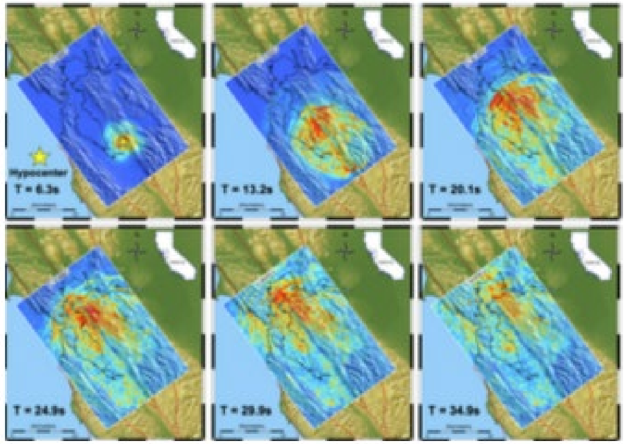
2025 PEER LBNL Workshop on the Regional Scale Simulated Ground Motion Database (SGMD) for the San Francisco Bay Area

Use of Physics-based Simulated Ground Motions for Enhanced Damage and Loss Assessments

Chiara Smerzini & Roberto Paolucci

POLITECNICO MILANO 1863

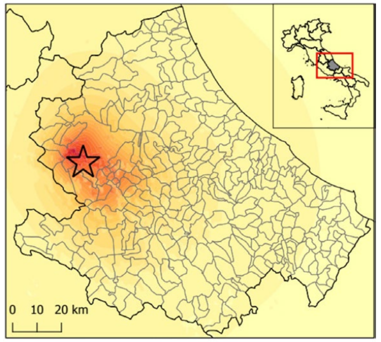


Banatao Auditorium, UC Berkeley

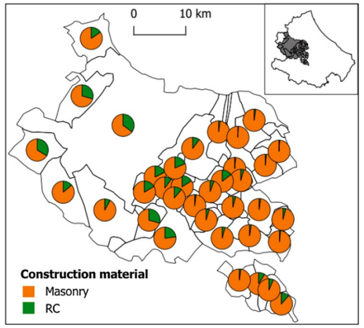
March 24, 2025

Seismic damage and loss scenarios in urban areas: background

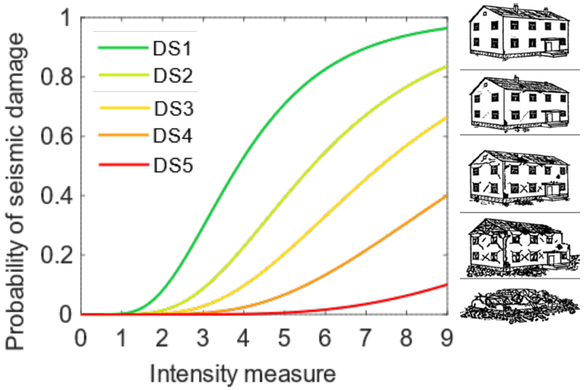
Ground Shaking Scenario
(e.g. PGA)



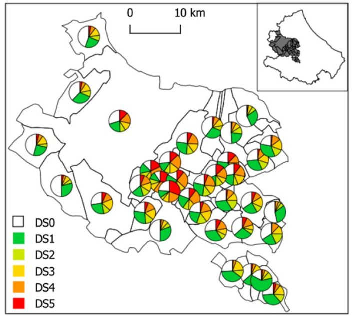
Exposure
(assets at risk)



Fragility Curves
(typological)



Damage
(physical damage)



Losses
(fatalities, economic losses)

Damage and loss scenarios are fundamental for Civil Protection authorities for emergency planning and management purposes

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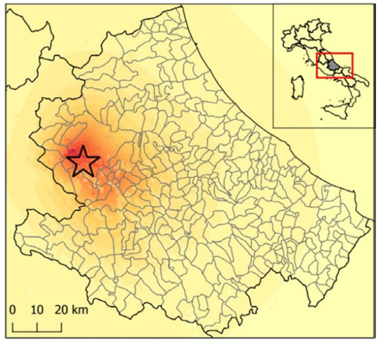
(e.g. PGA)



