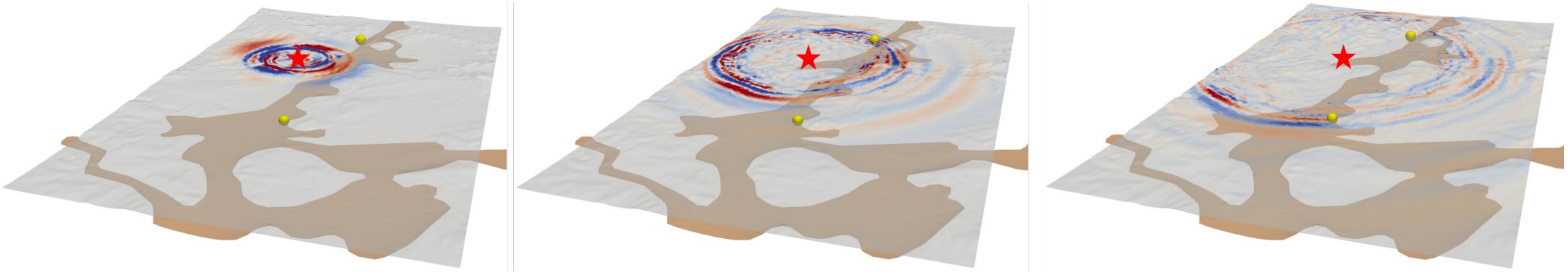


Using sets of realizations of kinematic slip distributions along the Marmara Sea fault to produce site-specific ground motion models for Istanbul

Roberto Paolucci & Marco Stupazzini

POLITECNICO MILANO 1863

Munich RE

PEER

2024 PEER - LBNL Workshop

Simulated Ground Motions for the San Francisco Bay Area

January 18-19, 2024

BERKELEY LAB

Software for physics-based ground motion simulations (PBS): SPEED @PoliMI

SPEED

OPEN-SOURCE

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

SPEED – SPectral Elements in Elastodynamics with Discontinuous Galerkin

People | The Project | Applications | Publications | Download | Earthquake Web Repository | Computing | News&Press Review | Contact

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

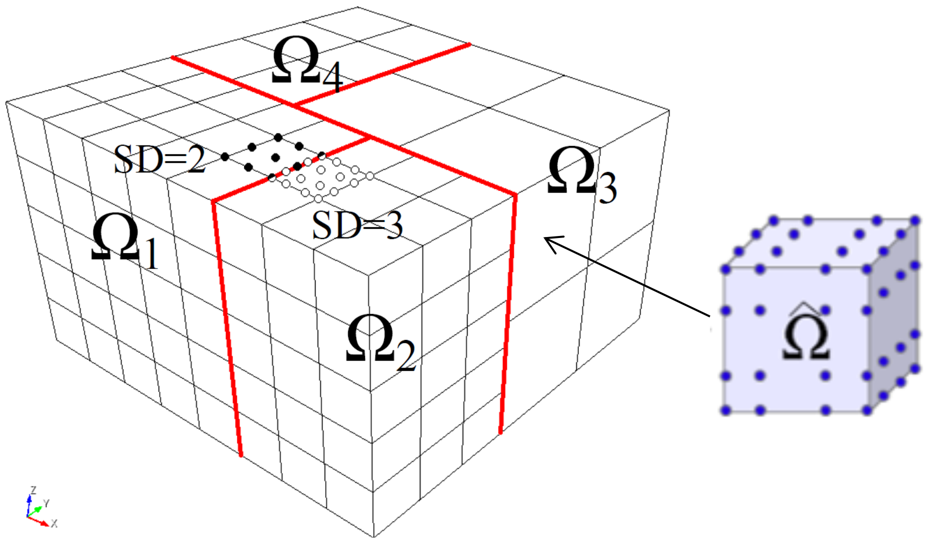
MOX | POLITECNICO MILANO 1863 | Dipartimento di Ingegneria Civile e Ambientale

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

Introduction of the Spectral Element Method enhanced by Discrete Galerkin approach

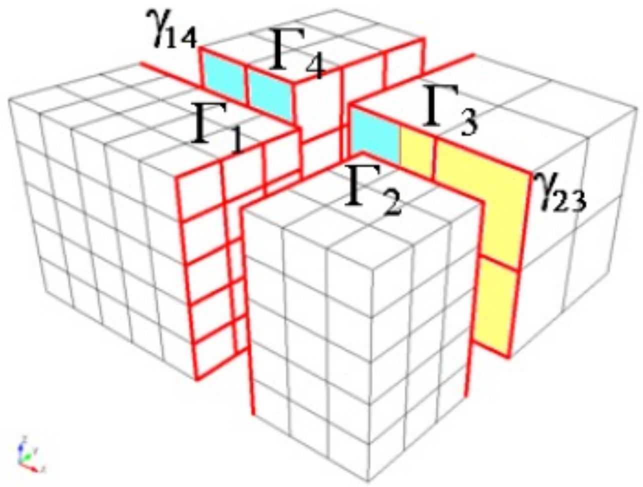
Features

- 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., Leonardo@CINECA)

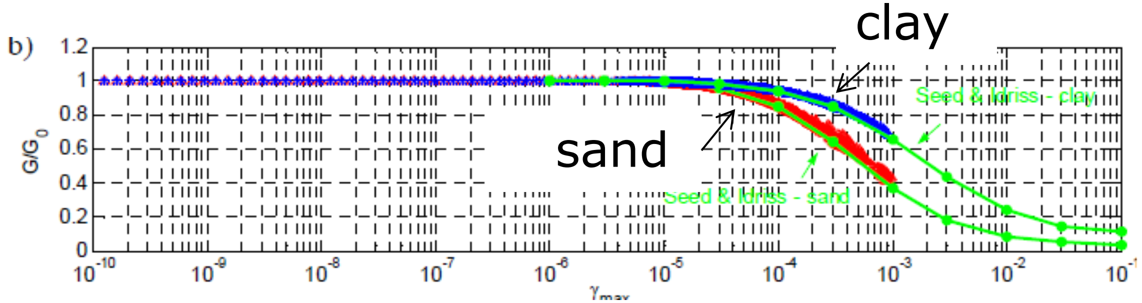


Soil modelling in SPEED

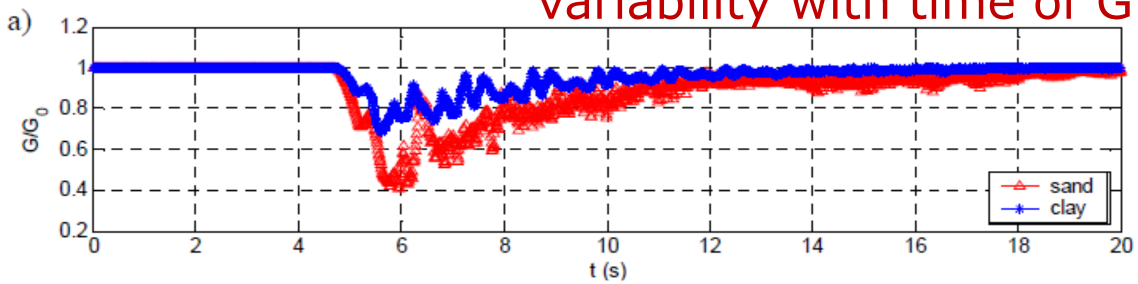
viscoelastic models

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

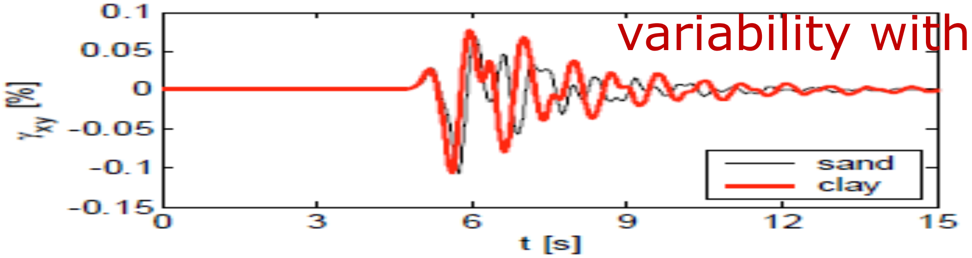
non-linear elasticity



variability with time of G



variability with time of γ



Kinematic modeling of the 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 $f(\delta_f,\lambda_f,\varphi_f)$

