SIGMA-2 Closing Symposium, Avignon

Advances and open challenges in engineering use of physics-based numerical simulation of earthquake ground motion

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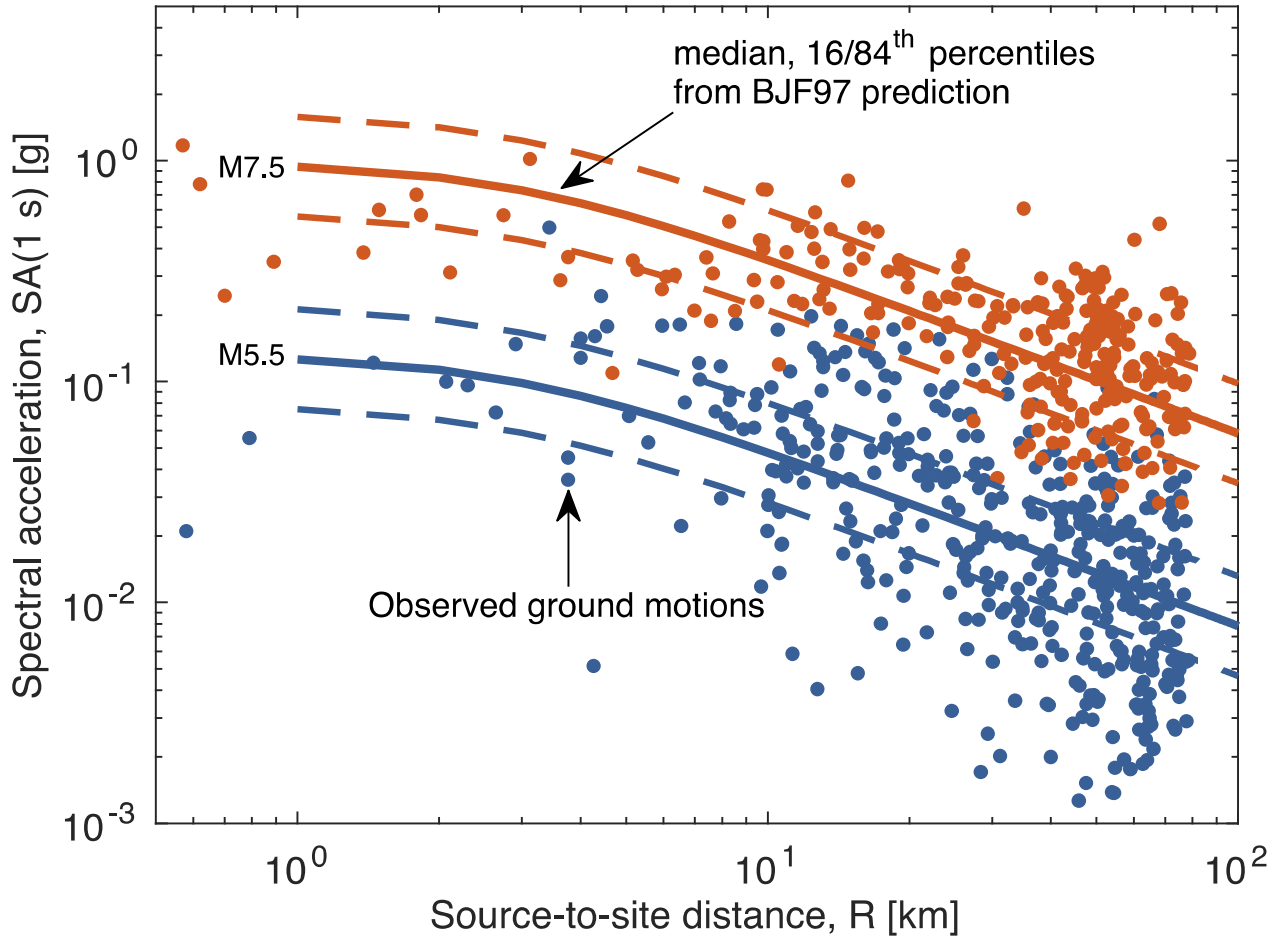
Empirical Ground Motion Models (GMMs): advances and limitations

Remarkable evolution in recent years in terms of:

- Exponentially growing size of databases
- Conceptual and statistical modeling framework (e.g. robust mixed-effect regressions)
- Non-ergodic models (i.e. region- and site-specific)

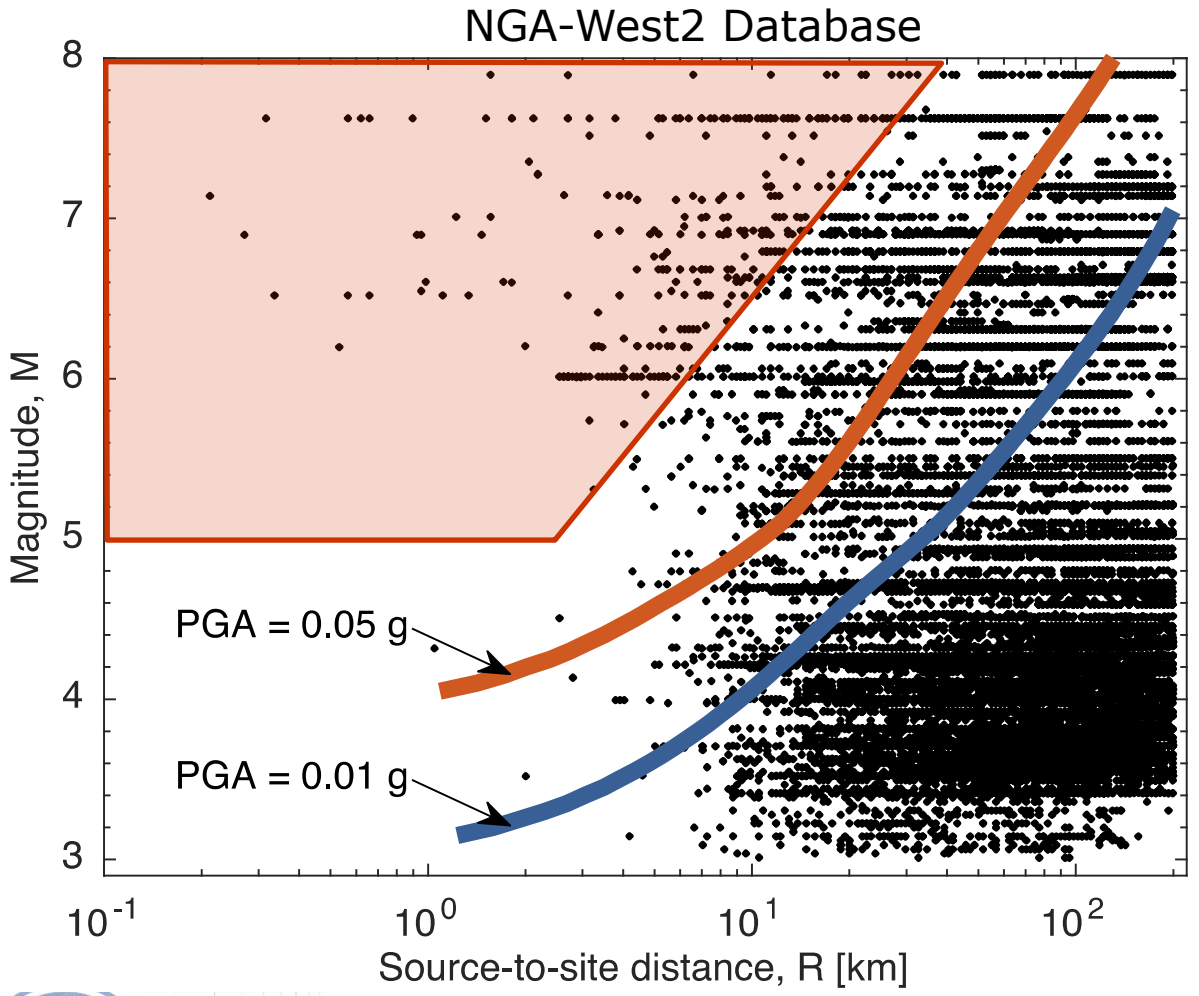


Baker, Bradley and Stafford (2021)

Empirical Ground Motion Models (GMMs): advances and limitations

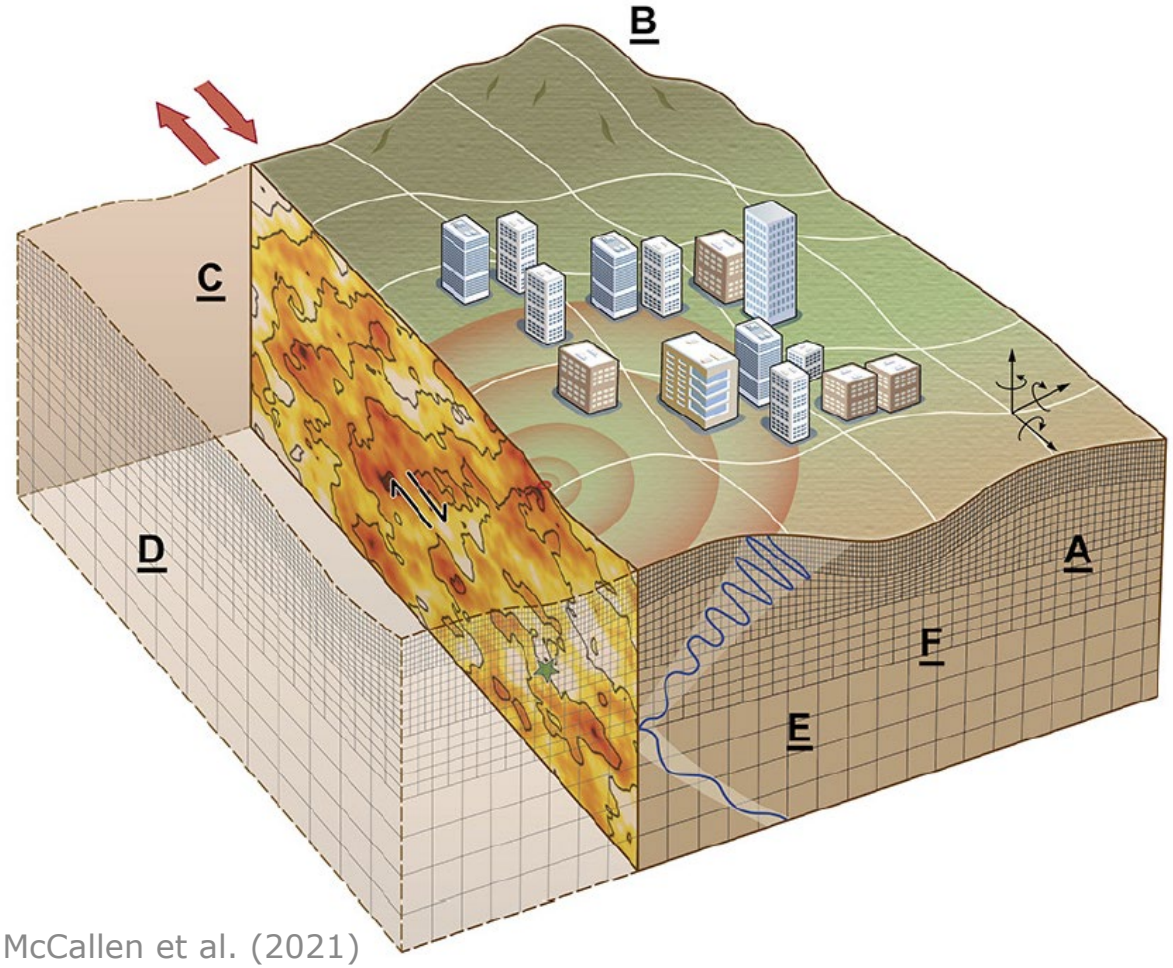
However,

- Paucity of near-source recordings still persists, leading to high uncertainty for relevant (damaging) scenarios
- Ground motion time series are not available, in spite of increasing engineering needs for response history analysis of structures
- Spatial correlation is accounted for by oversimplified models



Baker, Bradley and Stafford (2021)

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



McCallen et al. (2021)

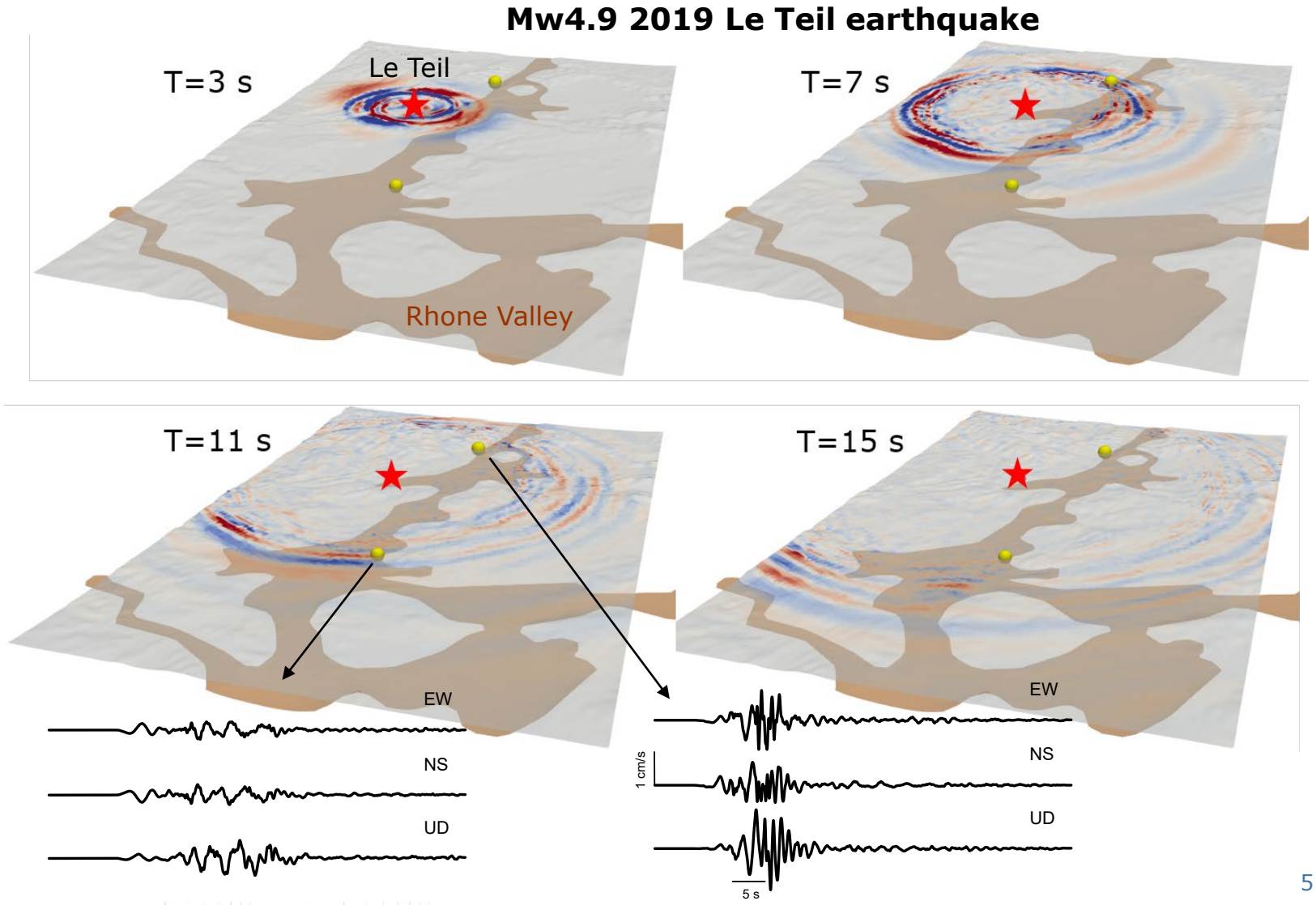
"Source-to-site(-to-structure)" numerical simulation of seismic wave propagation, including:

