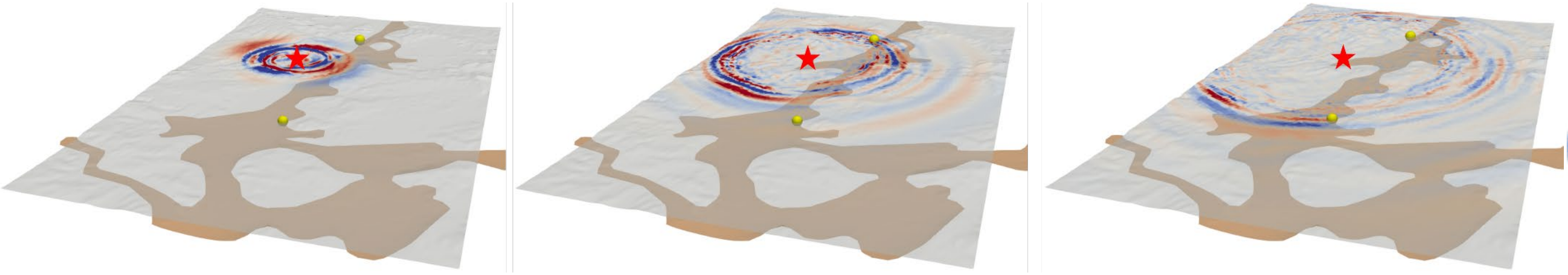
Toward Data Lakes for Recorded and Simulated Earthquake Ground Motions

2 - 4 September 2024, GFZ Potsdam

Applications and challenges of 3D physics-based numerical simulations in engineering seismology

Chiara Smerzini

Politecnico di Milano, Italy



Thanks to

swissnuclear

URBASIS-EU

Munich RE

PROTEZIONE CIVILE NAZIONALE

reluis

…and the SPEED team!


A. Quarteroni


P. Antonietti


I. Mazzieri


R. Paolucci


M. Stupazzini


M. Vanini


S. Sangaraju


V. Hernandez

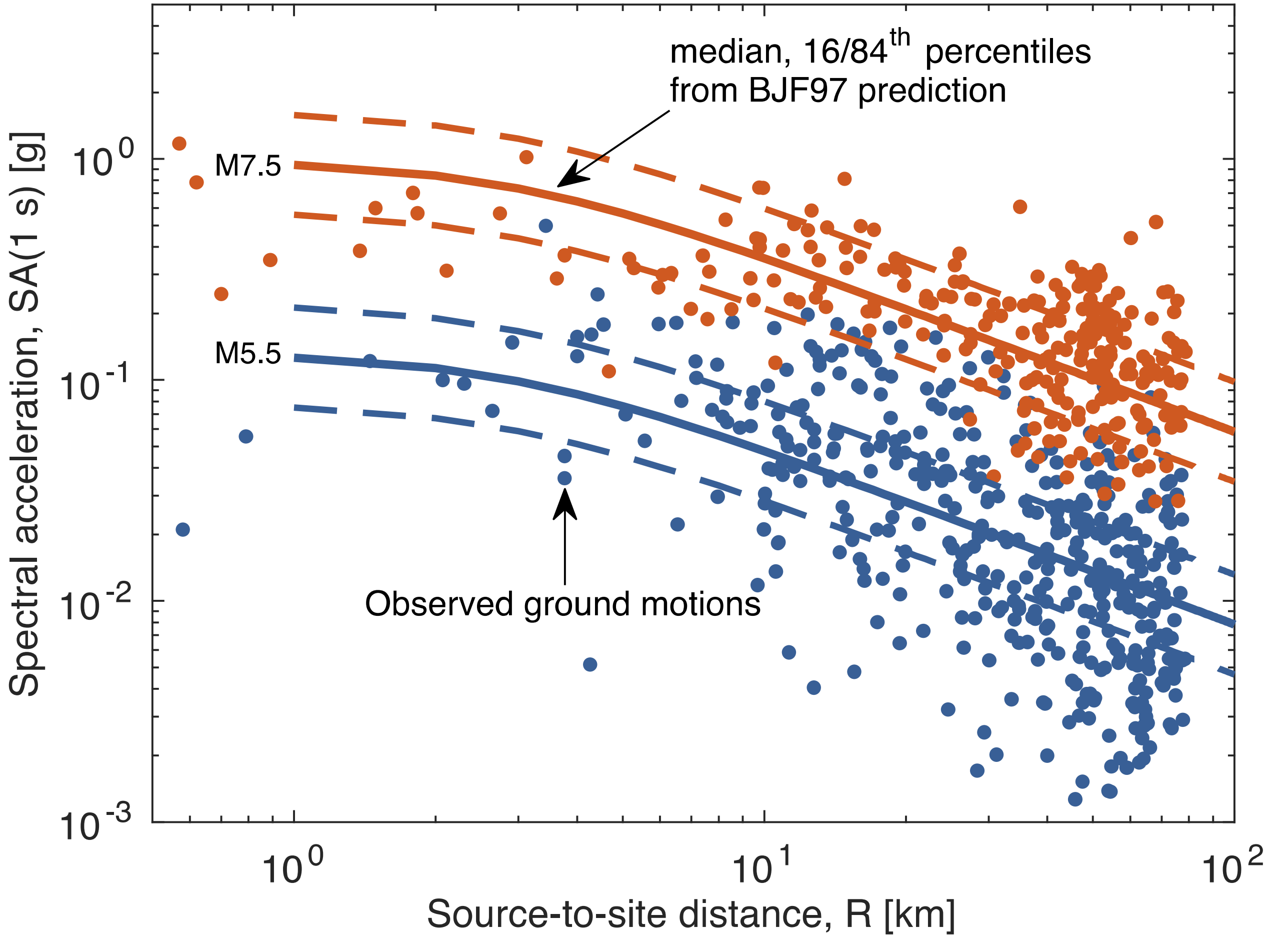

J. Lin


C. Amendola

Empirical Ground Motion Models (GMMs)

The standard approach for ground motion estimation relies on empirical GMMs which provide the probability distribution of ground motion intensity measures as a function of basic explanatory variables (magnitude, source-to-site distance, site conditions,…)

- Data-driven
- Ease of use within probabilistic frameworks for seismic hazard and risk analyses
- Non-ergodic models



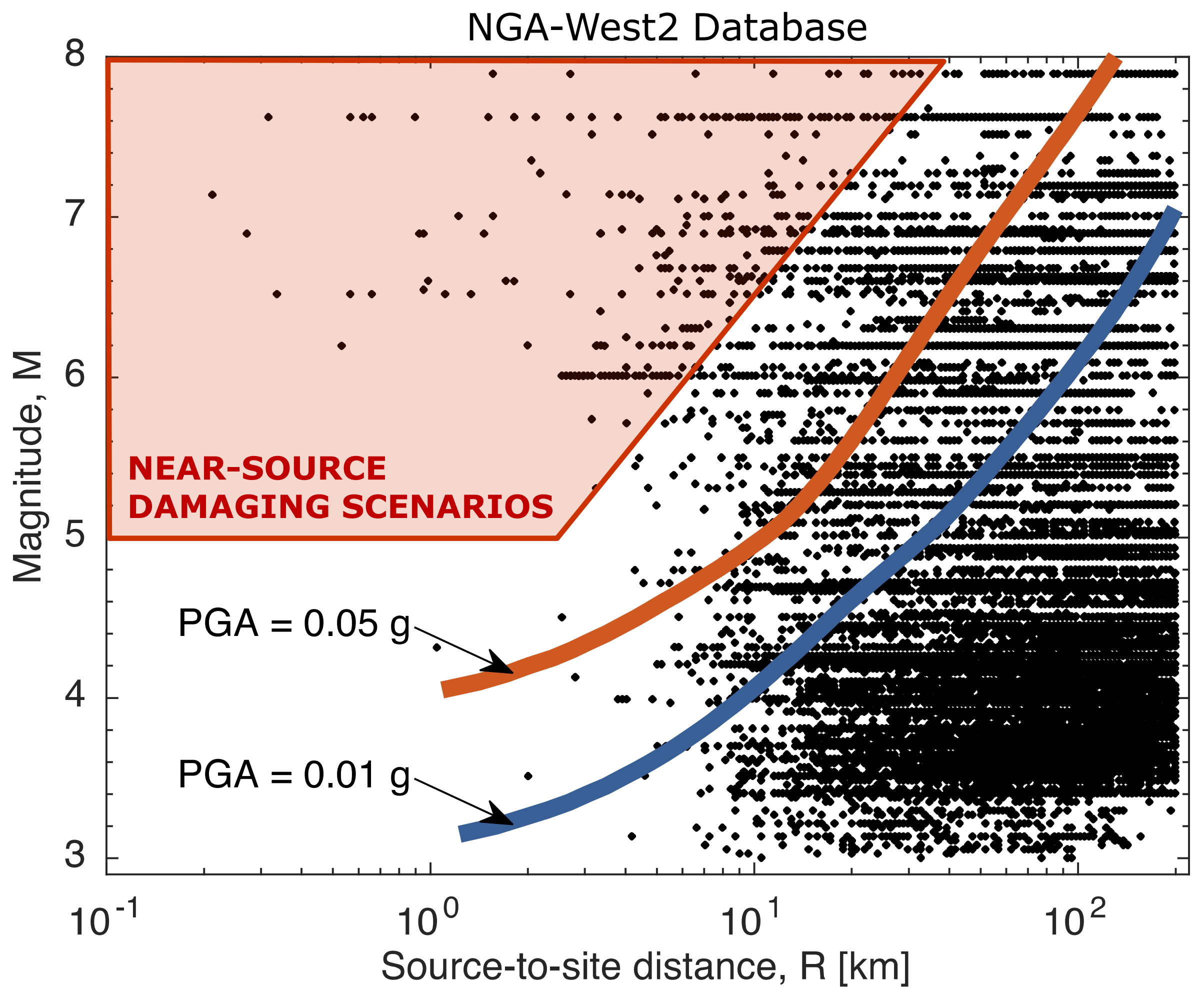
Baker, Bradley and Stafford (2021)

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 geographical region, fault style, site conditions (e.g. very soft soils) is typically undersampled