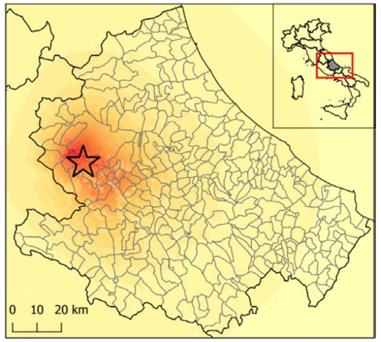
- ShakeMap
- Empirical Ground Motion Model (GMM)

However …

- ✓ Poorly calibrated in near-source conditions
- ✓ Only peak ground-motion intensity measures (IMs) used (e.g. PGA or SA)
- ✓ Region- and site-specific features disregarded (unless fully non-ergodic GMMs are used)
- ✓ Spatial correlation of ground shaking is typically oversimplified

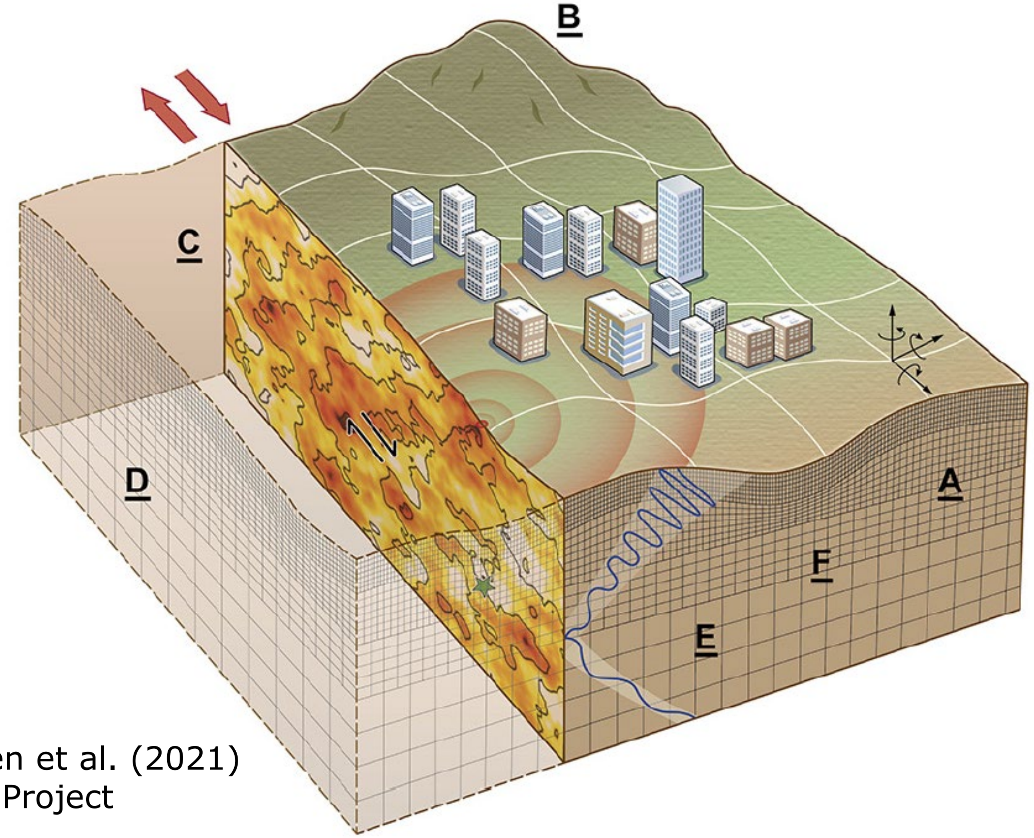
Seismic damage scenarios by enhancing the characterization of ground motion

Ground Shaking Scenario
(e.g. PGA)