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

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

Outputs of PBS include:

- At a single location, three-component ground motion waveforms
- At local and regional scale, realistic description of spatial variability of earthquake ground motion



Knowledge gaps addressed by 3D PBS in earthquake ground motion prediction

- Complement earthquake records in those conditions where they are still insufficient:
  - near-source region
  - complex geology
- Gain insights into the physics of the complex interactions between the source process and ground response
- Provide spatially dense waveforms and ground shaking scenarios for region- and site-specific hazard and risk applications

ΣIGMA2

SPEED – Spectral Elements in Elastodynamics with Discontinuous Galerkin @PoliMI

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

SPEED – SPectral Elements in Elastodynamics with Discontinuous Galerkin

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SPEED – SPectral Elements in Elastodynamics with Discontinuous Galerkin

SPEED is an open-source code designed with the aim of simulating large-scale seismic events in three-dimensional complex media: from far-field to near-field including soil-structure interaction effects.

SPEED combines the flexibility of discontinuous Galerkin methods to connect together, through a domain decomposition paradigm, Spectral Element blocks where high-order polynomials are used. SPEED heavily exploits parallelism in the framework of explicit time integration and features optimal scalability properties making use of the open-source libraries METIS and MPI for mesh partitioning and message passing.

SPEED is jointly developed at Politecnico di Milano by The Laboratory for Modeling and Scientific Computing MOX of the Department of Mathematics and by the Department of Civil and Environmental Engineering

MOX POLITECNICO MILANO 1863 Dipartimento di Ingegneria Civile e Ambientale

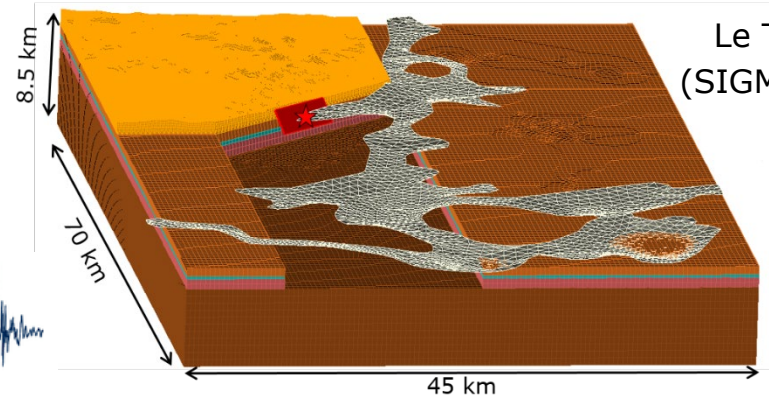
ΣIGMA2

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

Methodology to compute broadband seismic motions from PBS

3D PBS by the numerical code up to f_{max}

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



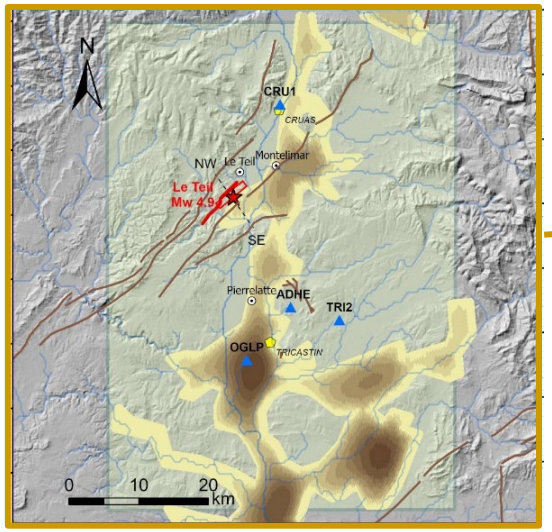
Le Teil earthquake
(SIGMA-2 benchmark)

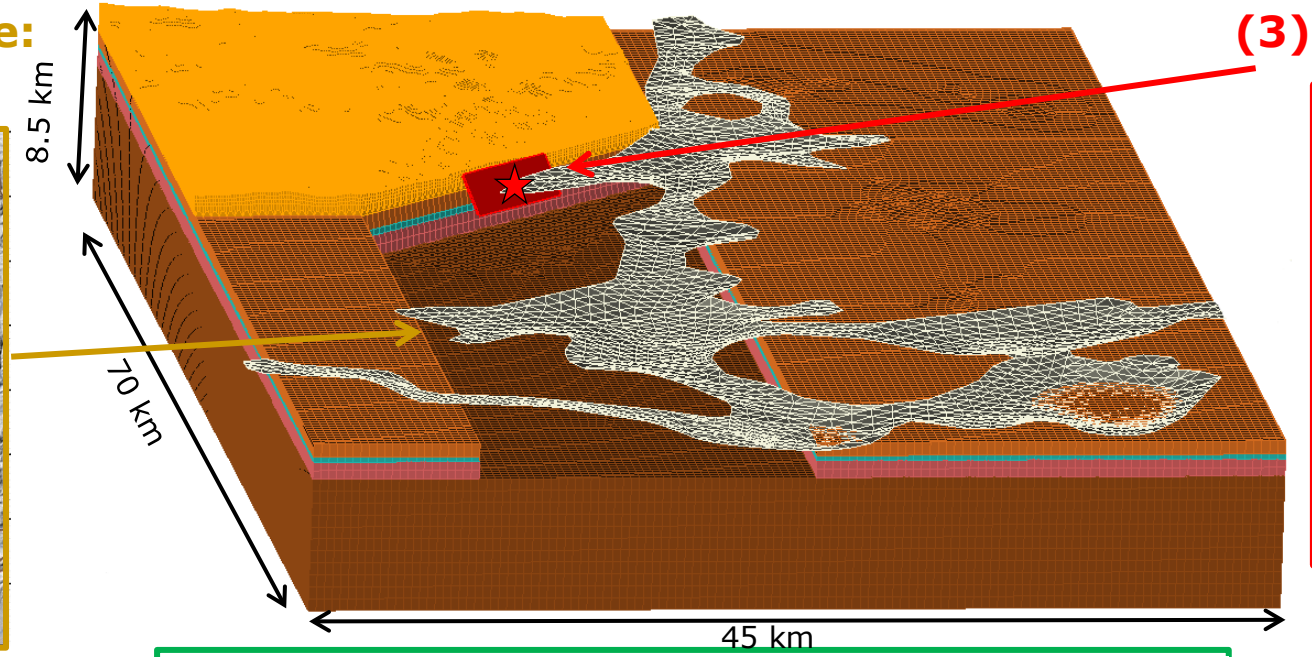
Enrichment of PBS signals at high frequency to compute broadband (BB) ground motions

- Hybrid approaches: low-frequency PBS + high-frequency stochastic signal by matching filters
- Machine learning techniques on spectral shape or time histories

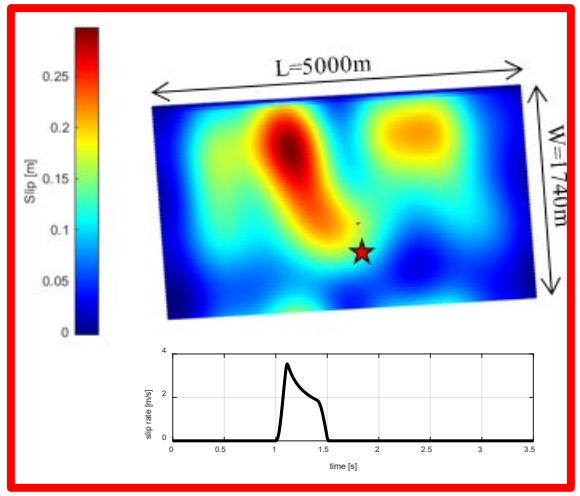
Methodology to compute broadband seismic motions: 1) PBS (Le Teil earthquake)

(1) Geological structure: Rhône River Valley

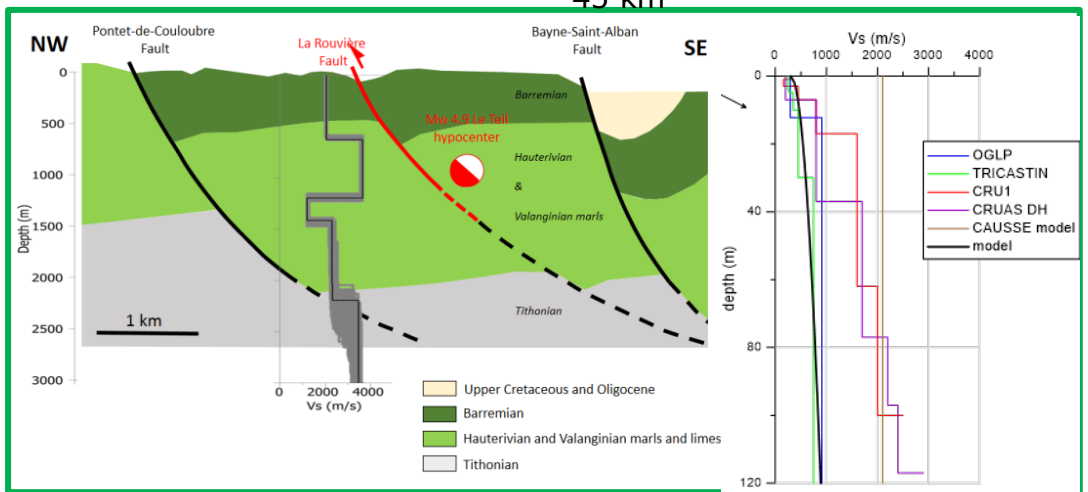




(3) Kinematic source model



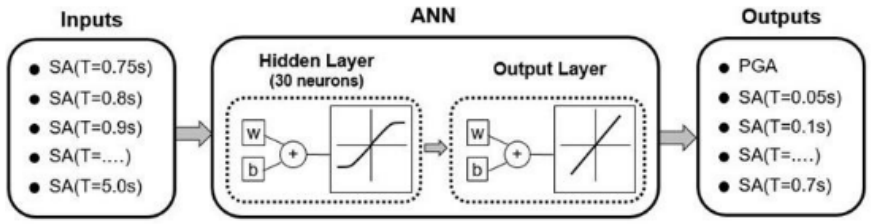
(2) 3D variation of geophysical and geotechnical parameters at regional scale



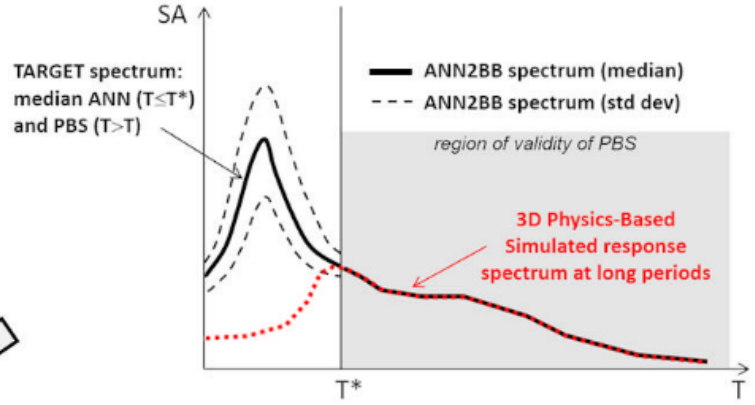
Computational Features	
Min. Element size	120 m
Elements	1’254’000
Nodes (*SD=4*)	82’222’349
Max freq.	8 Hz
Time step	0.01
Time window	35 s
Vs min	300 m/s
Vp max	5800 m/s

Methodology to compute broadband seismic scenarios: 2) ANN2BB

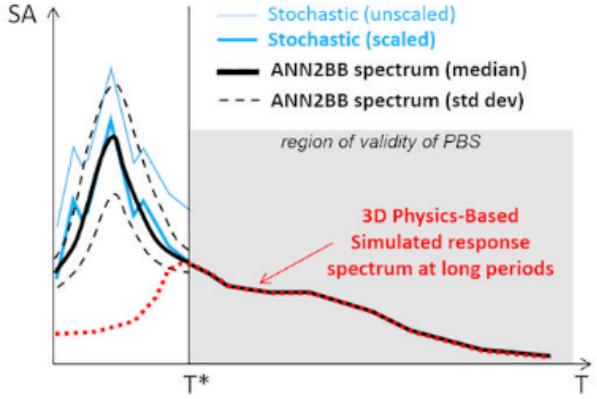
(1) Training of an Artificial Neural Network (ANN) based on a dataset of strong-motion recordings



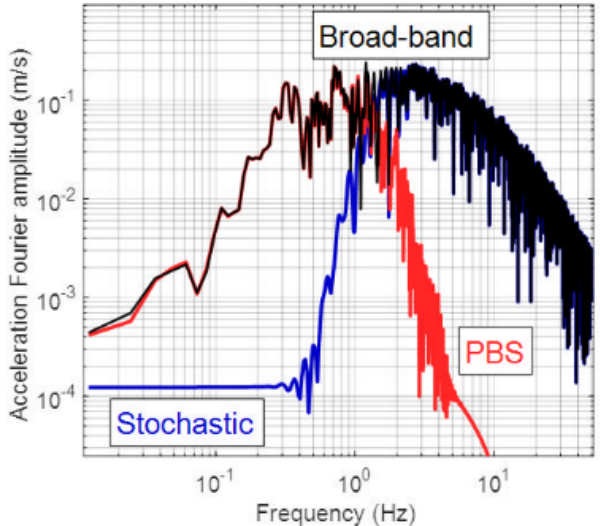
(2) Application of ANN to predict short period spectral ordinates based on PBS results (T≥T*)