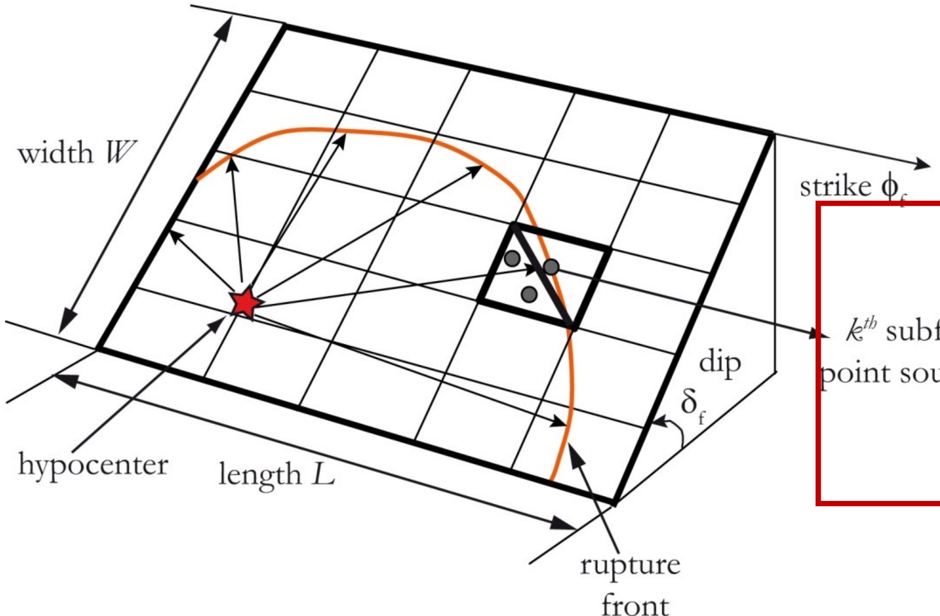
$$M_0^{k}(\underline{x},t)=\mu^{k}\Delta u^{k}A^{k}s(t-\Delta t^{k};\tau_R^{k})$$

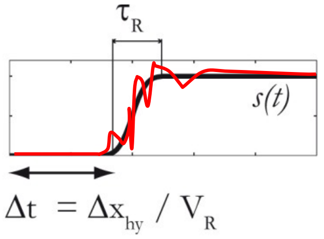
area

Slip source function

shear modulus

co-seismic slip





k^{th} subfault point source x_s^n

- shear modulus μ^k
- slip Δu^k
- area A^k
- rise time τ_R^k
- rupture velocity V_R^k
- rake angle λ_f^k
- delay Δt^k

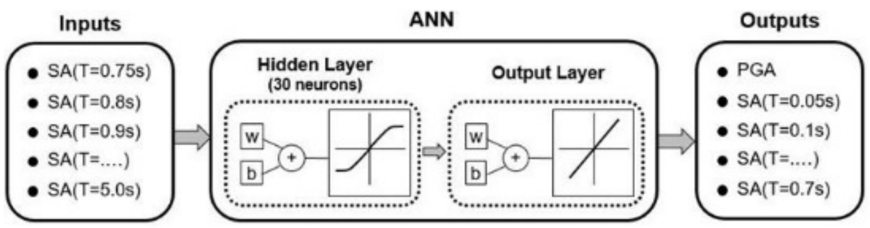
ANN2BB: BB ground motions using Artificial Neural Networks

Bulletin of the Seismological Society of America, Vol. 108, No. 3A, pp. 1272–1286, June 2018, doi: 10.1785/0120170293

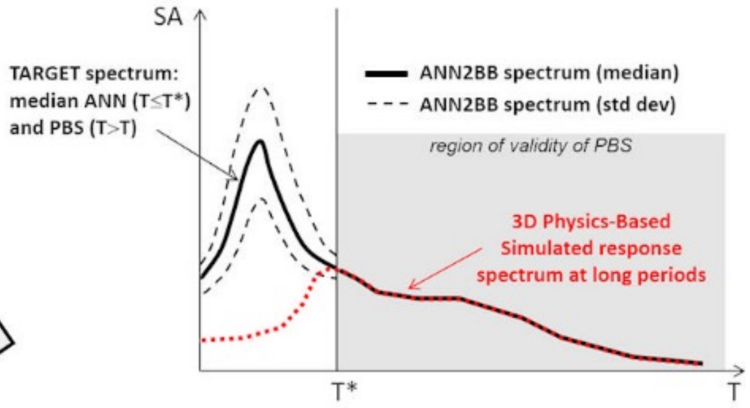
Broadband Ground Motions from 3D Physics-Based Numerical Simulations Using Artificial Neural Networks

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

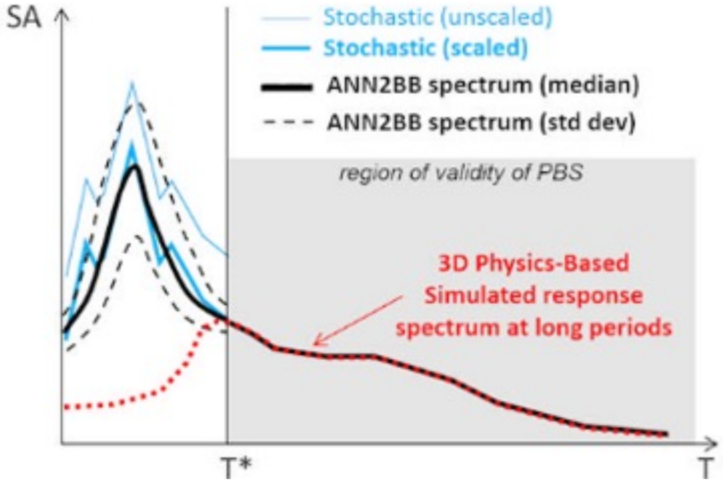
(1) Training of an Artificial Neural Network (ANN) based on a dataset of strong-motion recordings



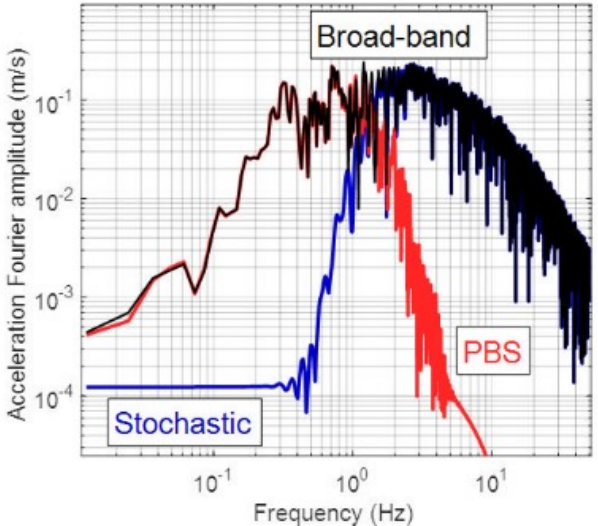
(2) Application of ANN to predict short period spectral ordinates based on PBS results (T≥T*)



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



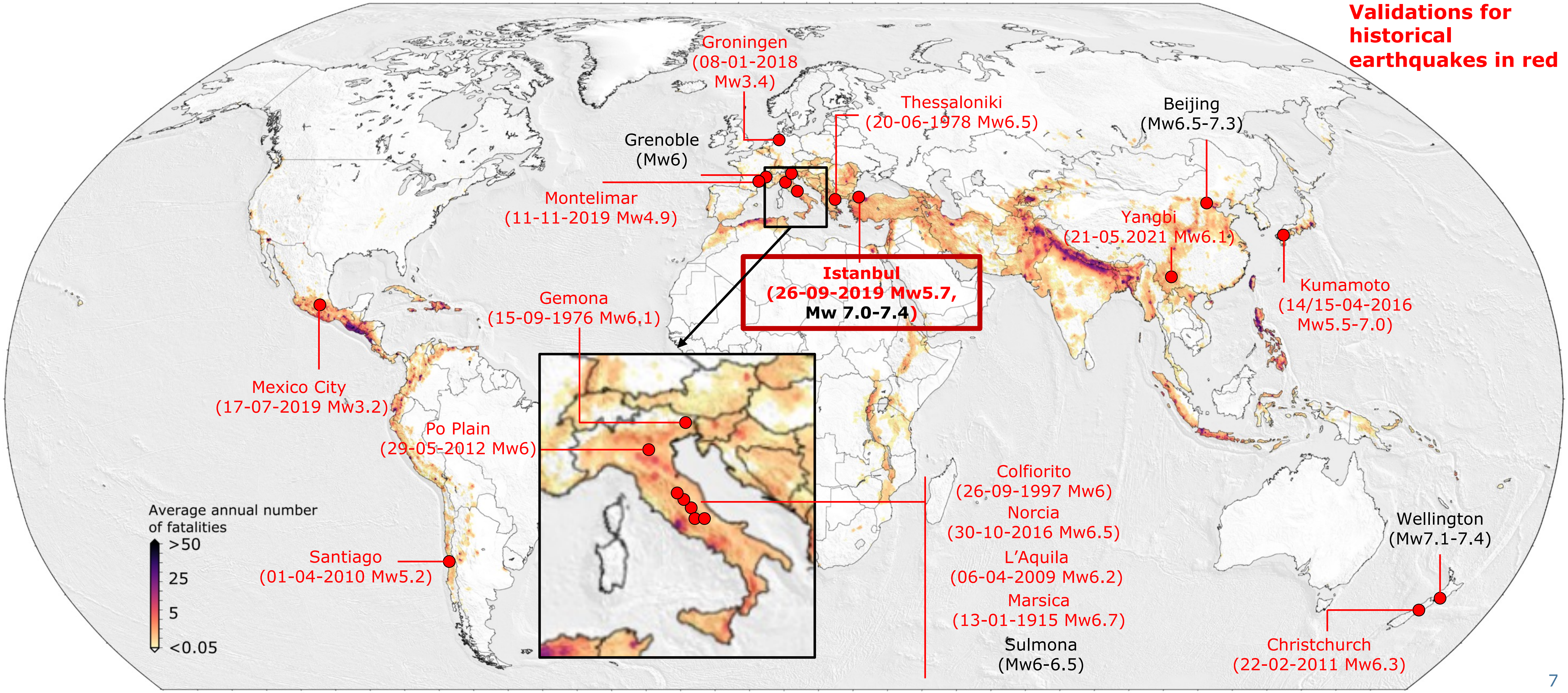
(4) Combination of stochastic and PBS signals



