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POLITECNICO DI MILANO

3D physics-based numerical simulations: advantages and current limitations of a new frontier to earthquake ground motion prediction

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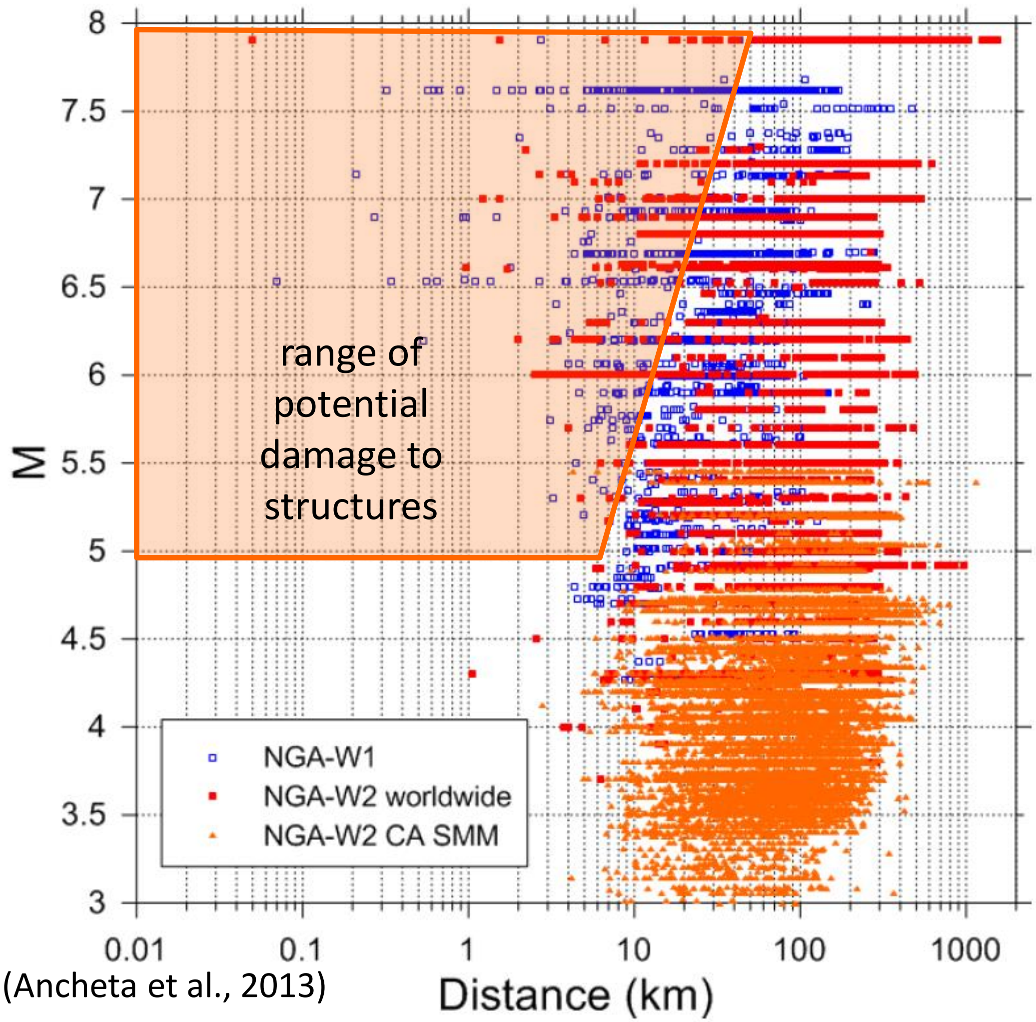
CONTENTS

- motivations and limits of 3D physics-based numerical simulations
- a numerical tool for 3D PBS: SPEED
- an application to Istanbul
- ANN2BB procedure to create broad-band ground motions from 3D PBS using Artificial Neural Networks
- how to exploit results of 3D PBS within probabilistic seismic hazard assessment

MOTIVATIONS AND LIMITS OF 3D PHYSICS-BASED NUMERICAL SIMULATIONS

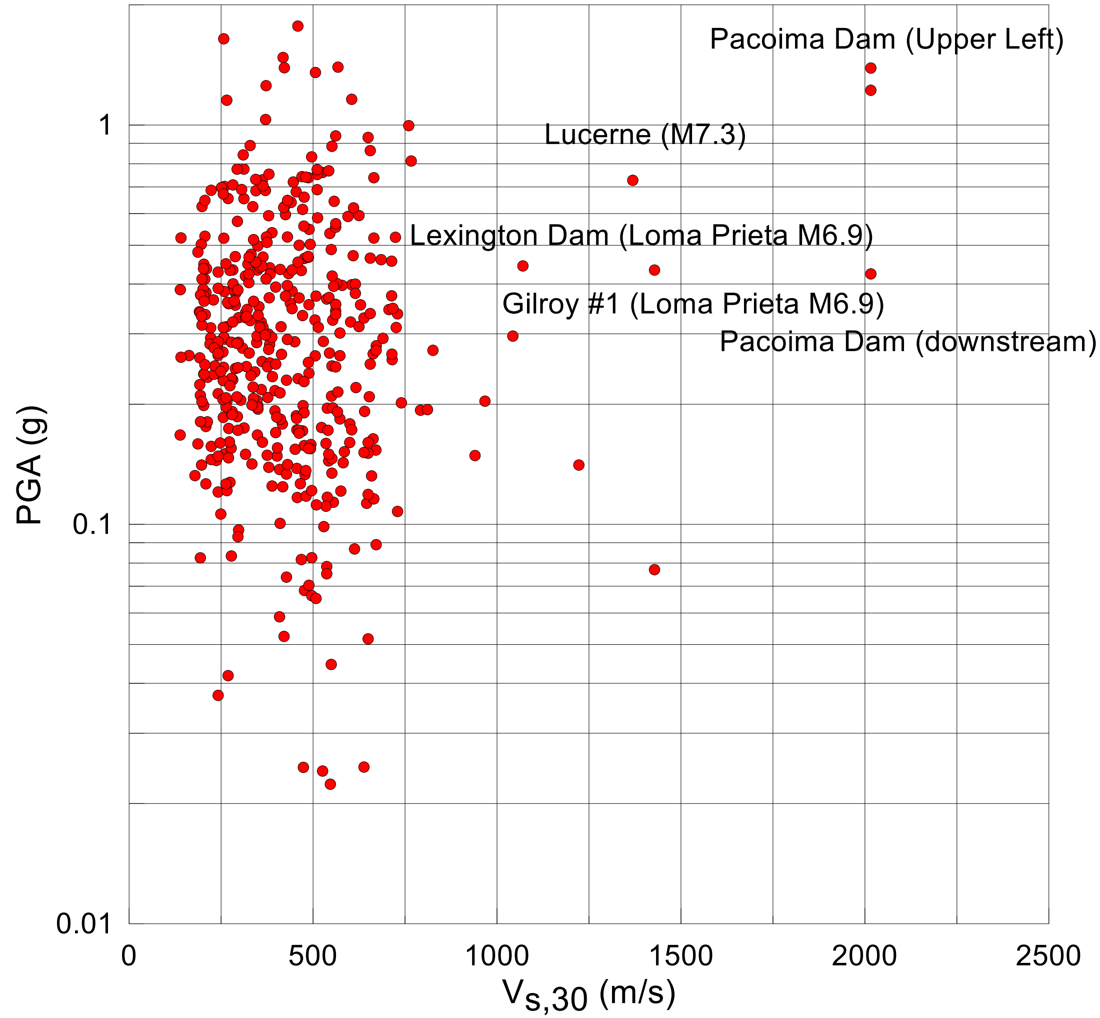
Availability of near-source records still insufficient



NGA West2 database (Ancheta et al., 2013)

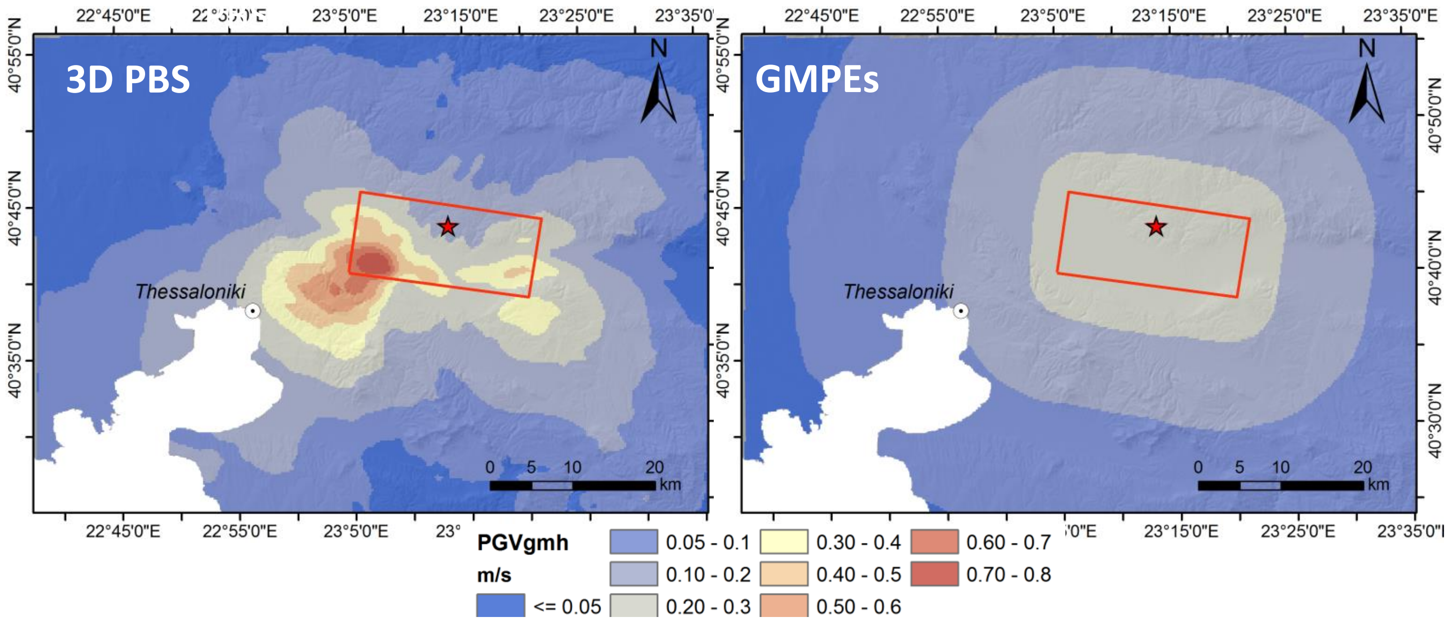
Motivations and Limits of 3D Physics-Based Numerical Simulations

Inhomogeneous distribution of site conditions and lack of records for rock and very soft soils



Selection of earthquake records from the NGA 2014 dataset, with M > 6 and R_{JB} < 20 km, as a function of $V_{S,30}$.

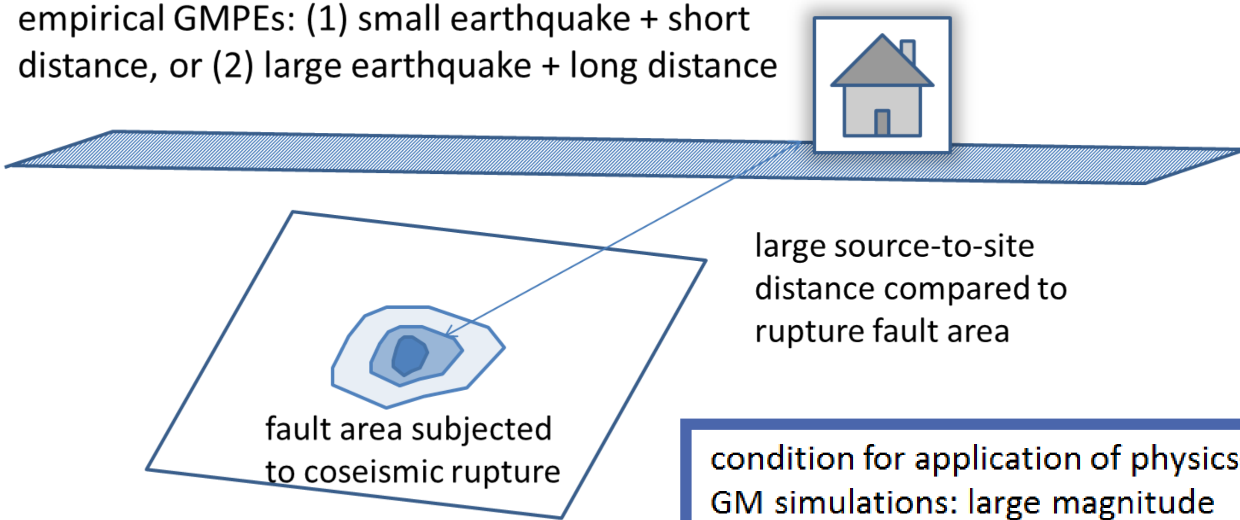
Spatial correlation issues on the use of GMPEs