(3) Simulation and linear scaling of a stochastic signal to approach the target ANN2BB spectrum



(4) Combination of stochastic and PBS signals



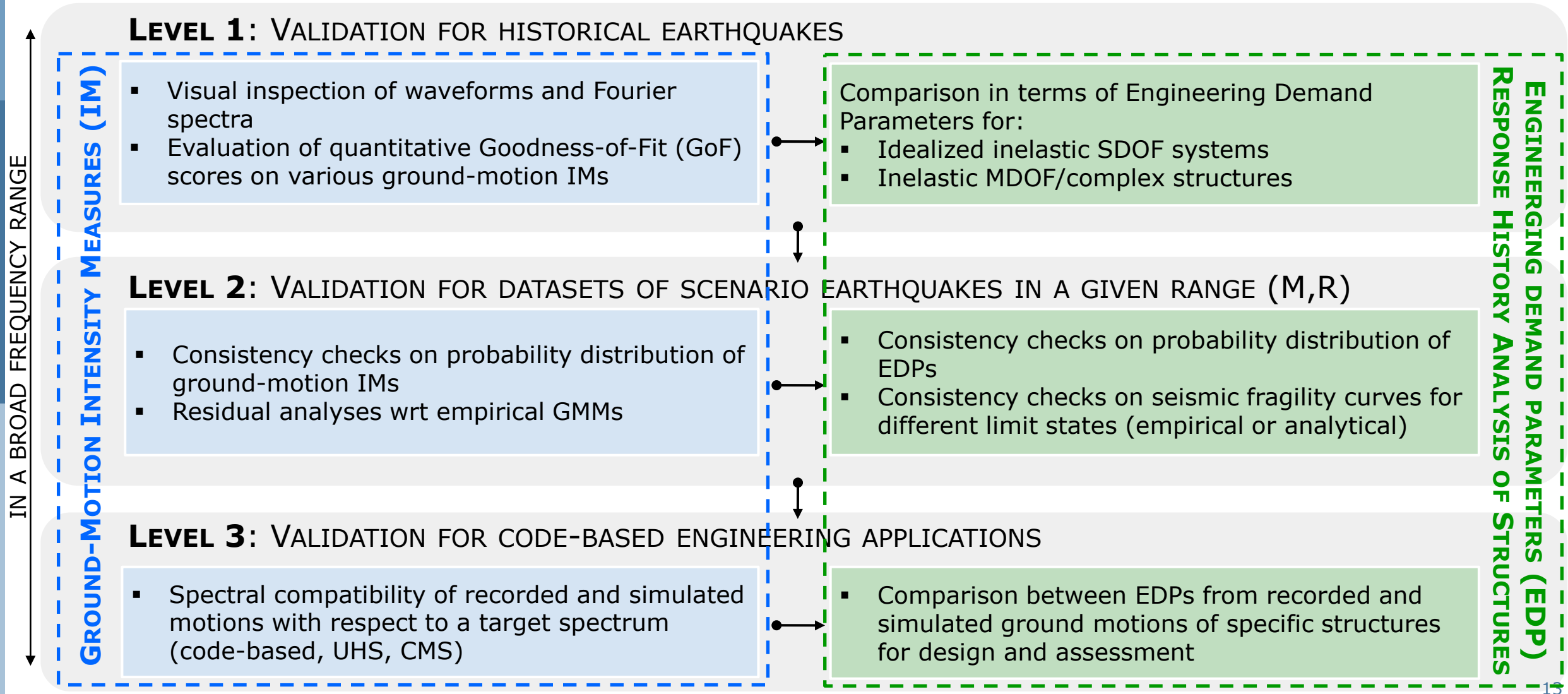
Paolucci et al. (2018) BSSA

Multi-level validation framework for engineering utilization of simulated motions

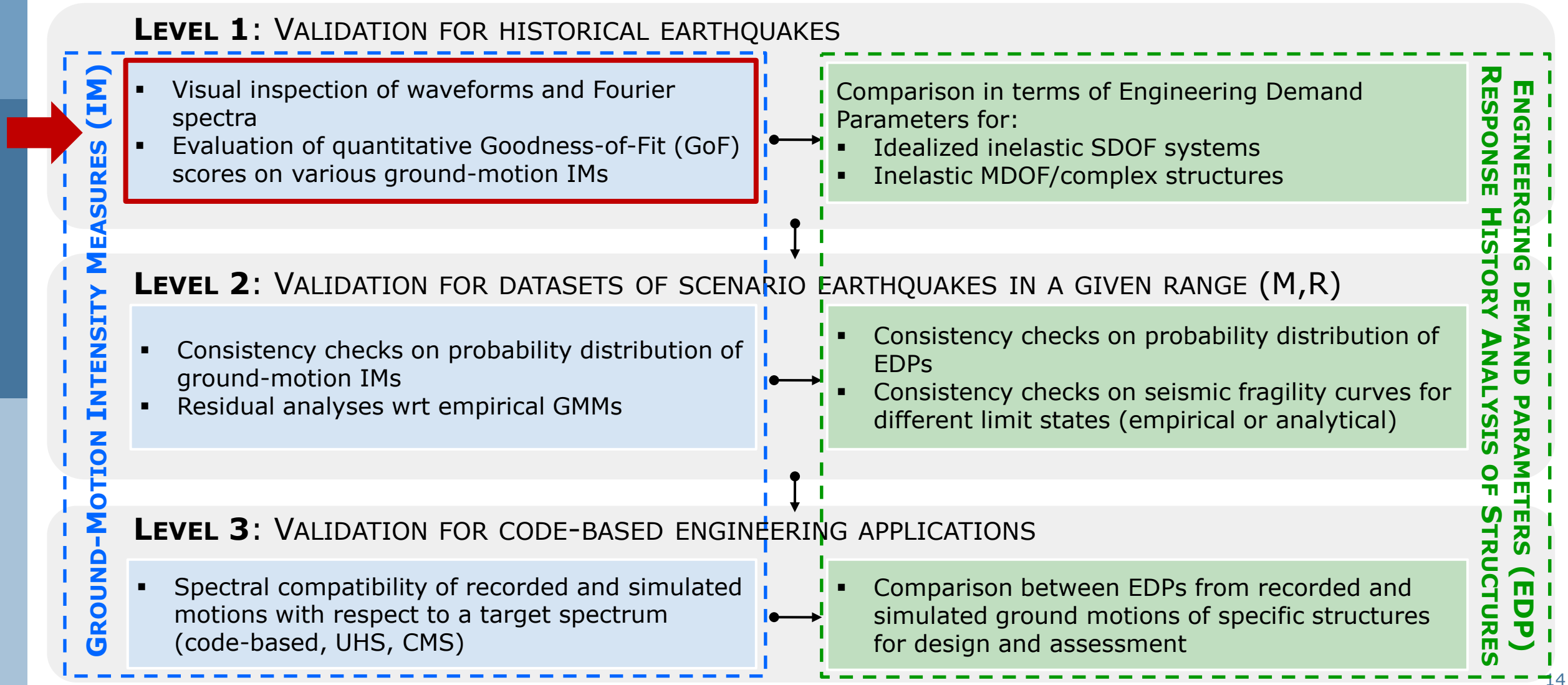
- To build confidence in engineering use of numerical simulations, simulated ground motions need to be validated in a comprehensive way

- In general, validation evaluates whether a simulation is representative of reality as measured using experimental data

Multi-level validation framework for engineering utilization of simulated motions



Multi-level validation framework for engineering utilization of simulated motions



Case studies of PBS by SPEED

Case Study	Fault (SoF)	M_w	Model size (km^3)	f_{max} (Hz)	Validation (V)/Scenario(S)	References
Grenoble, France	Belledonne (SS)	6.0	41x50x8	3	V: Benchmark	Stupazzini et al. (2009)
Gubbio plain, Italy	Colfiorito (NF)	6.0	85x62x10	3	V: 26 Sept 1997	Smerzini et al. (2011)
Tagliamento plain, Italy	Gemona Faults (TF)	6.1	57x53x12	2.5	V: 15 Sept 1976	Smerzini (2010)
L'Aquila, Italy	Paganica (NF)	6.2	58x58x20	2.0	V: 6 Apr 2009	Evangelista et al. (2017)
Sulmona, Italy	Mt. Morrone (NF)	6.0	49x42x13	2.5	S(#10)	Villani et al. (2014)
		6.5			S(#10)	
Christchurch, New Zealand	Lyttelton (TF)	6.3	60x60x20	2.0	V: 22 Feb 2011	Guidotti et al. (2011)
Po Plain, Italy	Mirandola (TF)	6.0	74x51x20	1.5	V: 29 May 2012	Paolucci et al. (2015)
Marsica, Italy	Fucino (NF)	6.7	56x46x20	2.0	V: 13 Jan 1915	Paolucci et al. (2016)
Thessaloniki, Greece	Gerakarou (NF)	6.5	82x64x31	1.5	V: 20 Jun 1978	Smerzini et al. (2017)
	Anthemountas (NF)	7.0			S(#1)	Smerzini et al. (2018)
Norcia, Italy	Mt.Vettore-Mt.Bove (NF)	6.5	50x40x21	1.5	30 Oct 2016 + S(#7)	Özcebe et al. (2019)
		5.8			S(#1)	
		5.5			S(#1)	
Wellington, New Zealand	Wellington–Hutt (SS)	7.1-7.2	60x56x26	1.5	S(#40 -#42)	On-going
		7.4-7.4			S(#25 - #14)	
Mexico City	NF	3.2	60x60x10	1	V: 17 July 2019	Hernandez et al. (2022)
Santiago, Chile	San Ramon (TF)	5.2	97x77x19	2.0	V: 1 Apr 2010	Pilz et al. (2011)
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Istanbul, Turkey	North Anatolian Fault Marmara Sea (SS)	5.7	165x100x30	1.5	V: 26 Sept 2019	Infantino et al. (2021); Stupazzini et al. (2021)
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Beijing, China	Shunyi-Qianmen-Liangxiang (TF)	6.5	70x70x30	1.5	S (#15)	Antonietti et al. (2020)
		6.9			S (#10)	
		7.3			S (#5)	
Groningen, the Netherlands	NF (induced seismicity)	3.4	20x20x5	10	V: 8 Jan 2018	Paolucci et al. (2021)
Montelimar, France	La Rouvière (TF)	4.9	45x70x8.5	8	V: 11 Nov 2019	Smerzini et al. (2022)
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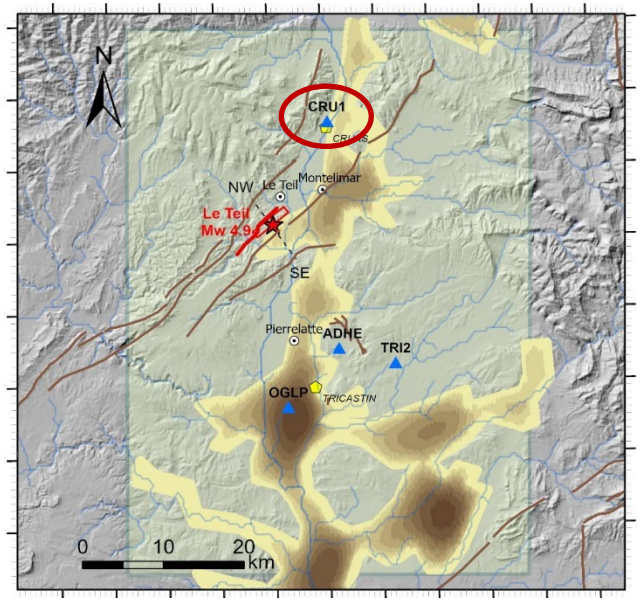
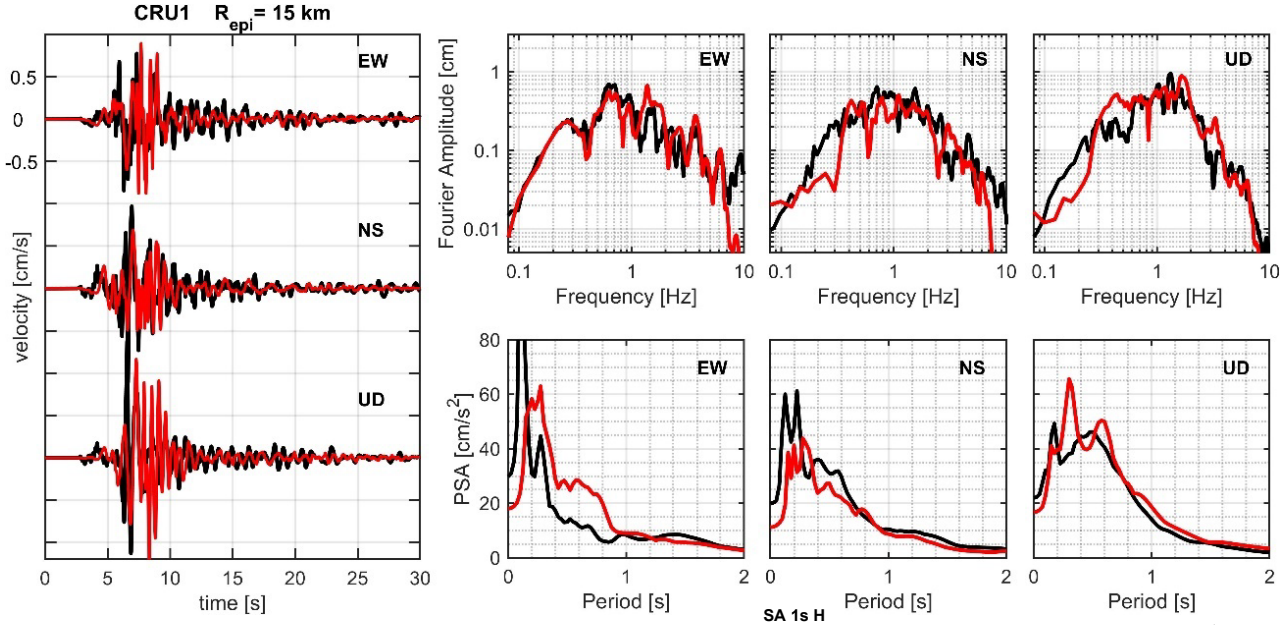
	Hinagu-Futagawa (SS)	6.1			V: 14 Apr 2016	
	Aso Caldera (SS)	5.5			V: 15 Apr 2016	