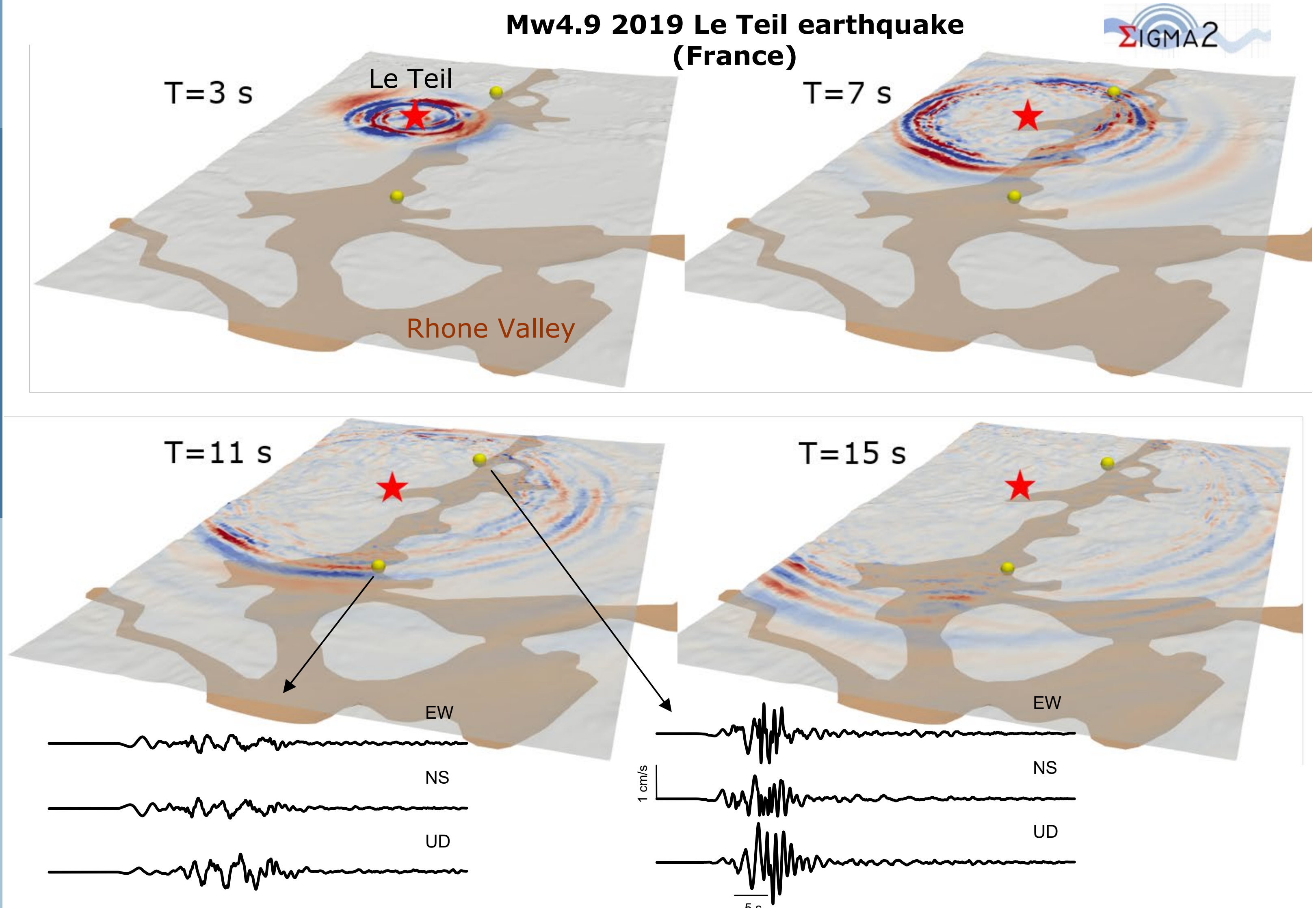
- ShakeMap
- Empirical Ground Motion Model (GMM)
- Physics-Based numerical Simulation of earthquake ground motion (PBS)

Source-to-site numerical simulation of seismic wave propagation, based on 3D realistic models of the fault rupture process, the propagation path and local site conditions