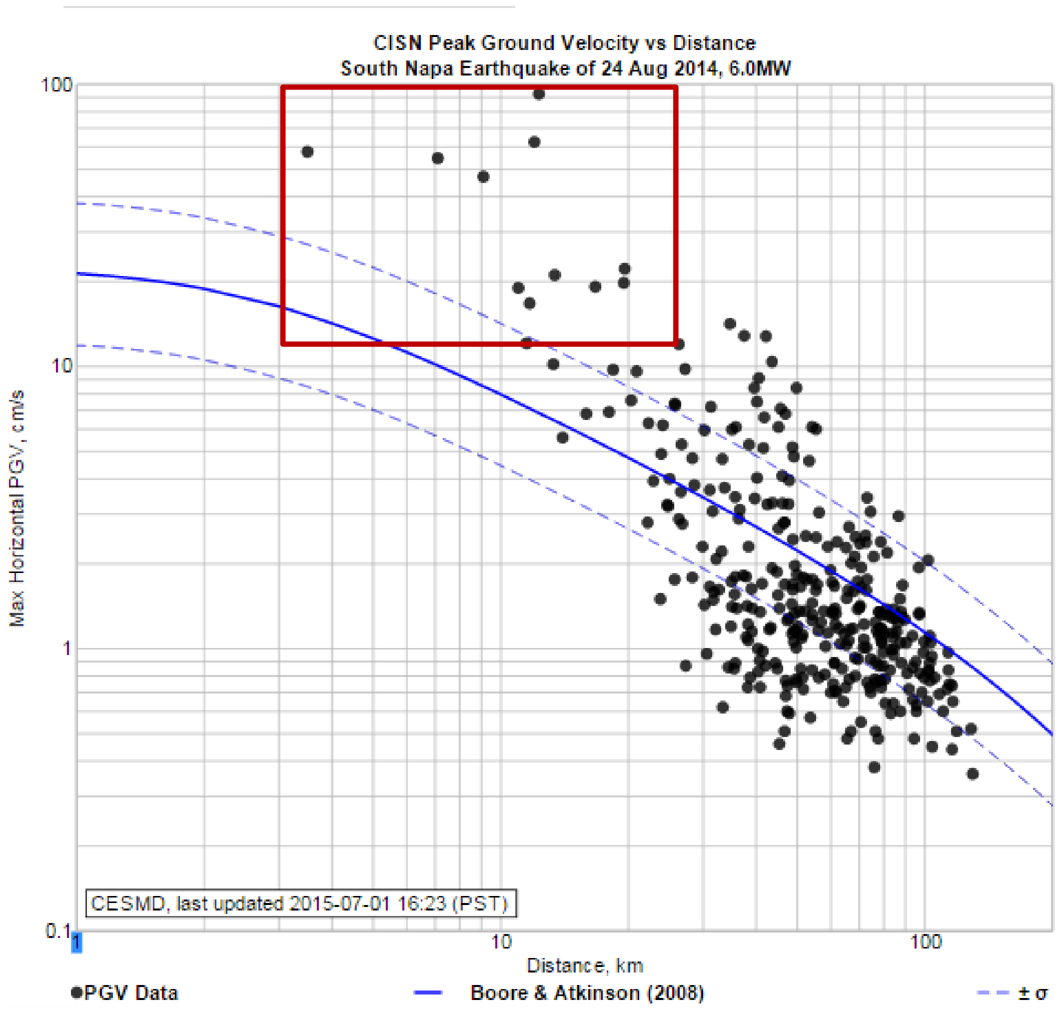
- **Ground motion time series**, especially from spatially dense arrays, are not available



Baker, Bradley and Stafford (2021)

Empirical Ground Motion Models (GMMs): limitations

Underestimation of recorded peak ground motion values at short source-to-site distances by empirical GMMs



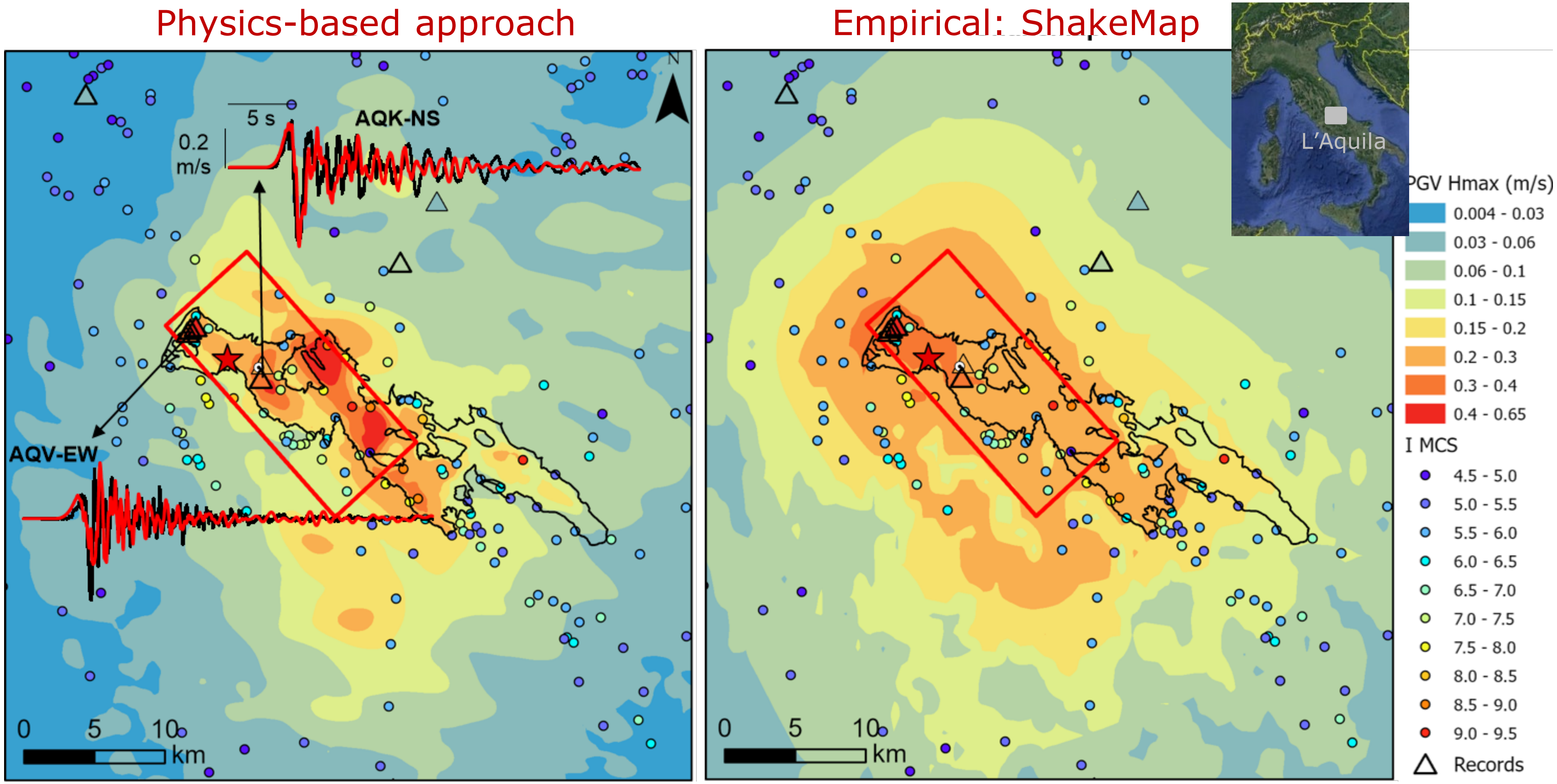
Mw6 Napa Valley earthquake
Aug 24, 2014
Source: CESMD

Empirical Ground Motion Models (GMMs): limitations

Spatial variability of ground motion is typically oversimplified in empirical GMMs

Physics-based approach

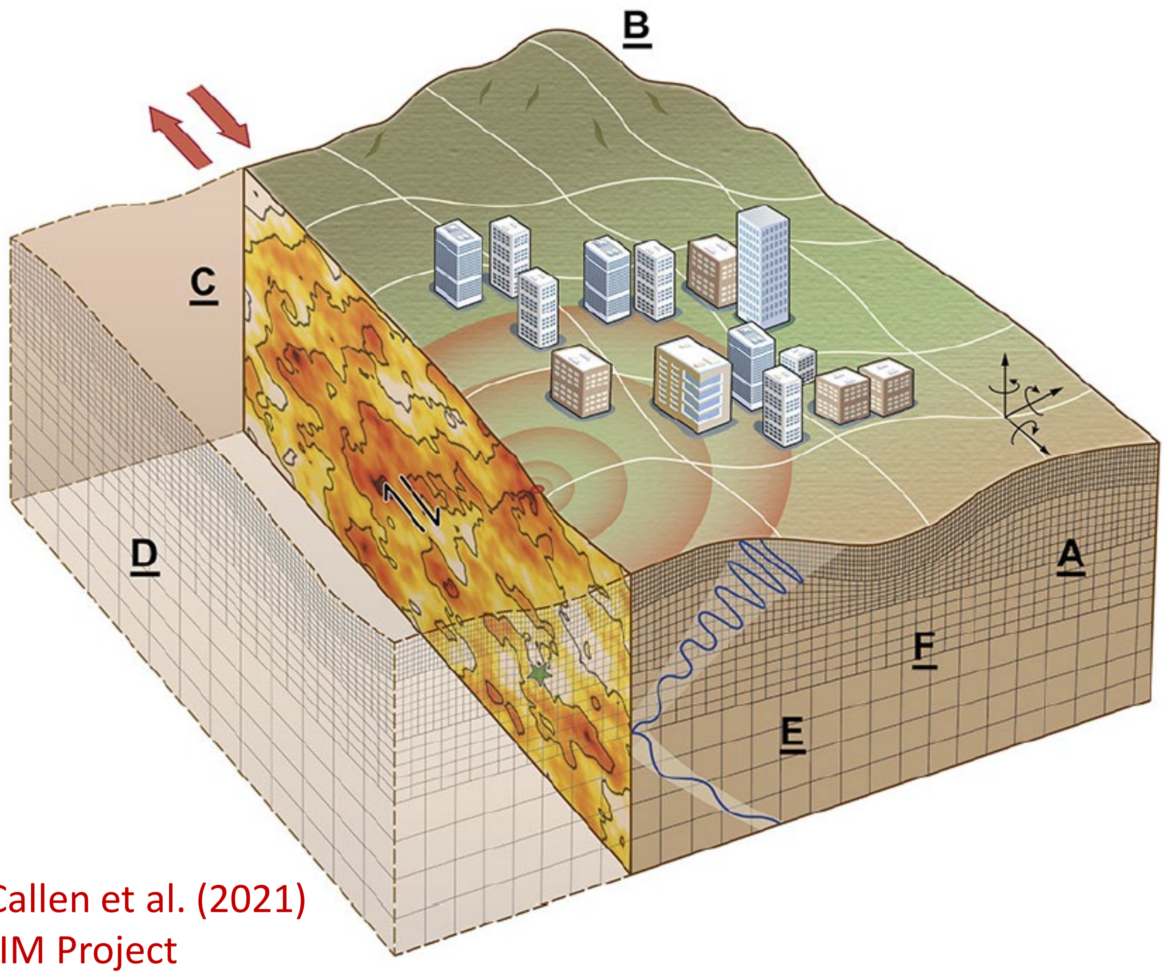
Empirical: ShakeMap



Mw6.2 Apr 6, 2009 L'Aquila earthquake, Central Italy

Rosti et al. (2023)