Validations for historical earthquakes

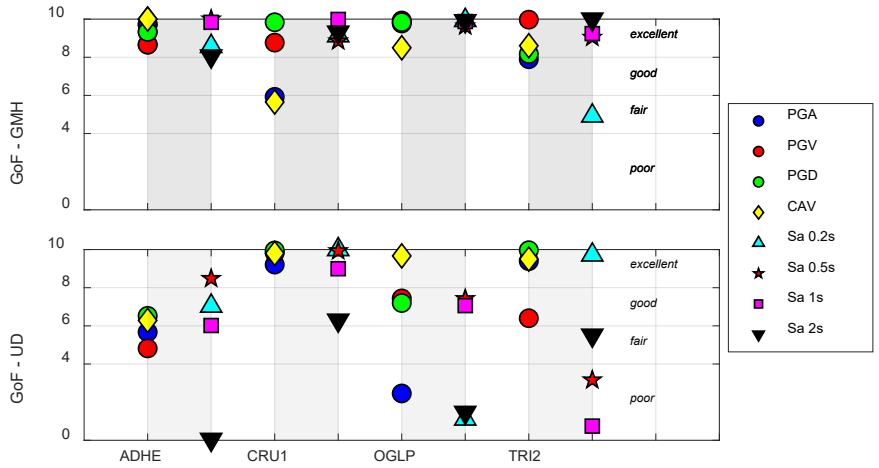
Comparison between simulated and recorded ground motions: the case of the Le Teil event

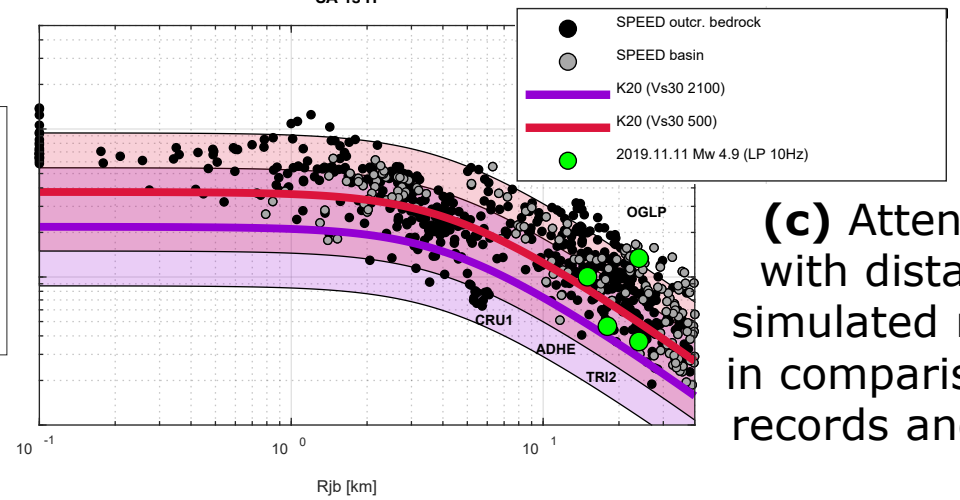




(a) Recorded Vs simulated waveforms and spectra at CRU1 station

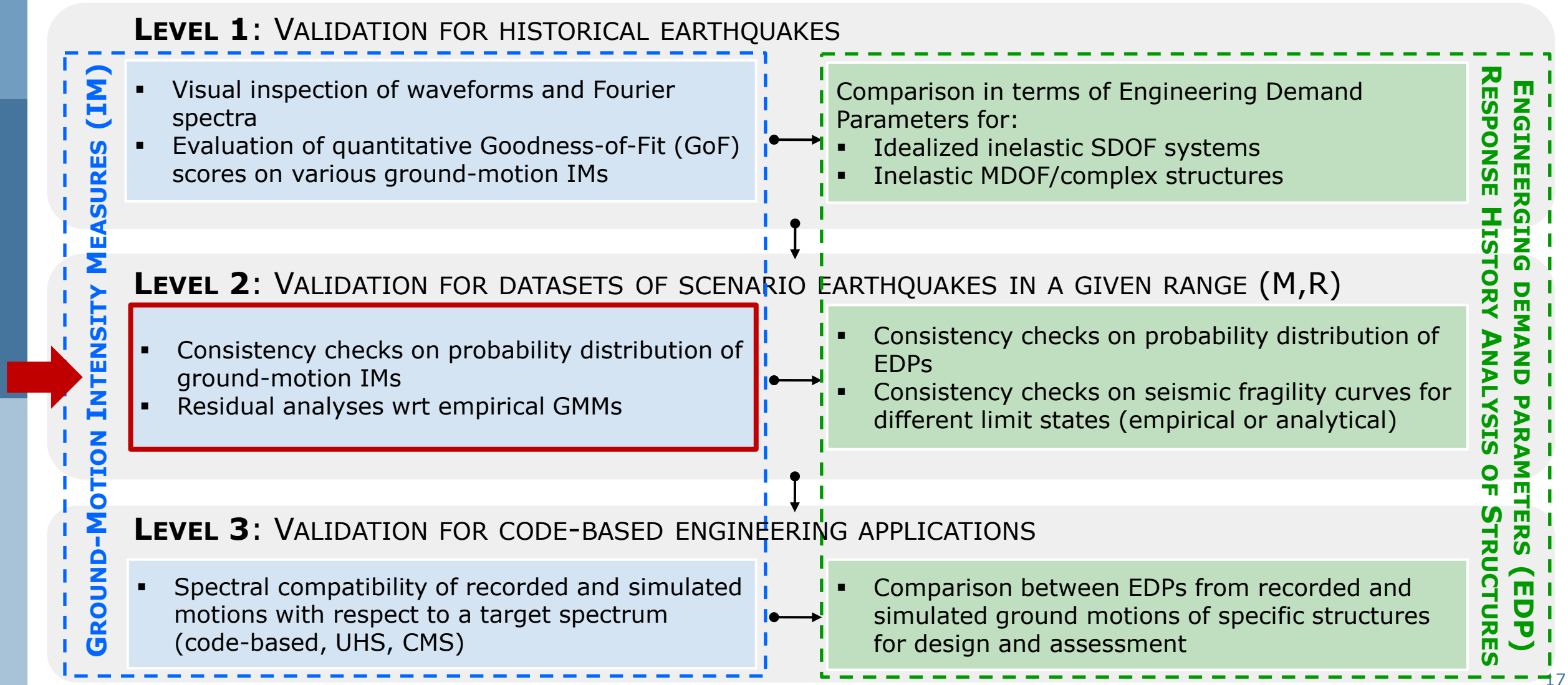
(b) GoF scores (Anderson, 2004) for different IMs on horizontal and vertical components





(c) Attenuation with distance of simulated motions in comparison with records and GMMs

Multi-level validation framework for engineering utilization of simulated motions



BB-SPEEDset: an open-source dataset of BB near-source ground motions from PBS

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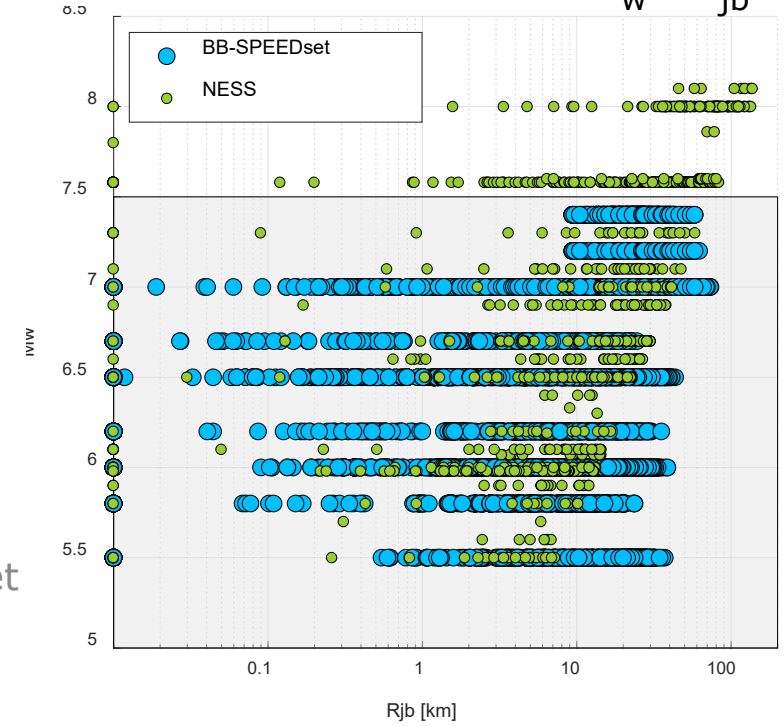
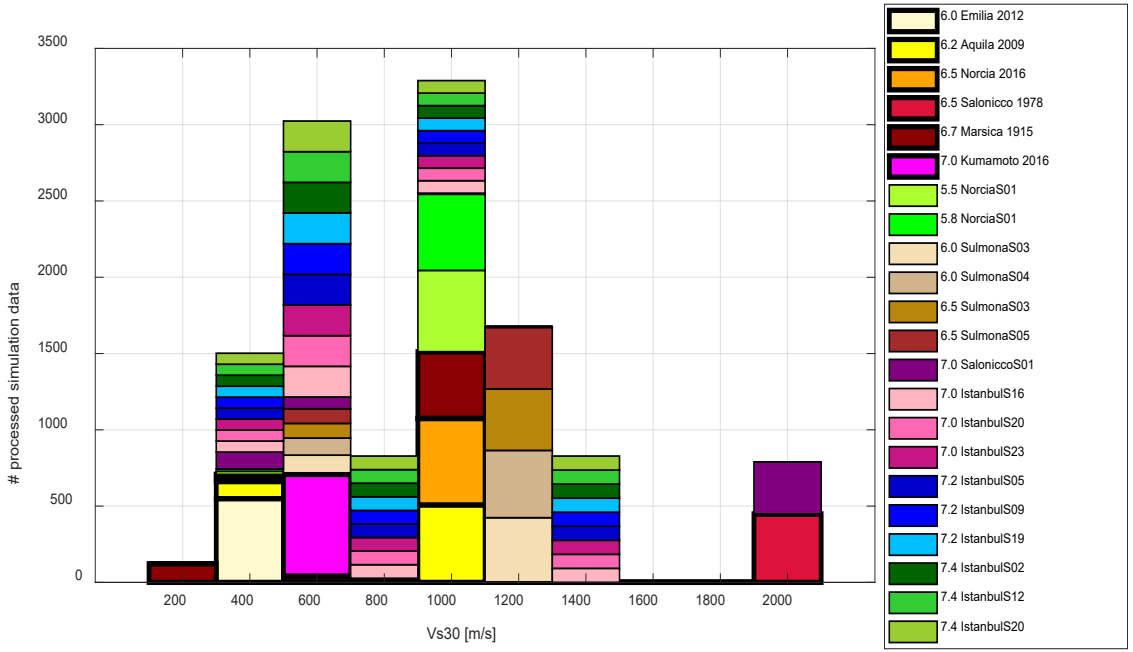
Scenarios in the BB-SPEEDset (v1.0)

BB-SPEEDset: an open-source dataset of BB near-source ground motions from PBS

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

NESS2.0 (Sgobba et al. 2021)





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.

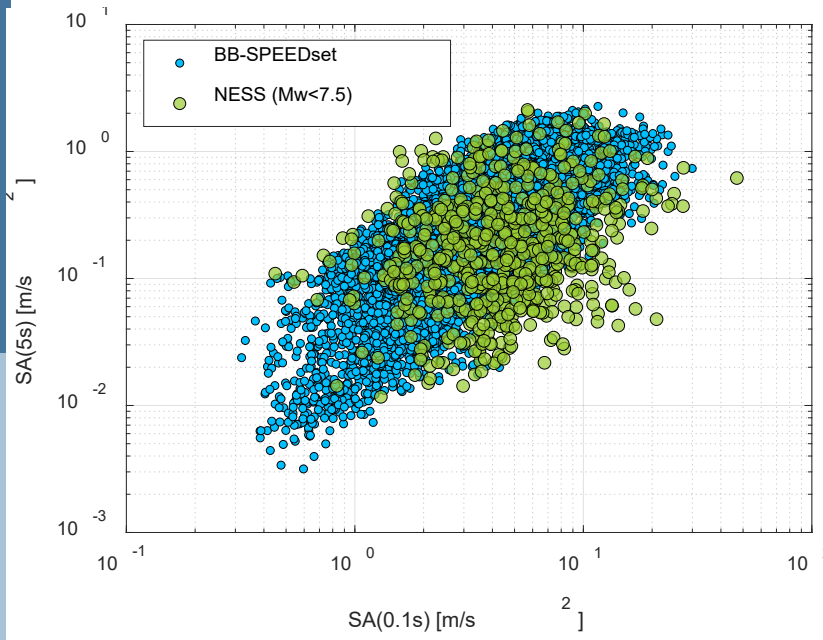
https://doi.org/10.1785/0120210089 **Article history**

Open-source:
http://speed.mox.polimi.it/bb-speedset/

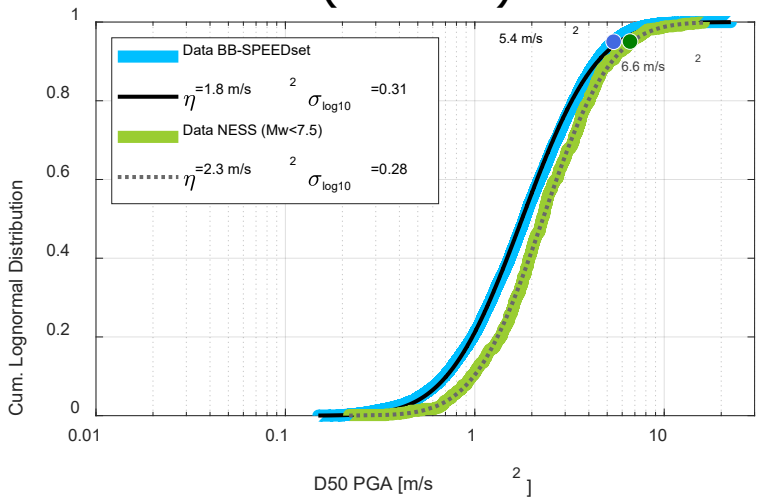
- Flatfile
- 3-component broadband accelerograms (~12’000)