Thessaloniki, Northern Greece
1978 Volvi earthquake

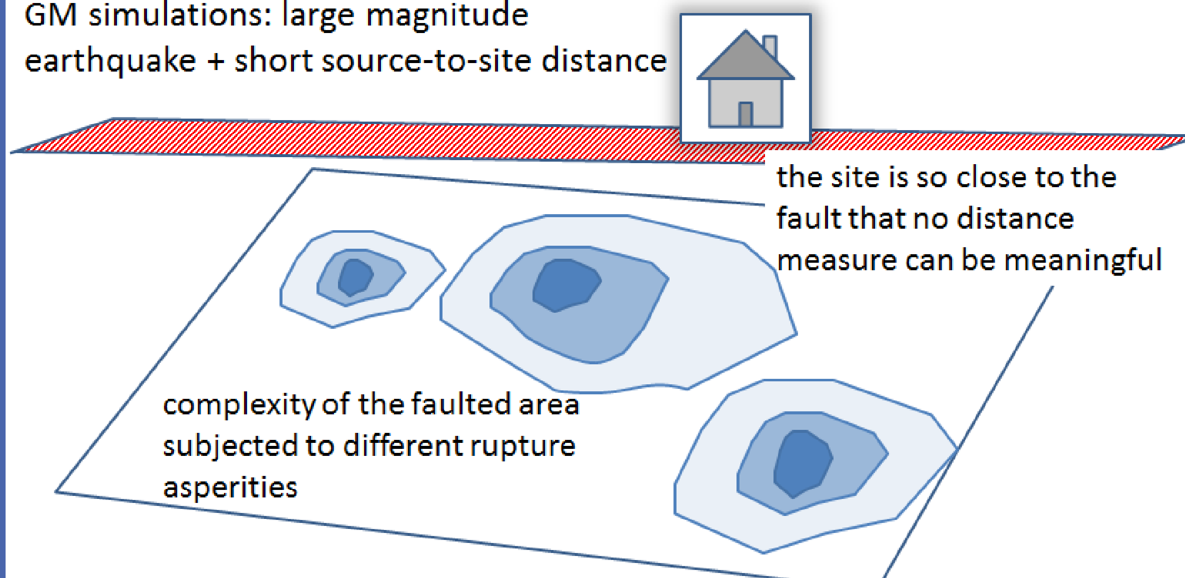
MOTIVATIONS AND LIMITS OF 3D PHYSICS-BASED NUMERICAL SIMULATIONS

"standard" condition for application of empirical GMPEs: (1) small earthquake + short distance, or (2) large earthquake + long distance



when relying on GMPEs ?

condition for application of physics-based GM simulations: large magnitude earthquake + short source-to-site distance



when relying on 3D PBSs ?

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SPEED – Spectral Elements in Elastodynamics with Discontinuous Galerkin

SPEED

speed.mox.polimi.it

publised **verification**

- ✓ Grenoble benchmark (2006)

published **validations** on near-source earthquake records

- ✓ L'Aquila (2009)
- ✓ Christchurch (2011)
- ✓ Po-Plain (2012)
- ✓ Norcia (2016)

MOX

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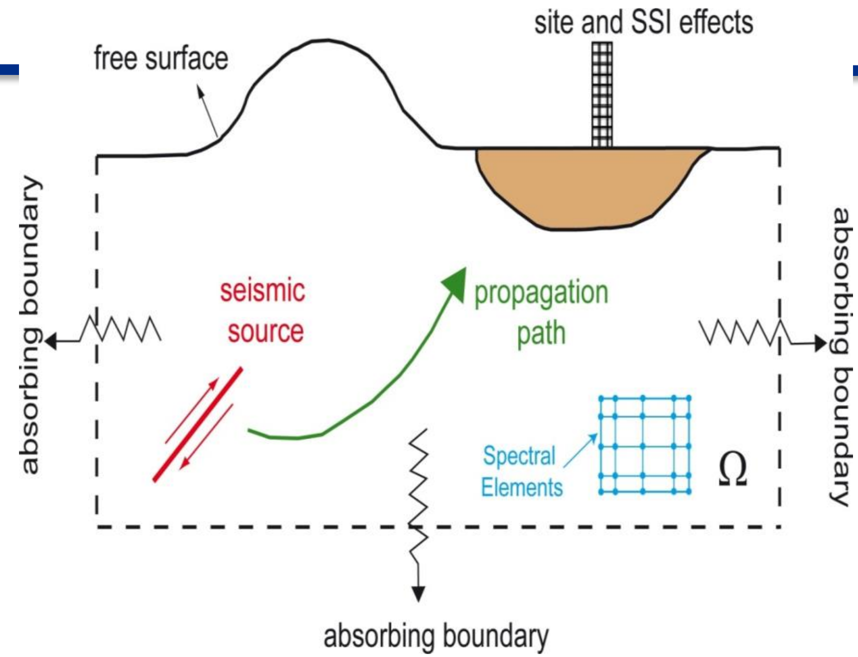
Dipartimento di Ingegneria Civile e Ambientale

SPEED – SPECTRAL ELEMENTS IN ELASTODYNAMICS WITH DISCONTINUOUS GALERKIN

Full **"source-to-site"** numerical simulation of seismic wave propagation, including:

- seismic source;
- propagation path;
- localized geological features or/and SSI



PROs:

- Insight into the earthquake physics
- Complex geology accounted for
- Spatial correlation of eqk ground motion
- Suitable to simulate future eqks in arbitrary source and site conditions
- Suitable for site-specific PSHA

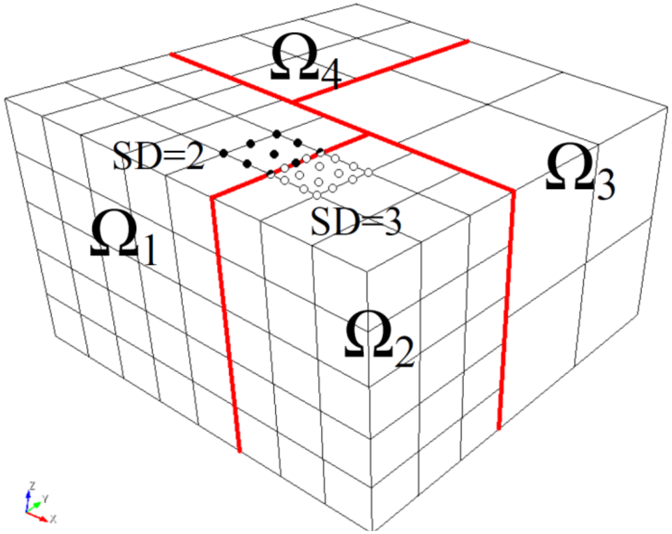
CONs:

- Limitation to low frequencies (~ 1.5-2 Hz in 3D)
- Level of detail of input data
- High computational cost
- Need of expert users
- Large epistemic uncertainties

SPEED – SPECTRAL ELEMENTS IN ELASTODYNAMICS WITH DISCONTINUOUS GALERKIN

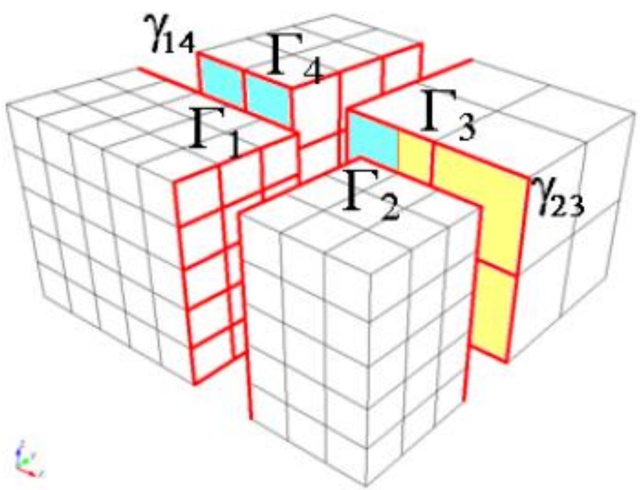
Features

- 3D unstructured **conforming** and **non-conforming hexahedral meshes** (e.g., between sub-domains $\Omega_{1,2}$, Ω_3 and Ω_4)
- **Non uniform polynomial approximation orders** (e.g., between sub-domains Ω_1 and Ω_2)
- leap-frog FD time advancing scheme
- **visco-elastic and non-linear elastic soil behaviour**



Kernel

- hybrid parallel programming based on MPI and Open-MP
- METIS software library to handle partitioning and load balancing
- designed for multi-core machines or large clusters - optimized for HPC clusters (e.g., Marconi@CINECA)



Kinematic modeling of an extended seismic source

$$m_{ij}^{k}(\underline{x},t) = \frac{M_0^{k}(\underline{x},t)}{V^{k}}\left(v_i^{k} n_j + v_j^{k} n_i\right)$$

volume of the k^{th} subfault

slip and normal fault vectors $f(\delta_f, \lambda_f, \varphi_f)$

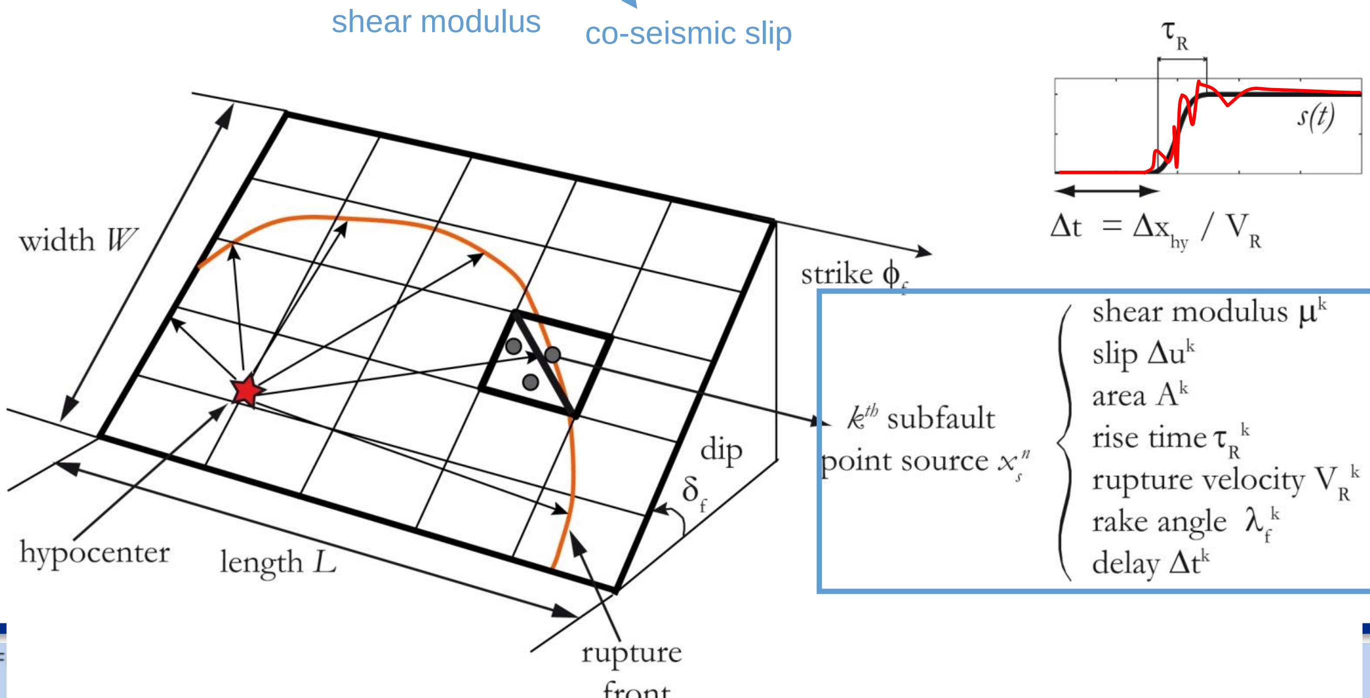
$$M_0^{k}(\underline{x},t) = \mu^{k} \Delta u^{k} A^{k} s(t-\Delta t^{k};\tau_R^{k})$$

area

Slip source function

shear modulus

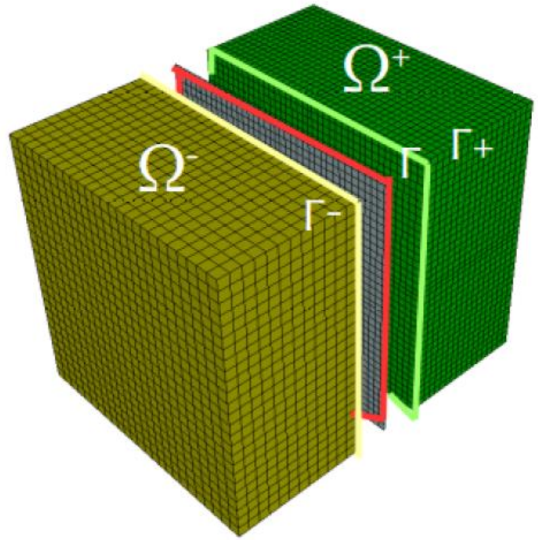
co-seismic slip



Dynamic rupture modeling of an extended seismic source

- Fault is defined as an internal planar interface Γ across which displacement discontinuities are allowed:

Slip vector $\Delta \mathbf{d} = \mathbf{d}^{+} - \mathbf{d}^{-}$ Slip Rate vector $\Delta \mathbf{v} = \Delta \dot{\mathbf{d}}$



- Coulomb criterion for friction

$$|\boldsymbol{\tau}| \le \tau_s = \mu_f \sigma_n$$

Fault strength (τ_s); Friction coefficient (μ_f)

$$\left(|\boldsymbol{\tau}| - \tau_s\right)|\Delta v| = 0$$

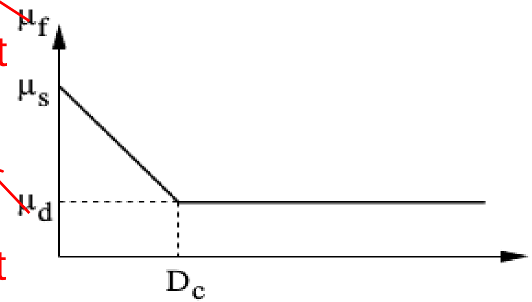
$$\Delta \mathbf{v}|\boldsymbol{\tau}| + |\Delta \mathbf{v}|\boldsymbol{\tau} = 0$$

- Linear slip-weakening frictional law

$$\mu_f = \max\left(\mu_s - \frac{(\mu_s - \mu_d)|\Delta \mathbf{d}|}{D_c}; \mu_d\right)$$

Static friction coefficient

Dynamic friction coefficient



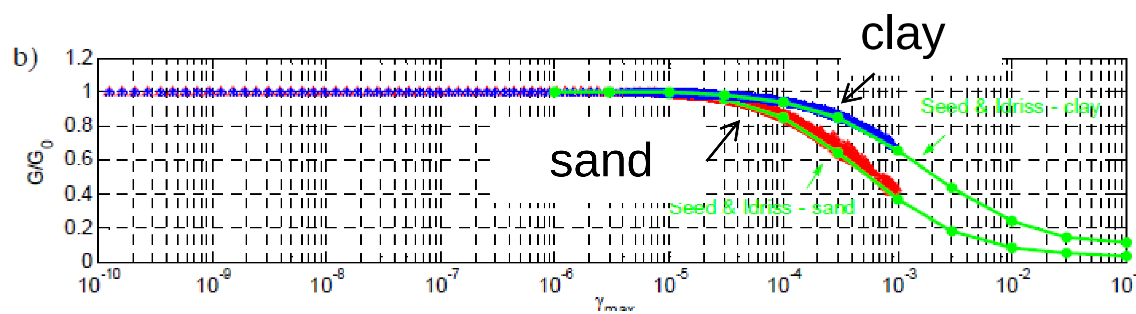
Critical slip distance $|\Delta \mathbf{d}|$

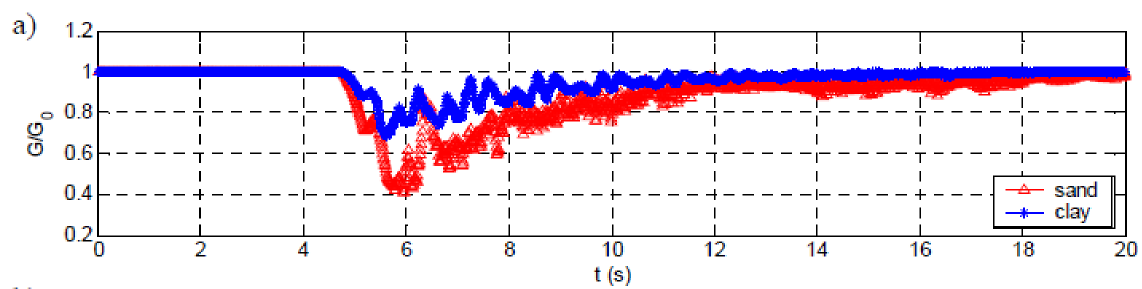
Soil modelling in SPEED

different viscoelastic models

- ✓ Q = cost
- ✓ $Q = Q_0 f$
- ✓ Rayleigh damping

non-linear elasticity





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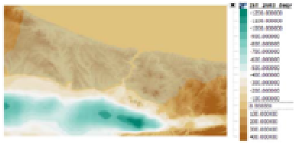
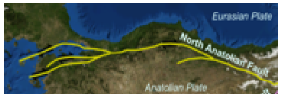
SPEED – SPECTRAL ELEMENTS IN ELASTODYNAMICS WITH DISCONTINUOUS GALERKIN

INPUT DATA

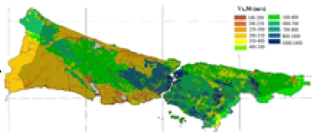
Topography and bathymetry model



Regional seismotectonic context, identification of the active faults



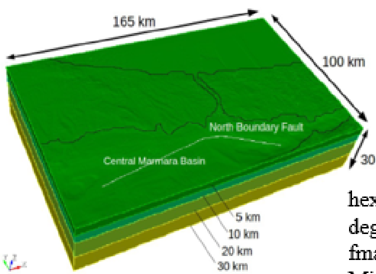
Geological and geothecnical characterization of the area



NUMERICAL MODEL

MESH DESIGN [Software: CUBIT]

Topography /Bathymetry + fault geometry + velocity model

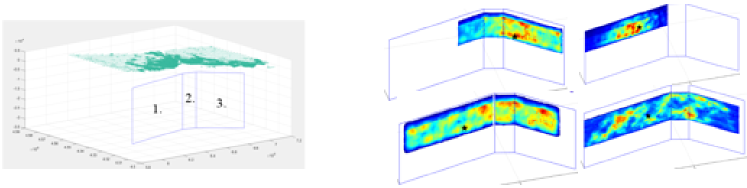


Crustal model

Depth (km)	V_S (m/s)	V_P (m/s)	ρ (kg/m³)	Q
0-5	Fig.5. 7	Fig.5. 7	Fig.5. 7	V_S/10
5-10	3490	5770	2600	350
10-20	3500	6390	2700	350
20-30	3920	6790	2800	400

hexahedral elements: 2,257,482
degrees of freedom: 475 million
fmax: 1.5 Hz
Min and max element size: 180 and 1800 m

GENERATION OF SCEARIO EQKs [Software: Matlab]



For a given fault (M_{max}) the eqk scenario is defined by:

- Mw
- Position of rupture area
- Slip distribution
- Hypocenter location
- Rupture length and width (L,W)
- Rake angle
- Rupture velocity
- Rise time

PRE-PROCESSING

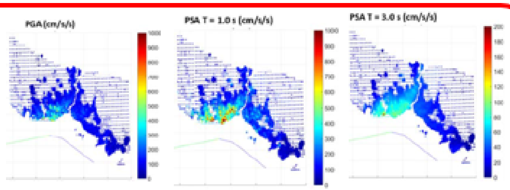
RUN SPEED ~14 hours on 2048 cores per simulation

POST-PROC

BROADBAND GROUND SHAKING MAPS [Software: Matlab]

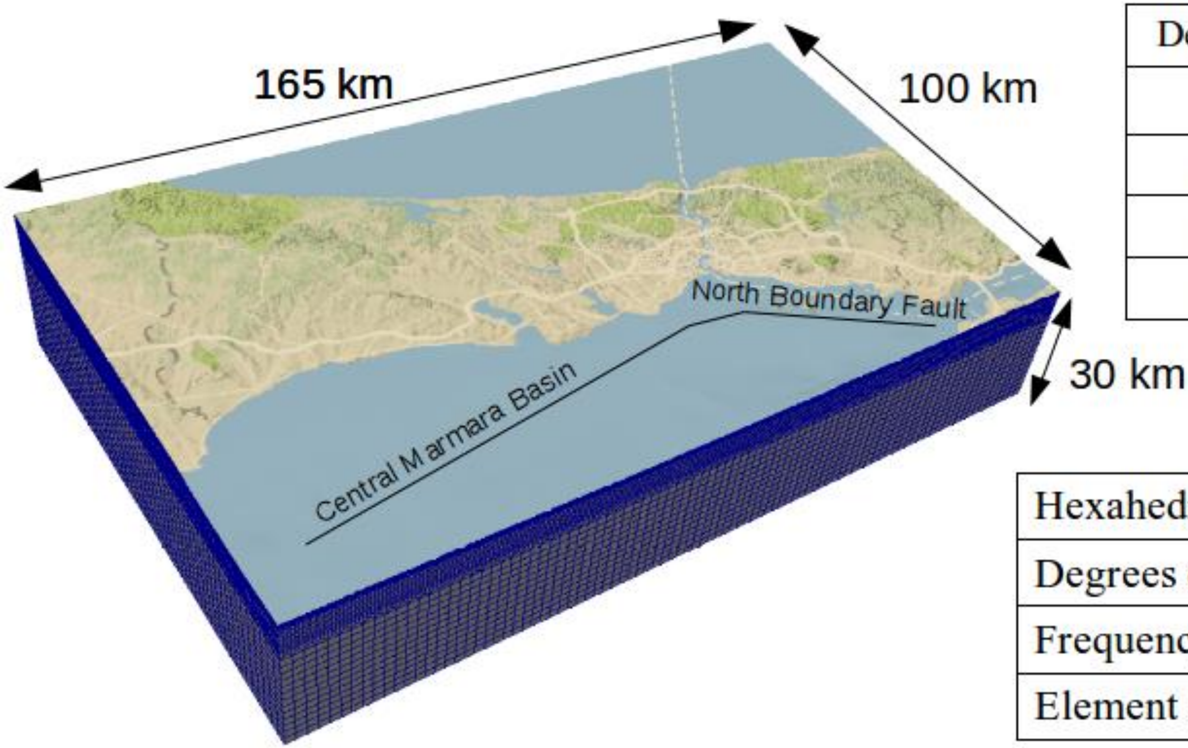
Artificial Neural Network (ANN) approach to generate broadband ground motions with realistic features in the entire frequency range of interest for engineering applications (0-25 Hz)

Long (°E)	Lat (°N)	PGD (cm)	PGV (cm)	PGA (cm/s/s)	PSA 0.3s (cm/s/s)	PSA 1.0s (cm/s/s)	PSA 3.0s (cm/s/s)	PSA 5.0s (cm/s/s)



SIMULATING SEISMIC SCENARIOS BY 3D PBS: THE CASE OF ISTANBUL

Spectral element numerical model of Istanbul (resolution: f_{max}= 1.5 Hz)



Horizontally stratified crustal model

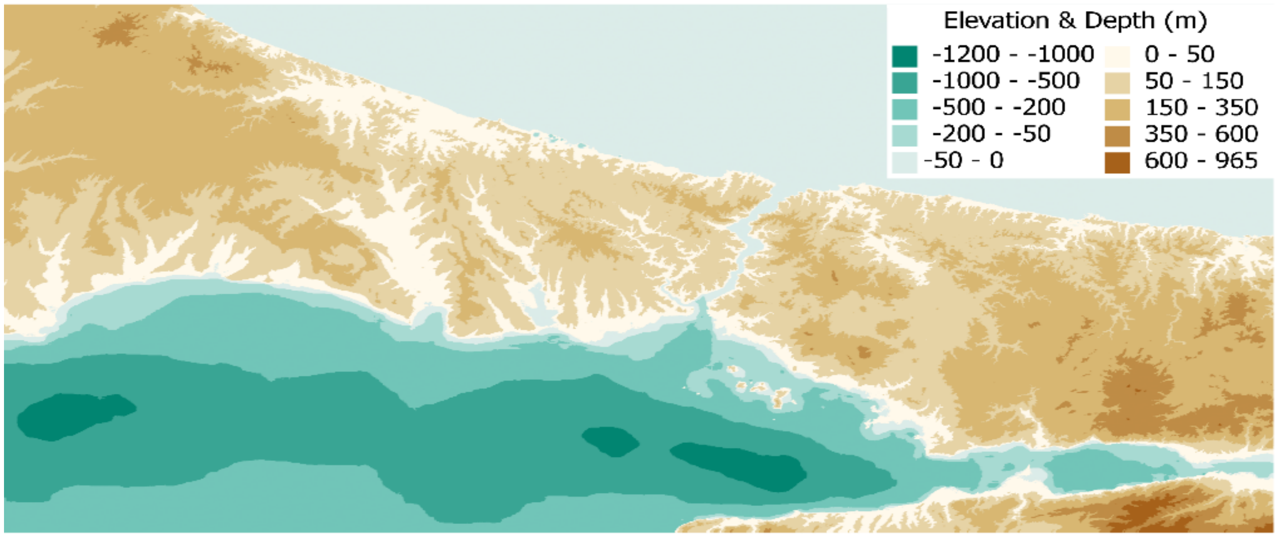
Depth (km)	V_S (m/s)	Q(-)
0-5	Fig. 3	V_S /10
5-10	3490	350
10-20	3500	350
20-30	3920	400