Advantages of ANN2BB

- ✓ realistic spatial correlation of ground motion
- ✓ realistic period-to-period correlation of response spectral ordinates

Case studies of PBS by SPEED and validations against historical earthquakes



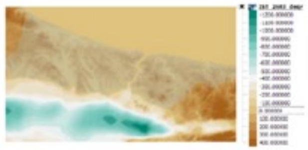
3D PBS ground motion scenarios for PSHA in Istanbul (BSSA, 2020)

3D Physics-Based Numerical Simulations of Ground Motion in Istanbul from Earthquakes along the Marmara Segment of the North Anatolian Fault

Maria Infantino*[1], Ilario Mazzieri[2], Ali Güney Özcebe[3], Roberto Paolucci[1], and Marco Stupazzini[4]

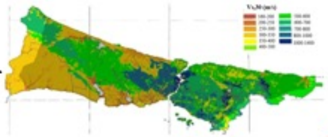
INPUT DATA

Topography and bathymetry model



Regional seismotectonic context, identification of the active faults

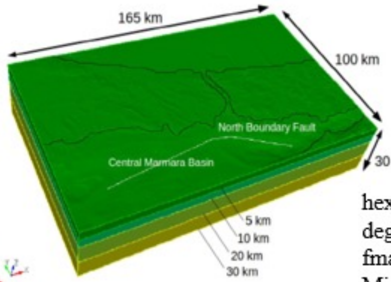
Geological and geotechnical characterization of the area



NUMERICAL MODEL

MESH DESIGN [Software: CUBIT]

Topography /Bathymetry + fault geometry + velocity model



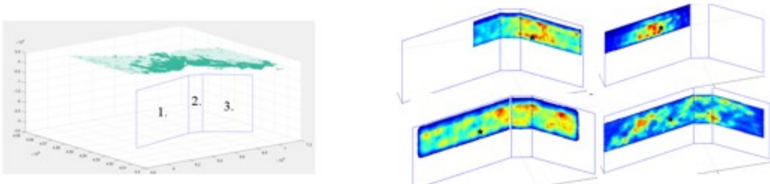
Crustal model

Depth (km)	Vs (m/s)	Vp (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

PRE-PROCESSING

GENERATION OF SCEARIO EQKs [Software: Matlab]



For a given fault (Mmax) 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

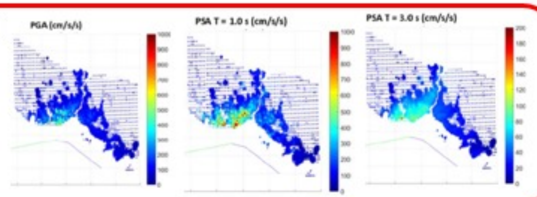
RUN SPEED ~14 hours on 2048 cores per simulation

POST-PROC

BROADBAND GROUND SHAKING MAPS [Software: Matlab]

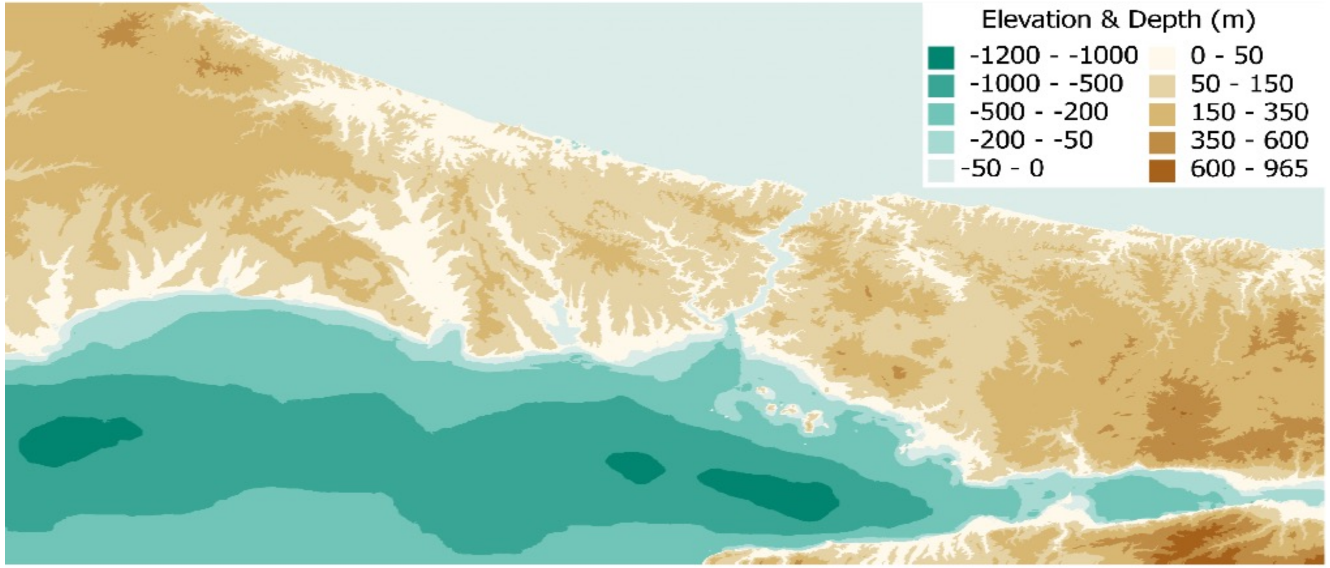
Artificial Neural Network (ANN) approach to generate broadband ground motions with realistic features in the entire frequency range of interest for engineering applications (0-25 Hz)

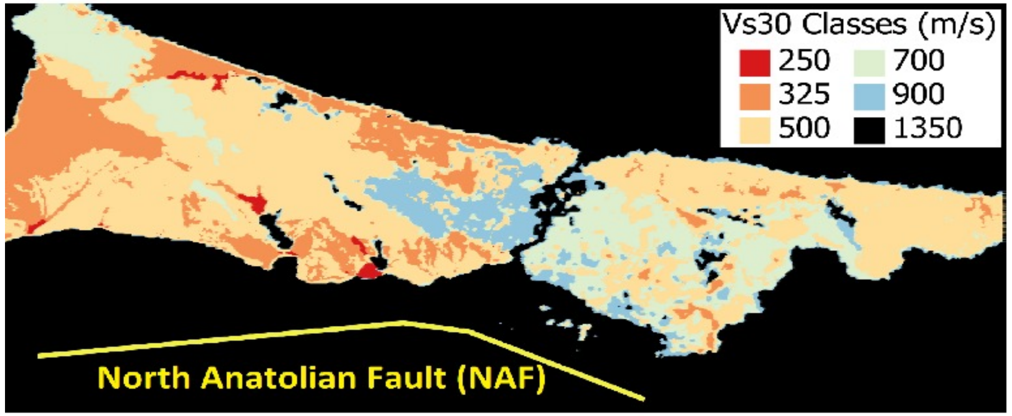
Long (°E)	Lat (°N)	PGD (cm)	PGV (cm)	PGA (cm/s/s)	PSA 0.3s (cm/s/s)	PSA 1.0s (cm/s/s)	PSA 3.0s (cm/s/s)	PSA 5.0s (cm/s/s)

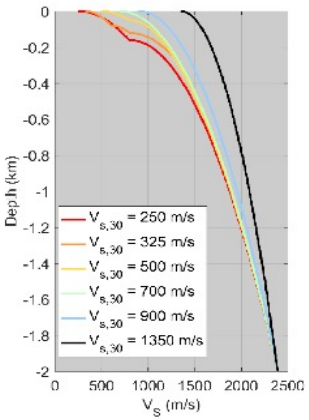


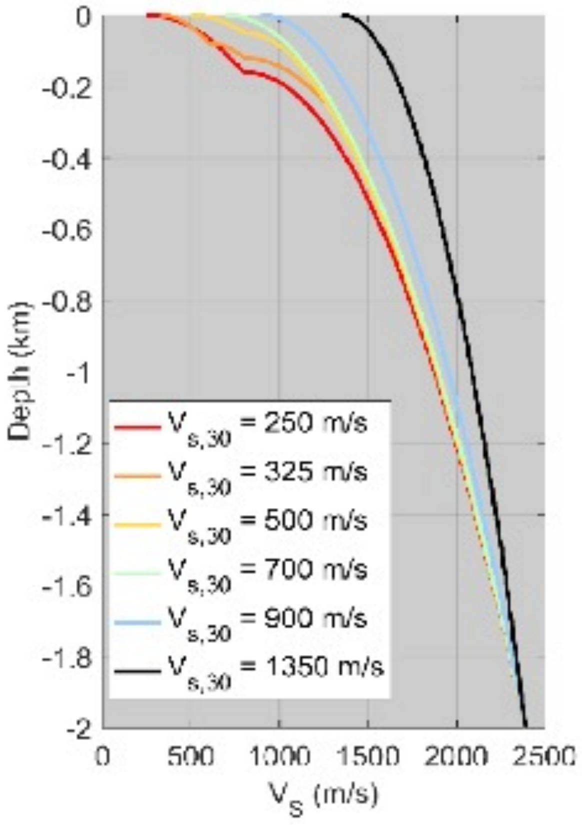
3D PBS scenarios in Istanbul: model construction