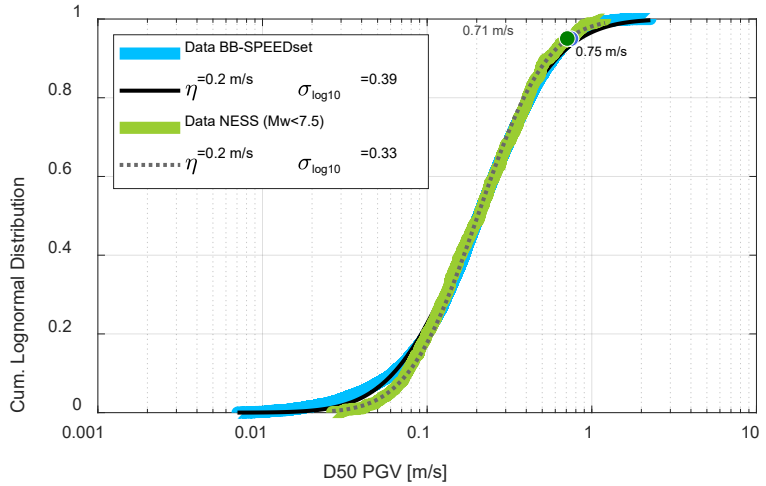
BB-SPEEDset: consistency checks with recorded near-source dataset (NESS2 @INGV)

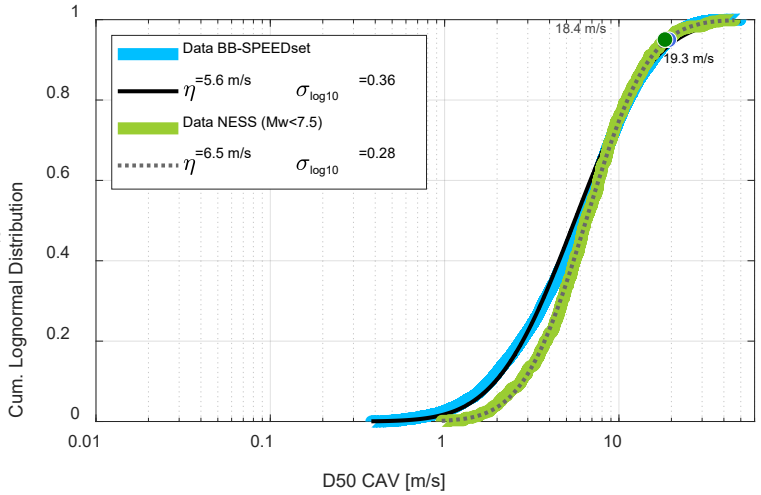
SA(0.1s)-SA(5s) correlation, in comparison with NESS2

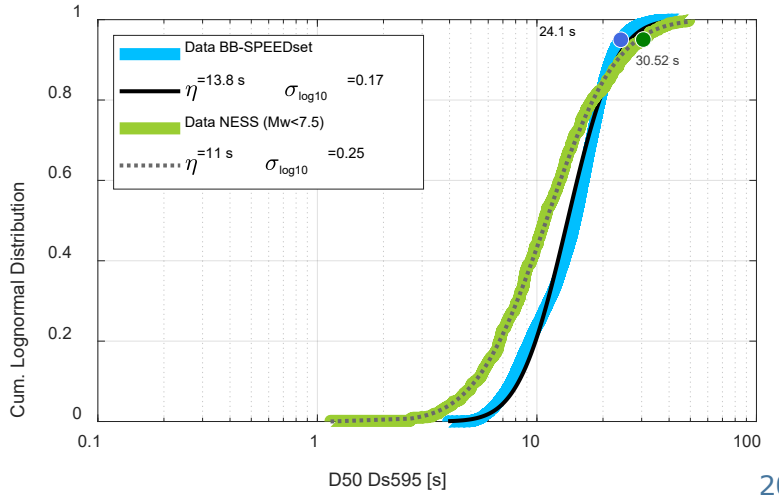


Cumulative distribution functions of PGA, PGV, CAV and duration (Ds595) from BB-SPEEDset and from NESS2



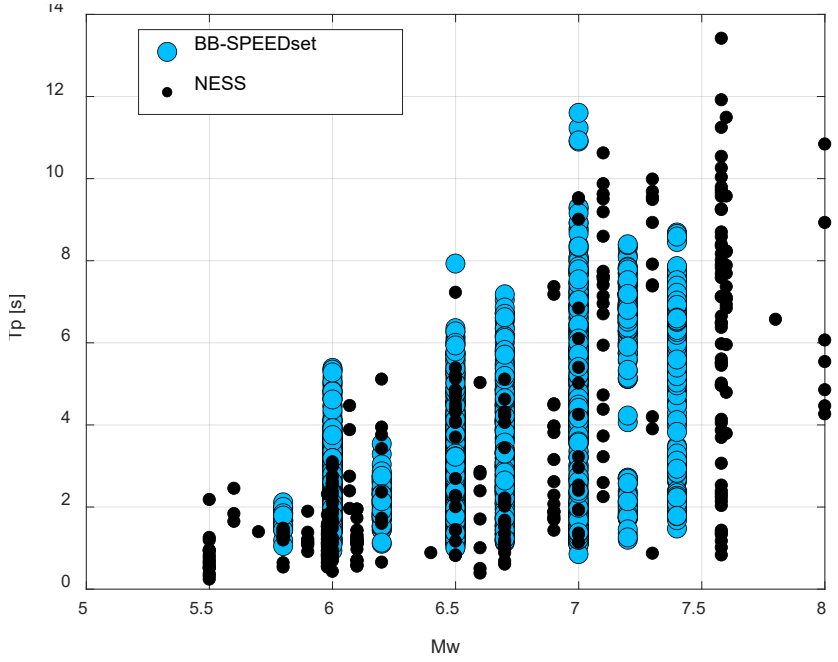


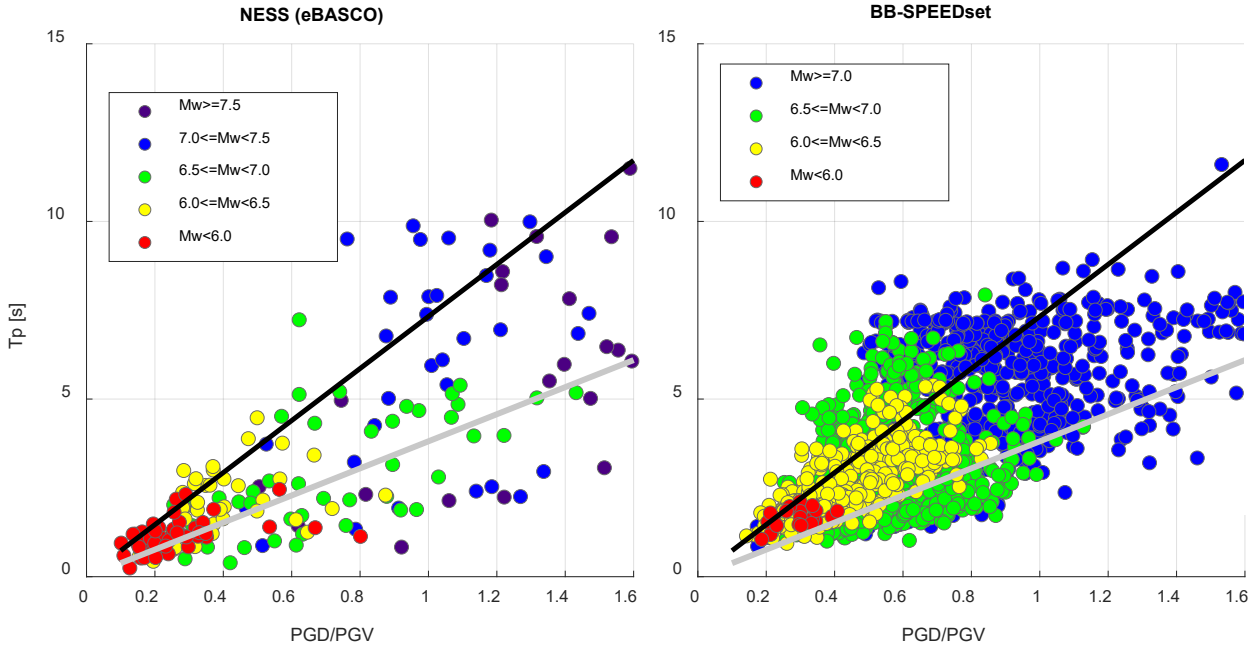


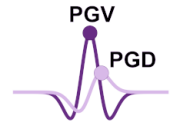


BB-SPEEDset: consistency checks with recorded near-source dataset (NESS2 @INGV)

Identification of pulse-like waveforms and of corresponding pulse period T_p according to the algorithm by Shahi and Baker (2014)



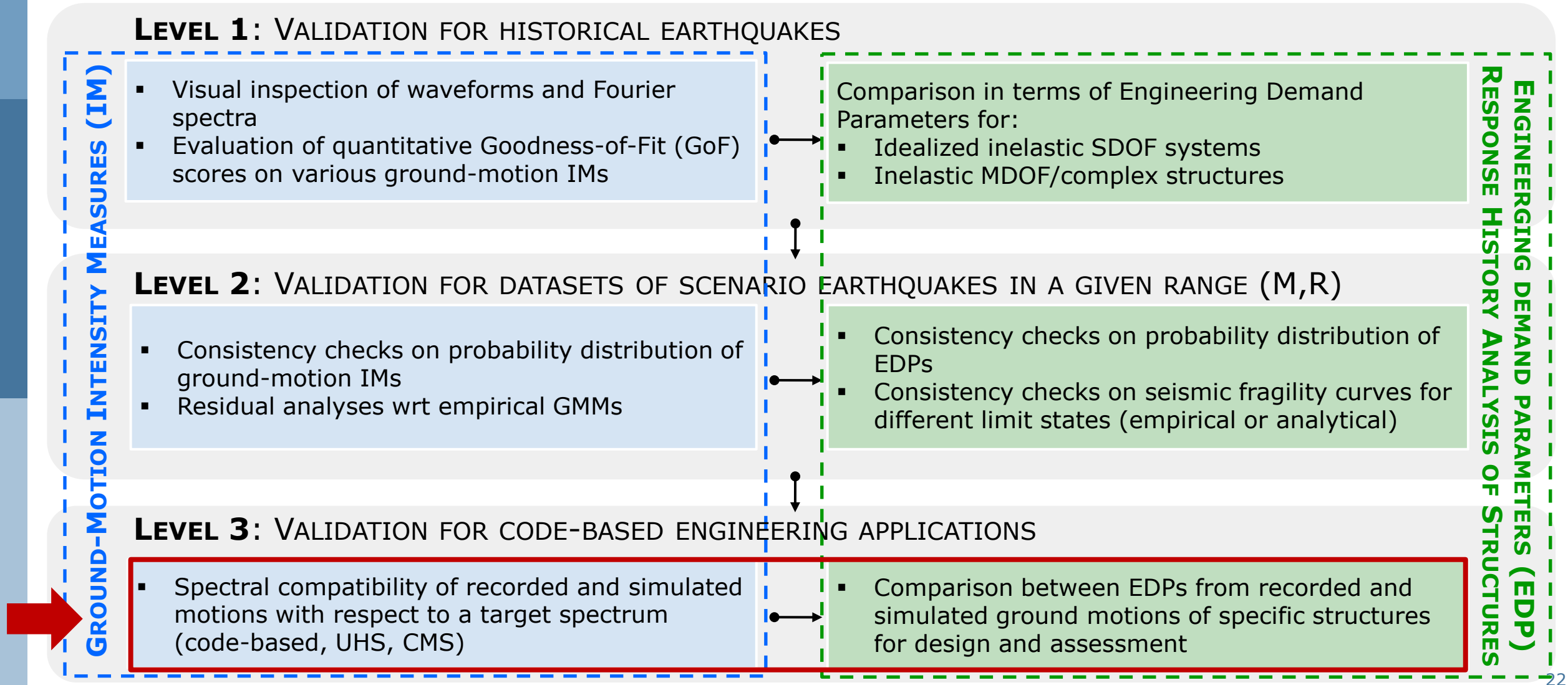




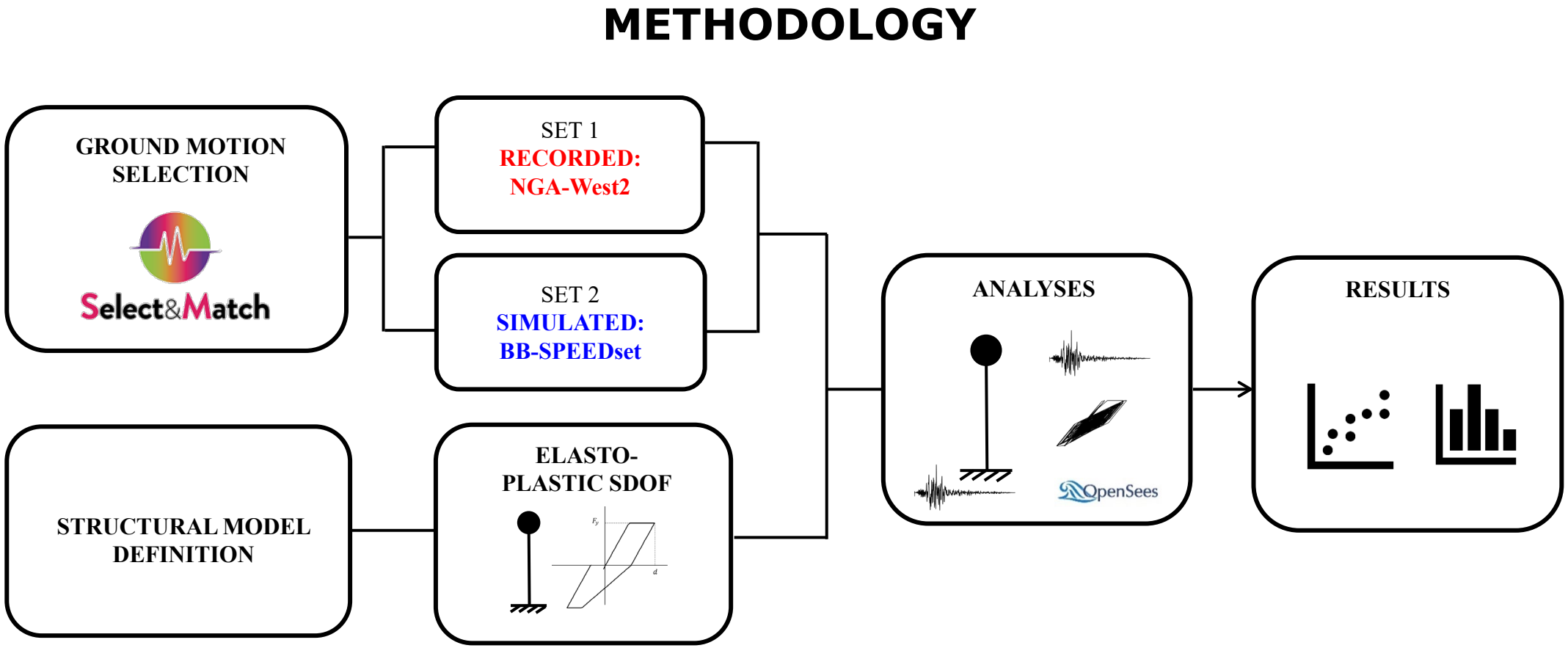
$$T_p = \pi\sqrt{2e}\,\frac{PGD}{PGV}$$

$$T_p = \frac{2\pi}{\sqrt{e}}\,\frac{PGD}{PGV}$$

Multi-level validation framework for engineering utilization of simulated motions