McCallen et al. (2021)
EQSIM Project

Seismic damage scenarios by enhancing the characterization of ground motion



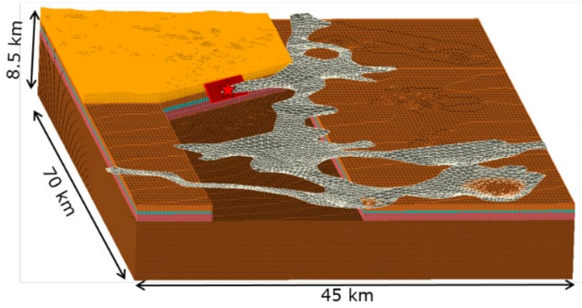
SPectral **E**lements in **E**lastodynamics with **D**iscontinuous Galerkin

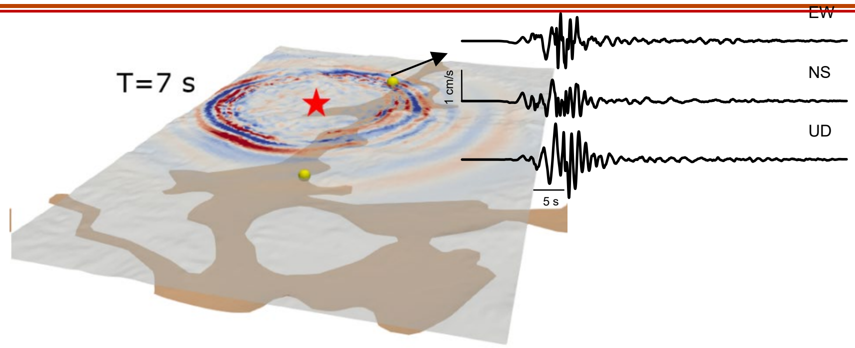
http://speed.mox.polimi.it/

- ✓ Specificity of the seismotectonic and geologic context is intrinsically accounted for
- ✓ Entire time history of ground motion is produced at any site
- ✓ Physics-based spatial variability of ground shaking

Exploring different approaches using physics-based numerical ground motion simulation

Regional scale PBS by the high-performance computer code SPEED





Coupling of PBS ground shaking scenarios with existing fragility curves

.. with specifically calibrated fragility curves

1

Need of broad-band ground motions to cover the variety and region-dependence of the building typologies (Masonry, RC) of the Italian building stock

2

Coupling of PBS *broad-band* ground motions with mechanics-based structural models

3

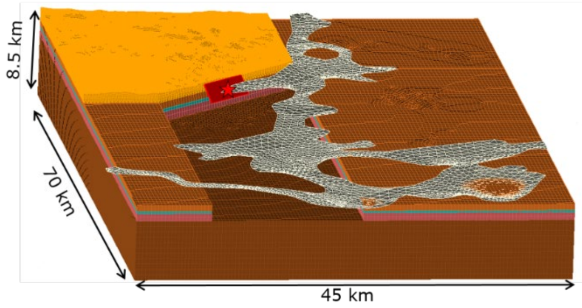
Fully coupled 3D numerical approach for the PBS of ground motion and structural response at city level

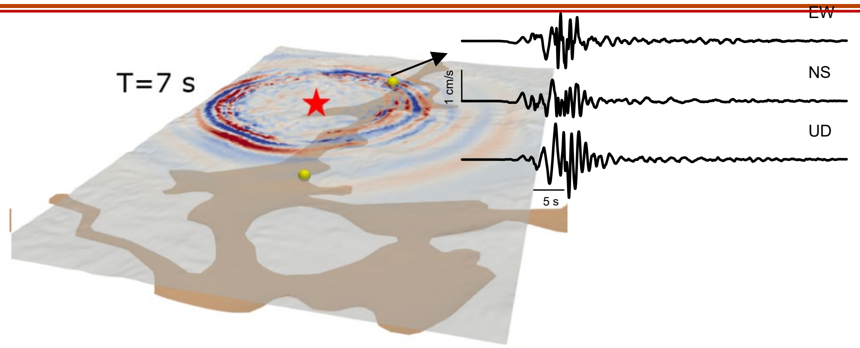
Increasing complexity

Exploring different approaches using physics-based numerical ground motion simulation

