6th National Conference on Earthquake Engineering
&
2nd National Conference on Earthquake Engineering and Seismology

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POLITECNICO DI MILANO

3D PHYSICS-BASED NUMERICAL SIMULATIONS: ADVANTAGES AND LIMITATIONS OF A NEW FRONTIER TO EARTHQUAKE GROUND MOTION PREDICTION

Roberto Paolucci

Department of Civil and Environmental Engineering, Politecnico di Milano

Contents

- ✓ Motivation for 3D physics-based earthquake ground motion simulations
- ✓ the spectral element code SPEED
- ✓ 3D physics-based earthquake ground motion simulations in Istanbul
- ✓ producing broadband ground motions

Approaches to earthquake ground motion prediction

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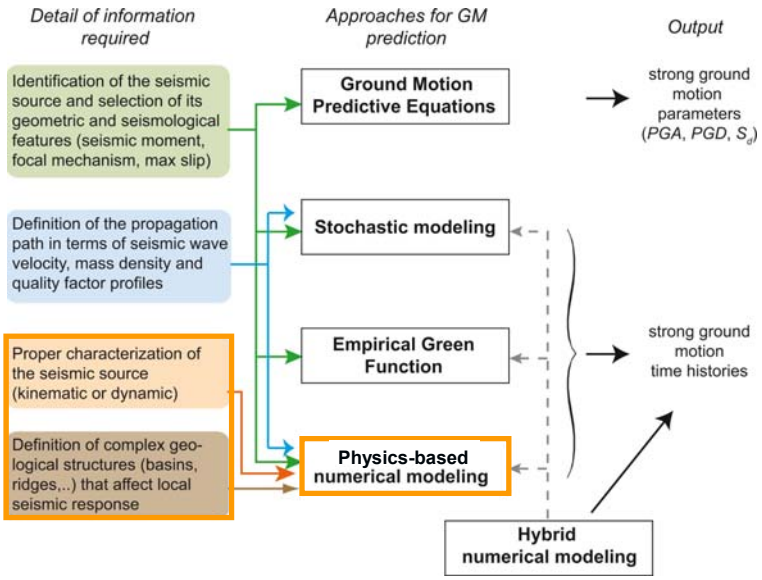
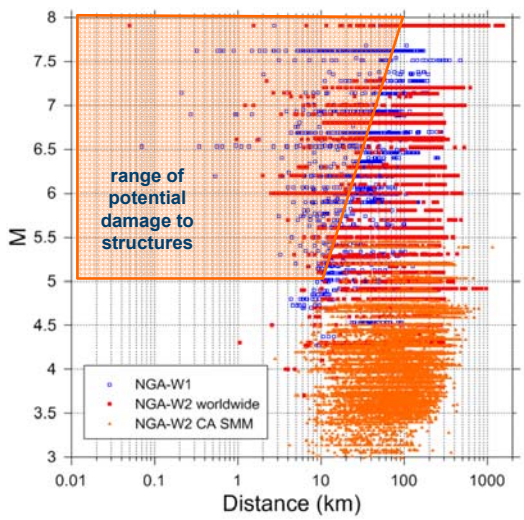


Limitations in the use of GMPEs

4



NGA West2 database (Ancheta et al., 2013)

Limitations in the use of GMPEs

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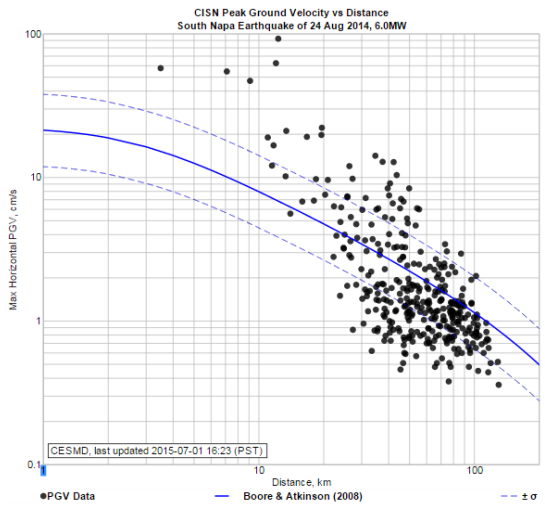
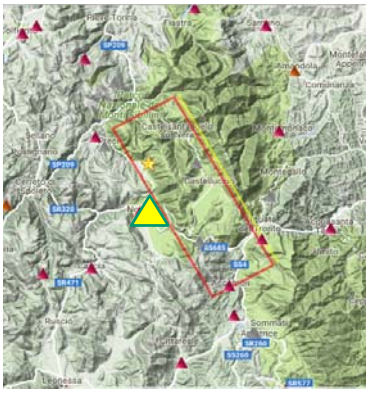
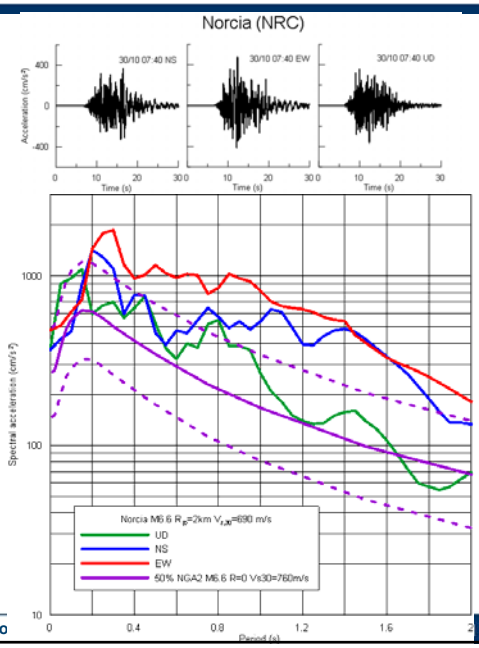