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



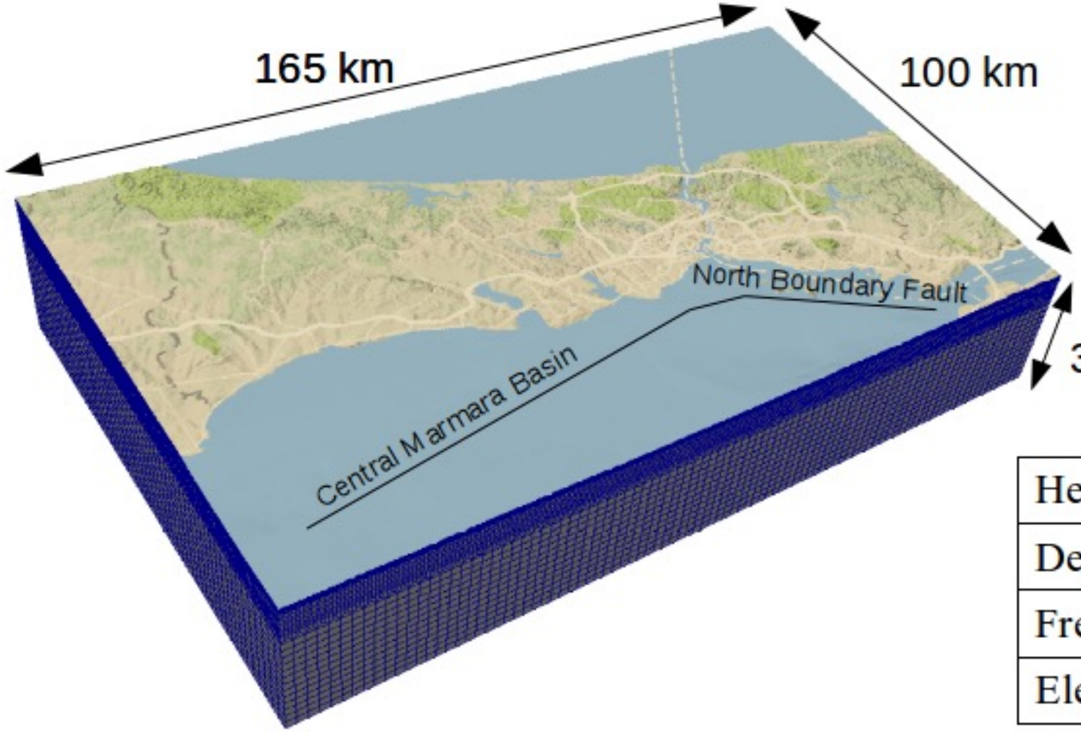






3D PBS scenarios in Istanbul: model construction

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



Horizontally stratified crustal model

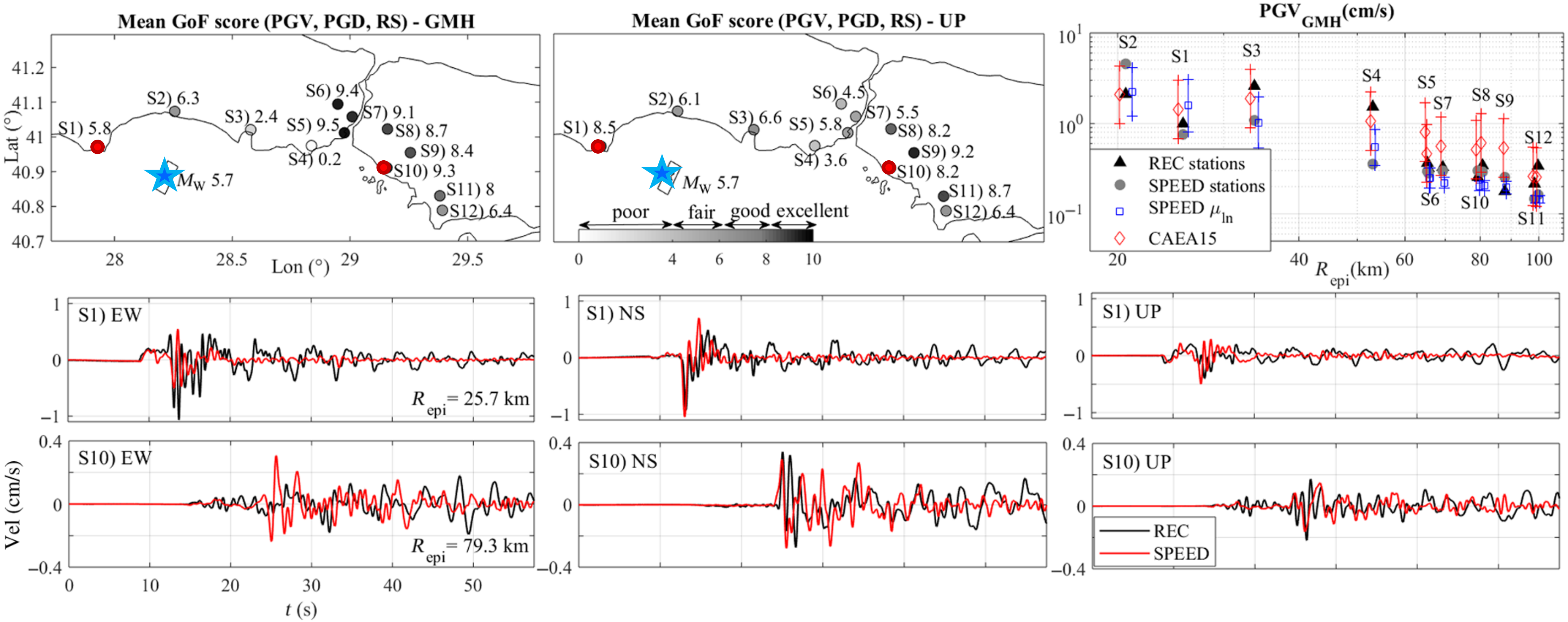
Depth (km)	V_S (m/s)	Q(-)
0-5	Fig. 3	V_S /10
5-10	3490	350
10-20	3500	350
20-30	3920	400

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

3D PBS in Istanbul: validation

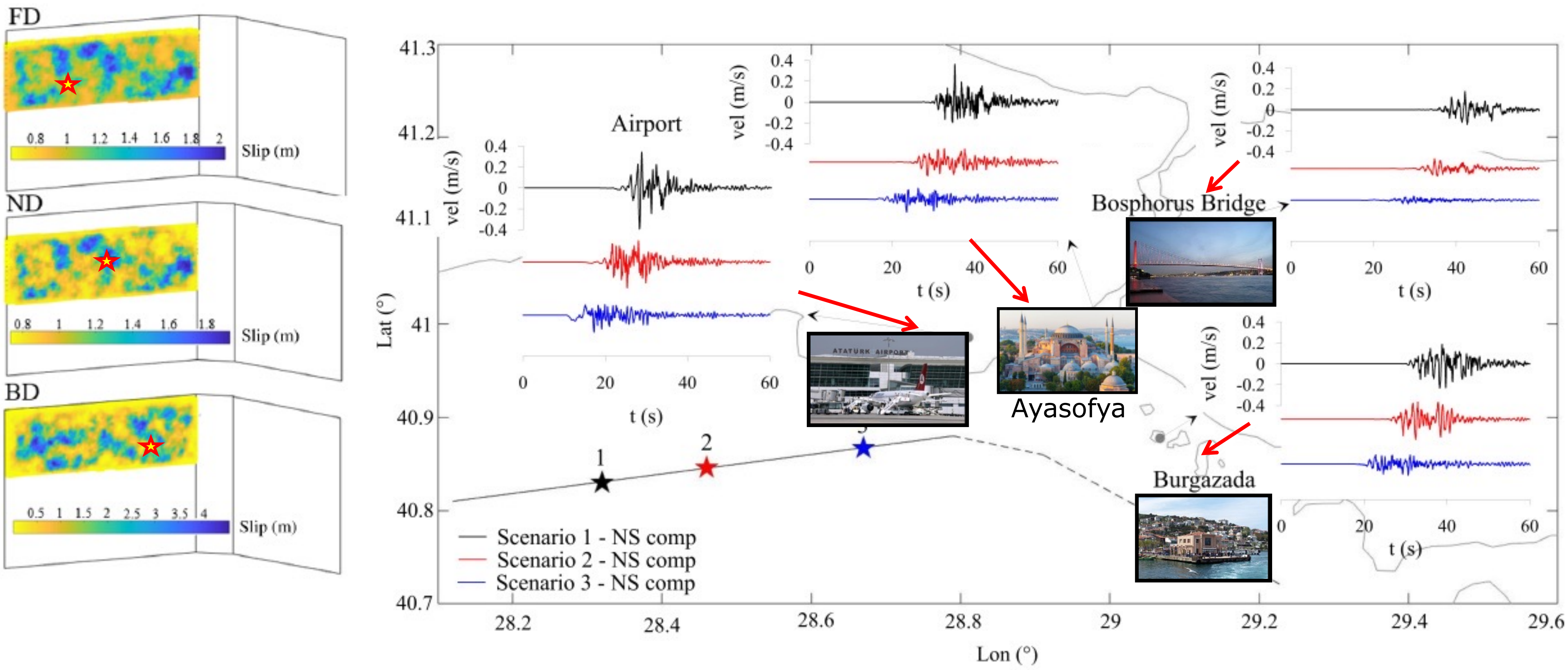
Validation with records of 26 September 2019 M_w5.7 Marmara Sea earthquake and numerical simulations. Data bandpass filtered between 0.05 and 1.5 Hz.