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



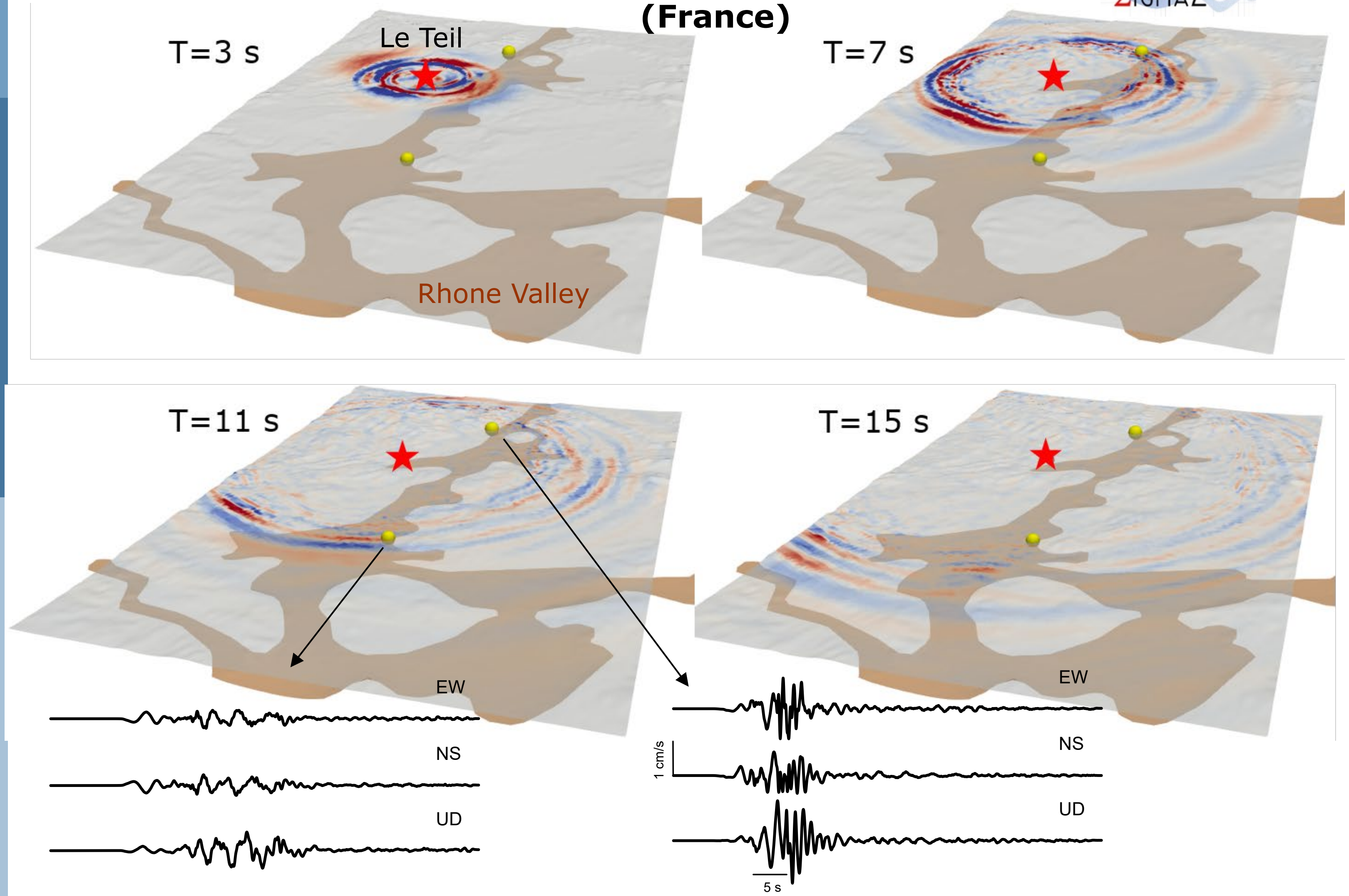
McCallen et al. (2021)
EQSIM Project

"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

Computer code for PBS: SPEED@PoliMI

Mw4.9 2019 Le Teil earthquake (France)



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

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

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

General requirements on the numerical scheme

- ✓ Accuracy
- ✓ Flexibility
- ✓ Scalability / Efficiency

Workflow to generate regional-scale PBS

Input data

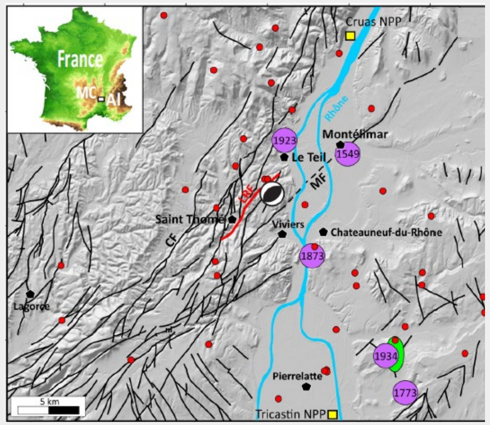
SEISMOTECTONIC CONTEXT (FAULTS)

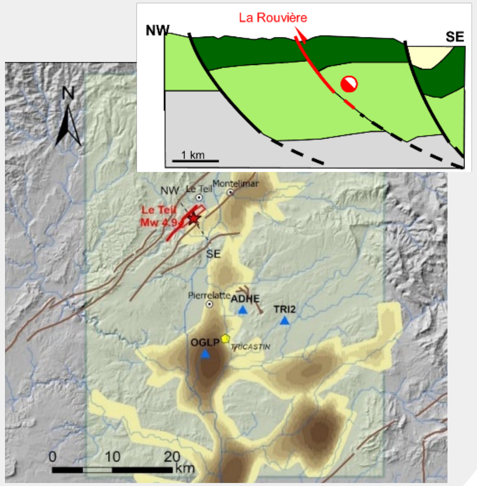
+

TOPOGRAPHY /BATHYMETRY

+

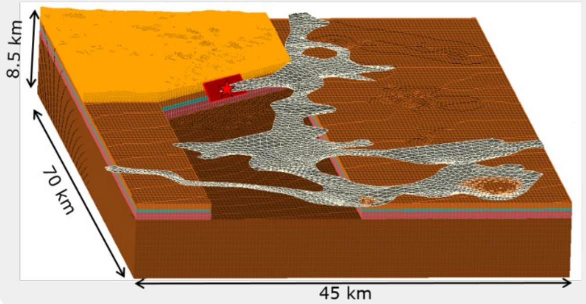
GEOLOGICAL-GEOTECHNICAL-GEOPHYSICAL MODEL



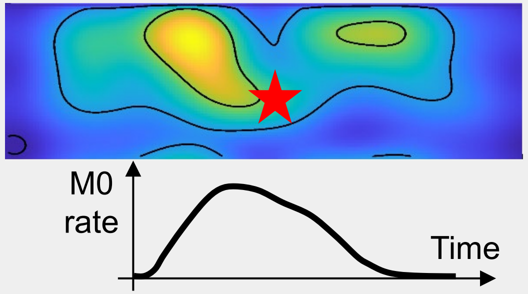


2019 Mw4.9 Le Teil earthquake

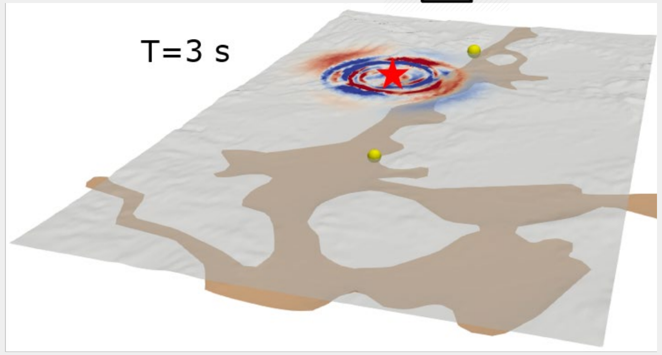
Set-up of the 3D numerical model

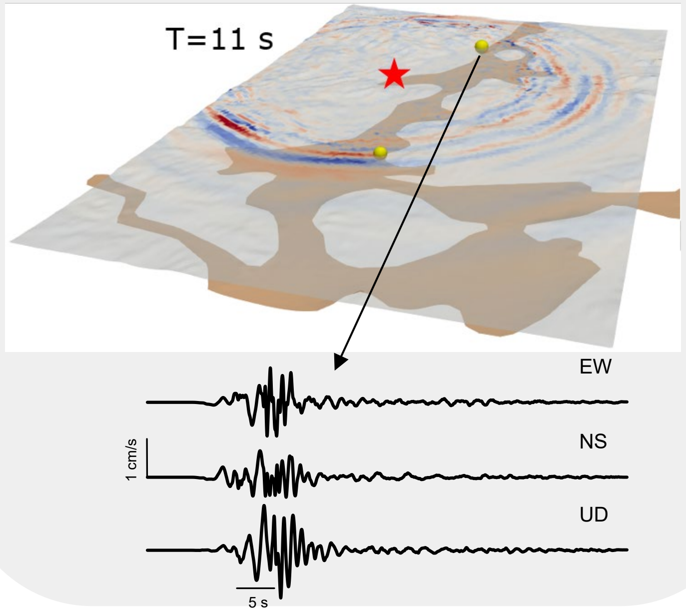


Fault rupture scenario



PBS

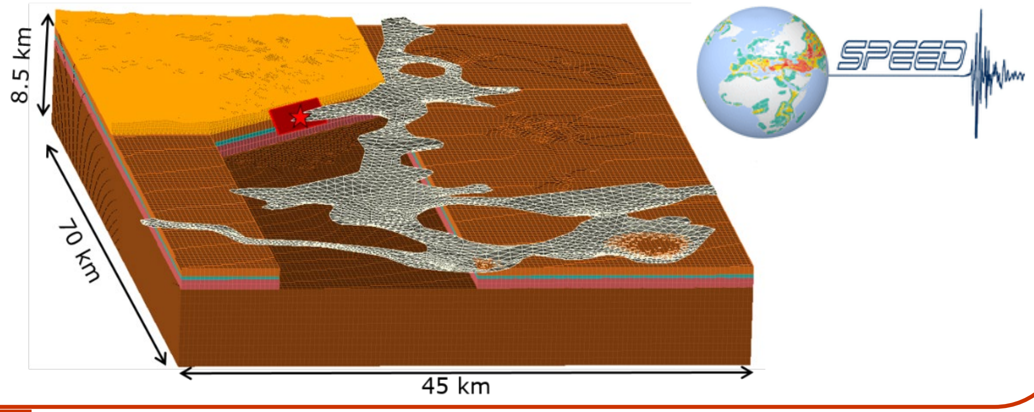




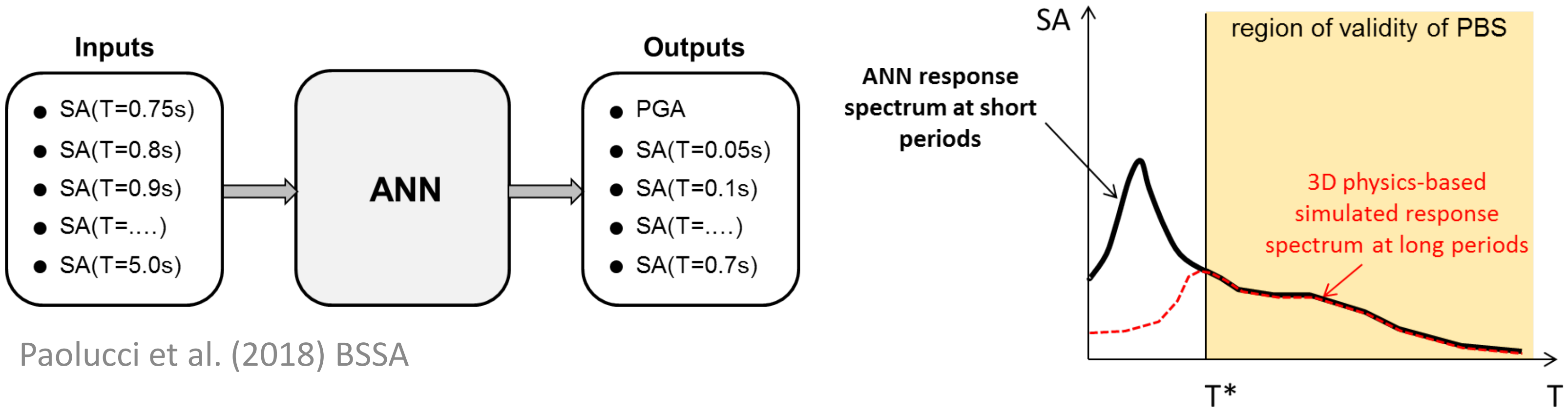
…and to compute broadband ground motions