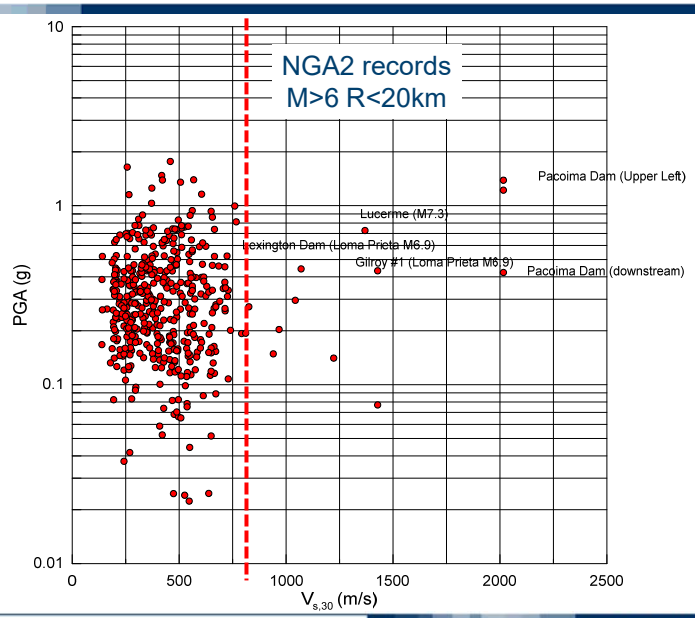
Limitations in the use of GMPEs

6



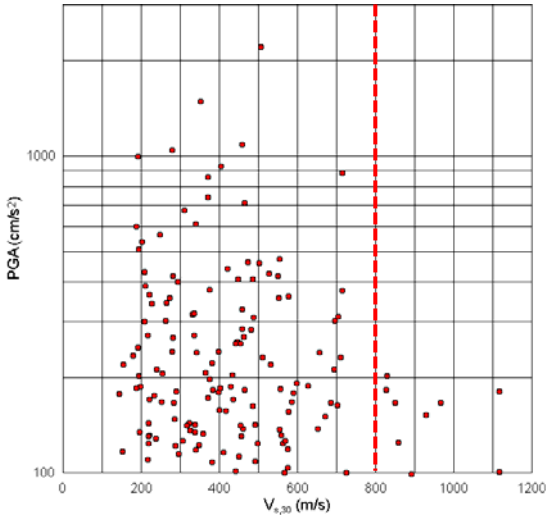


Limitations in the use of GMPEs



Limitations in the use of GMPEs

INGV wordlwide near source dataset
6 < M < 7 & PGA > 100 cm/s2



Physics-based 3D earthquake ground motion simulations

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Objective

To create a numerical laboratory to simulate "earthquake ground shaking scenarios" as realistic as possible in terms of:

- ✓ the complexity of the seismic source
- ✓ the complexity of the geological and morphological environment
- ✓ the frequency range of the seismic excitation and of resulting ground motion

Physics-based 3D earthquake ground motion simulations

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GMPEs → 3D physics based GM simulations

… but you need

- ✓ 3D numerical models
- ✓ high frequency
- ✓ verifications on real earthquakes

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SPEED (speed.mox.polimi.it)

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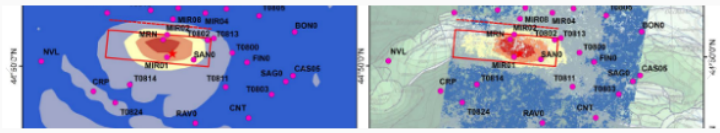
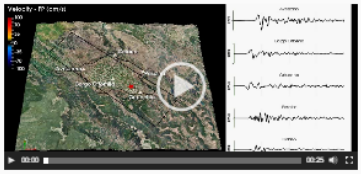
SPEED

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





On January 13, 1915, at 6:52 local time, a catastrophic earthquake devastated Marsica, Southern Abruzzi, Central Italy, causing around 33,000 fatalities. Among the most important municipalities hit by the earthquake, the ruin of Avezzano was completed, with 10,700 fatalities, 95% of the total population (CFTI, 2015). A single reinforced concrete building in Avezzano, one of the very first ones at those times, withstood the earthquake and was later declared national monument.

MOX POLITECNICO MILANO 1863 Dipartimento di Ingegneria Civile e Ambientale

SPEED: some references

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Faccioli E, Maggio F, Paolucci R, Quarteroni A.
2D and 3D elastic wave propagation by a pseudo-spectral domain decomposition method
Journal of Seismology, 1997

Stupazzini M., Paolucci R., Igel H.
Near-fault earthquake ground motion simulation in the Grenoble Valley by a high-performance spectral element code
Bulletin of the Seismological Society of America, 2009

Mazzieri I., Stupazzini M., Guidotti R., Smerzini C.
SPEED-Spectral Elements in Elastodynamics with Discontinous Galerkin. A non-conforming approach for 3D multi-scale problems.
International Journal for Numerical Methods in Engineering, 2013

SPEED: main features

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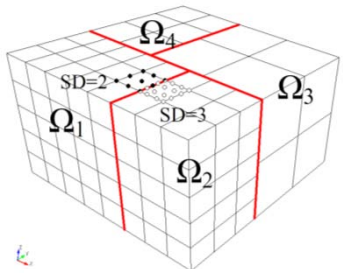
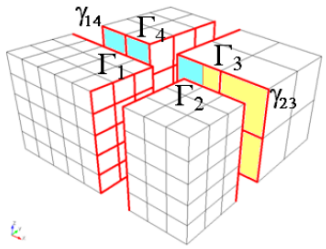
Features

- 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



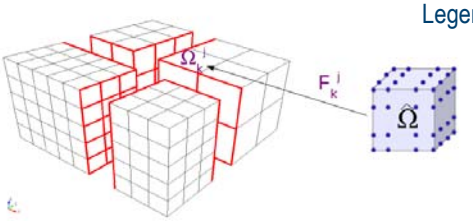
Kernel

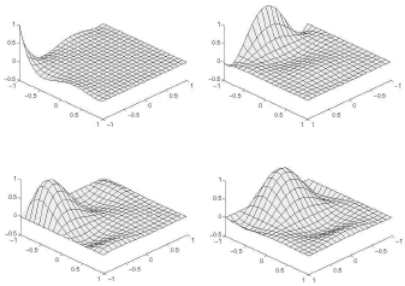
- hybrid parallel programming based on MPI and Open-MP
- METIS software library to handle partitioning and load balancing
- designed for multi-core machines or large clusters - optimized for HPC clusters (e.g., FERMI Blugene/Q)



SPEED: spatial discretization

Legendre-Gauss-Lobatto points





Lagrange polynomials

SPEED: Treatment of seismic input

Kinematic modeling of an extended seismic source

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

volume of the kth subfault

slip and normal fault vectors $f(\delta_i, \lambda_i, \varphi_i)$

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

area

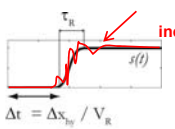
shear modulus

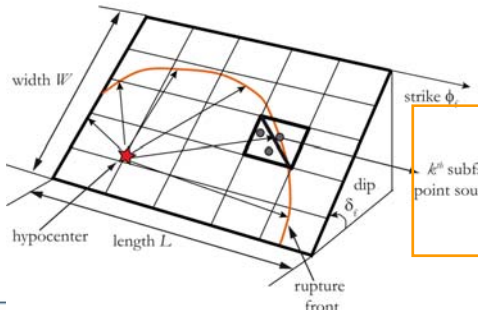
co-seismic slip

Slip source function

How to introduce high-frequency components ?