Validation of simulated ground motions for code-based engineering applications



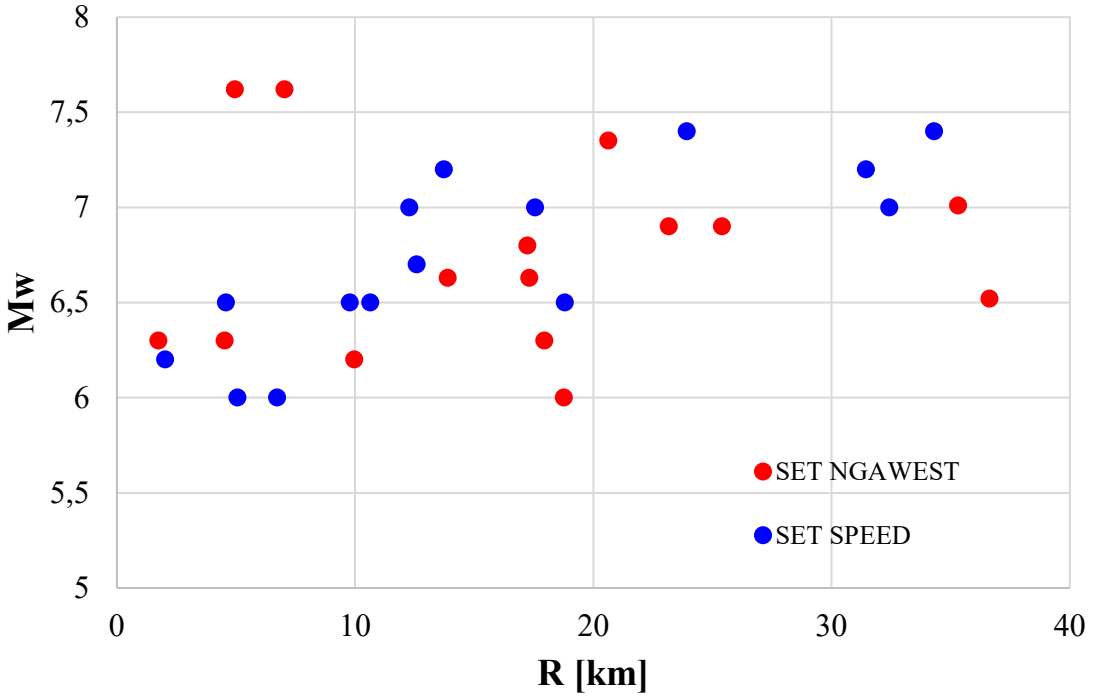
Software tool for ground motion selection enhanced by simulated datasets

Select&Match

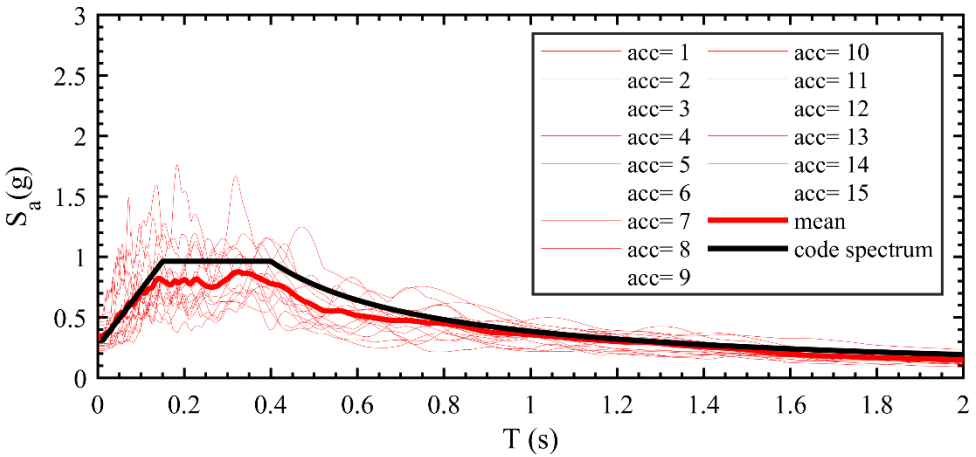
Versio

Consistent selection criteria:

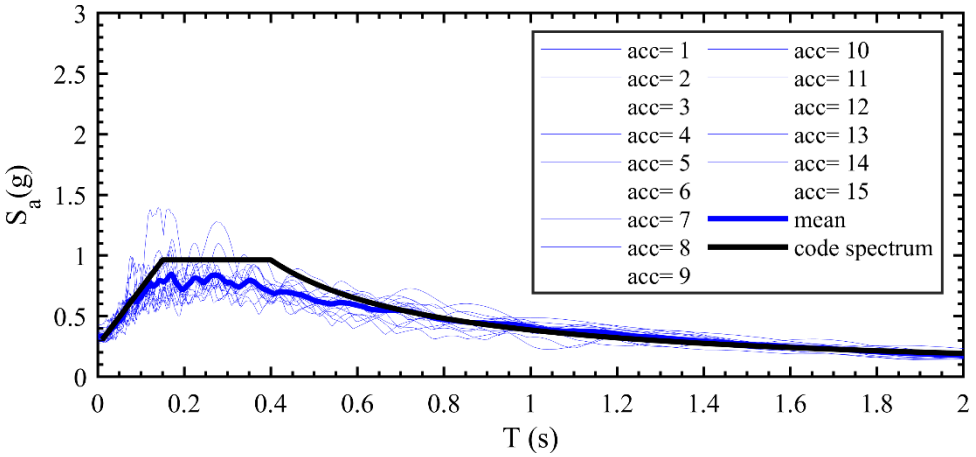
- 975 yrs return period elastic design spectrum (Central Italy)
- Reference rock site
- T=0.1-4 s within prescribed upper and lower tolerances
- Unscaled accelerograms



RECORDED SET: NGA-West2



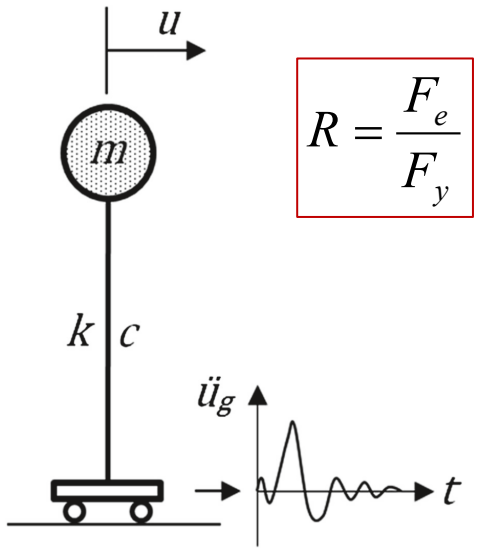
SIMULATED SET: BB-SPEEDset



Structural model and inelastic EDPs

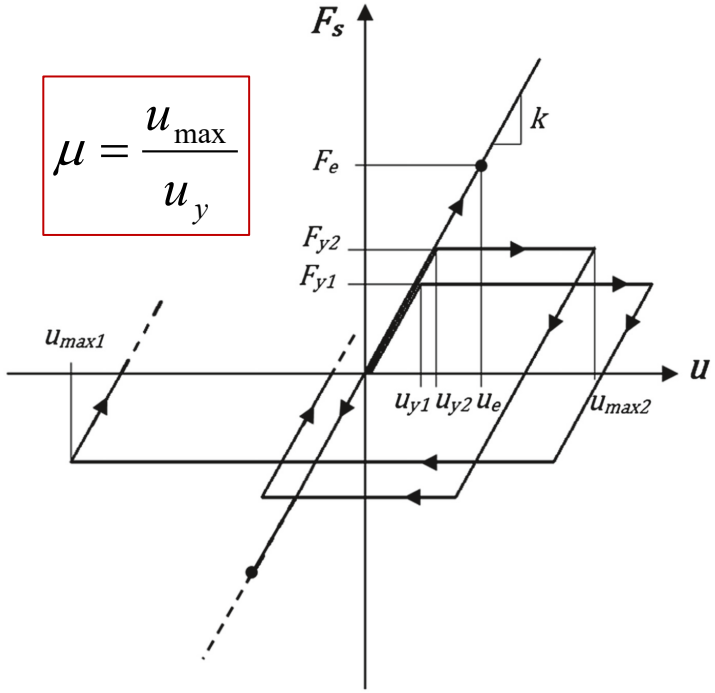
Inelastic SDOF systems with:

- Elasto-plastic backbone curve (EPP)
- Vibration period from T=0.1 to 1.5 s
- Strength reduction factors R=2, 4, 6
- Constant-strength systems

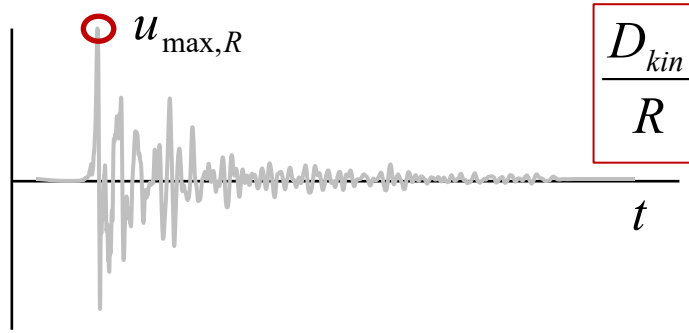


$$R = \frac{F_e}{F_y}$$

$$\mu = \frac{u_{\max}}{u_y}$$

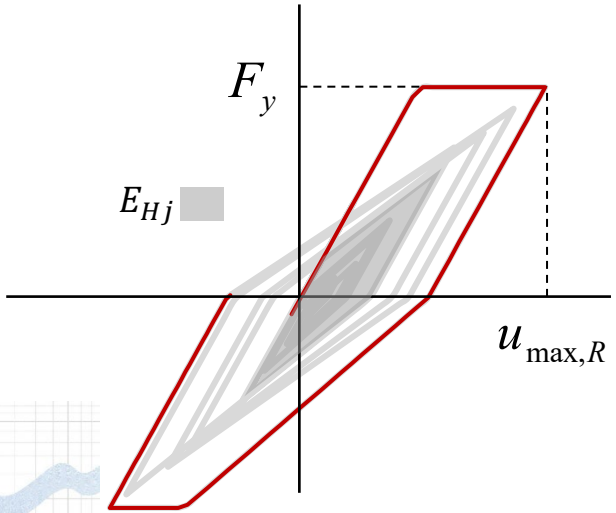


- Peak Response: displacement ductility over strength reduction factor



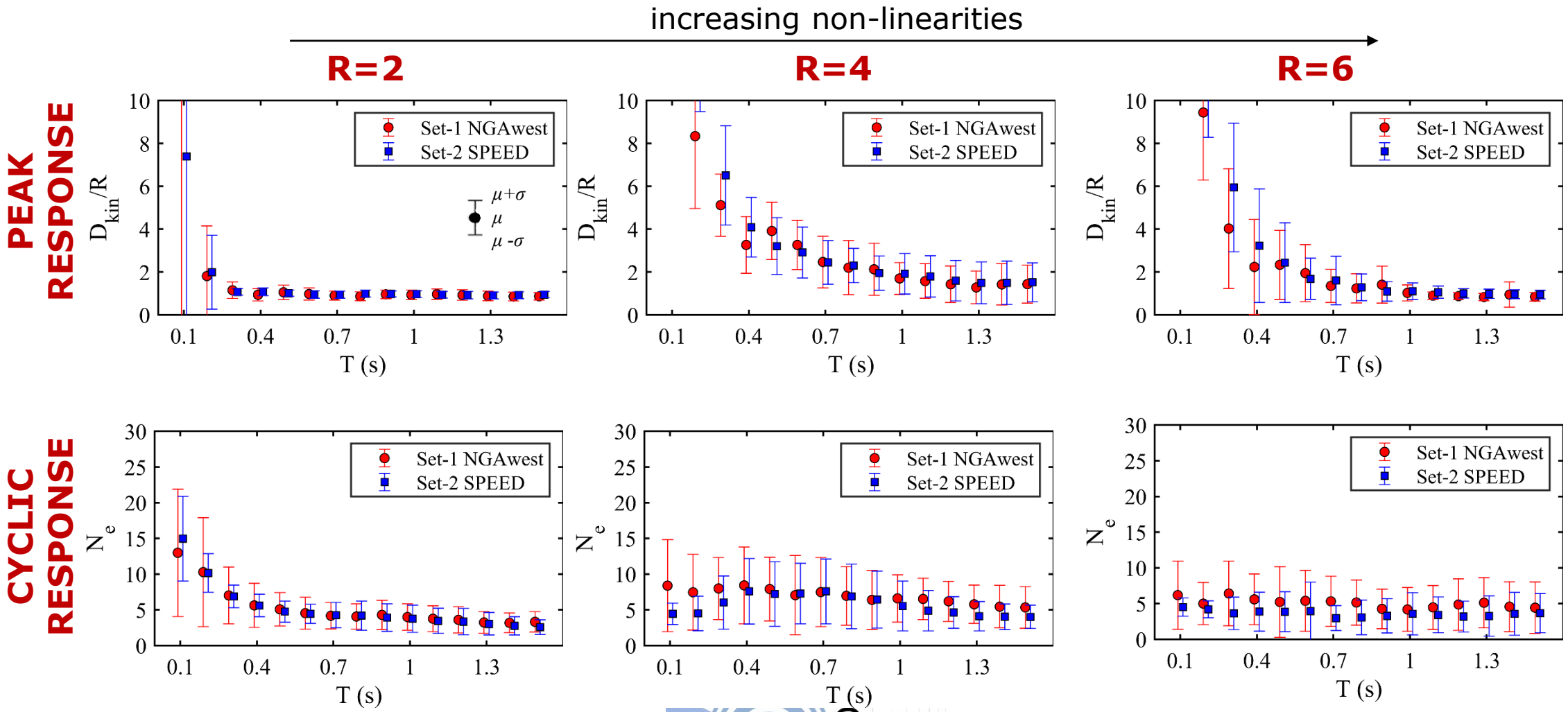
$$\frac{D_{kin}}{R} = \frac{u_{\max}}{R \cdot u_y}$$

- Cyclic Response: equivalent number of hysteresis cycles



$$N_e = \frac{\sum E_{Hj}}{F_y \cdot \left(u_{\max} - u_y\right)}$$

Statistical distribution of EDPs from recorded and simulated ground-motion sets



Conclusions

- PBS are gaining increasing interest because of their potential to complement recordings when they are sparse (near-source conditions, complex geology and spatial variability studies)
- Building confidence in utilization of regional-scale PBS for earthquake engineering applications requires a comprehensive validation of simulated ground motions in a broad frequency range
- Validation should encompass consistency checks on both ground-motion IMs and EDPs, from historical and sets of scenario earthquakes, to encourage a broader use of PBS in both ground motion characterization studies and response history analyses of structures
- Availability and dissemination of simulated ground motion datasets, such as BB-SPEEDset, is a key step for this purpose.