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

Examples of application of PBS

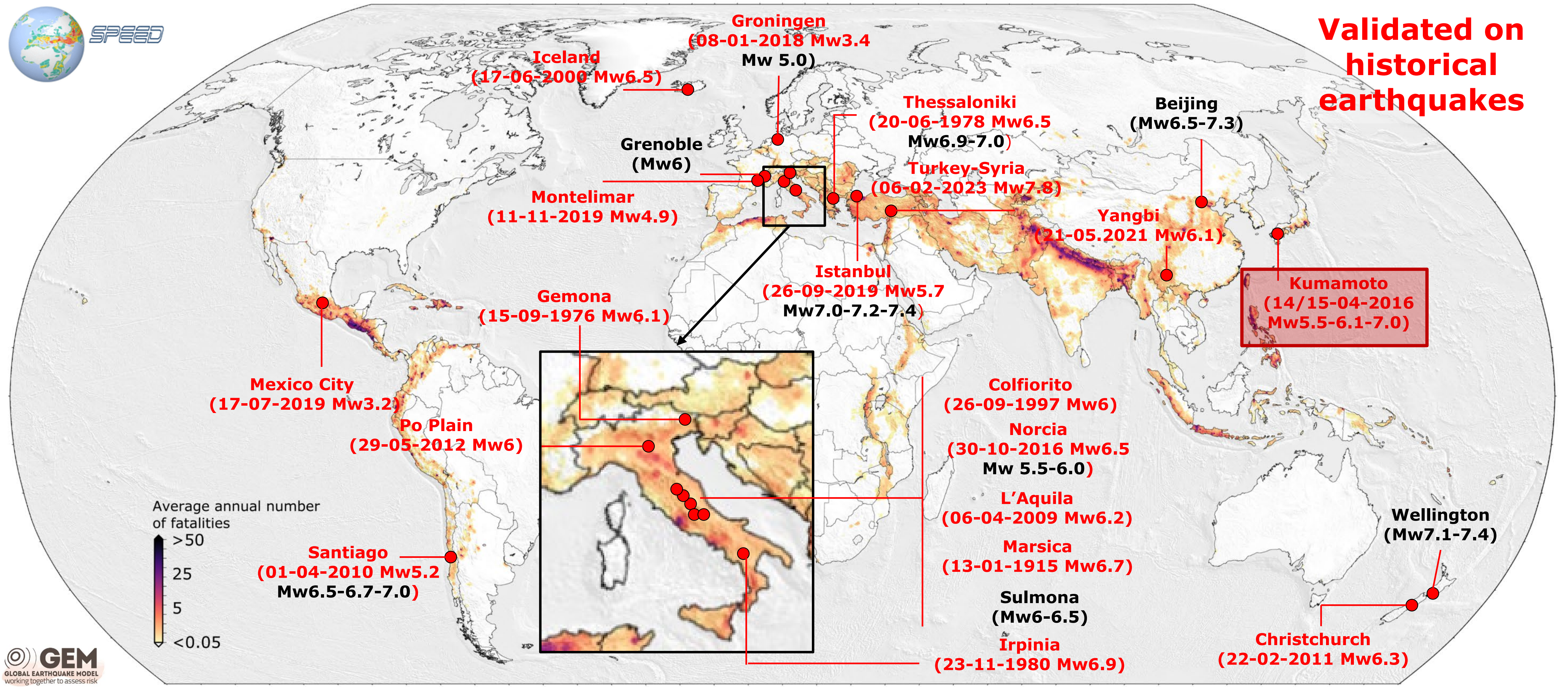
- Simulation of real earthquakes with complex source and soil behavior models

- BB-SPEEDset: a validated dataset of physics-based broadband simulated ground motions from multiple regions

- Select&Match: a software tool for ground motion selection and scaling enhanced by PBS datasets

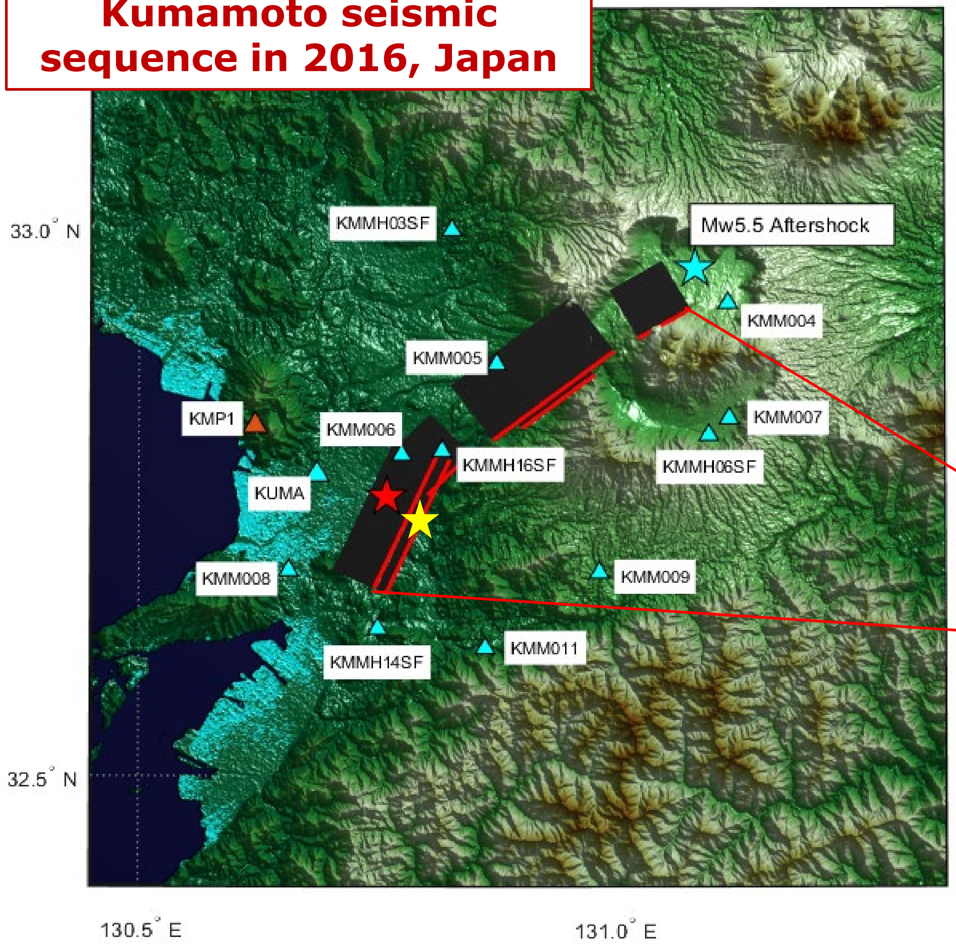
- Utilization of simulated ground motions for structural non-linear time history analyses and for seismic fragility studies

Overview of case studies simulated by SPEED



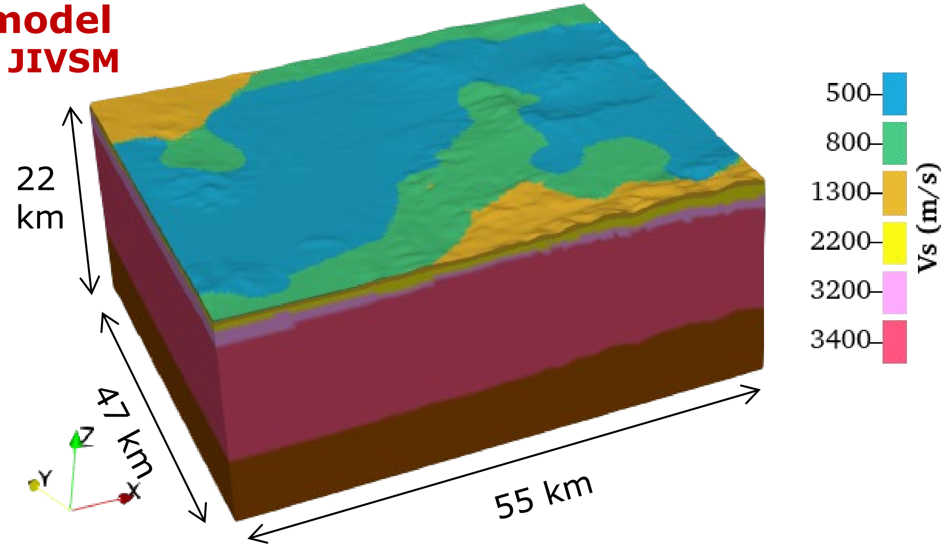
Validation on real earthquakes: the ESG6 benchmark on the 2016 Kumamoto events

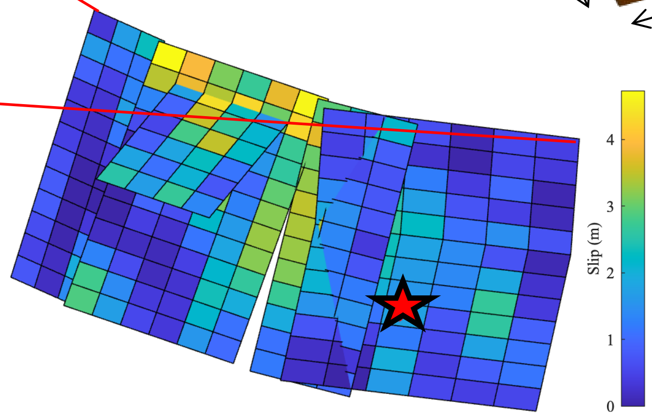
Kumamoto seismic sequence in 2016, Japan