How to introduce spatial incoherency?





k^{th} subfault point source x_i^k

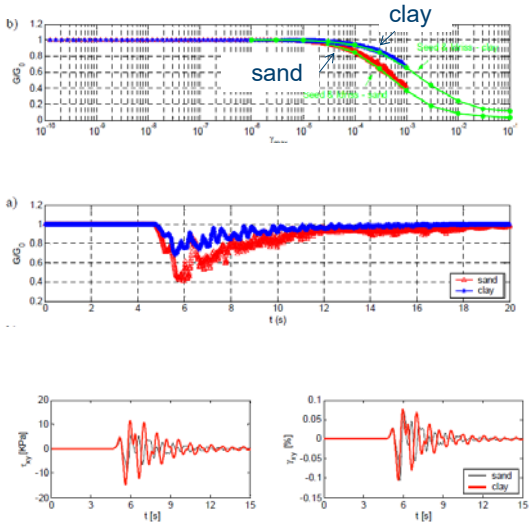
- shear modulus μ^k
- slip Δu^k
- area A^k
- rise time τ_R^k
- rupture velocity V_R^k
- rake angle λ_i^k
- delay Δt^k

SPEED: soil modelling

Viscoelastic models

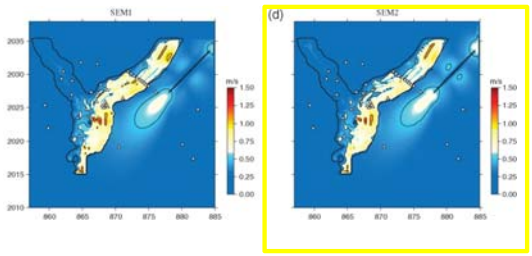
- ✓ Q = cost
- ✓ $Q = Q_0 f$
- ✓ Rayleigh damping

Non-linear elasticity

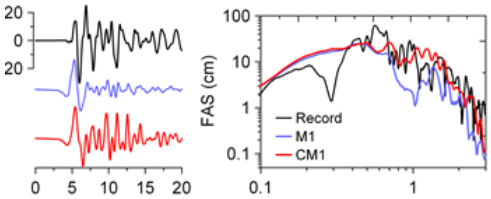


Previous applications of SPEED (1)

Stupazzini M, Paolucci R, Igel H (2009)
Near-fault earthquake ground-motion simulation in the **Grenoble valley** by a high-performance Spectral Element code. *BSSA , 99: 286–301*.



Smerzini C, Villani M (2012)
Broadband numerical simulations in complex near field geological configurations: the case of the M_W 6.3 2009 **L'Aquila earthquake**, *BSSA, 102: 2436–2451*



Previous applications of SPEED (2)

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- ✓ Gubbio (Central Italy)
- ✓ Sulmona (Central Italy)
- ✓ Santiago de Chile
- ✓ Christchurch earthquake February 22, 2011 (New Zealand)
- ✓ Wellington (New Zealand)
- ✓ Po Plain earthquake May 29, 2012 (Northern Italy)
- ✓ Marsica earthquake 1915 (Central Italy)
- ✓ Thessaloniki (Greece)
- ✓ Istanbul (Turkey)
- ✓ Beijing (China)

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Past century earthquakes along the North Anatolian Fault

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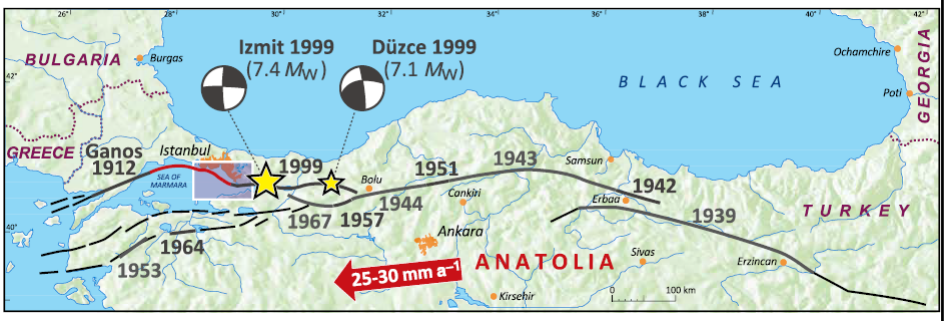

after Bohnhoff et al., 2013

Princes Islands segment of the NAF

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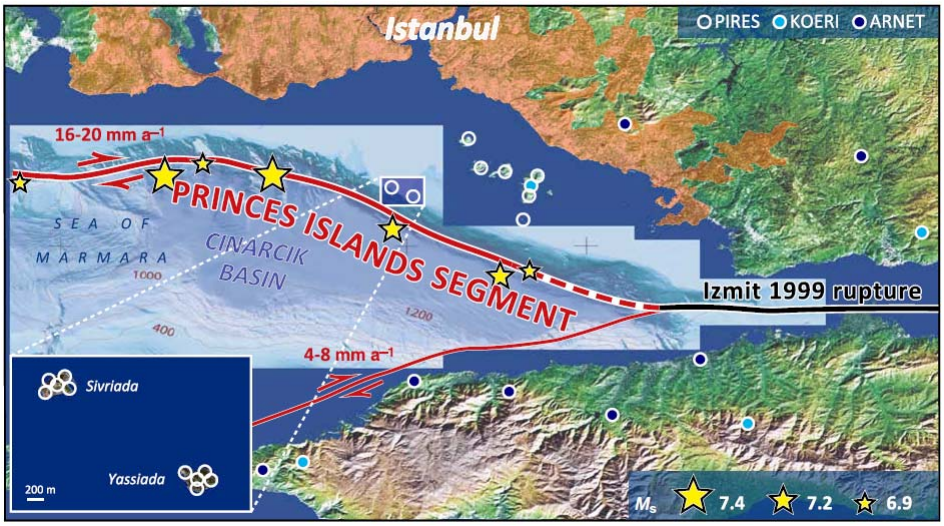