Acknowledgements

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M. Vanini

M. Stupazzini

S. Sangaraju

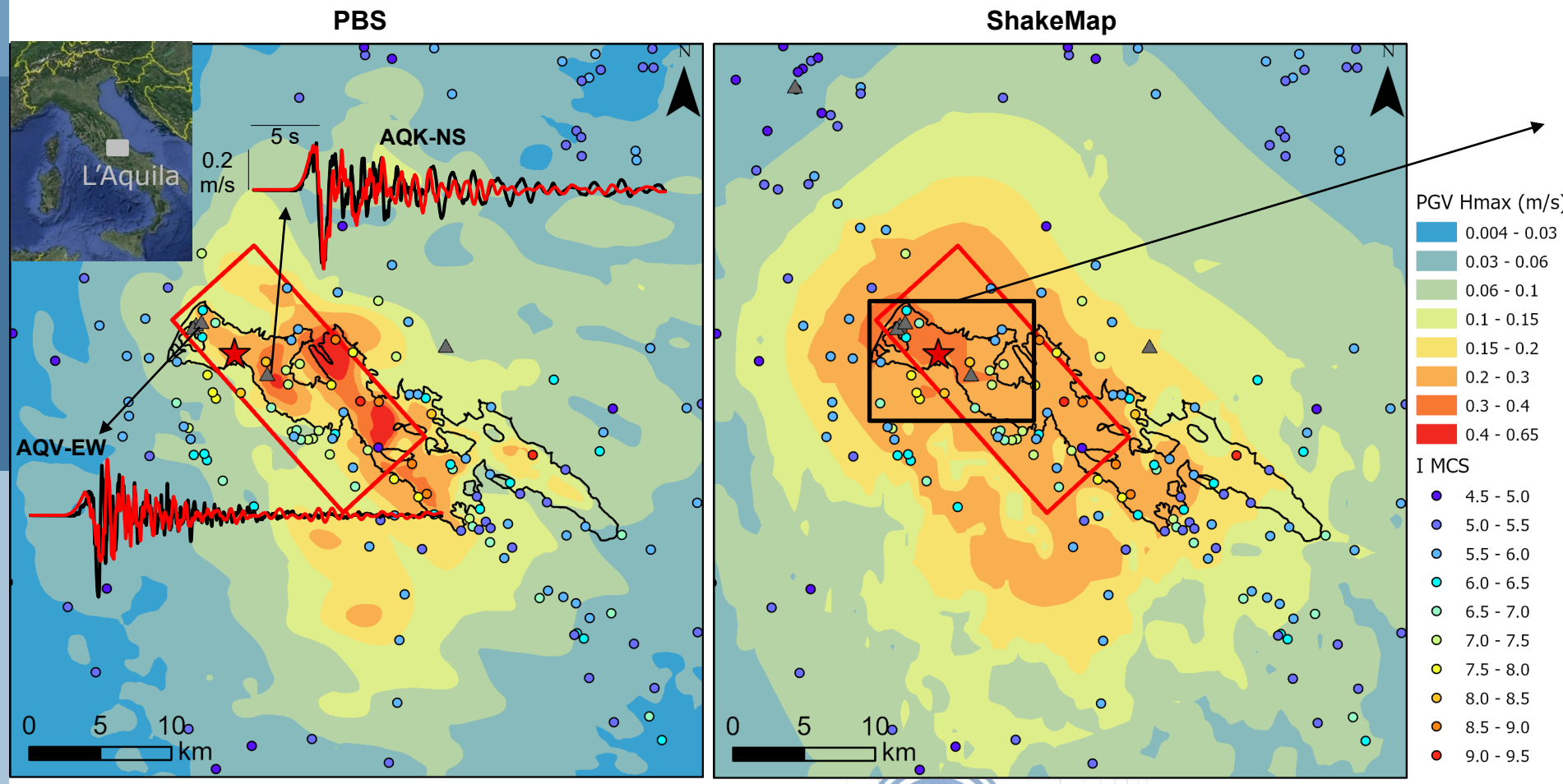
C. Amendola

J. Lin

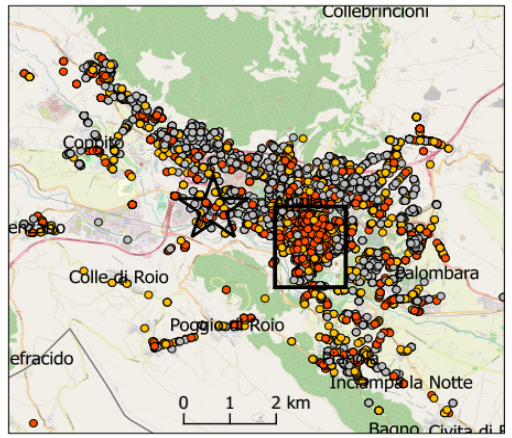
ΣIGMA2

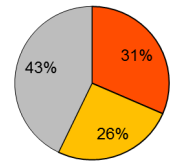
Thank you!

Building empirical fragility curves from PBS: the case of the 2009 L'Aquila earthquake



L'Aquila damage database



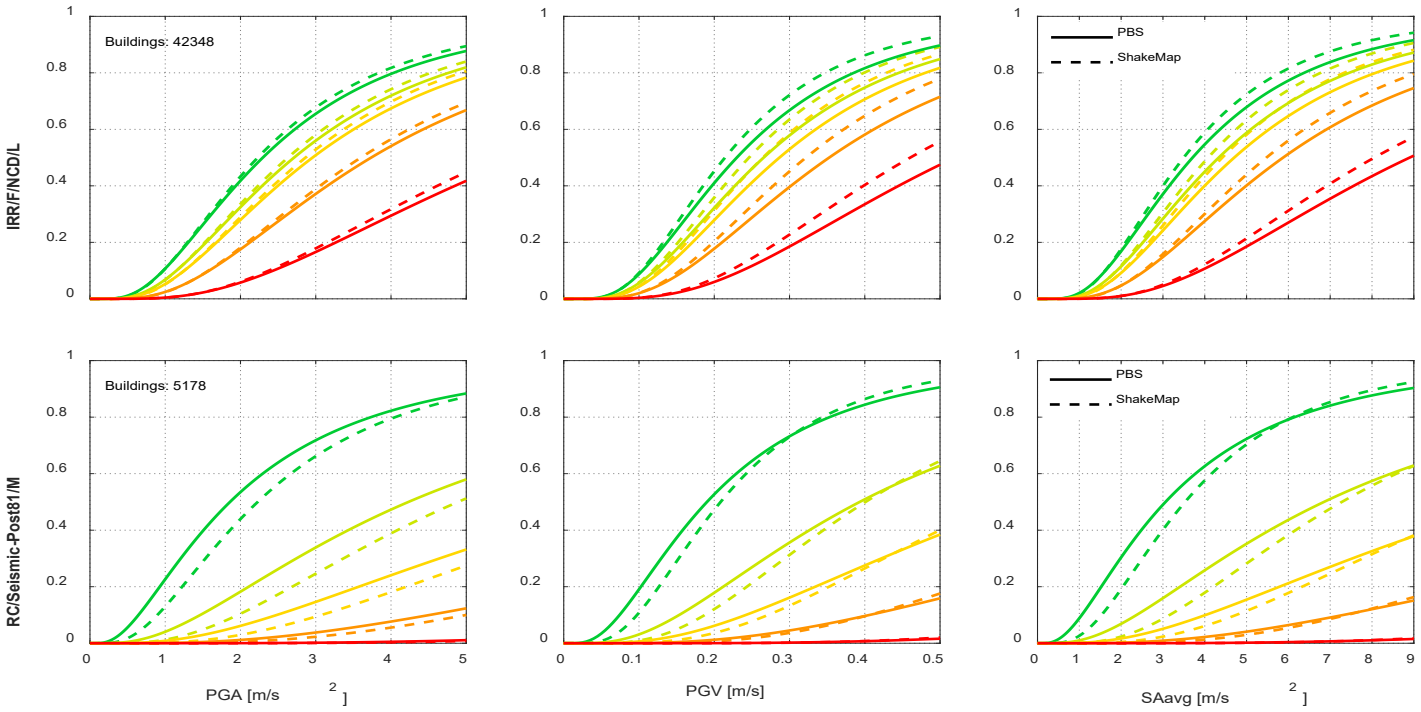


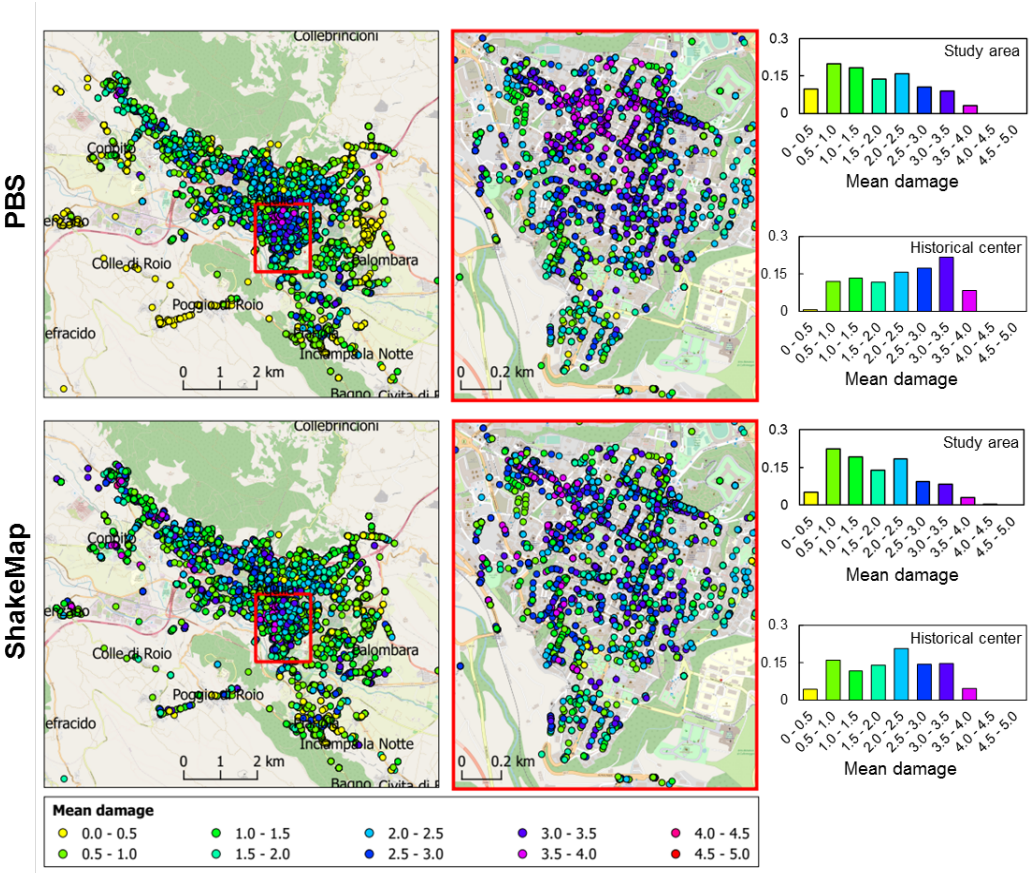
Construction material

- Irregular layout or poor-quality masonry
- Regular layout and good-quality masonry
- RC

Rosti et al. (2022)

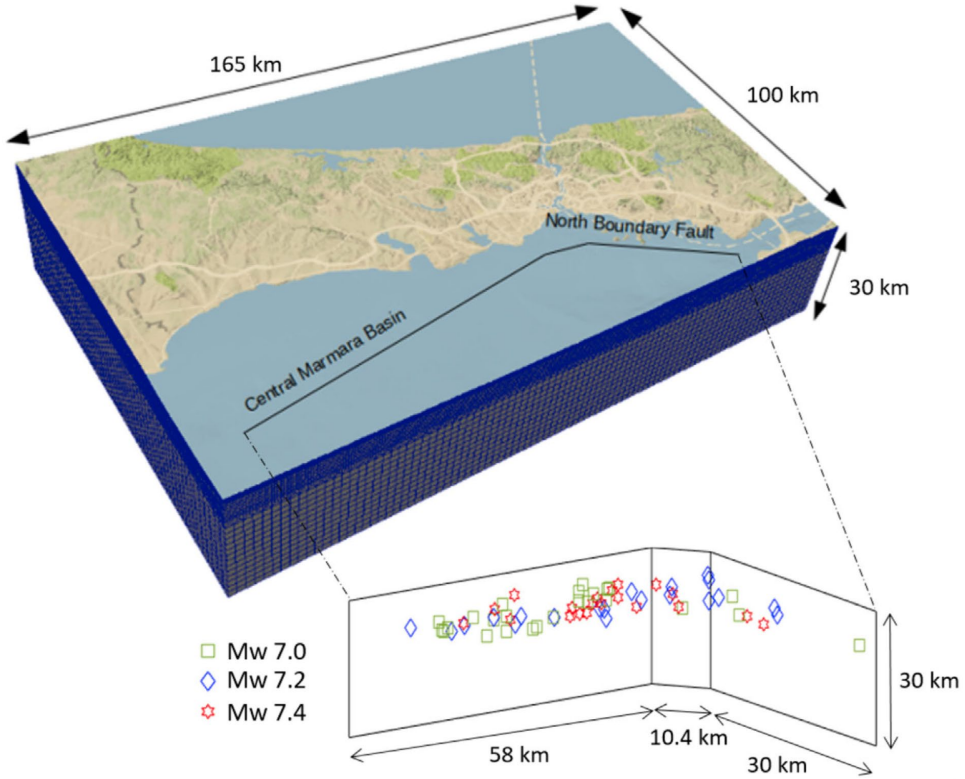
Building empirical fragility curves from PBS: the case of the 2009 L'Aquila earthquake