Mw 7.0 Mw 6.1 Mw 5.5

3D velocity model
(Modified from JIVSM model)





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

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

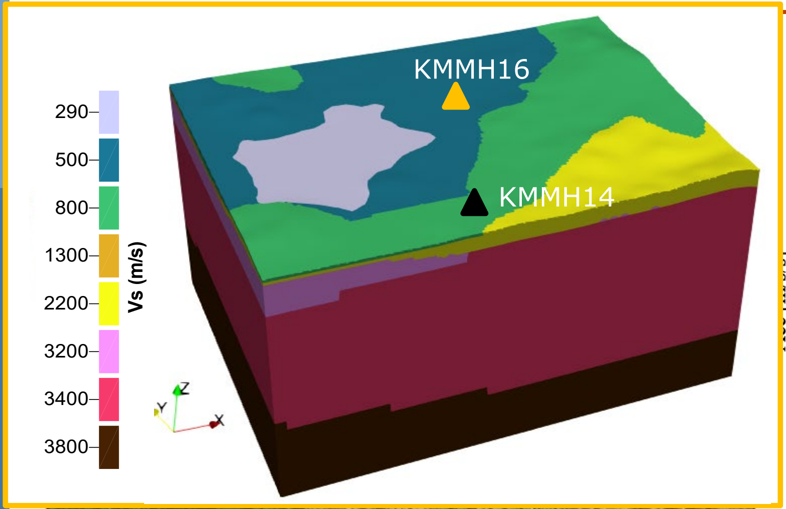
Sangaraju et al (2021)

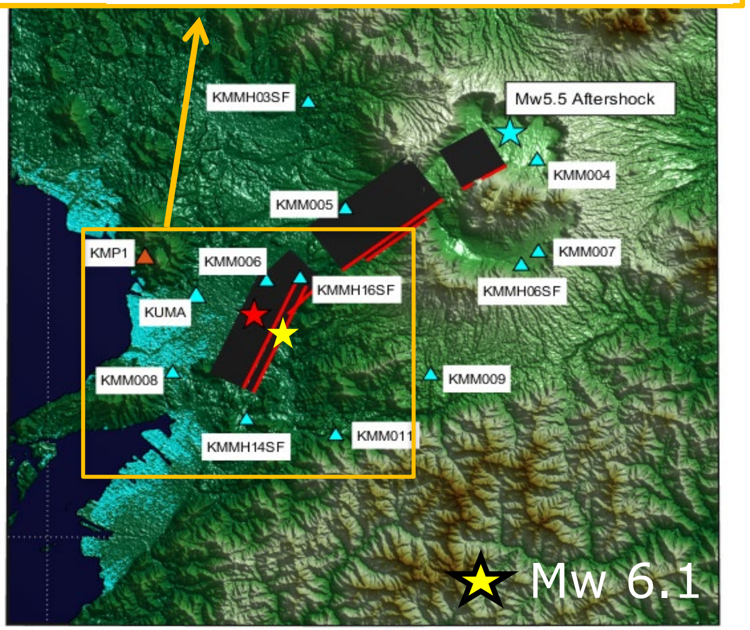
Validation on real earthquakes: the ESG6 benchmark on the 2016 Kumamoto events

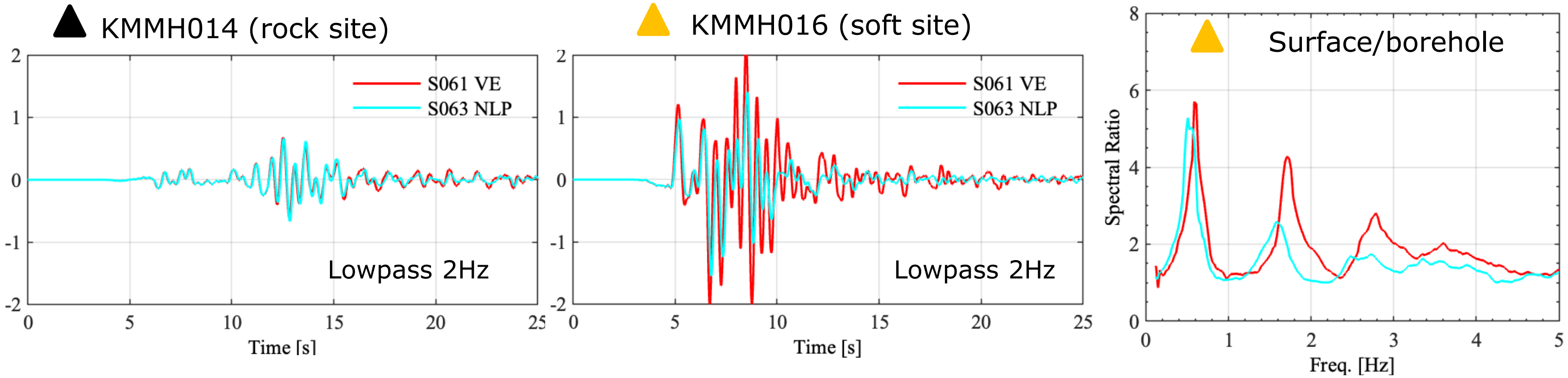
Vel

Mw6.1 Kumamoto: 3D Non-Linear Plastic (NLP) simulation

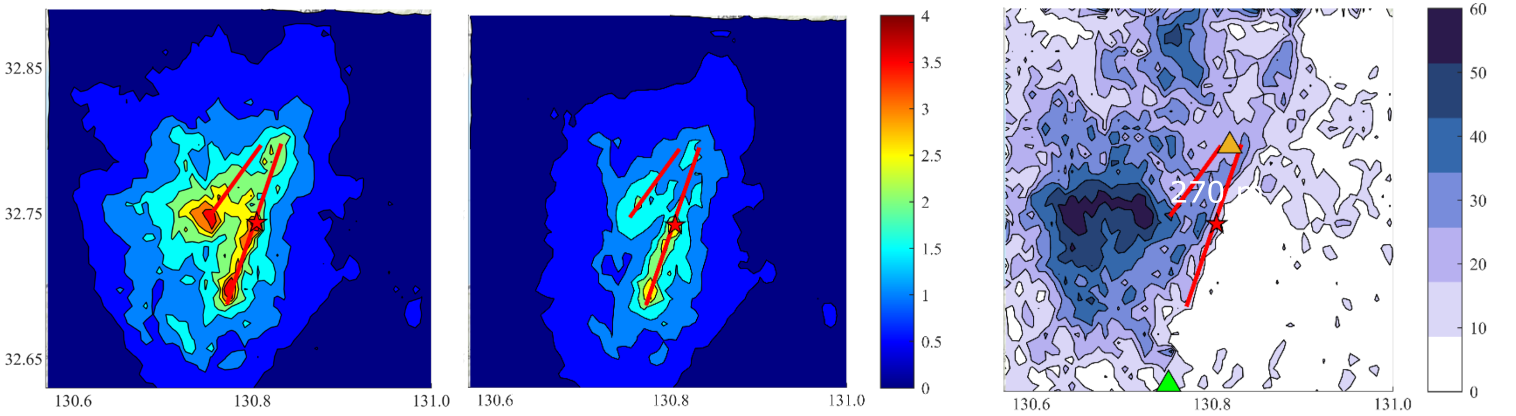
→ **NLP simulation with a new module implemented in SPEED**
(Oral, 2016; Oral & Bonilla, 2017)







Simulated Horizontal (GMH) PGA (m/s²)



Srihari Sangaraju, PhD thesis (2024)

Examples of application of PBS

- Simulation of real earthquakes with complex source and soil behavior models

- BB-SPEEDset: a validated dataset of physics-based broadband simulated ground motions from multiple regions

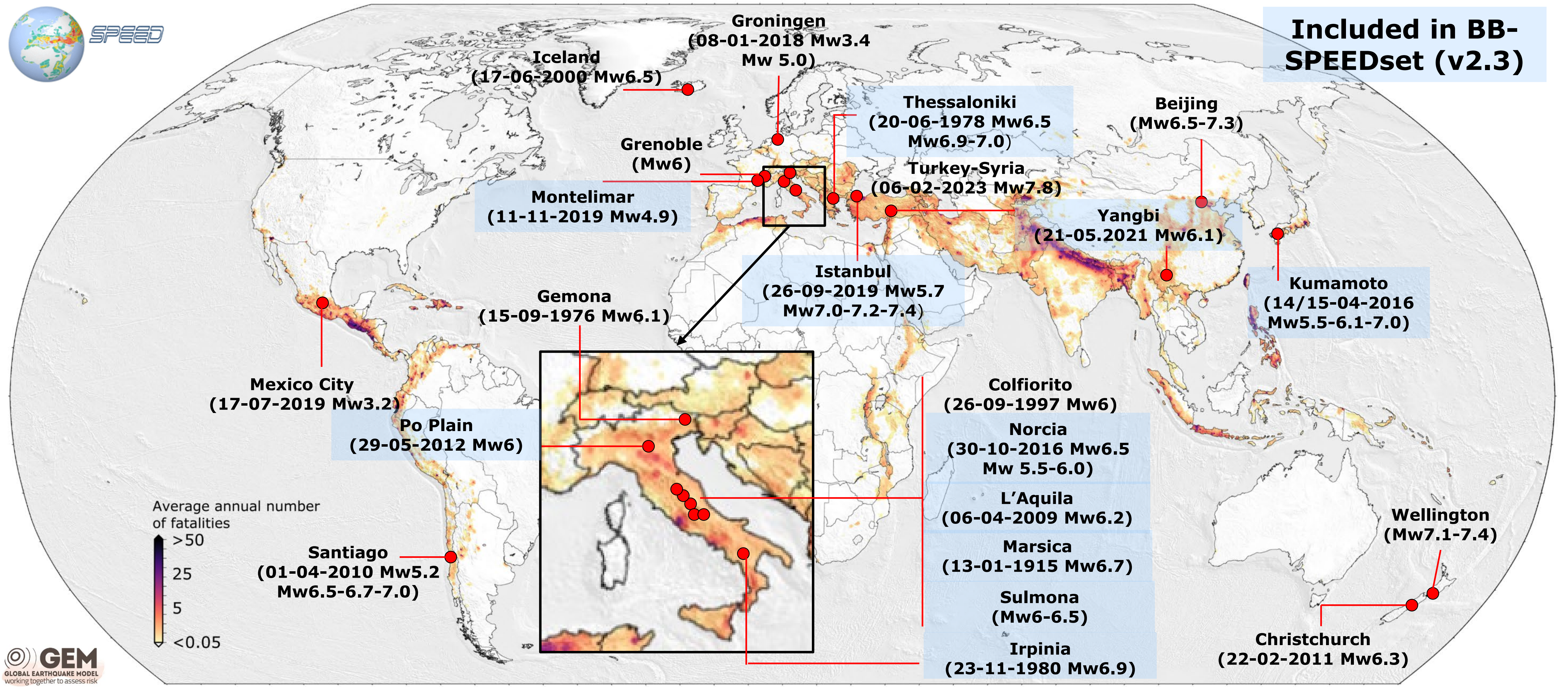
- Select&Match: a software tool for ground motion selection and scaling enhanced by PBS datasets