Yellow stars mark estimated epicentres of major earthquakes along the Princes Islands segment during the last 2,000 years. After Bohnhoff et al., 2013

Setup of the 3D physics-based numerical simulations

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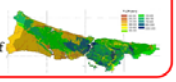
INPUT DATA

Topography and bathymetry model

Regional seismotectonic context, identification of the active faults

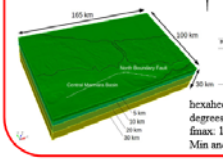
Geological and geotheenical characterization of the area



NUMERICAL MODEL

MESH DESIGN [Software: CUBIT]

Topography /Bathymetry + fault geometry + velocity model

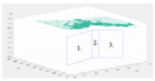


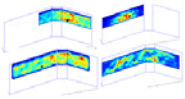
Crustal model

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:

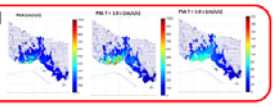
- Mw
- Position of rupture area
- Slip distribution
- Hypocenter location
- Rupture length and width (L, W)
- Rake angle
- Rupture velocity
- Rise time

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)



Construction of the numerical model (1)

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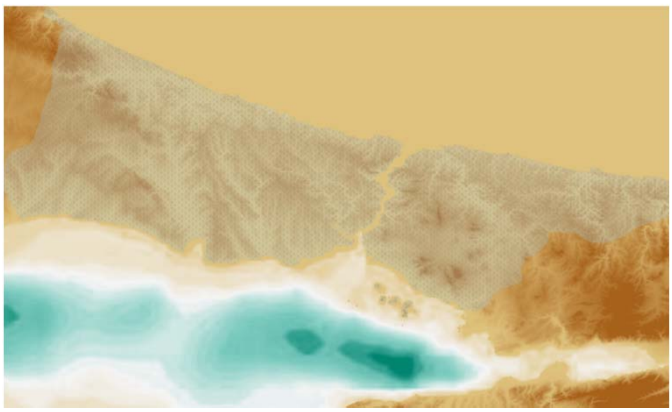
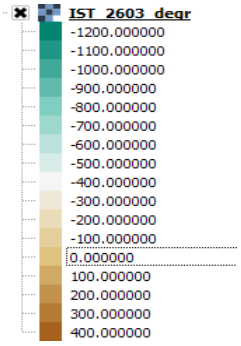
Combined digital elevation/bathimetry model





Construction of the numerical model (2)

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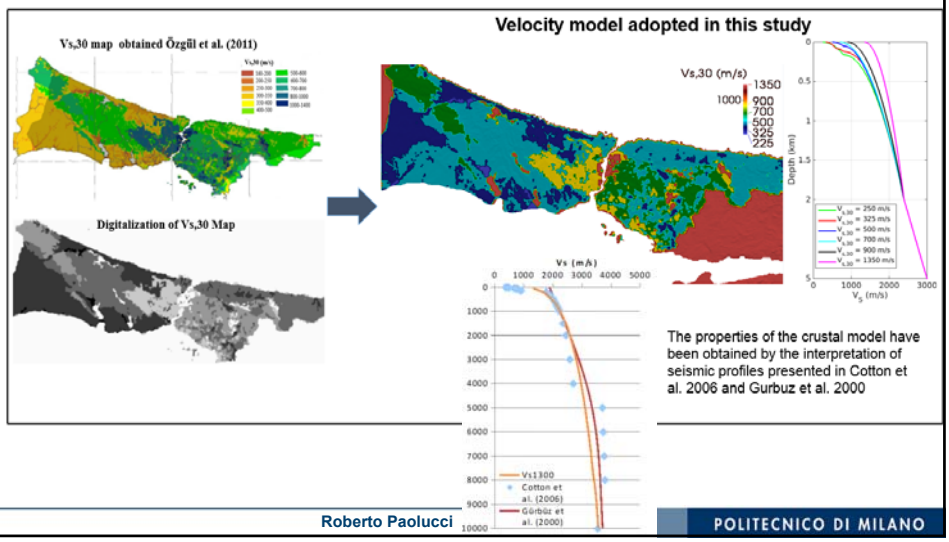
Vs model



The properties of the crustal model have been obtained by the interpretation of seismic profiles presented in Cotton et al. 2006 and Gurbuz et al. 2000

Construction of the numerical model (3)

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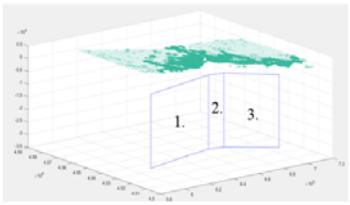
Fault geometry model

Seismic Fault model used in this study



Segment	Strike (deg)	Dip (deg)	Rake (deg)	L_{max} (m)	W_{max} (m)	F.O.* (Lon[°N];Lat[°E])	Top depth(m)
1	81.5	90	0	58000	30000	28.12;40.81	836.5
2	99.6	90	0	10400	30000	28.79;40.88	655.7
3	119.3	90	0	30000	30000	28.91;40.86	543.8

*F.O. is the Fault Origin defined as the point of the fault at zero strike and zero slip

Construction of the numerical model (4)

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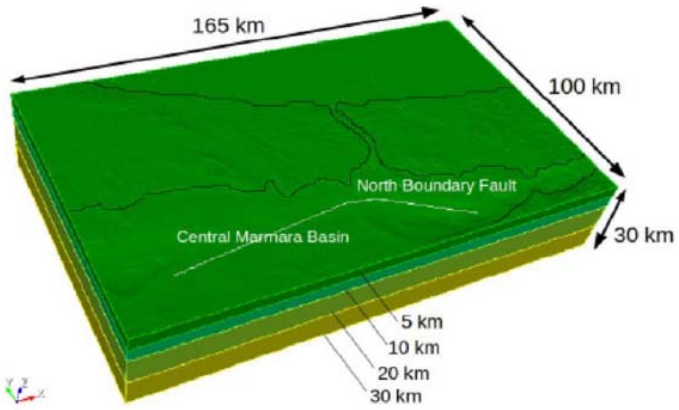
Spectral element numerical model (resolution: f_{max}= 1.5 Hz)