SPEED

Regional scale PBS by the high-performance computer code SPEED





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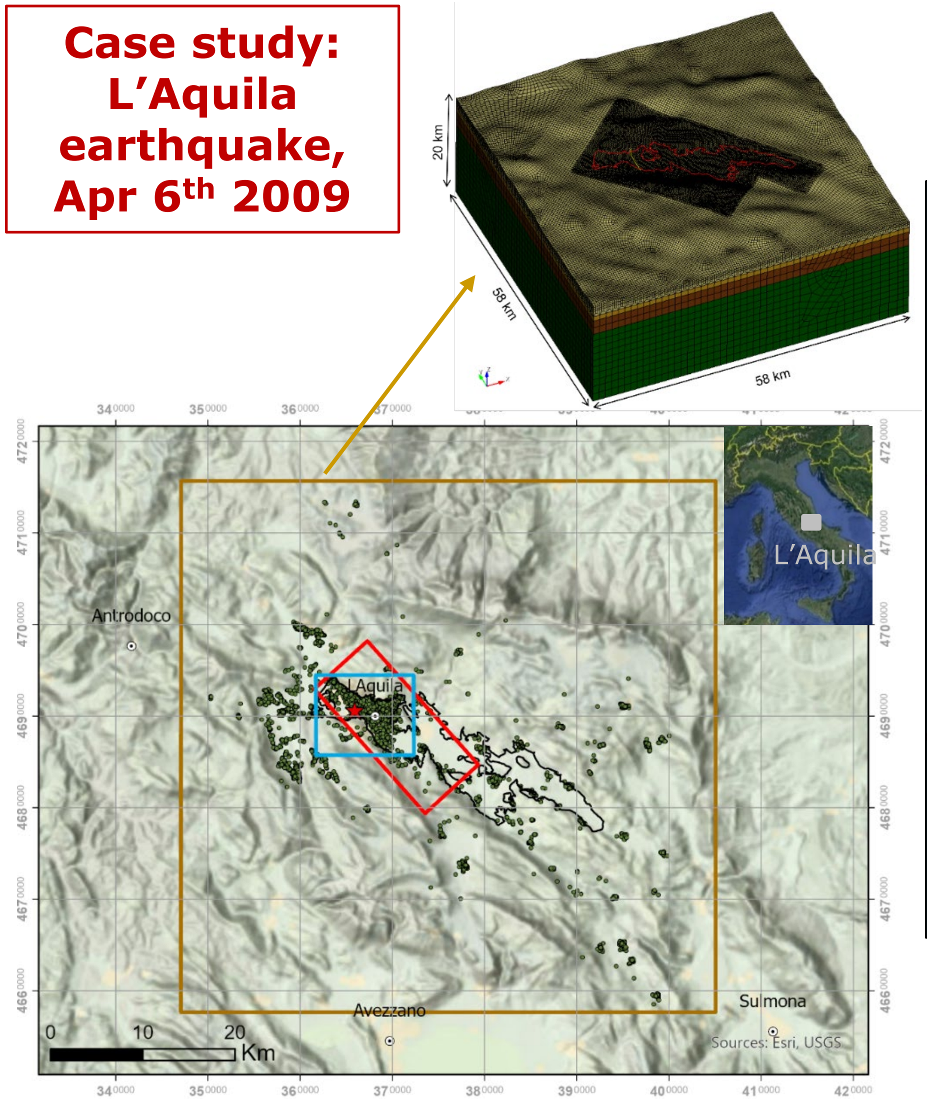