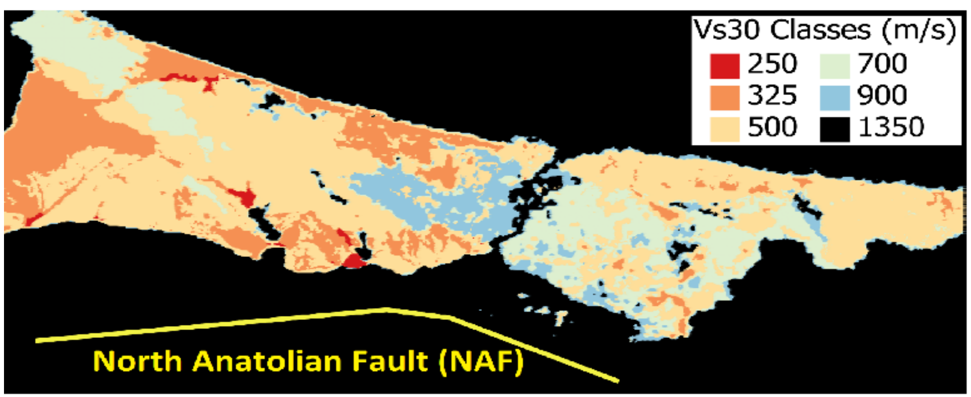
Computational model

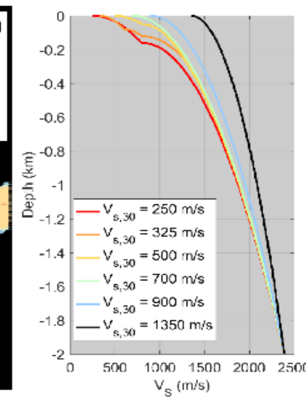
Hexahedral elements	2.257.482
Degrees of freedom	~500 million
Frequency range	0 to 1.5 Hz
Element size range	180 m to 2 km

SIMULATING SEISMIC SCENARIOS BY 3D PBS: THE CASE OF ISTANBUL

Digital elevation model and map of classes of $V_{s,30}$ implemented in SPEED

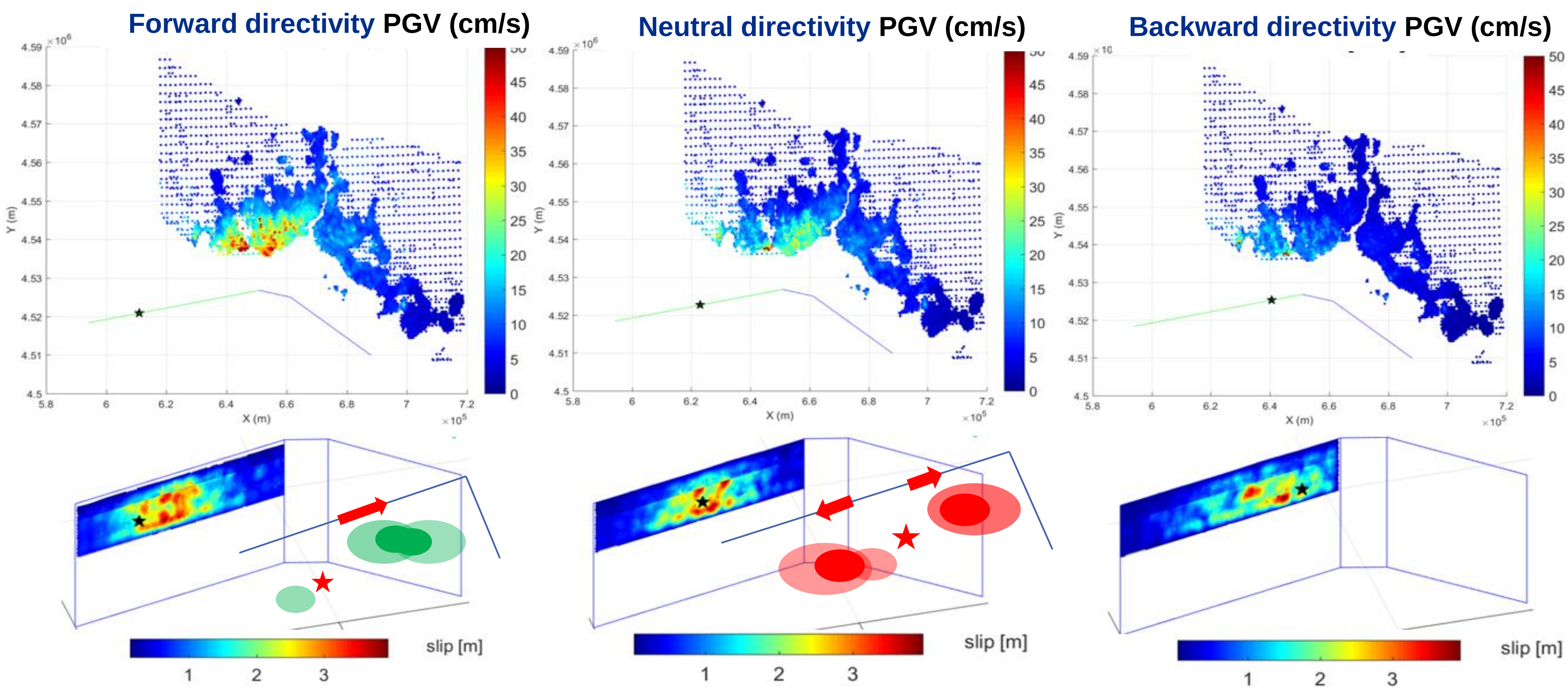






SIMULATING SEISMIC SCENARIOS BY 3D PBS: THE CASE OF ISTANBUL

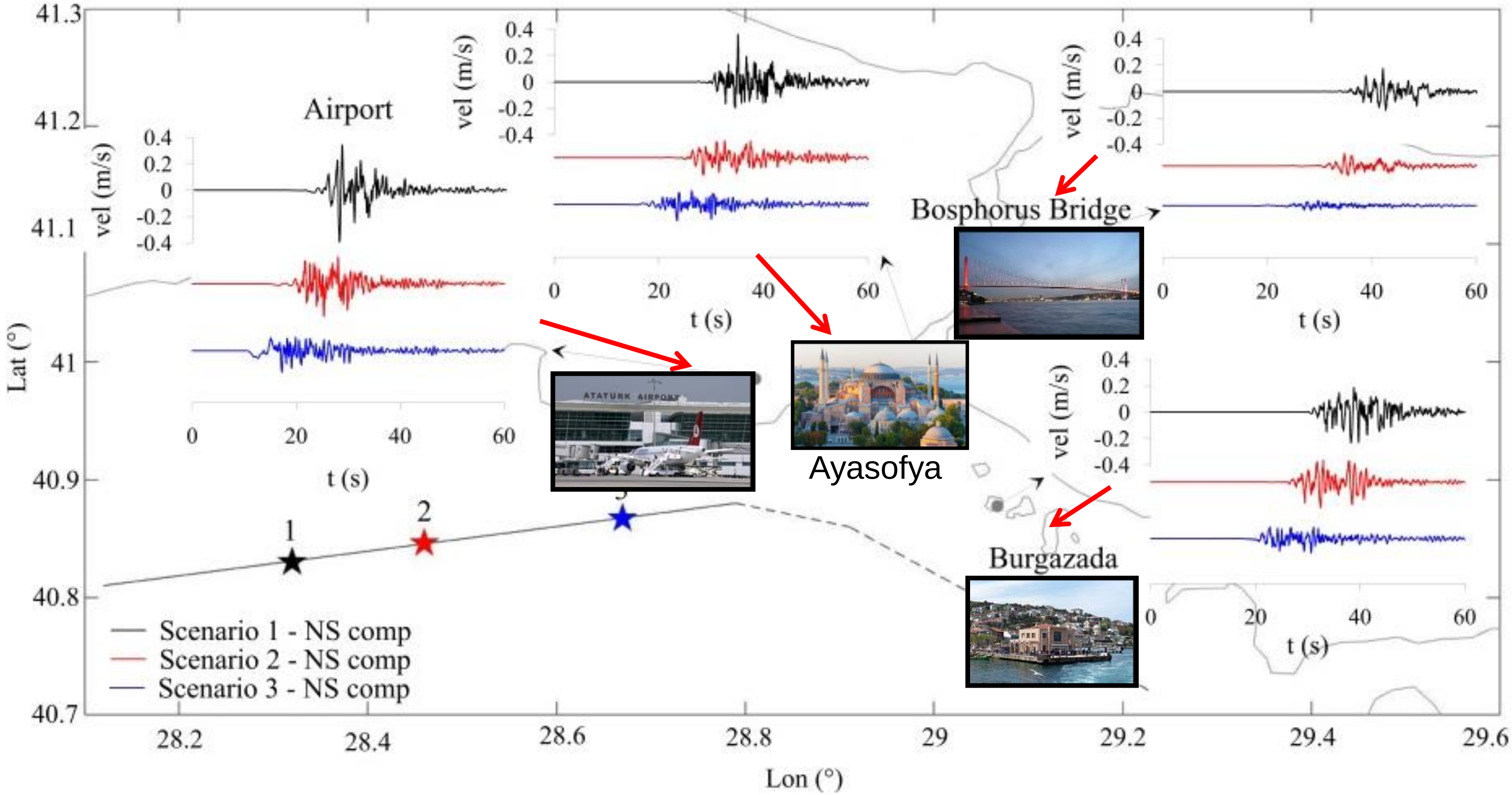
Different M7 ground motion scenarios in Istanbul (about 30 produced with M=7.0)



kinematic slip distributions randomly generated according to Crempien and Archuleta (2015)