SD	Elements#	Degree of freedom	$\Delta t_{simulation}$(s)	Total simulated time (s)	Total time for simulation (min)	Cores#
4	2,257,482	475 million	0.001	60	840 (~ 14h)	2048

Slip distribution along the fault

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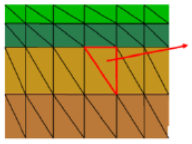
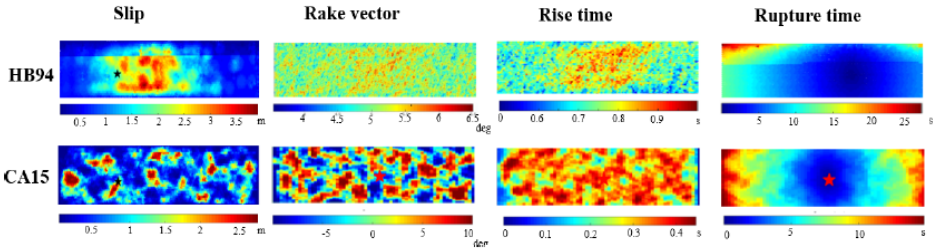
Kinematic slip distribution models



1.Triangulation of the physical fault

2. For each triangle is defined:
- seismic moment : f (slip)
- rake vector
- rise time
- rupture time



HB94: Herrero and Bernard (1994)
CA15: Crempien and Archuleta (2015)

Construction of scenario earthquakes

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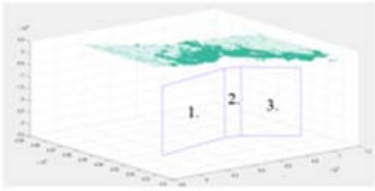

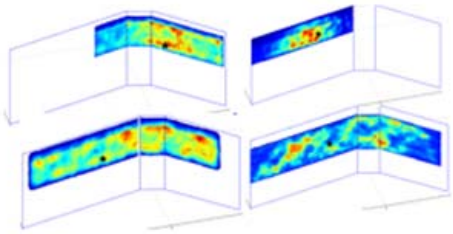

45 scenario earthquakes of M ranging from 7 to 7.4 where constructed by considering randomly generated hypocenter and slip distribution models, with both HB94 and CA15 approaches

Post-processing 45 shaking scenarios ($7.0 \leq M_w \leq 7.4$)

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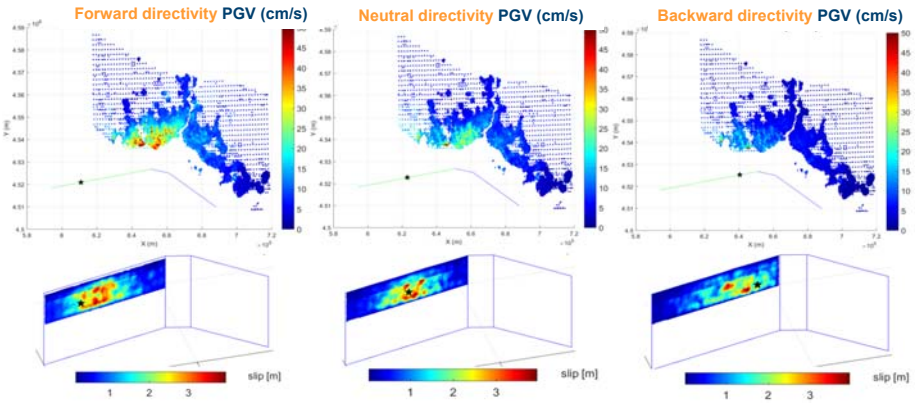
Comparison of M_w7 scenarios: effect of directivity



Post-processing 45 shaking scenarios ($7.0 \leq M_w \leq 7.4$)

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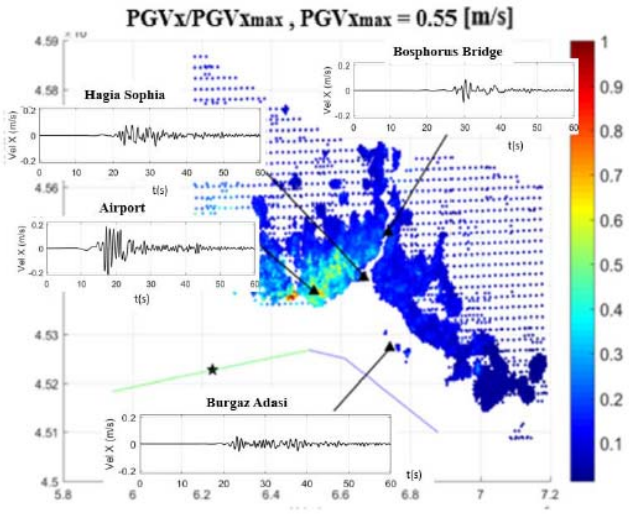
Ground motions for a selected scenario



Post-processing 45 shaking scenarios ($7.0 \leq M_w \leq 7.4$)