3D PBS scenarios in Istanbul: slip distributions

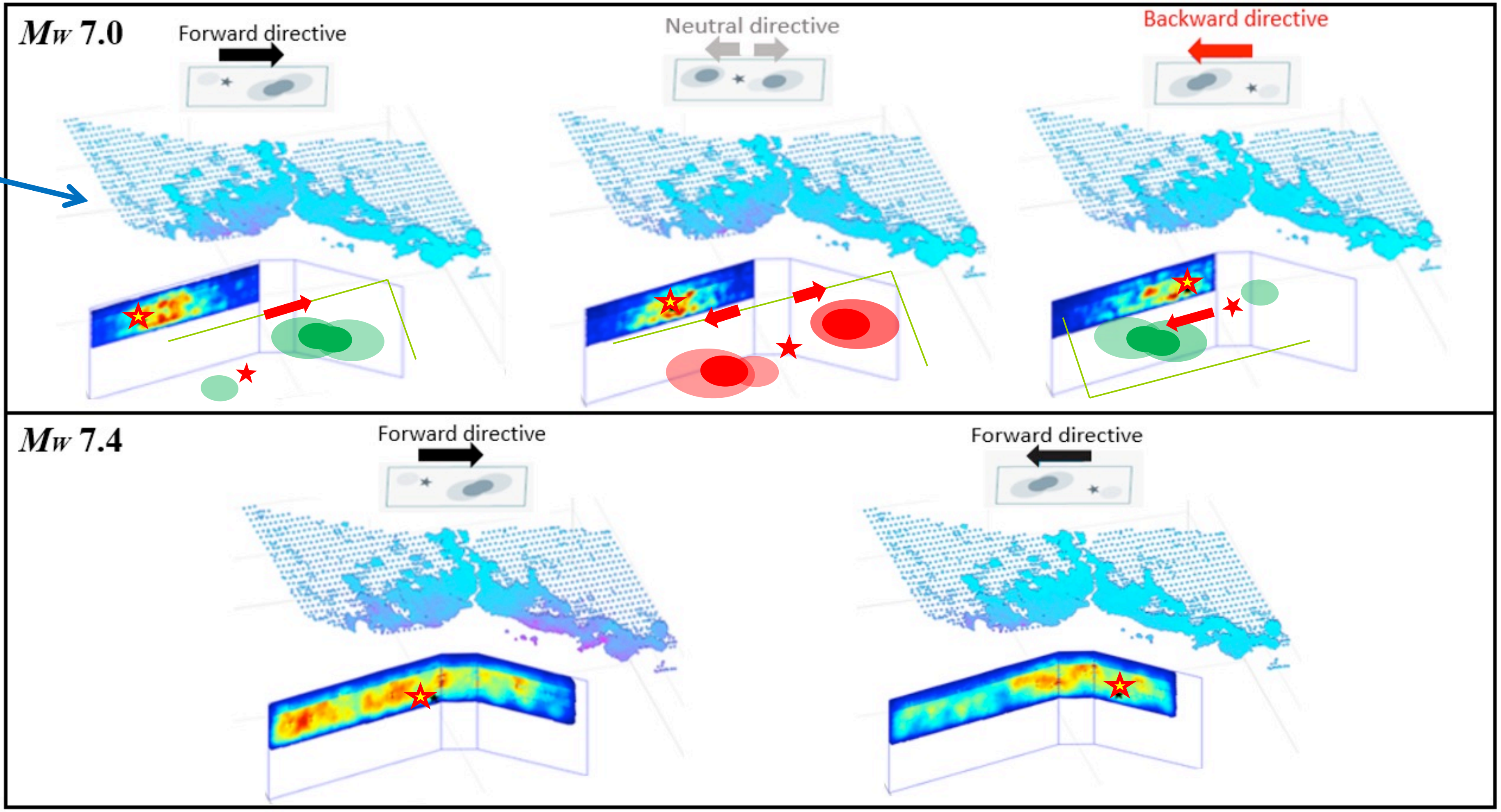
about 60 kinematic slip distributions (M7-7.4) were randomly generated according to Crempien and Archuleta (2015)

Velocity time histories for different scenarios



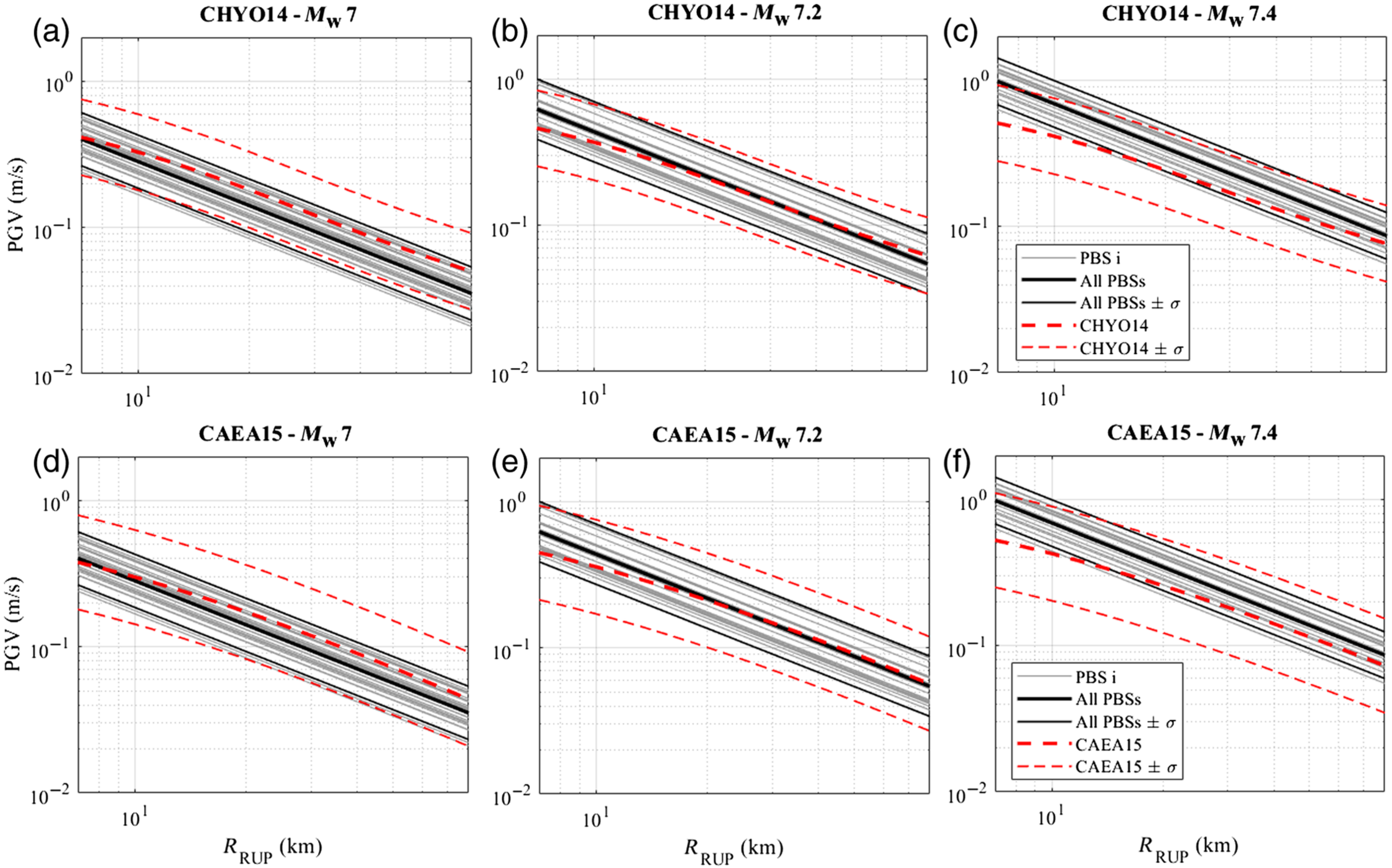
3D PBS scenarios in Istanbul: directivity effect

PGV map in Istanbul



most slip distributions for the M7.4 earthquake implied forward directivity in at least some portions of Istanbul urban area