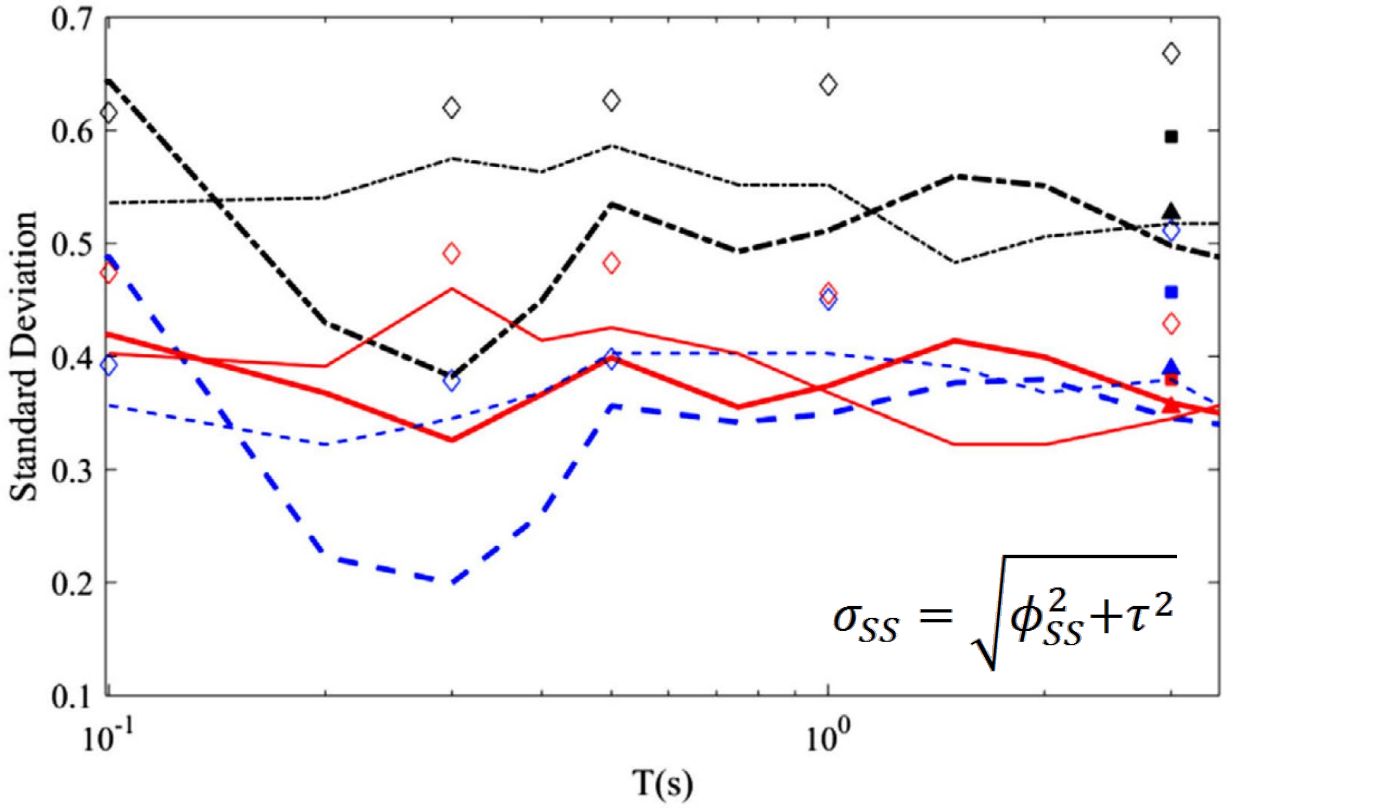




Assessing components of ground-motion variability from PBS

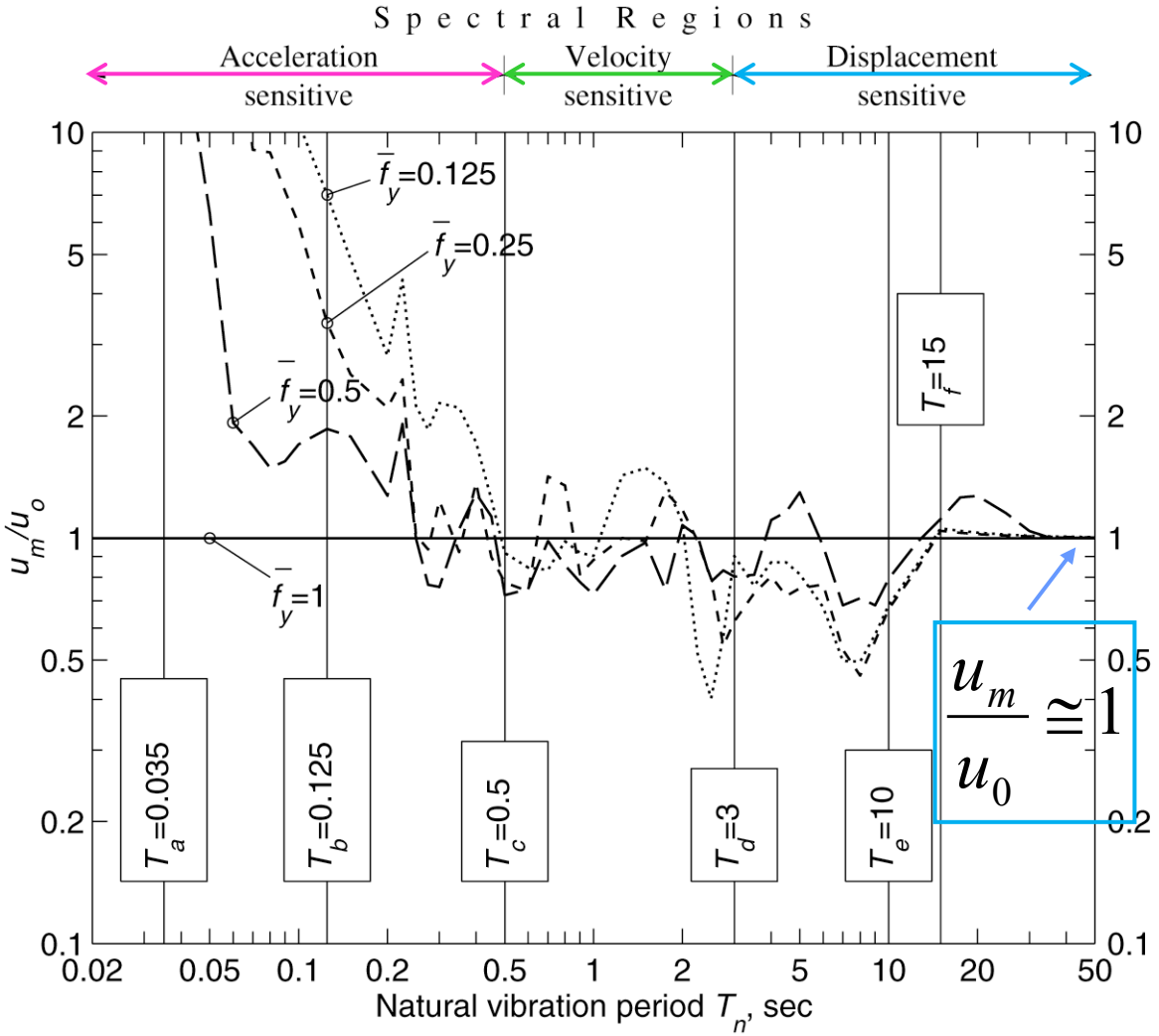
Istanbul case study





Stupazzini et al. (2021)

Response of elasto-plastic SDOF systems as a function of period



- Displacement-sensitive region:

$$\frac{u_m}{u_0} \cong 1 \qquad \mu \cong R_y$$

- Velocity-sensitive region:

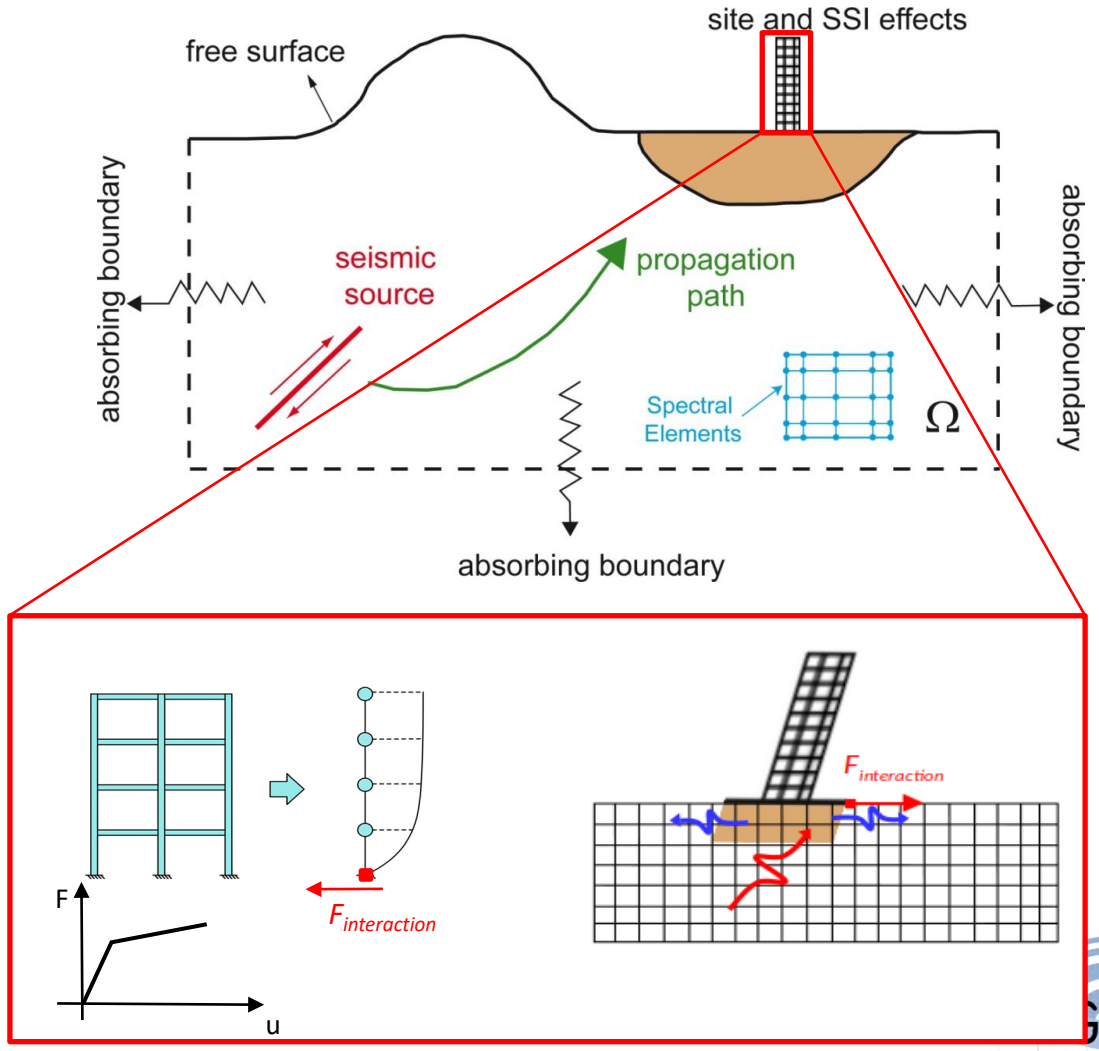
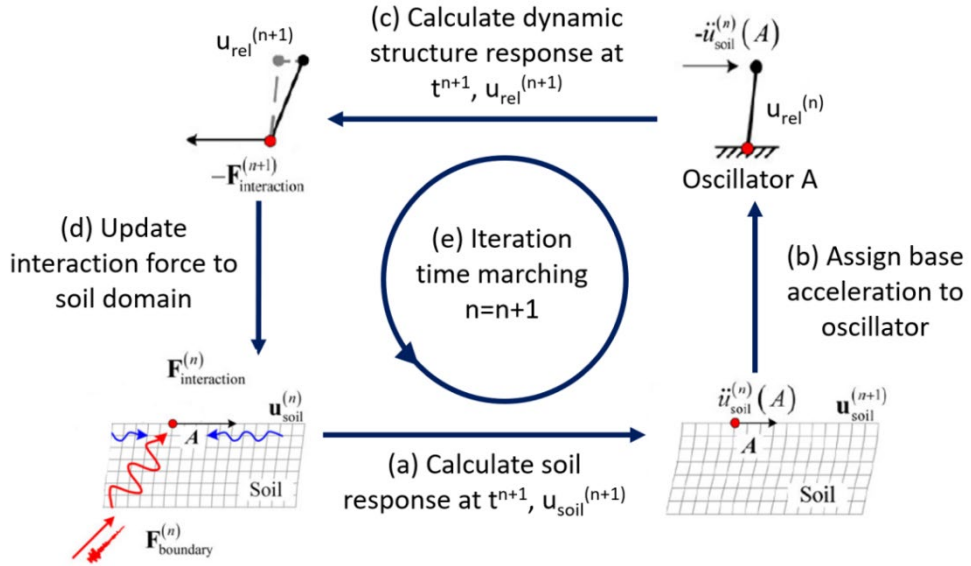
$$\frac{u_m}{u_0} \geq 1 \quad or \quad \frac{u_m}{u_0} \leq 1$$

- Acceleration-sensitive region:

$$\frac{u_m}{u_0} > 1 \;\; ; \mu >> R_y$$

u_m/u_0 increases decreasing yield strength

Fully coupled 3D PBS of earthquake ground motions and structural response



- Multi-scale numerical paradigm
- Non-linear SDOF/MDOF models for structural response
- Coupling algorithm embedded in SPEED kernel at each time step
- Effects of soil-structure interaction (SSI) and site-city interaction (SCI) accounted for