite of the enormous progress of PBS, simulated motions remain somehow simplified with respect to certain aspects (source characterization, high-frequency part, non-linear soil response, period-to-period correlation, SSI/SCI effects): where should we devote our main efforts for next-generation PBS?

- Which kind of strategy do you foresee to exploit recorded and simulated ground motion datasets for the general purpose of ground motion characterization and modelling? Shall they be merged/combined (how?) or not? How can Machine Learning / Artificial Intelligence contribute to this purpose?

Acknowledgements

swissnuclear

Munich RE

EDF

RSE Ricerca Sistema Energetico

Protezione Civile Nazionale

reluis

URBASIS-EU

Return

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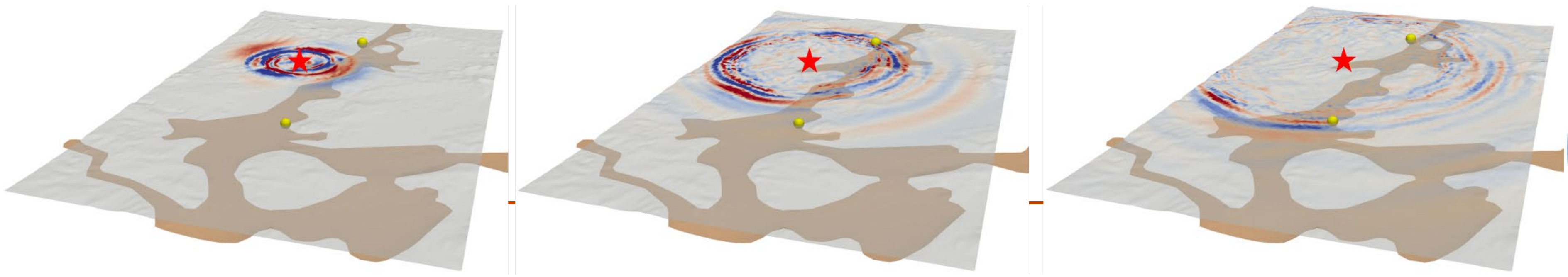
M. Vanini


S. Sangaraju


V. Hernandez


J. Lin


I. Monsalvo



Thank you for your attention

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