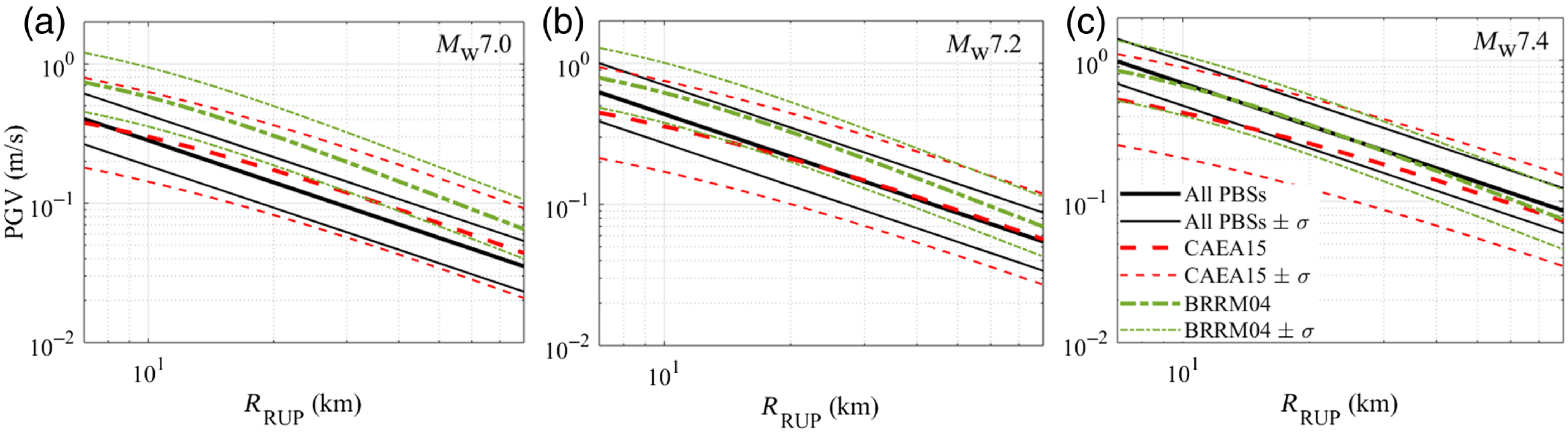
Comparison with GMMs



Chiou&Youngs, 2014 (CHY014)

Cauzzi&al, 2015 (CAea015)

Comparison with GMMs



Bray&Rodriguez-Marek (SDEE, 2004)
Characterization of forward-directive ground motions in the near-fault region

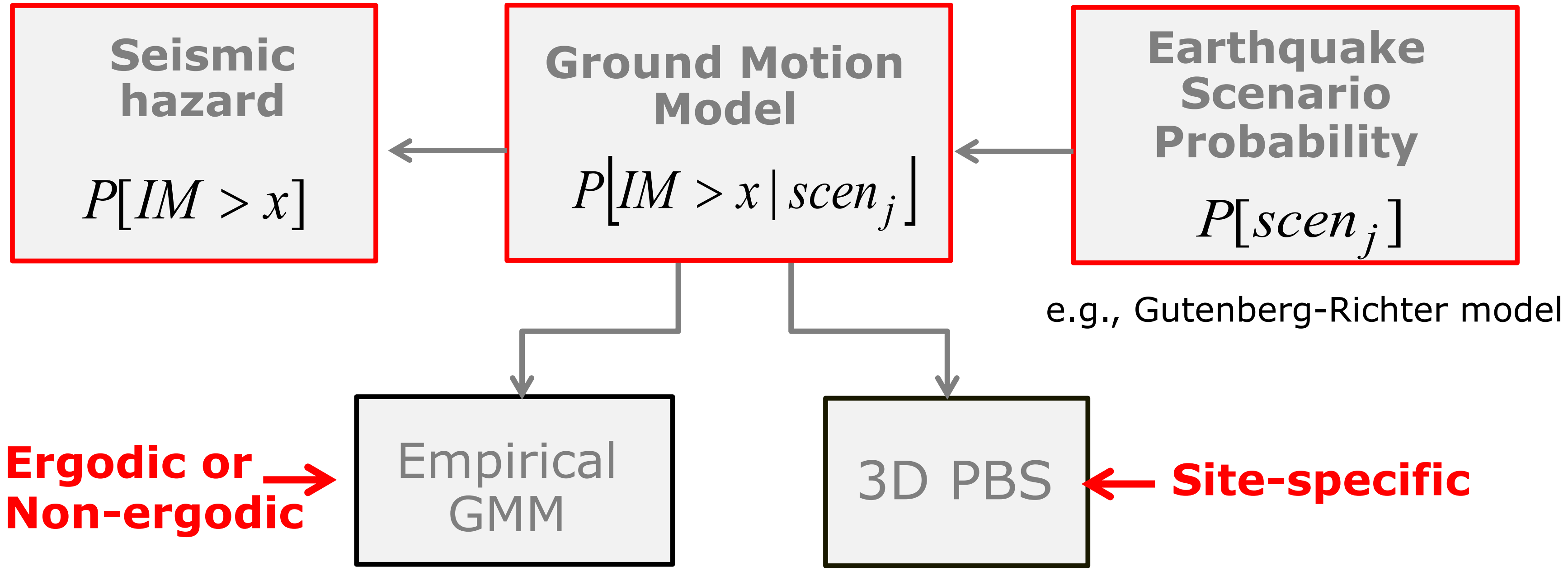
A general framework for PBS application into a PSHA

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

Physics-based probabilistic seismic hazard and loss assessment in large urban areas: A simplified application to Istanbul

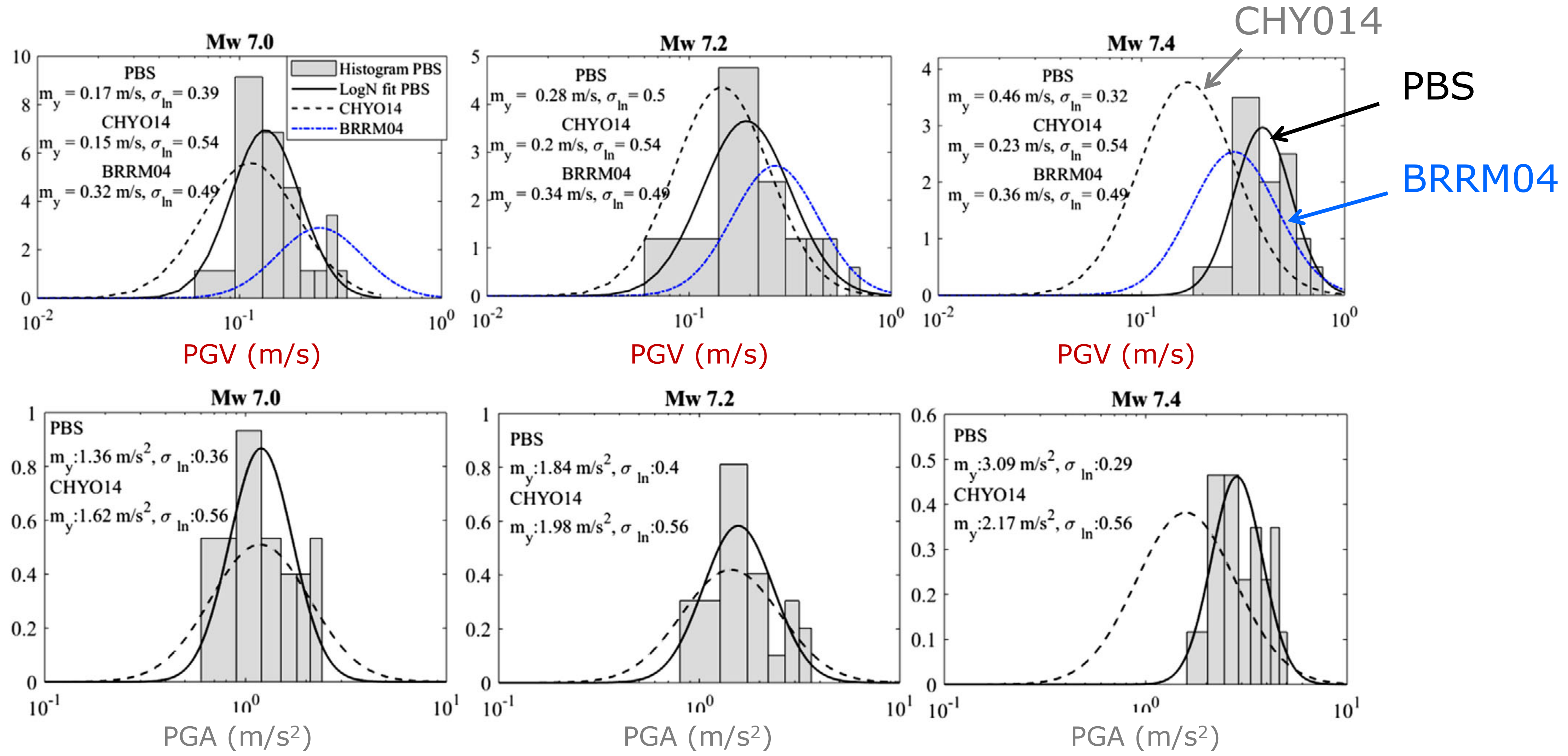
Marco Stupazzini[1] | Maria Infantino[2,3] | Alexander Allmann[1] | Roberto Paolucci[2]

Earthquake Engng Struct Dyn. 2021;50:99–115.