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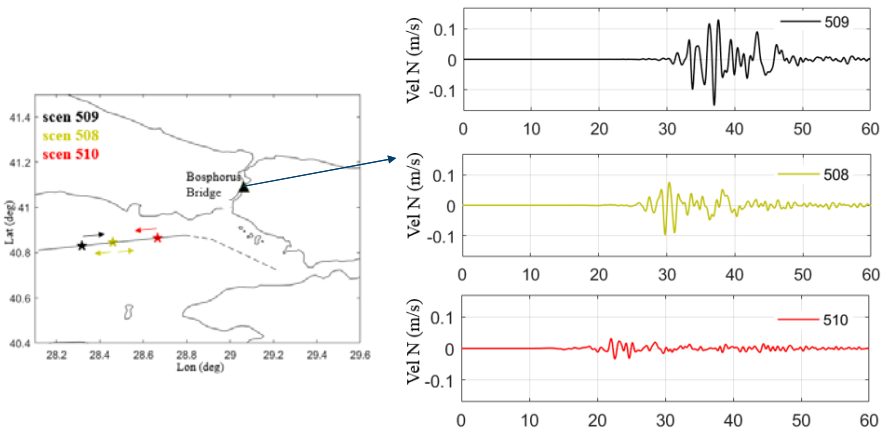
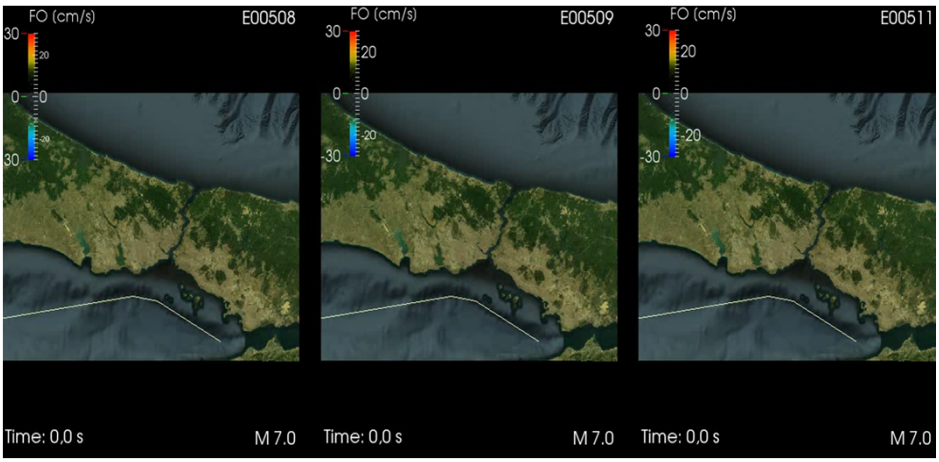
Ground motions for a selected site



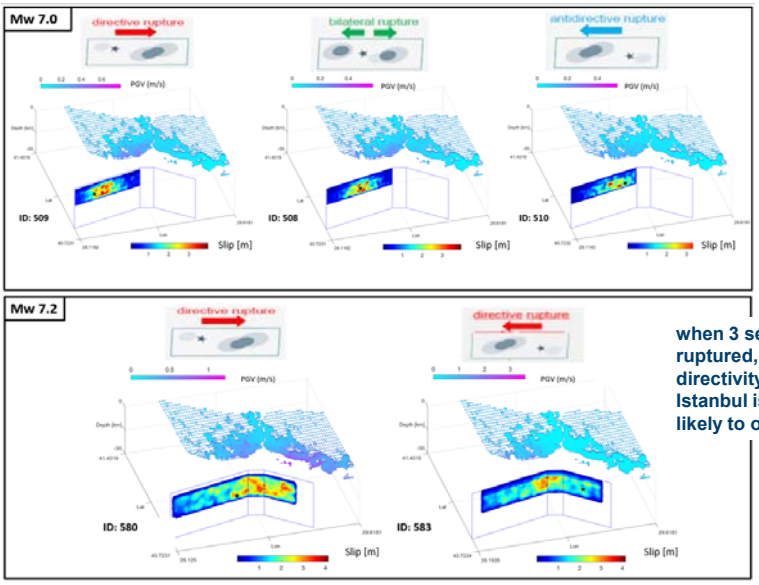
Post-processing 45 shaking scenarios ($7.0 \leq M_w \leq 7.4$)

Animation of ground motion: effect of directivity

Neutral | Forward | Backward



Dependendance of results on ruptured segments



when 3 segments are ruptured, the FW directivity scenario wrt Istanbul is the most likely to occur

Comparison with GMPEs

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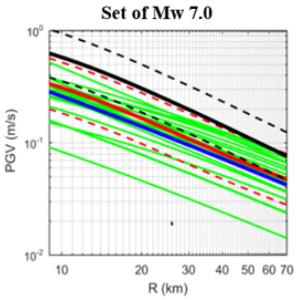

SGMPE Single Scen
SGMPE All Scen
CHYO08 ← Chiou and Youngs (2008)
CHYO08 + sd
CHYO08 - sd
BRR04 ← Bray & Rodriguez-Marek (2004) only FW directivity
BRR04 + sd
BRR04 - sd

Comparison with GMPEs

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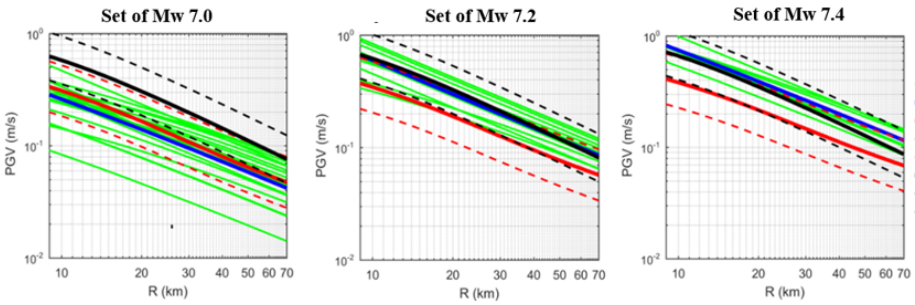

SGMPE Single Scen
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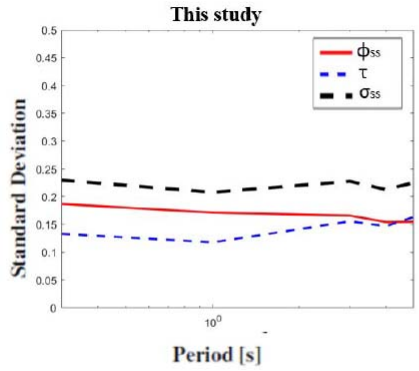
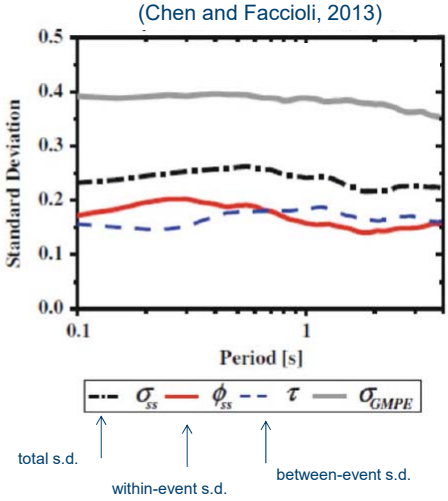
BRR04 + sd
BRR04 - sd