- Utilization of simulated ground motions for structural non-linear time history analyses and for seismic fragility studies

International efforts towards the construction of datasets of simulated accelerograms

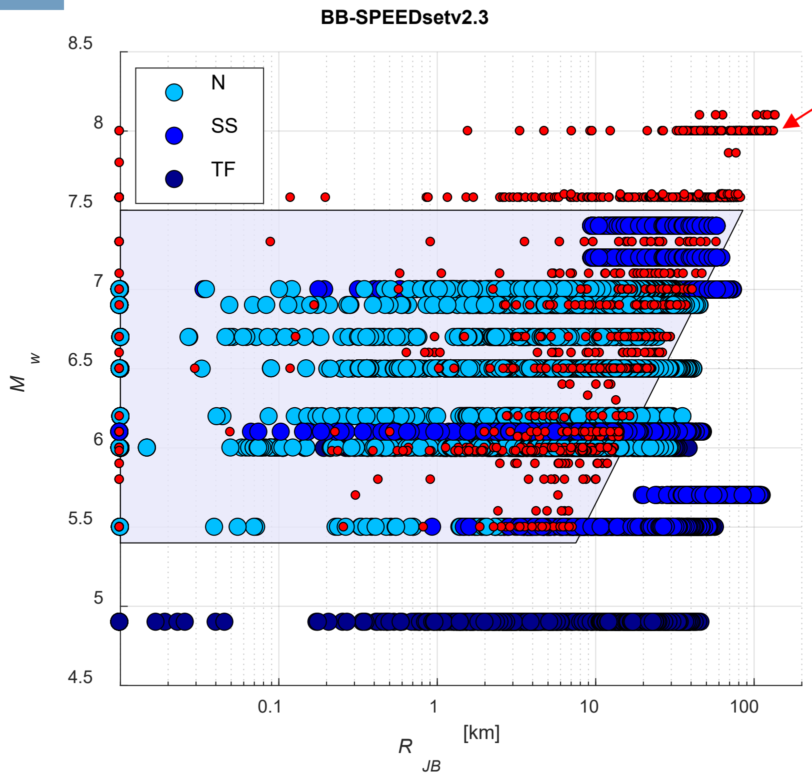
Database	Simulation Approach	Region	Mw-R range	References	Link
CyberShake Subset	PBS: Graves and Pitarka (2008; 2015)	California - Los Angeles	6.3-8.0 0-45 km	Baker et al. (2021)	https://zenodo.org/records/3875541
SIGMOID-TR	Stochastic Finite-Fault: EXSIM	Turkey	6.5-7.8 0-100 km	Altindal & Askan (2023)	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/

Construction of BB-SPEEDset (v1.0 → v2.3)



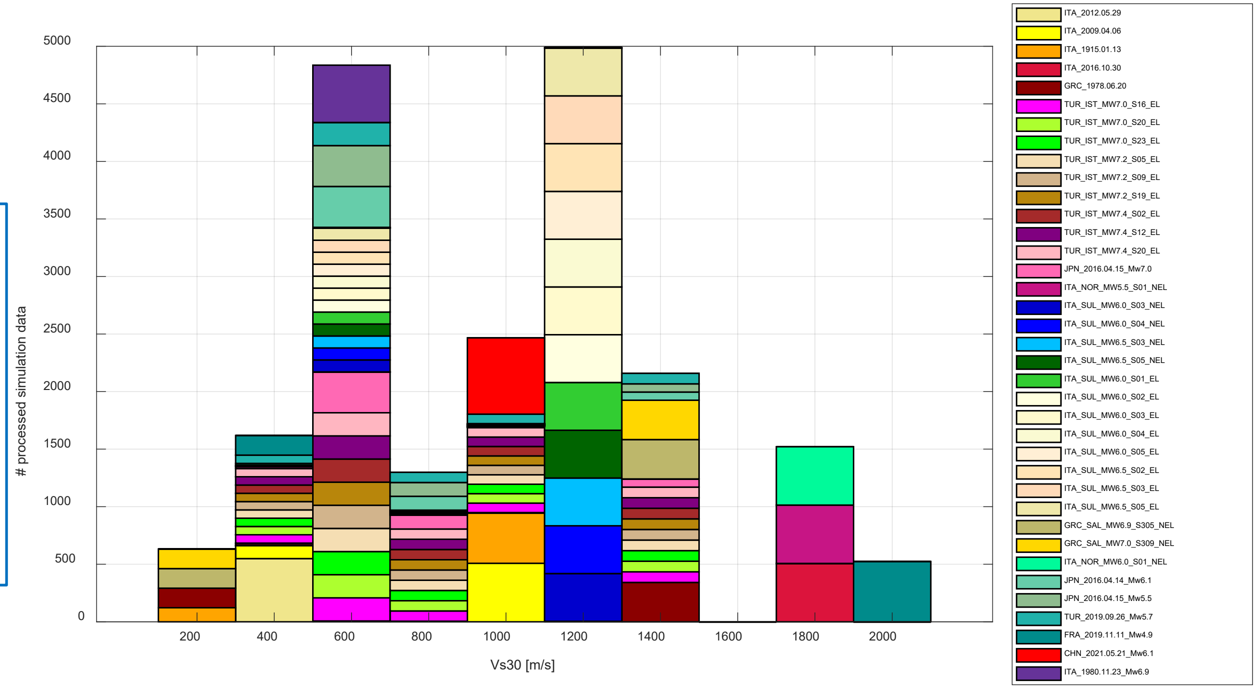
BB-SPEEDset (v2.3): a dataset of near-source accelerograms from PBS

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

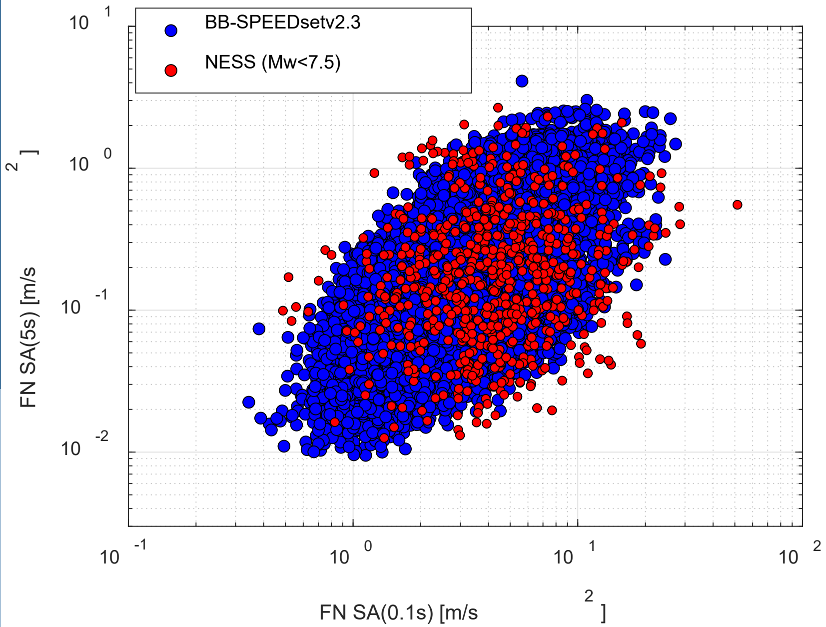
Bulletin of the Seismological Society of America (2021) 111 (5): 2527–2545.

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

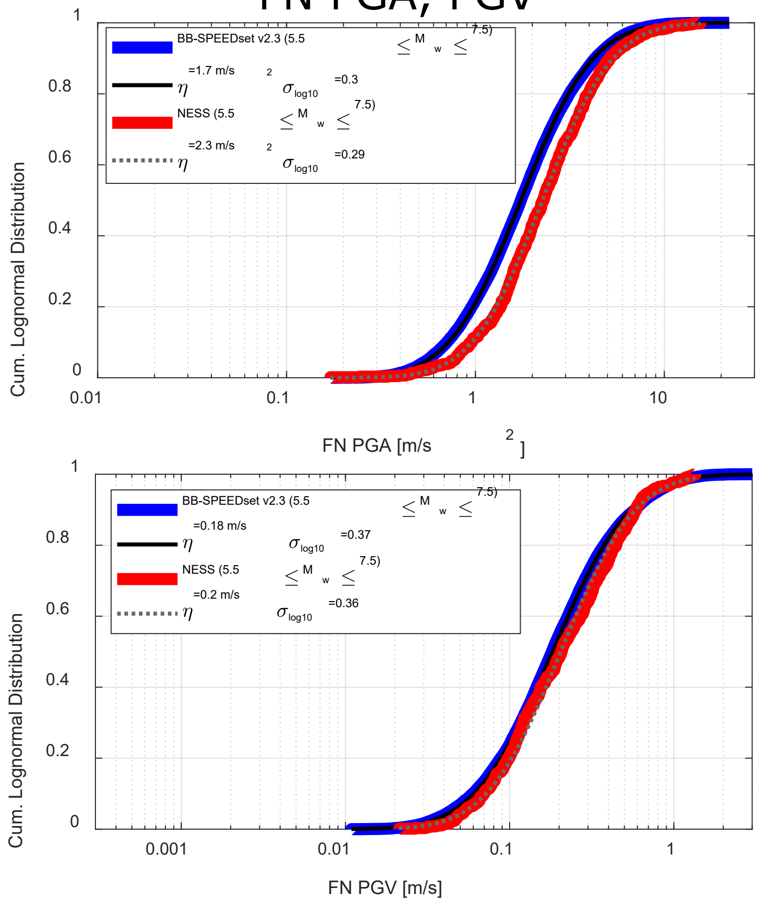
Validation tests on several ground motion features

Comparison, in the same (Mw,R) range, with respect to a dataset of near-source recordings NESS2.0 (Sgobba et al. 2021)