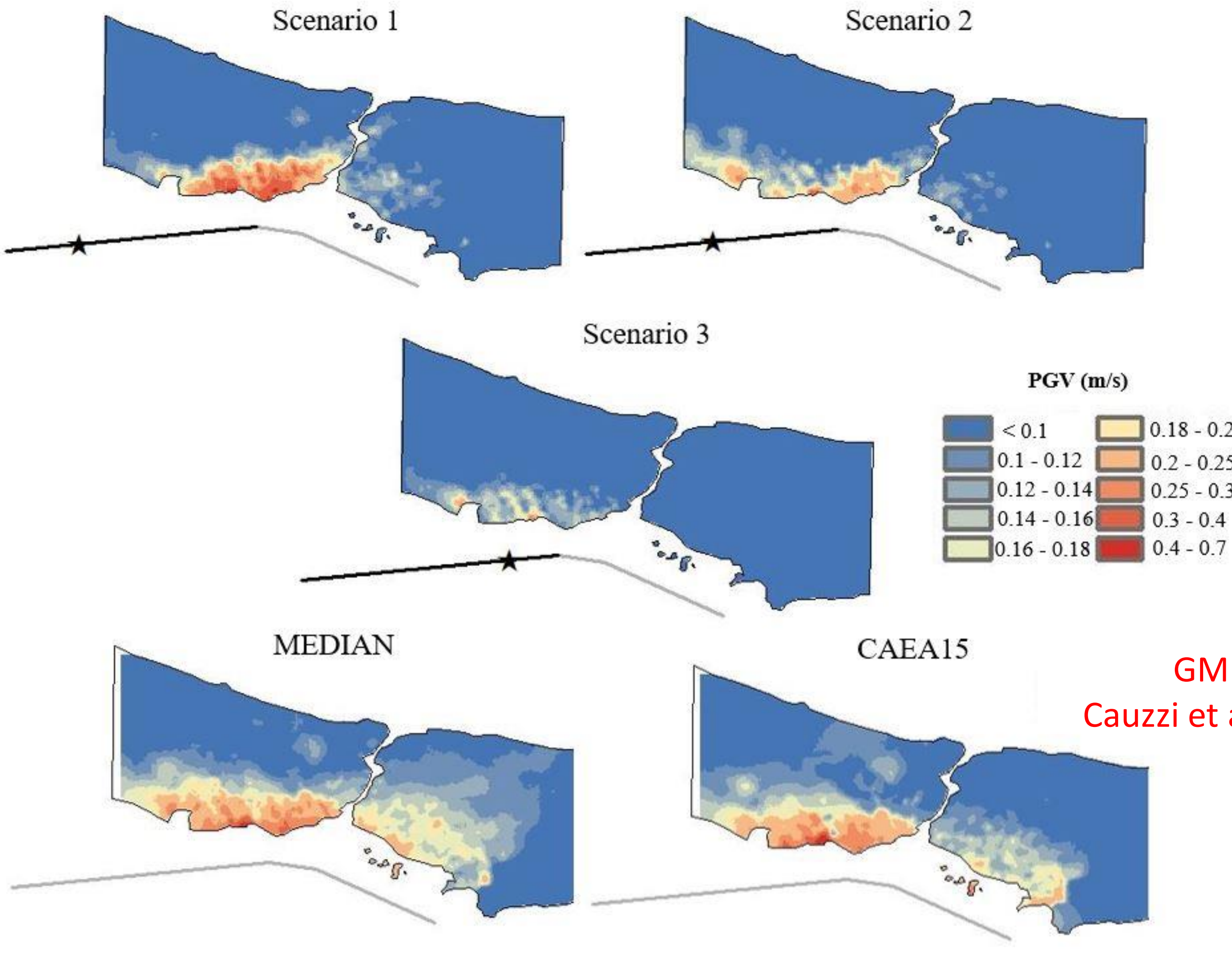
SIMULATING SEISMIC SCENARIOS BY 3D PBS: THE CASE OF ISTANBUL

Velocity time histories for different scenarios



SIMULATING SEISMIC SCENARIOS BY 3D PBS: THE CASE OF ISTANBUL

Comparison of specific scenario maps based on PBS (30 simulations) and GMPE



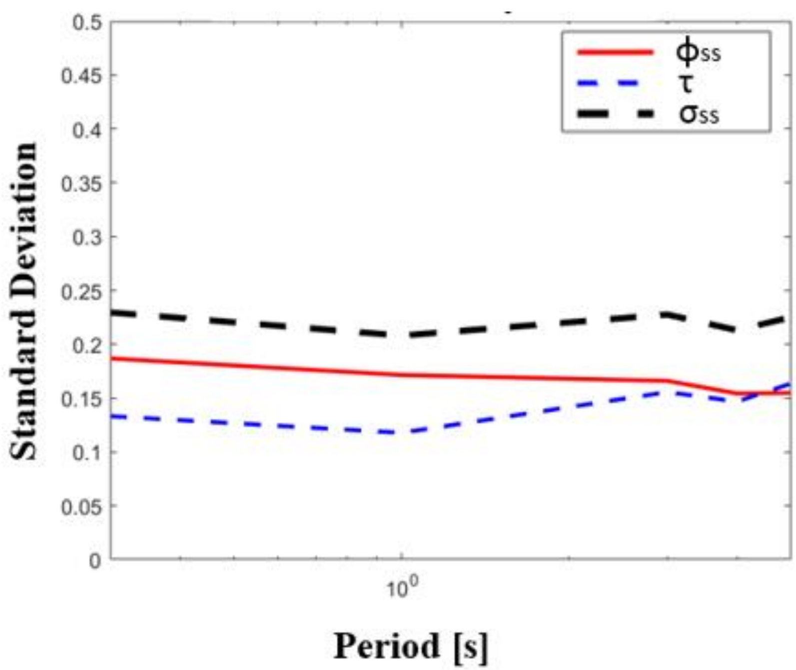
GMPE
Cauzzi et al., 2015

SIMULATING SEISMIC SCENARIOS BY 3D PBS: THE CASE OF ISTANBUL

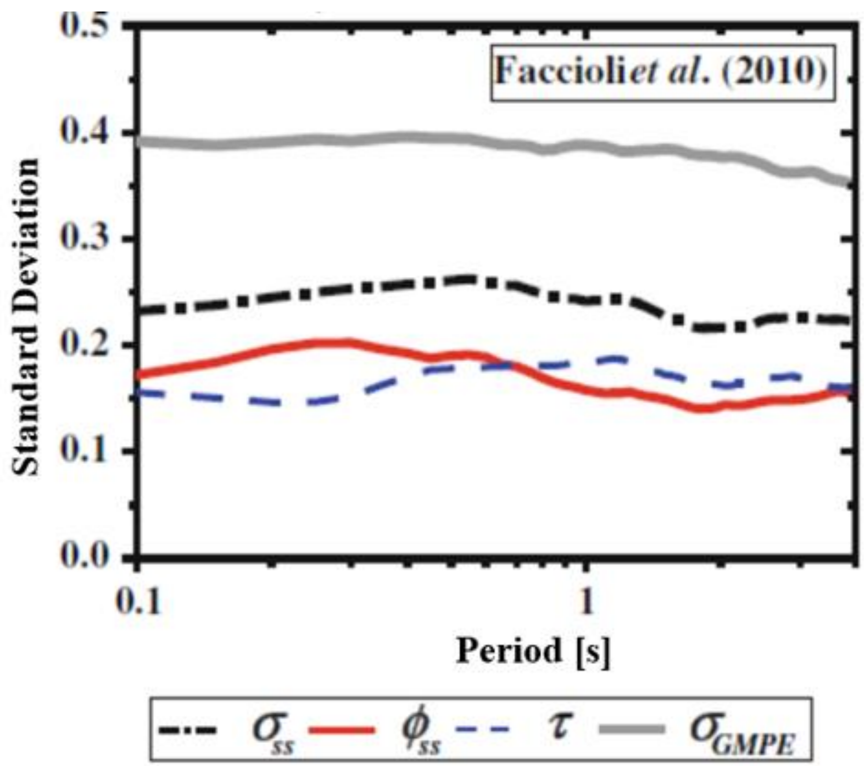
Comparison of contributions to single station standard deviation

→ improve understanding and quantifying uncertainty in GM prediction models

Istanbul - simulated



Christchurch - records



$$\sigma_{SS} = \sqrt{\phi_{SS}^2 + \tau^2}$$

within-event sigma   between-event sigma

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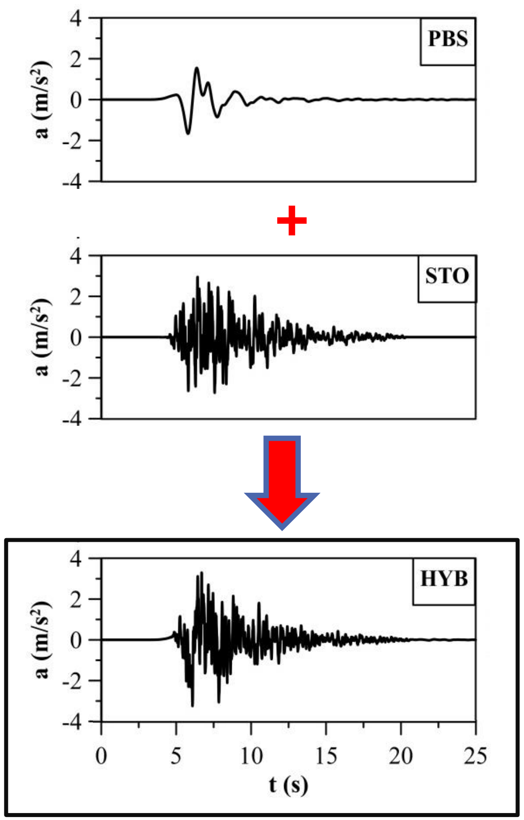
… so, using 3D PBSs, you have many advantages. However …

- you should account reliably with the complexity of the seismic source;
- you do not have detailed geological information to solve reliably short wavelengths;
- you have computer limitations.

→ hybrid approaches to solve the HF range

ANN2BB: BB GROUND MOTIONS USING ARTIFICIAL NEURAL NETWORKS

The "most popular" method to get broadband waveforms from hybrid PBS – stochastic approaches

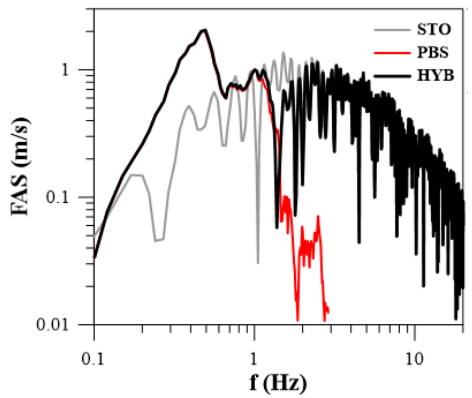


Simulated waveform for a given scenario

(e.g. T≥T*=0.75 s)

Stochastic waveform

Hybrid PBS+stochastic waveform



Resulting hybrid Fourier spectrum

An alternative approach: ANN2BB

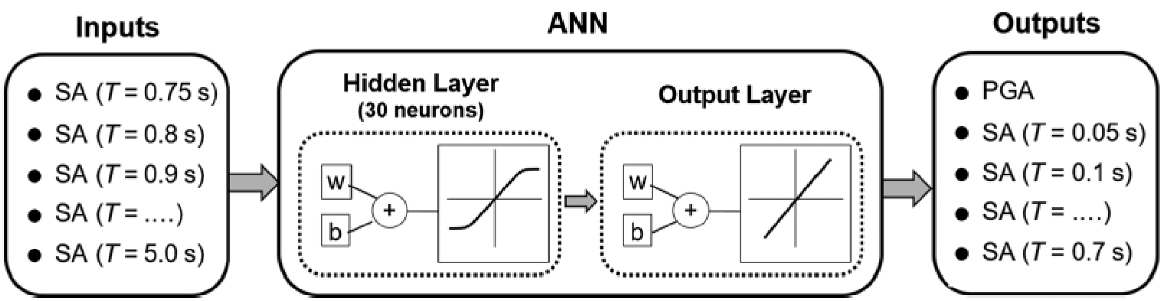
Bulletin of the Seismological Society of America, Vol. , No. , pp. –, , doi: 10.1785/0120170293

Broadband Ground Motions from 3D Physics-Based Numerical Simulations Using Artificial Neural Networks

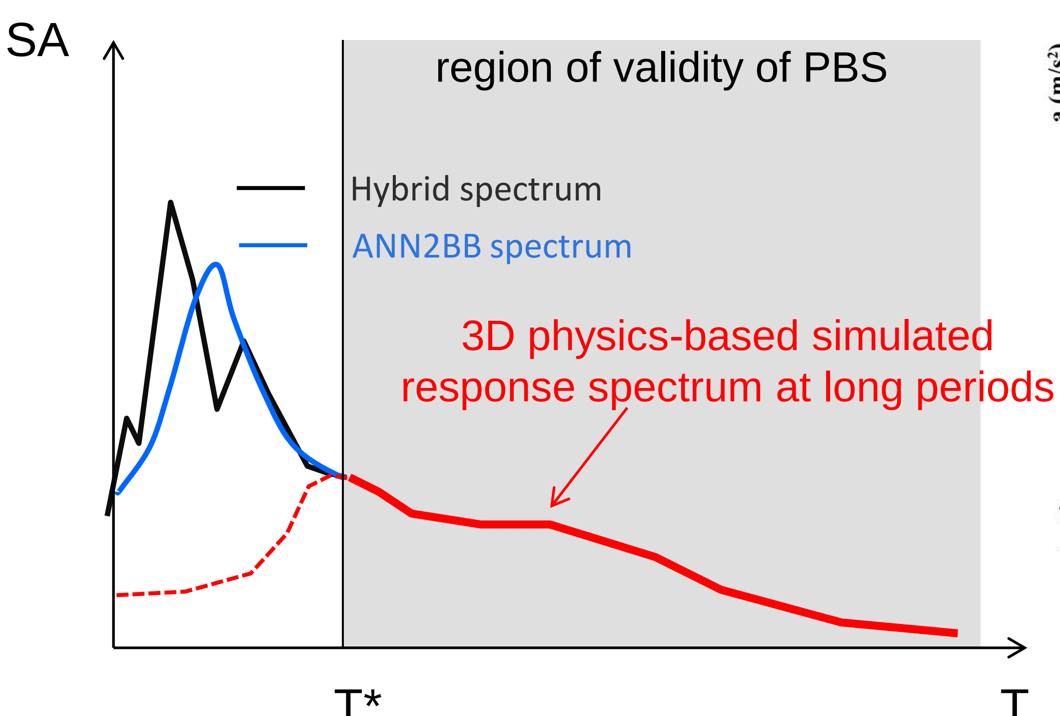
by Roberto Paolucci, Filippo Gatti, Maria Infantino, Chiara Smerzini, Ali Güney Özcebe, and Marco Stupazzini

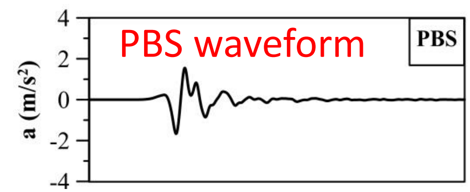
ANN2BB: BB GROUND MOTIONS USING ARTIFICIAL NEURAL NETWORKS

(1) Training of an ANN (*una tantum*) based on a strong motion database (SIMBAD, Smerzini et al. 2014)