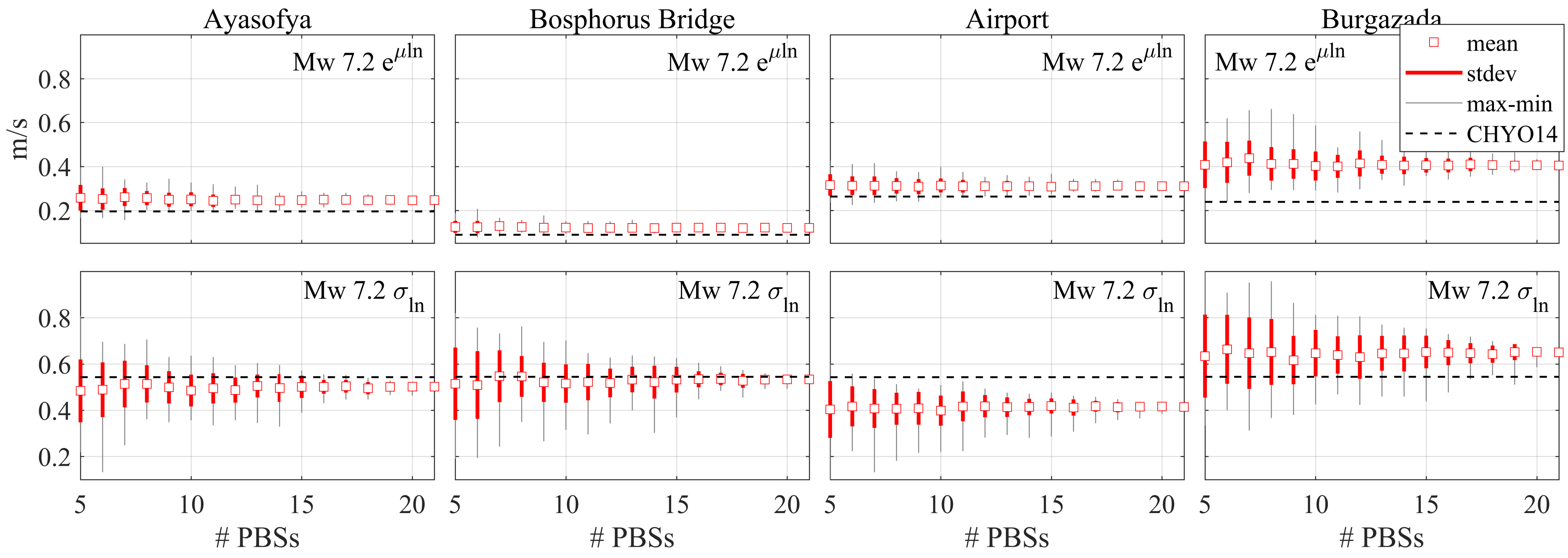


Note: PBS do not imply a deterministic approach to seismic hazard!

PBS-based GMM - Ayasofia

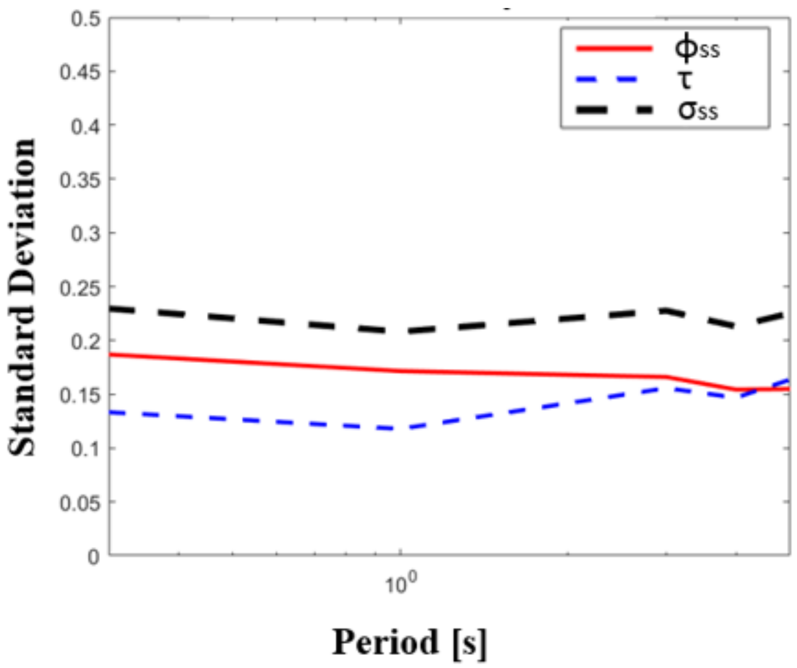


How many PBS realizations to obtain stable moments of the GMM distribution?

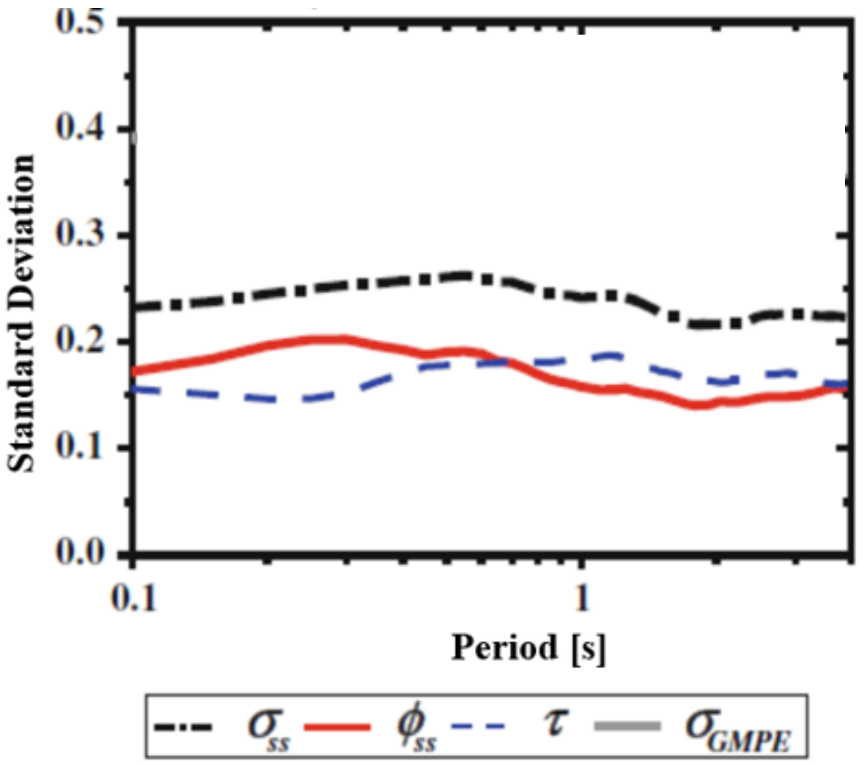


Are the results of PBS representing a realistic b-e and w-e variability?

PBS Istanbul



Christchurch – records (Faccioli et al., 2013)