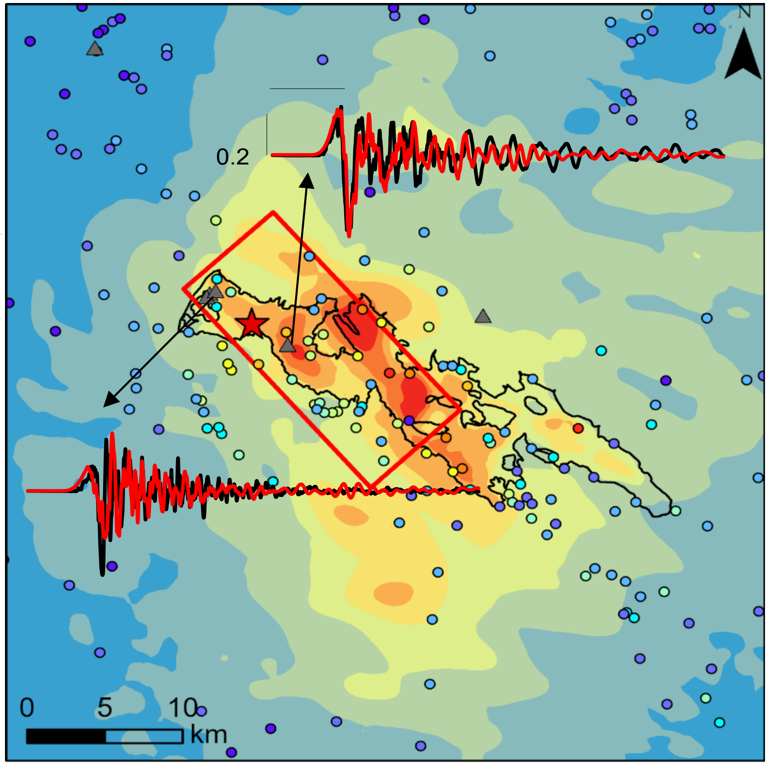
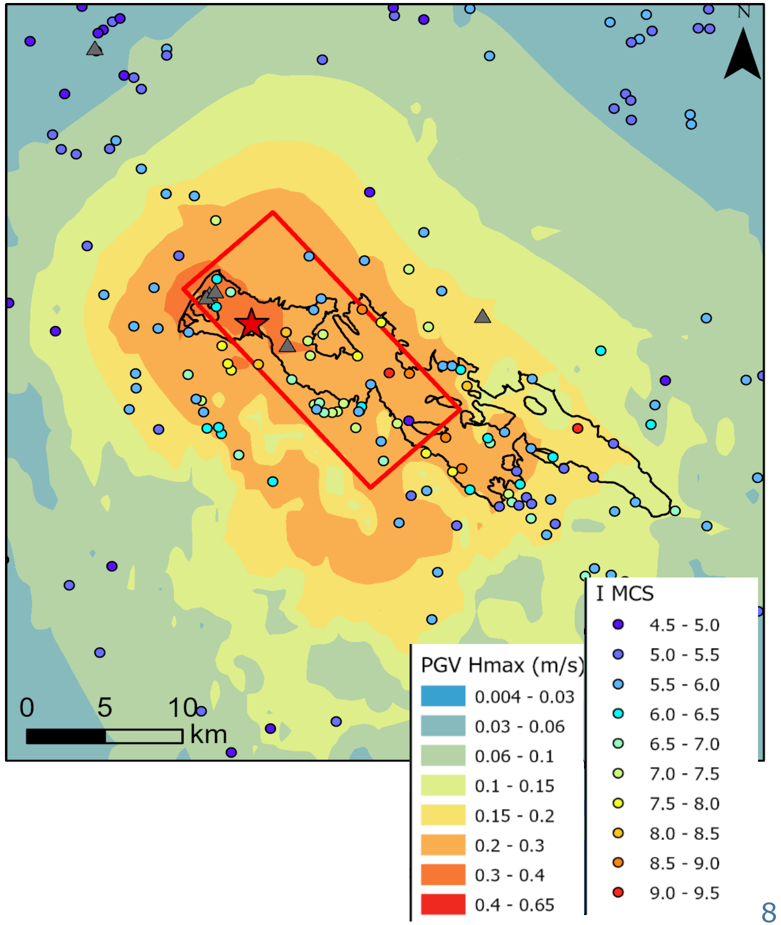
Case study: L'Aquila earthquake, Apr 6th 2009