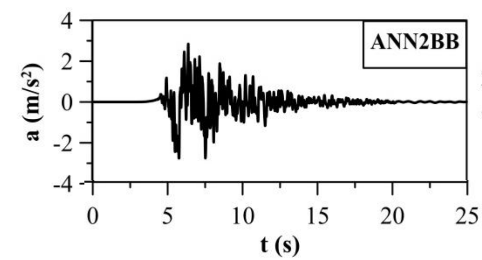


(2) Response spectrum at short periods predicted by the ANN

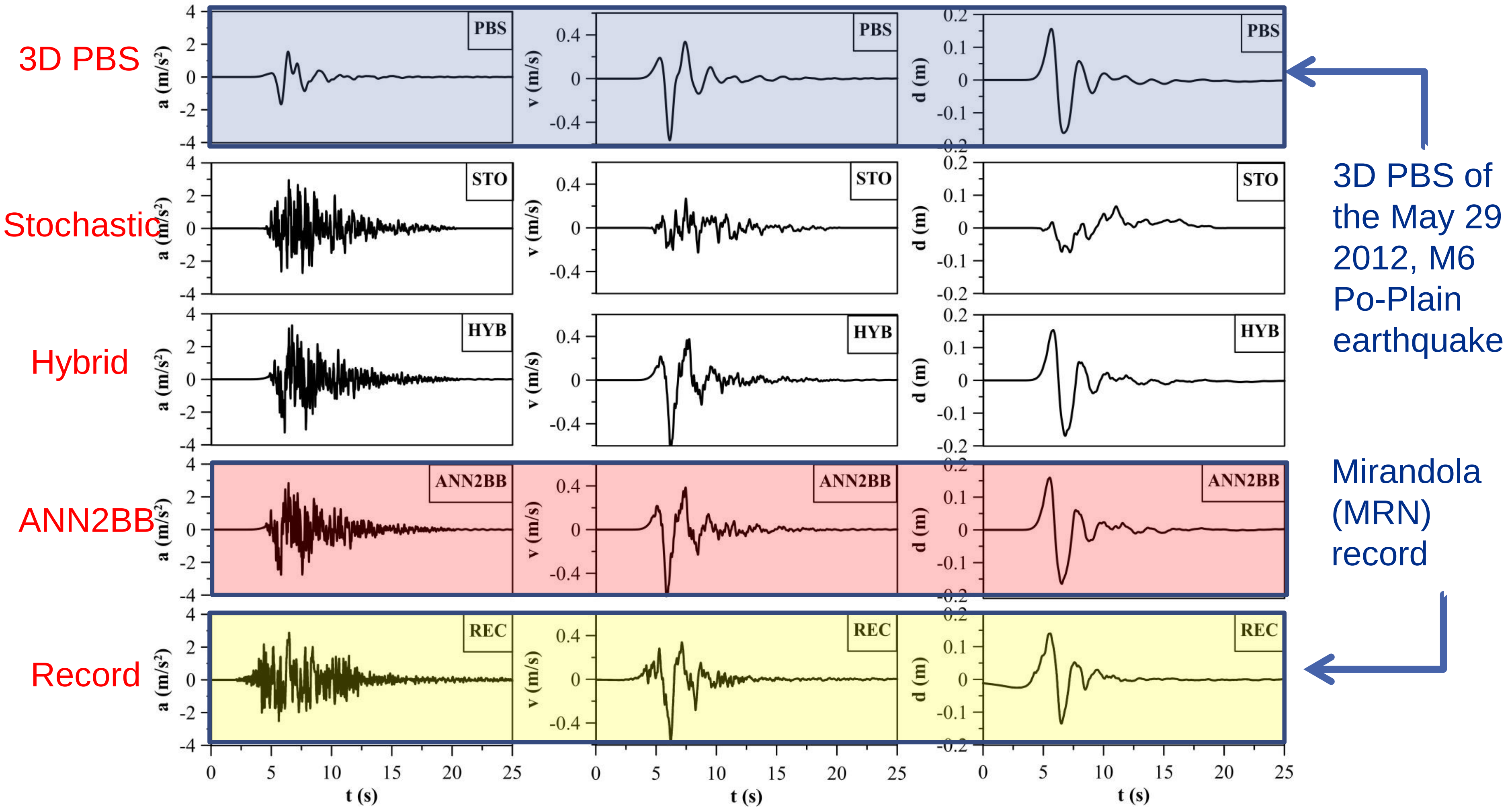




(3) Scaling the PBS waveform to spectral matching the AN2BB spectrum

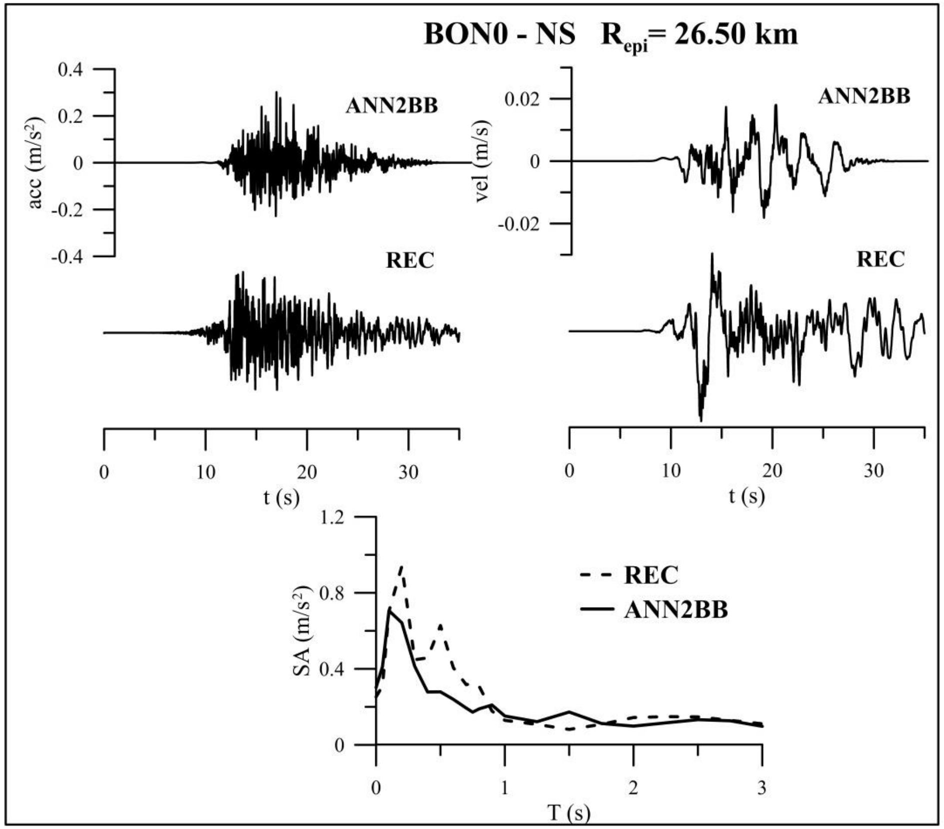


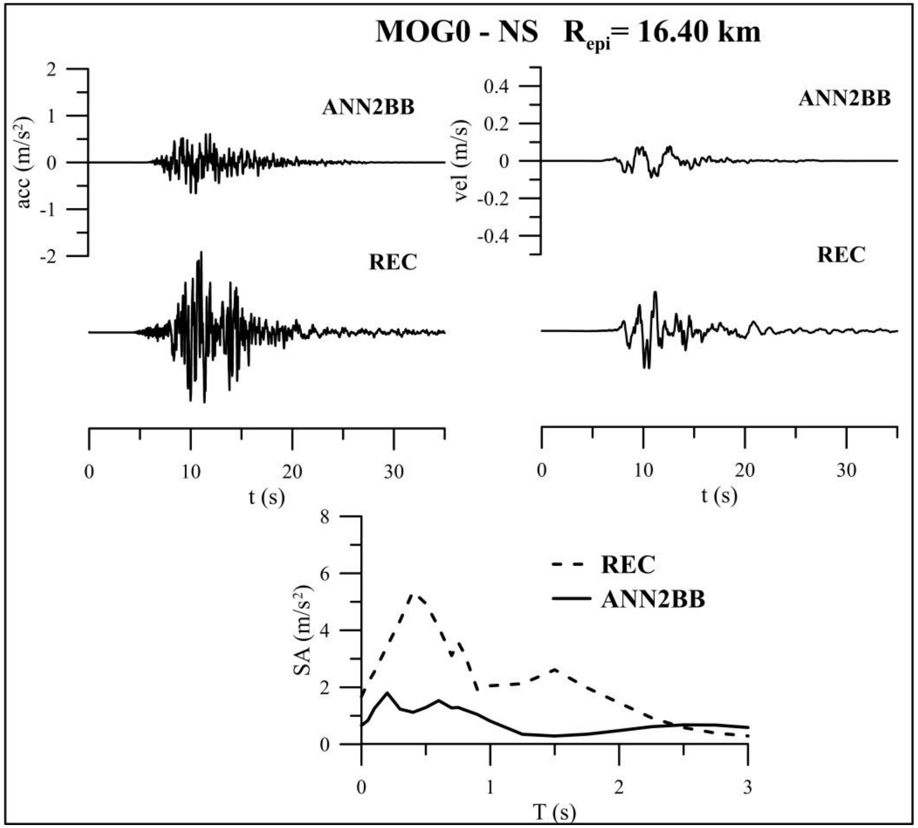
ANN2BB: BB GROUND MOTIONS USING ARTIFICIAL NEURAL NETWORKS



ANN2BB: BB GROUND MOTIONS USING ARTIFICIAL NEURAL NETWORKS

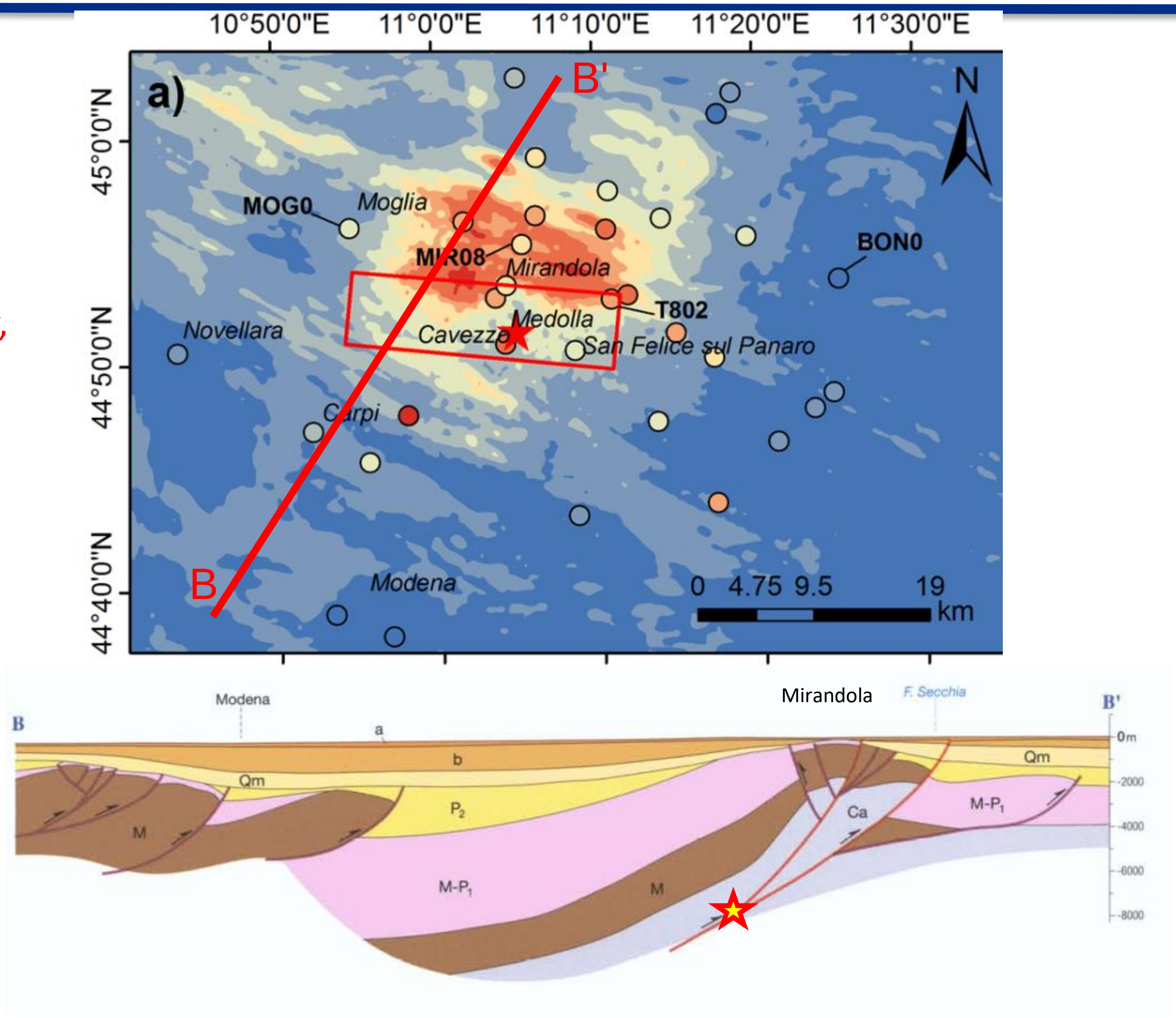
Other comparisons from the Po Plain earthquake case study