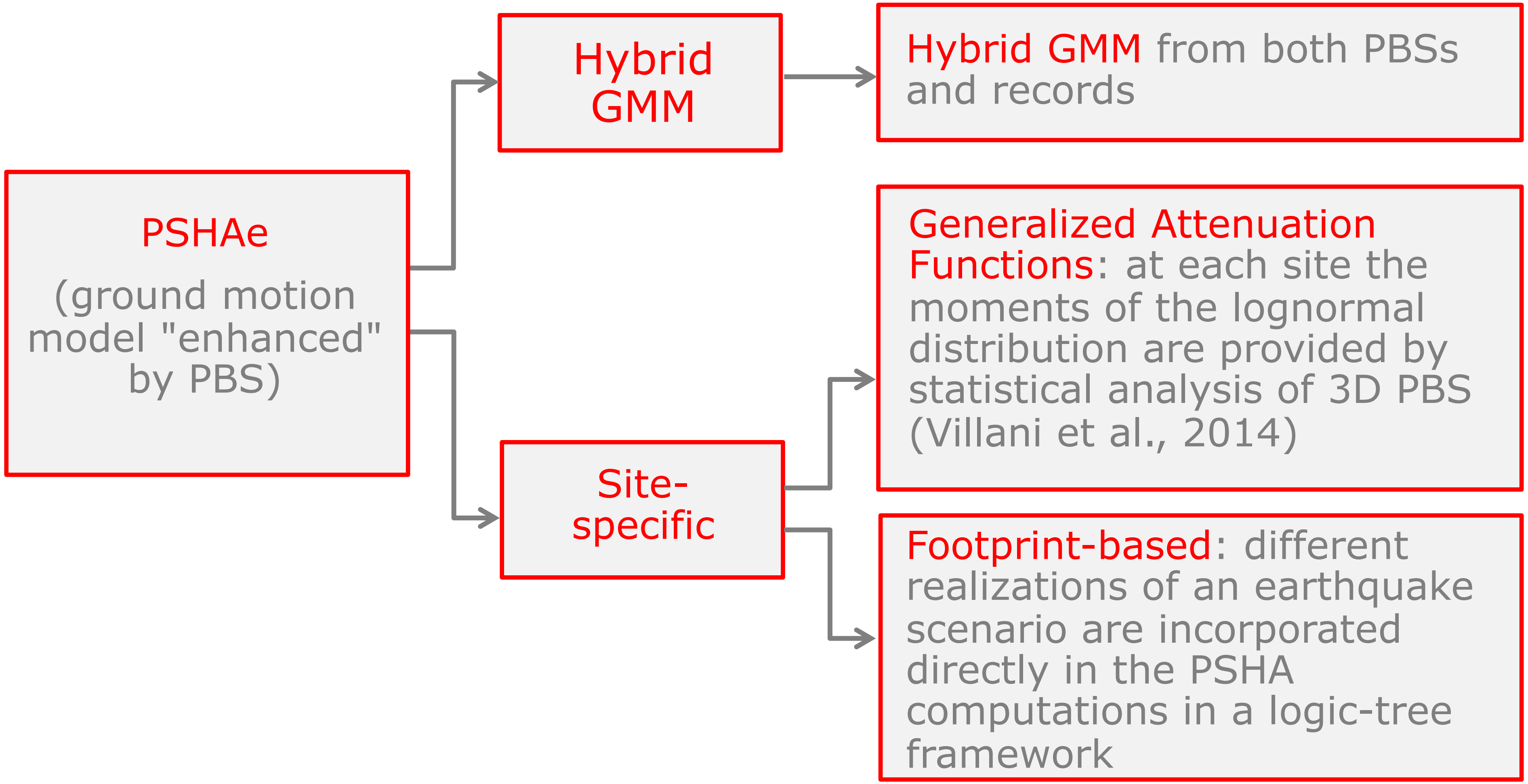


between-event sigma

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

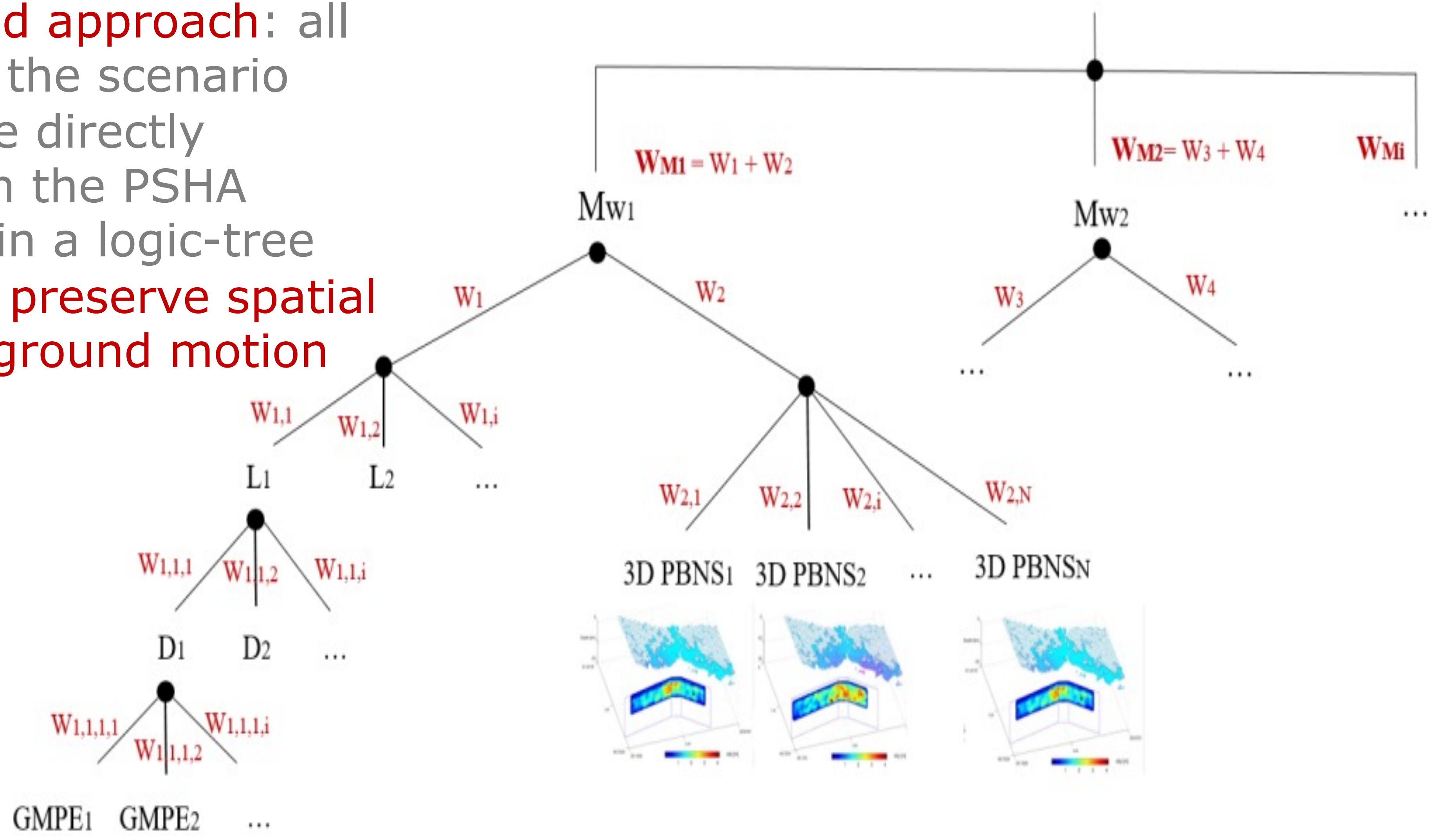
within-event sigma

How to exploit 3D PBS in the framework of PSHA?

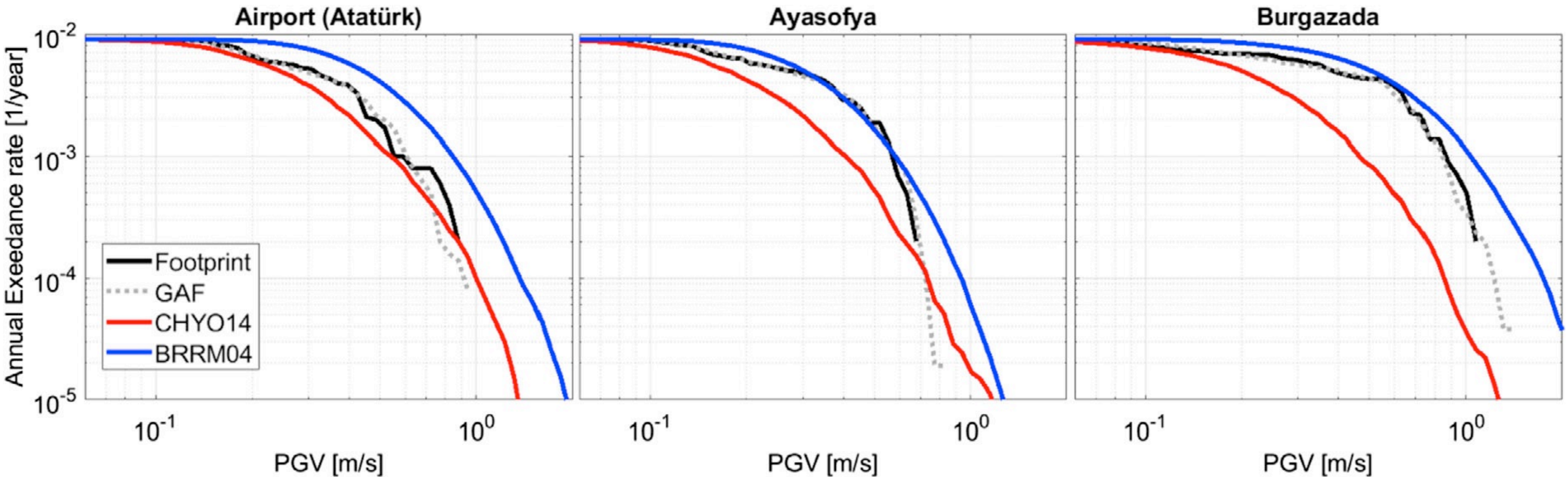


How to exploit 3D PBS in the framework of PSHA?

Footprint-based approach: all realizations of the scenario earthquake are directly incorporated in the PSHA computations in a logic-tree framework, to **preserve spatial correlation of ground motion**



How to exploit 3D PBS in the framework of PSHA?



Footprint-based and GAF provide similar outcomes, bounded by on the lower side by the CHY014 and on the upper side by the FD ground motion model by Bray&Rodriguez-Marek (2004)

Concluding remarks

- ✓ 3D PBS may provide site-specific (or area-specific) probabilistic ground motion models that can be used as either complementary or alternative approach to ergodic empirical models within a PSHA framework

- ✓ to make results of 3D PBS meaningful for this purpose, the numerical simulations should span a range of uncertainty on the fault model sufficient to provide stable moments (mean, sigma) of the GMM probability distribution. In the Istanbul case, 10-15 simulations were found sufficient for this purpose for each Magnitude interval.

- ✓ 3D PBS may also support a footprint approach to PSHA, where, instead of using a GMM, all PBS scenarios are input in a logic-tree based PSHA framework, is also suitable to properly account for the spatial correlation of ground motion

Thanks for your attention!

see also the related presentations by:

Chiara Smerzini
Marco Stupazzini