Components of single-station standard deviation



records of Christchurch earthquakes
(Chen and Faccioli, 2013)



Contents

- ✓ Motivation for 3D physics-based earthquake ground motion simulations
- ✓ the spectral element code SPEED
- ✓ 3D physics-based earthquake ground motion simulations in Istanbul
- ✓ producing broadband ground motions

Producing broadbands from SPEED

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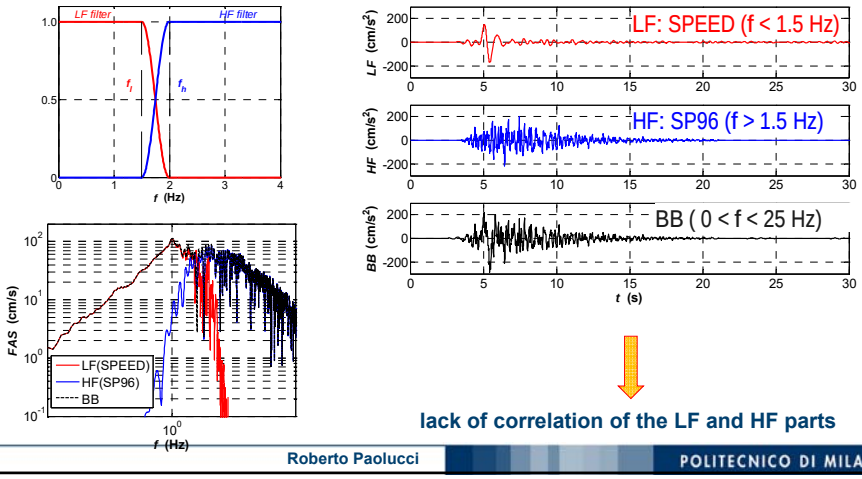
(1) A hybrid broadband is first produced by combining the low-frequency simulation with the high-frequency ground motion generated from stochastic approaches



lack of correlation of the LF and HF parts

Producing broadbands from SPEED

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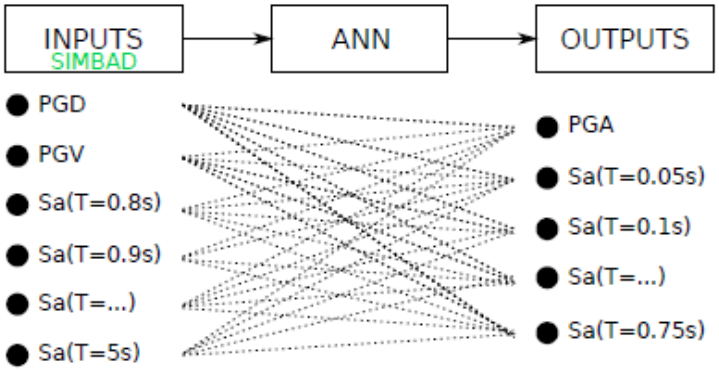
(2) An ANN is trained (una tantum) based on a strong motion dataset
(SIMBAD, Smerzini et al., 2014)



Producing broadbands from SPEED

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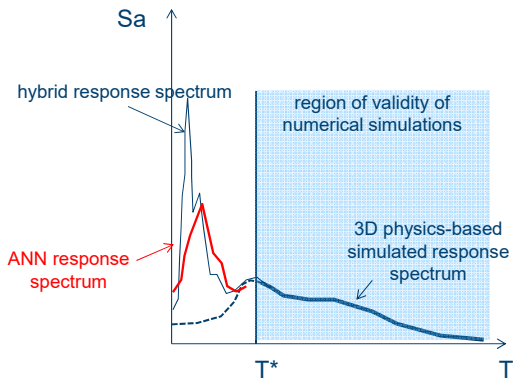
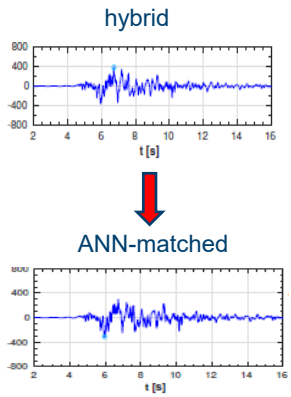
(3) The "hybrid" broadband is scaled in order to match the ANN trained response spectrum





Producing broadbands from SPEED

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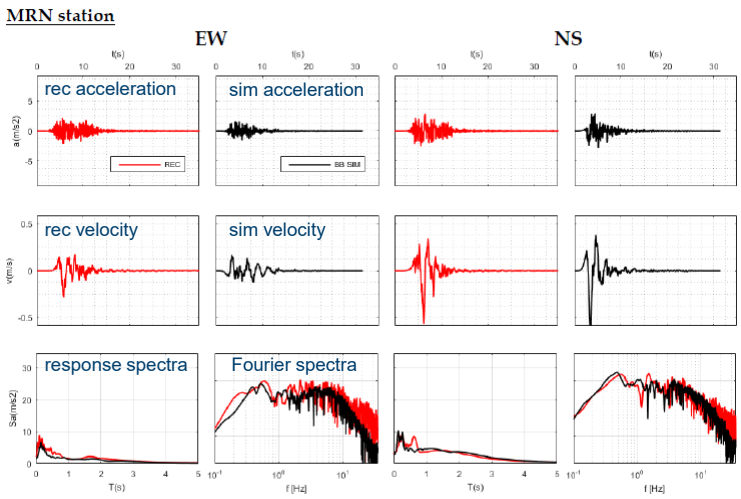
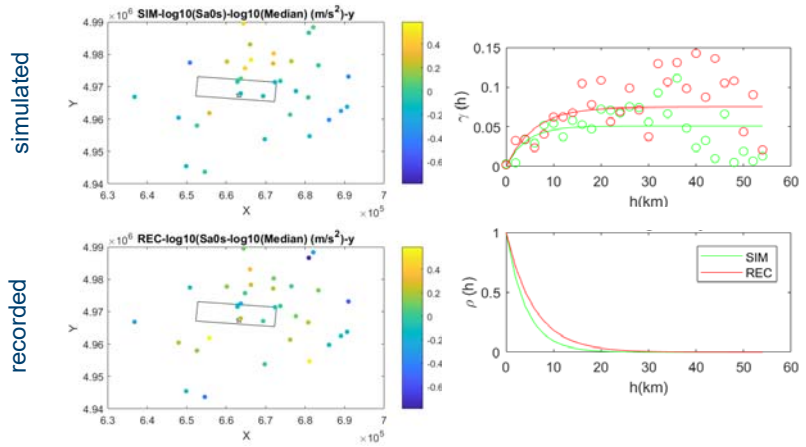
(4) Verification on real case studies: simulation of Po Plain eqk, May 29 2012