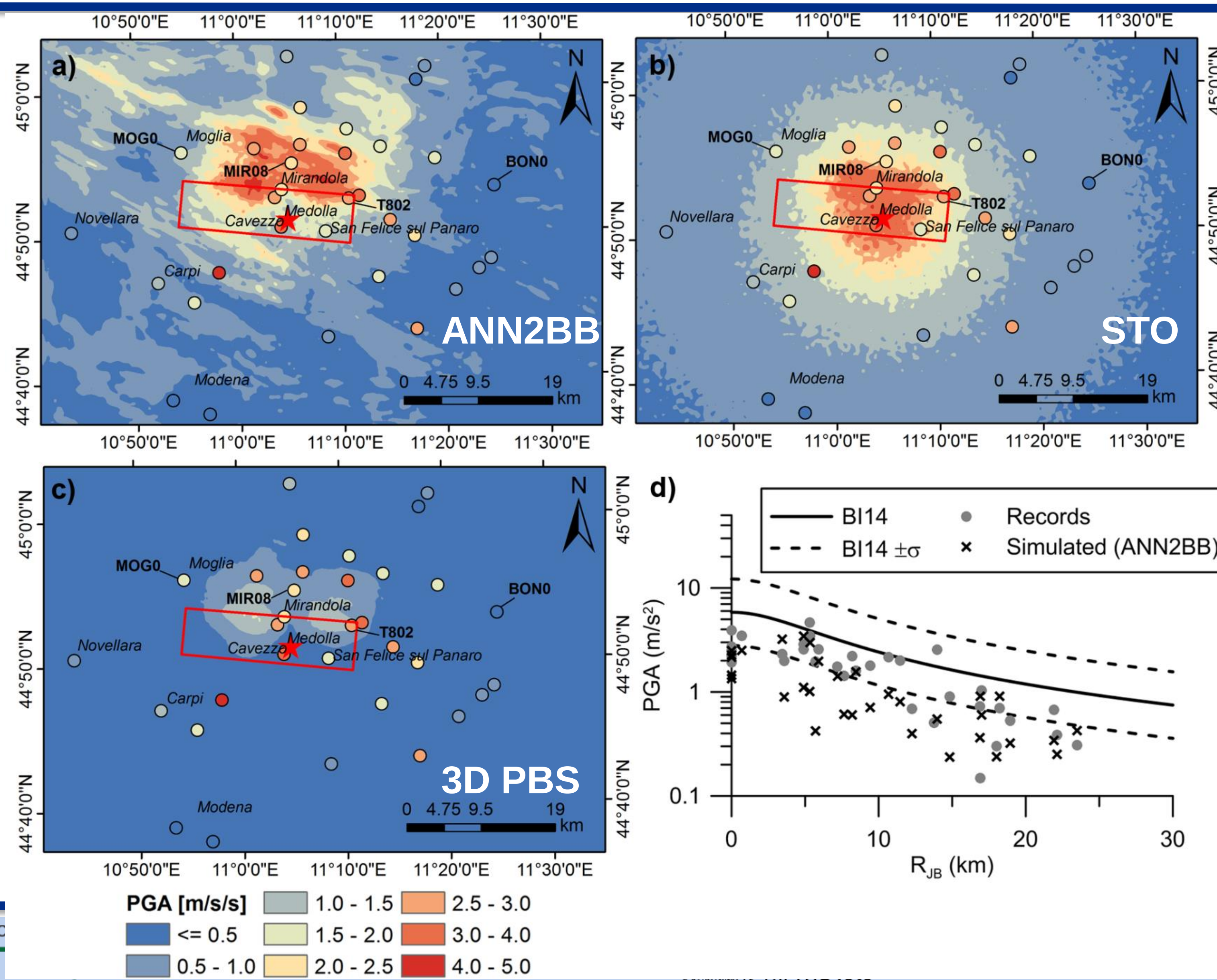


PGA MAPS FOR THE PO-PLAIN EARTHQUAKE CASE STUDY

site amplification related to coupling of up-dip directivity, subsurface topography and shallow soil layers



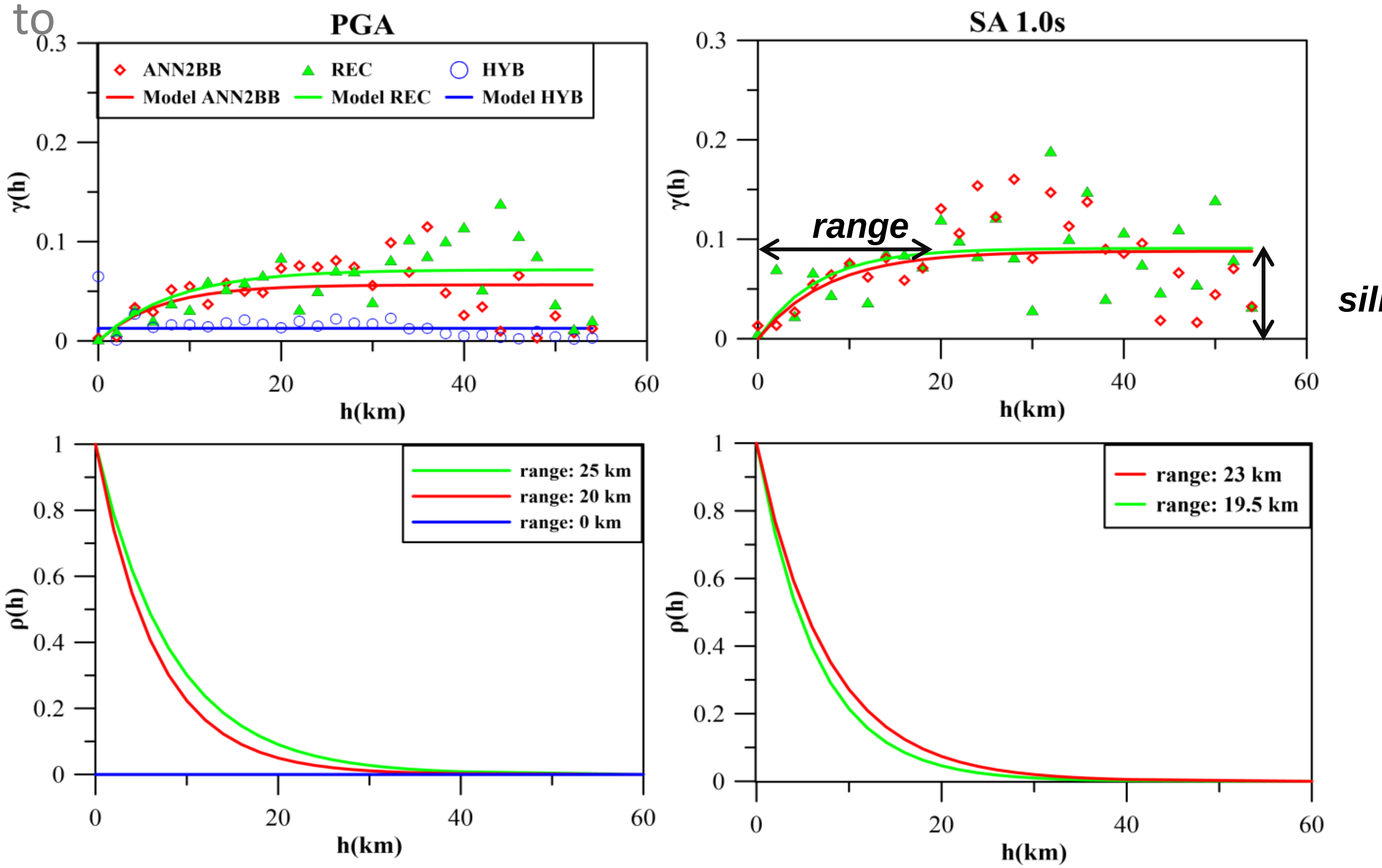
PGA MAPS FOR THE PO-PLAIN EARTHQUAKE CASE STUDY



Evaluating the Spatial Correlation of ANN2BB Ground Motions

Semivariograms and correlation models for the Po Plain earthquake case

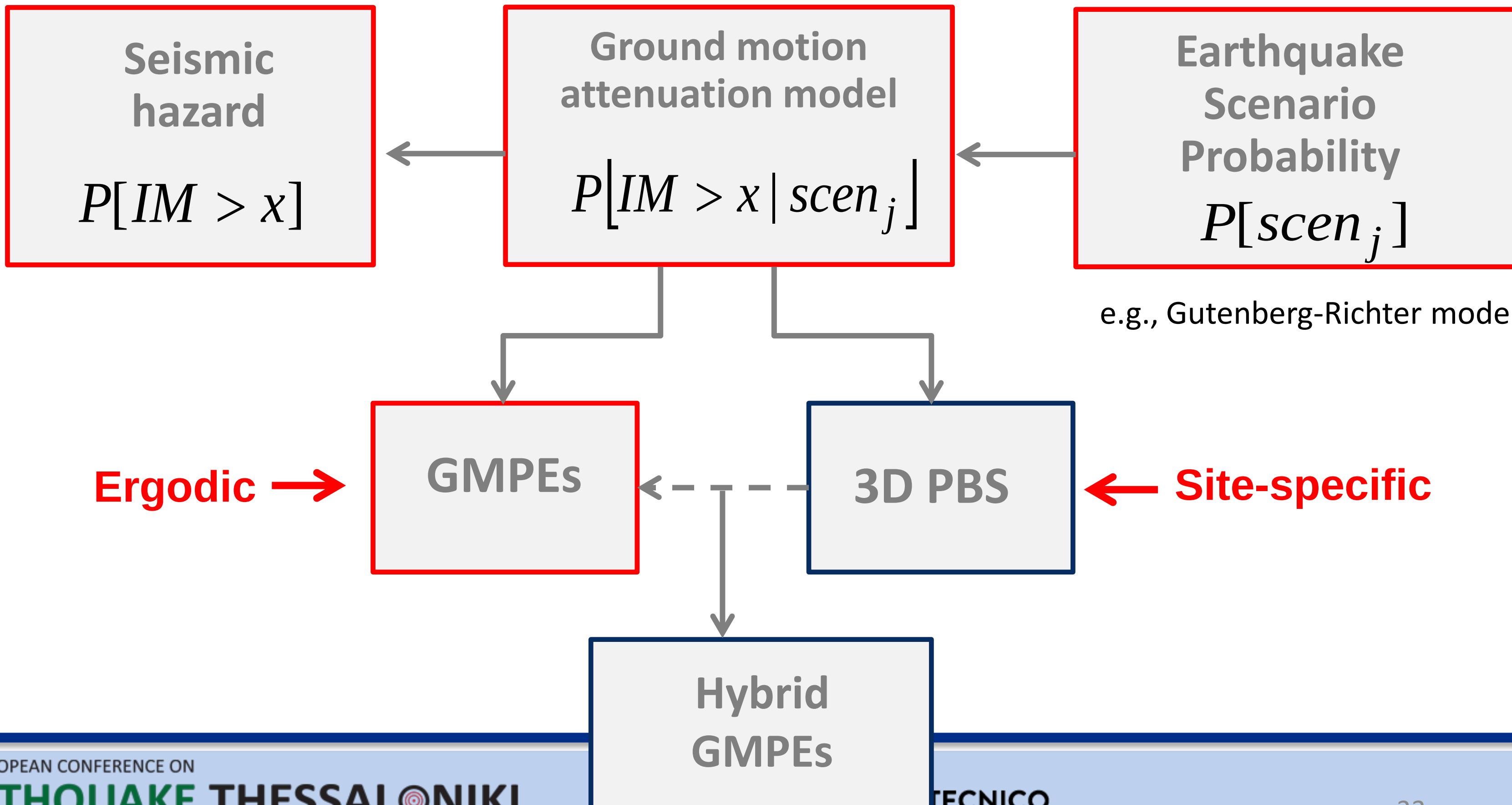
- ✓ Capability of PBS to reproduce accurately the observed spatial correlation from records
- ✓ Hybrid method produces fully uncorrelated ground motions