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

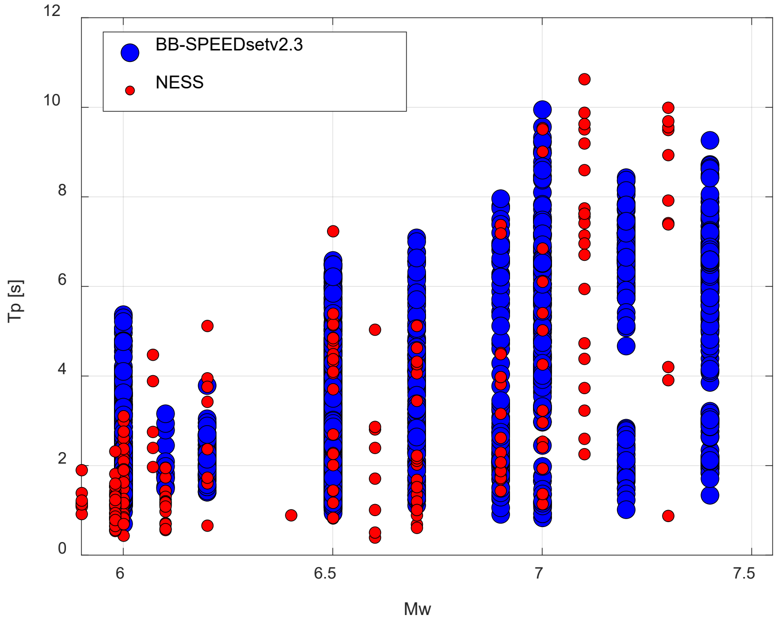


Cumulative Distribution Function FN PGA, PGV



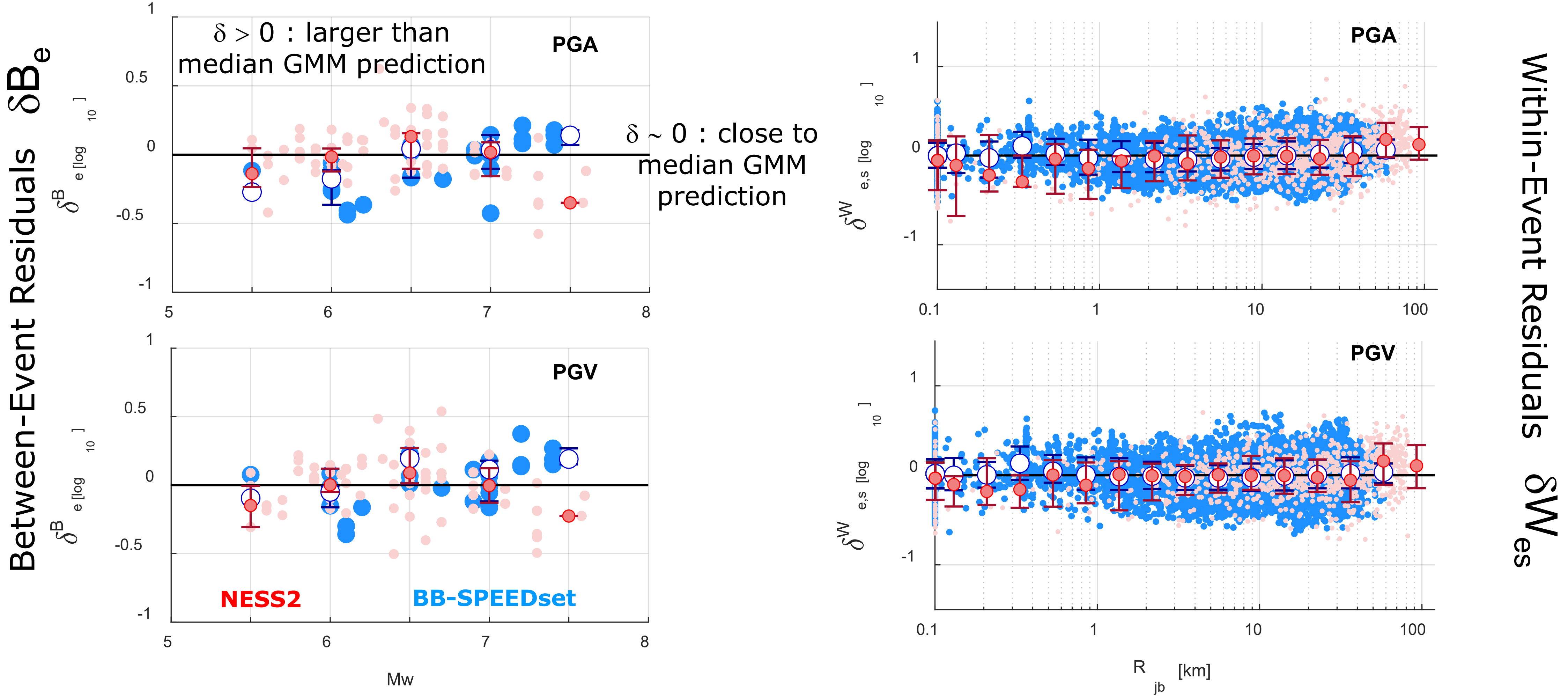
Pulse-like waveforms: Pulse Period T_P Vs M_W

(Shahi and Baker, 2014)



Variability analysis of BB-SPEEDset

Between- and within-event residuals of BB-SPEEDset and NESS2 with respect to the ITA18 GMM (Lanzano et al. 2019, adjusted by near-source effects)



Examples of application of PBS

- Simulation of real earthquakes with complex source and soil behavior models

- BB-SPEEDset: a validated dataset of physics-based broadband simulated ground motions from multiple regions

- Select&Match: a software tool for ground motion selection and scaling enhanced by PBS datasets

- Utilization of simulated ground motions for structural non-linear time history analyses and for seismic fragility studies

Select&Match: a software tool for ground motion selection enhanced by PBS

GM DATABASES
- NGA-WEST2, SIMBAD
- BB-SPEED SET

TARGET SPECTRUM
- USER-DEFINED
- NORMS (EC8, ASCE)

SELECTION OF A SET OF N MULTI-COMPONENT ACCELEROGRAMS APPROACHING A TARGET SPECTRUM

SELECTION CRITERIA
- NUM. ACCELEROGRAMS
- M, PERIOD RANGE
- MAX/AVG PERMIS. MISMATCH
- SITE-CONDITIONS
- PULSE-LIKE SELECTION
- 3-COMPONENT
- RANKING WEIGHTS

SPECTRAL MATCHING OF THE N SELECTED ACCELEROGRAMS (*OPTIONAL*)

MATCHING CRITERIA
- PERIOD RANGE
- VARIABILITY BAND
- PGA CONSISTENCY

SET OF N **UNSCALED OR SPECTRALLY-MATCHED REAL/SIMULATED ACCELEROGRAMS** COMPATIBLE WITH A TARGET SPECTRUM

POLITECNICO MILANO 1863

PROTEZIONE CIVILE NAZIONALE

reluis

Bulletin of Earthquake Engineering (2022) 20:4961–4987
https://doi.org/10.1007/s10518-022-01393-0

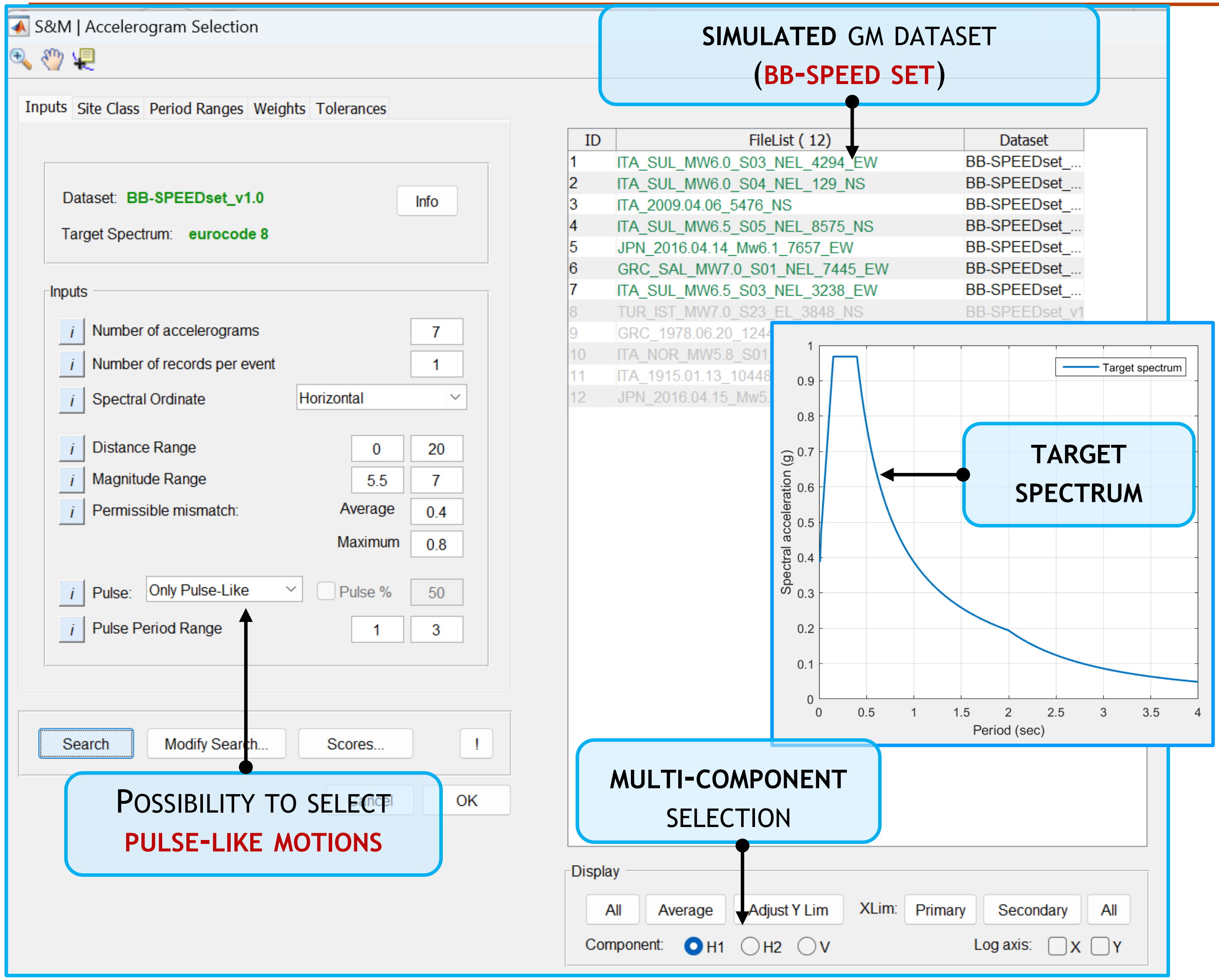
REVIEW ARTICLE

Selection and spectral matching of recorded ground motions for seismic fragility analyses