Producing broadbands from SPEED

(4) Verification on real case studies: simulation of Po Plain eqk, May 29 2012

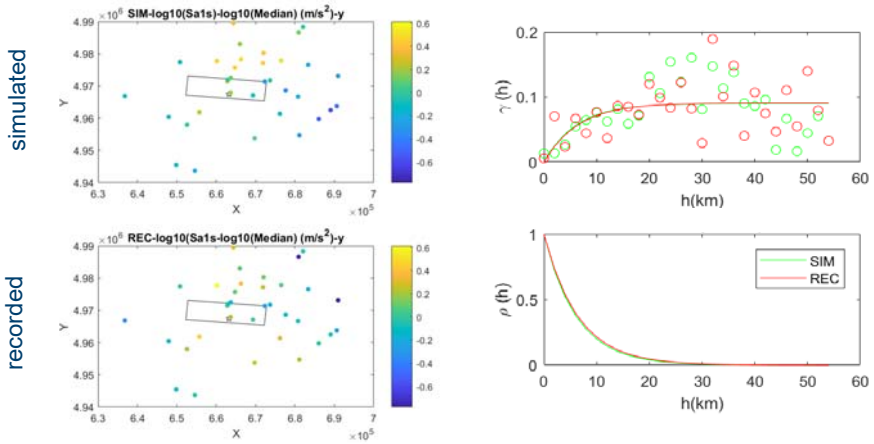
Spatial correlation of PGAs



Producing broadbands from SPEED

(4) Verification on real case studies: simulation of Po Plain eqk, May 29 2012

Spatial correlation of Sa=1s



3D numerical simulations of the May 29 2012 Po Plain earthquake

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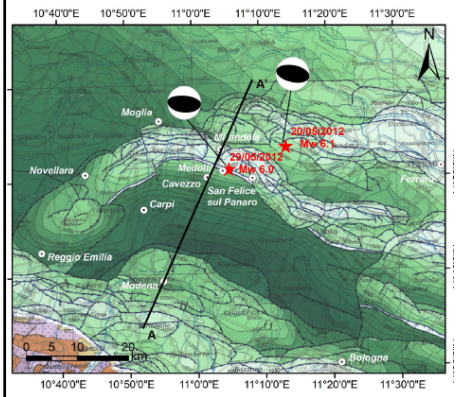

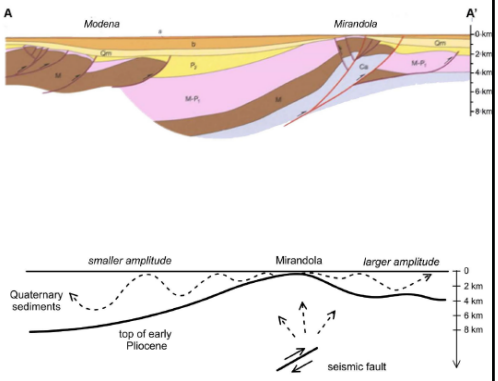

3D numerical simulations of the May 29 2012 Po Plain earthquake

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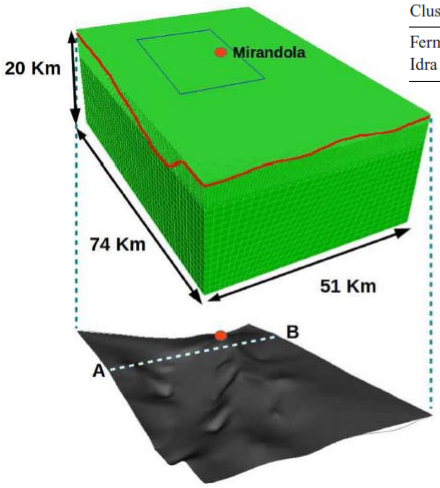
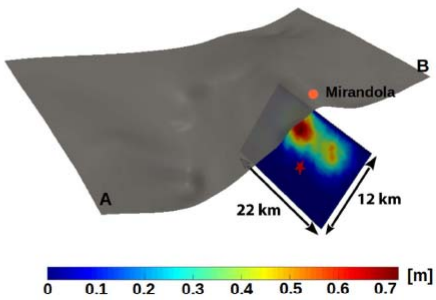
Table 5. Walltime for a single simulation of the Emilia earthquake, performed both on Fermi (CINECA) and Idra (MOX) clusters.

Cluster	Cores	Walltime (h)
Fermi (CINECA)	4096	4.98
Idra (MOX)	72	19.83





Producing ground motion movies: 2012 Po Plain eqk

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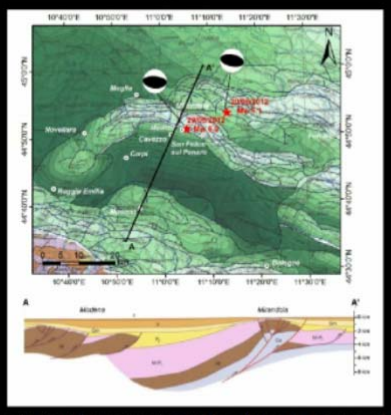
SPEED: 3D physics-based numerical simulation of the May 29 2012 Po Plain earthquake



Geological framework and focal mechanisms of the Po Plain seismic sequence

Numerical Model

Conclusions

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Pros

accounting for specific geologic and tectonic conditions

capturing physics of earthquake ground motion, especially near-source

proper spatial correlation of motion between adjacent sites

Cons

large number of scenarios needed: how to cluster them?

limited reliability in the high-frequency range, although in progress

need of vast amount of input data: suitable for large urban areas

Acknowledgements

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Munich Re (Germany)

"3D physics-based earthquake ground shaking scenarios in large urban areas"

Reluis (Italy)

RS2 Project :
"3D numerical simulations and near-source effects"

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