CONTENTS

How to exploit 3D PBS in the framework of PSHA

$$P[IM > x] = \sum_{j=1}^{N} P[IM > x \mid scen_j] \cdot P[scen_j]$$



How to exploit 3D PBS in the framework of PSHA

PSHAe

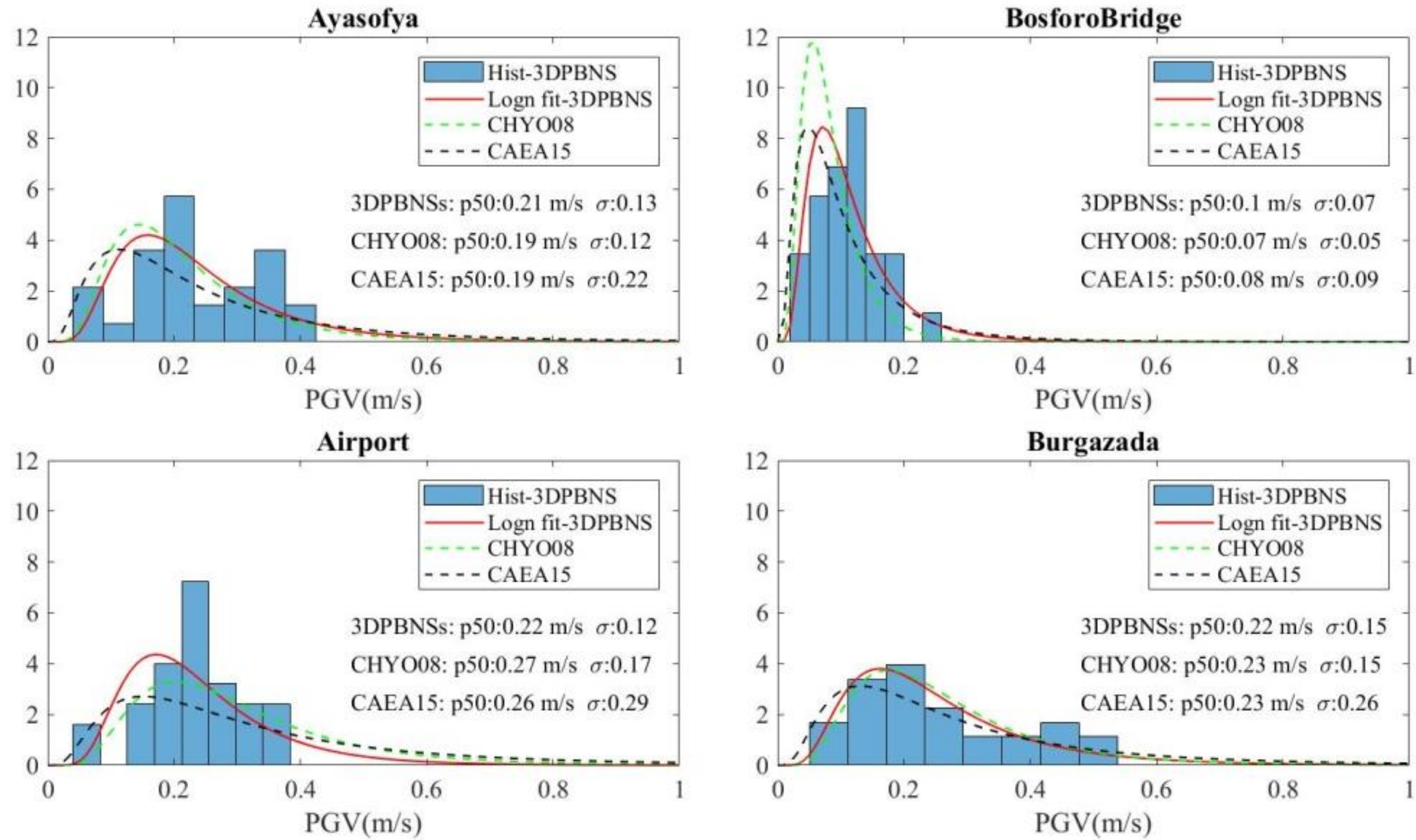
(ground motion model "enhanced" by PBS)

- **Ergodic** → **Hybrid GMPEs** from both synthetics and empirical data
- **Site-specific**
  - → **GAF-based**: at each site the moments of the lognormal distribution are provided by statistical analysis of 3D PBS

    (Villani et al., 2014)
  - → **Footprint-based**: different realizations of an earthquake scenario are incorporated directly in the PSHA computations in a logic-tree framework

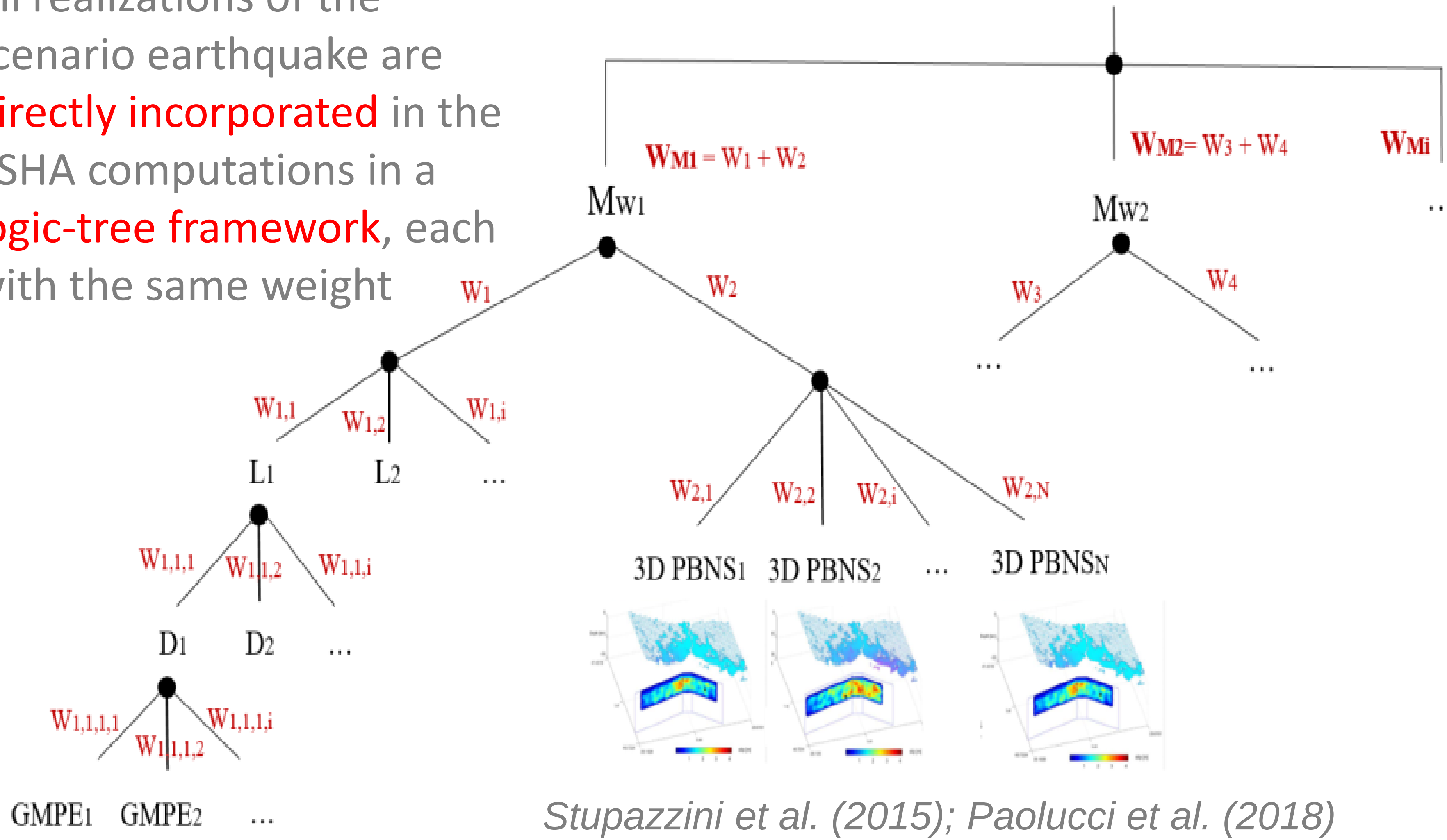
HOW TO EXPLOIT 3D PBS IN THE FRAMEWORK OF PSHA

Site-specific probability distributions of ground motion



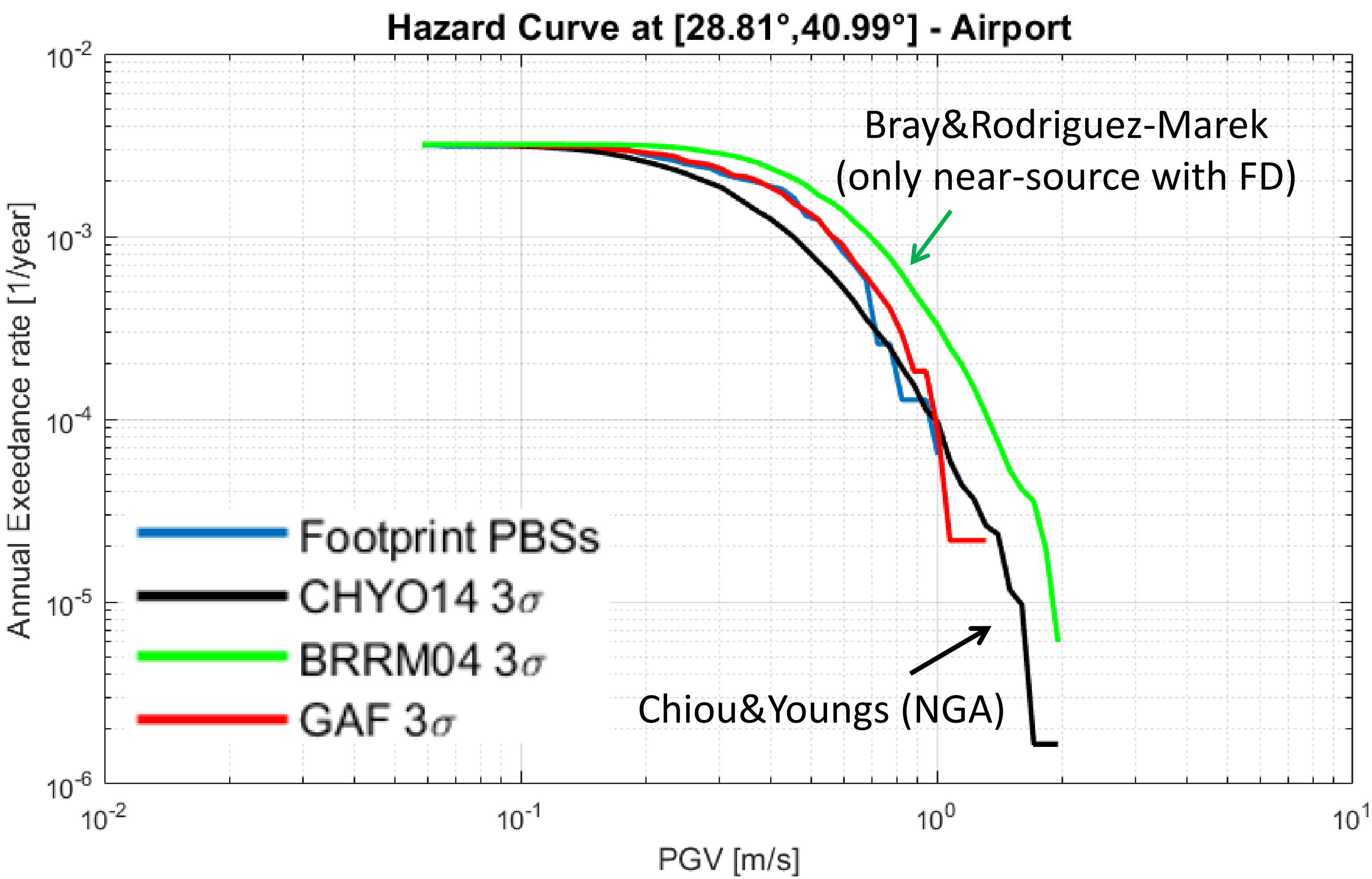
SITE-SPECIFIC PSHAE: FOOTPRINT-BASED APPROACH

All realizations of the scenario earthquake are **directly incorporated** in the PSHA computations in a **logic-tree framework**, each with the same weight



Stupazzini et al. (2015); Paolucci et al. (2018)

SITE-SPECIFIC PSHAE: COMPARISON OF APPROACHES



Conclusions

- ✓ the level of detail of available input data (geology, slip distribution, etc) for 3D PBS will be very hardly sufficient to solve frequencies larger than about 1.5 – 2 Hz: beyond this threshold, **taking advantage of stochastic or hybrid methods is almost unavoidable**;
- ✓ the ANN2BB approach provides a (black box) correlation between long and short period spectral ordinates that seems to be effective **to create earthquake ground motion scenarios presenting a realistic broad-band spatial correlation structure**;
- ✓ 3D PBS results are suitable to be implemented within **"enhanced" PSHA approaches**, especially for near-source conditions, either by deriving hybrid (simulated-recorded) GMPEs, or by exploiting site-specific distribution of ground motions (GAF or footprint-based);

CONCLUSIONS

"For a large earthquake, the epicenter is not as helpful for engineers as is the footprint" (Housner, 1999). With these words, one of the fathers of earthquake engineering commented the evidence from the August 17 1999 Turkish earthquake that the damage distribution could only be understood based on information of the dimensions of the faulted area and its position with respect to the site.

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