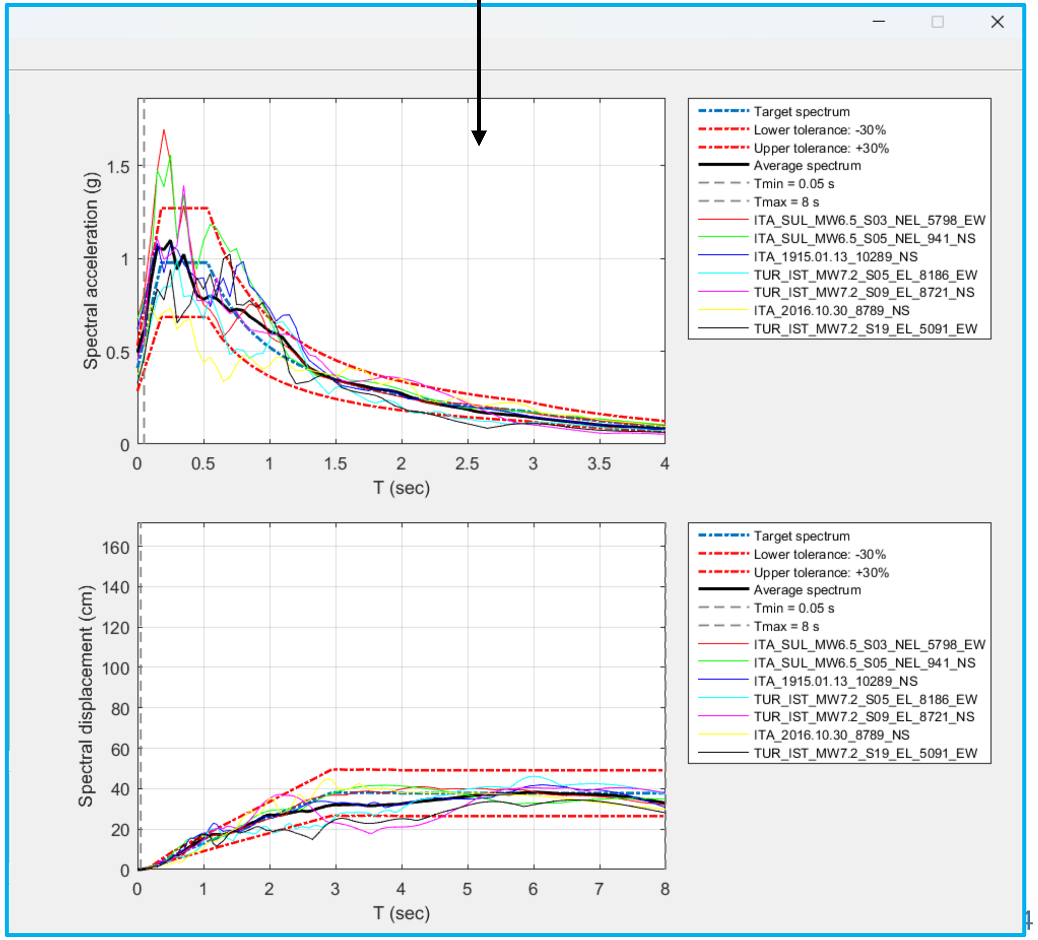
Vincenzo Manfredi[1] · Angelo Masi[1] · Ali Güney Özcebe[2] · Roberto Paolucci[3] · Chiara Smerzini[3]

Select&Match: a software tool for ground motion selection enhanced by PBS

Select&Match



SELECTION OF A SET OF N MULTI-COMPONENT ACCELEROGRAMS APPROACHING A TARGET SPECTRUM



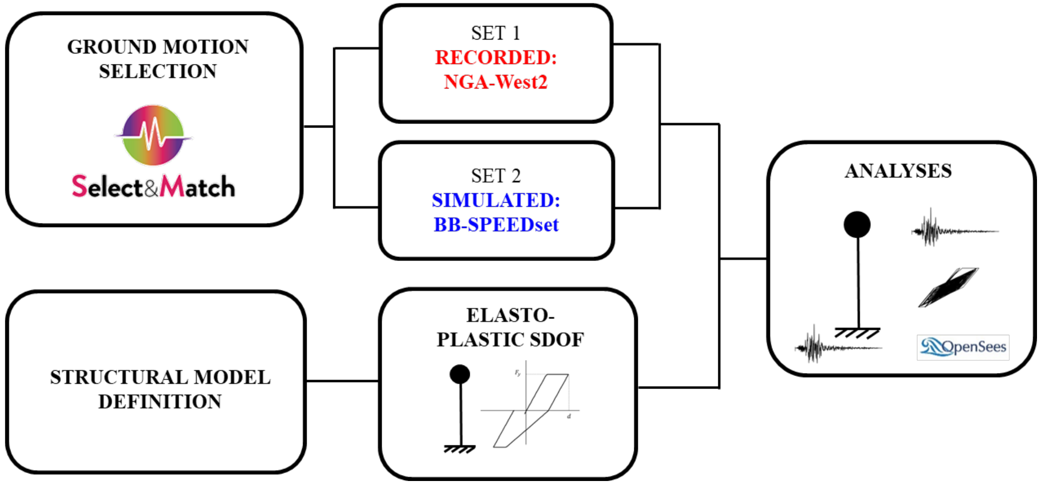
Examples of application of PBS

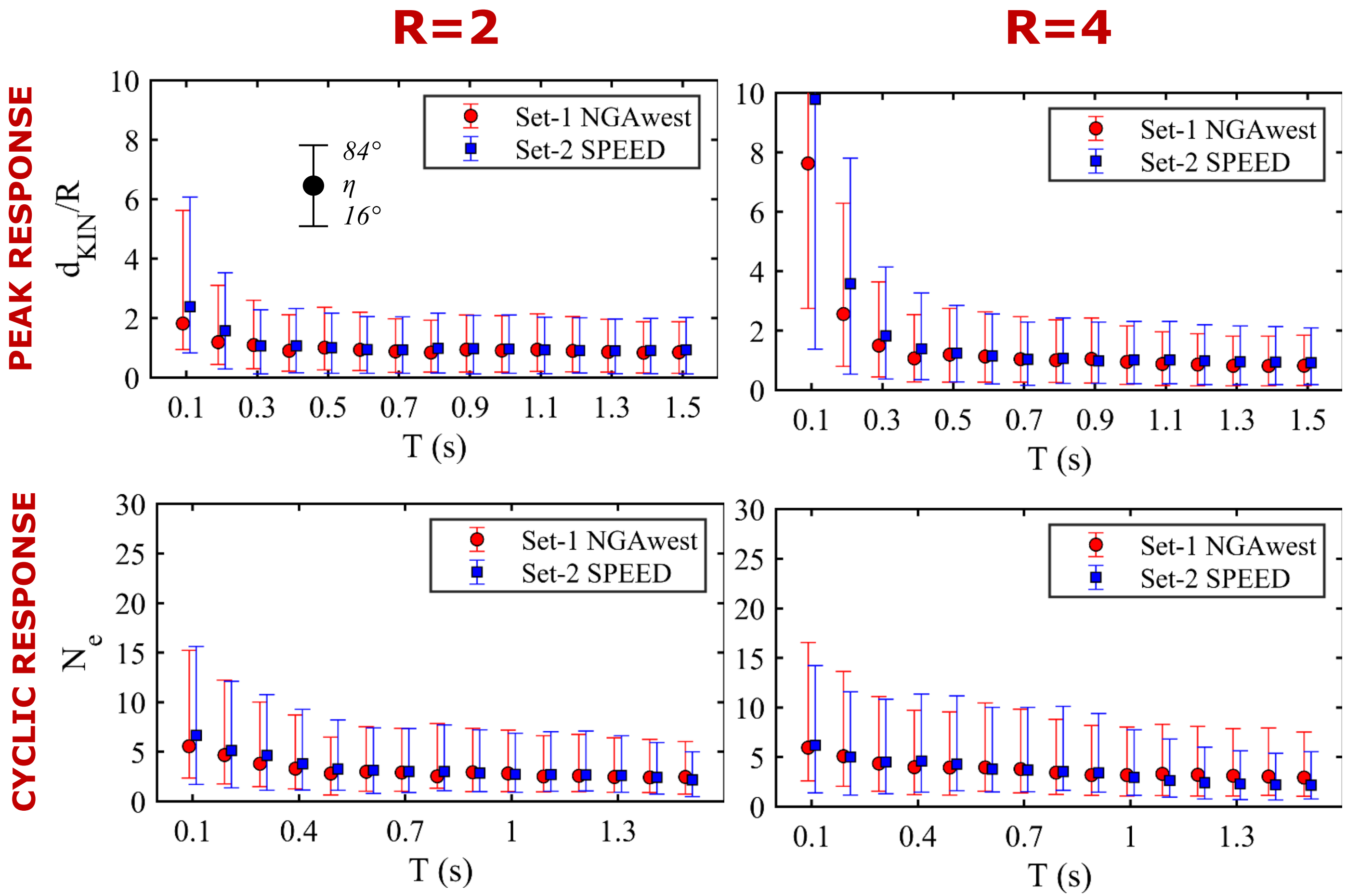
- Simulation of real earthquakes with complex source and soil behavior models
- BB-SPEEDset: a validated dataset of physics-based broadband simulated ground motions from multiple regions
- Select&Match: a software tool for ground motion selection and scaling enhanced by PBS datasets
- Utilization of simulated ground motions for structural non-linear time history analyses and for seismic fragility studies

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





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]

Concluding remarks

- PBS are 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).
- However, further efforts are still needed to build confidence in the utilization of PBS by the seismological and engineering community.
- Availability and dissemination of simulated ground motion datasets, validated and embedded in accredited ground-motion selection tools, is a key step for broadening community access and use.
- Validation of simulated datasets, in a broad frequency range, for both ground motion intensity measures and engineering demand parameters, on median and variability trends, is essential as a proof of the suitability of PBS for a variety of applications.

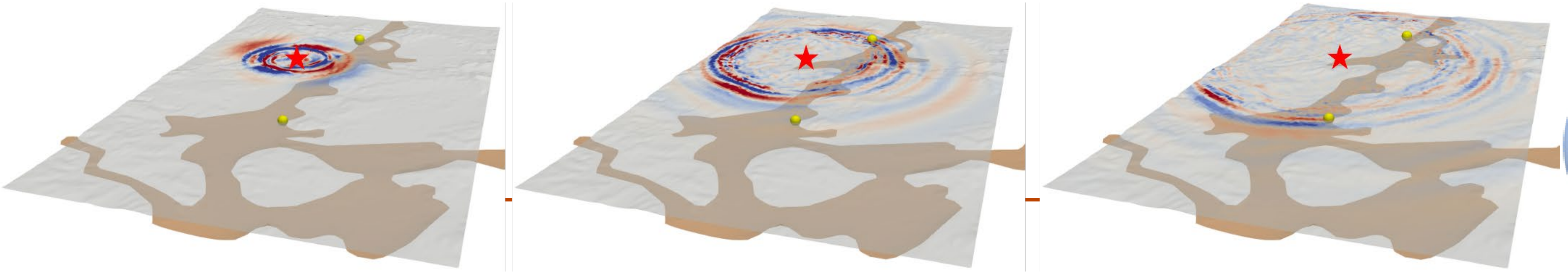
On-going challenges

- Simulation of real earthquakes deserves attention to: (i) gain insights into the physics of complex interaction of seismic source, path and local site effects (including soil non-linearity), (ii) verify/validate new algorithms and (iii) to inform modelers on the application needs.

- Approaches to generate broadband ground motions need enhancement in such a way that the physical features of spatial variability and period-to-period correlation are preserved also at high-frequency.

- Data and metadata format for simulated ground motions shall be as much similar as for recorded datasets but with some specificities. Such specificities shall be shared by the international community.

- Merging of recorded and simulated datasets (data fusion) for hybrid ground motion modeling strategies still requires research



Thank you for your attention

Chiara Smerzini

Dept. Civil and Environmental Engineering

Politecnico di Milano

chiara.smerzini@polimi.it