3D PBS BROADBAND
Evangelista et al. (2017)



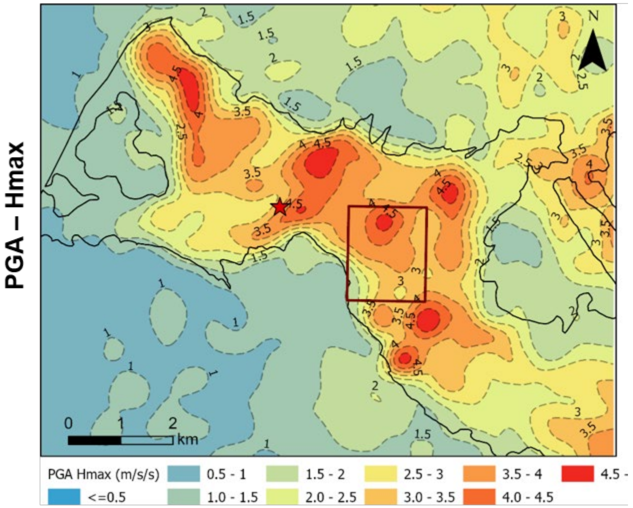
ShakeMap (V4)
Michelini et al. 2020



Rosti et al. (2023) BEE
Monsalvo et al. (2025) BEE

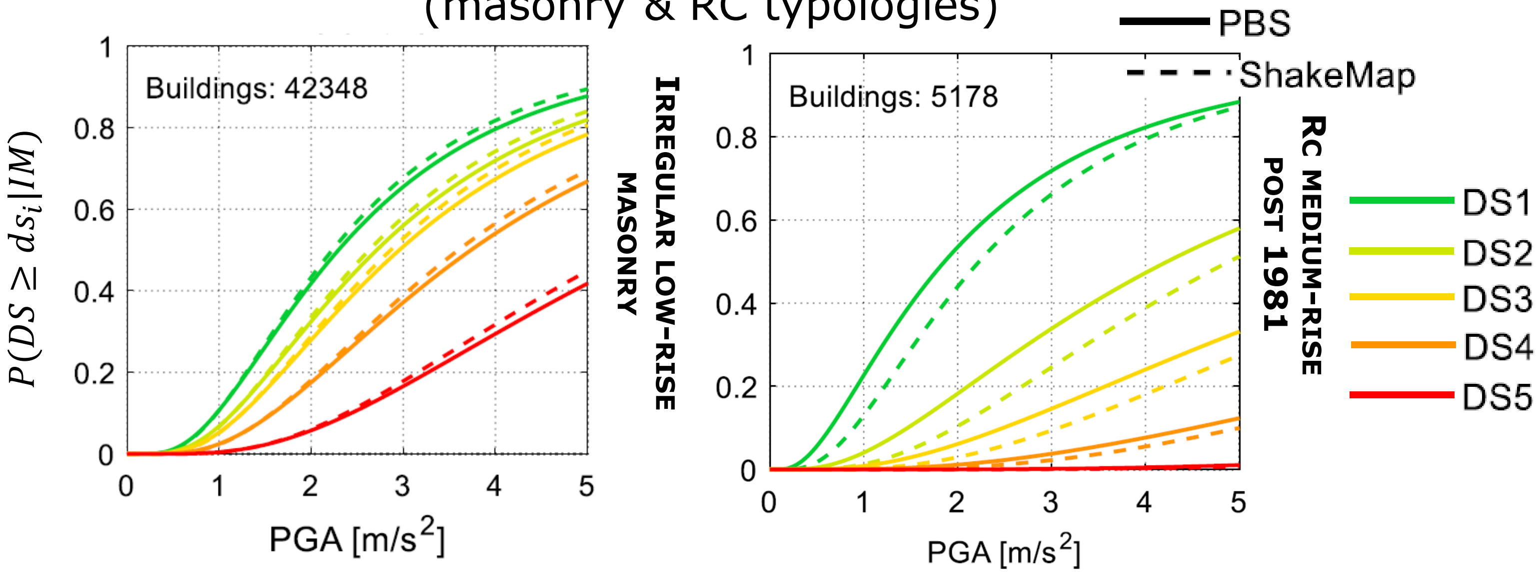
Coupling of PBS scenarios with specifically calibrated fragility curves

PBS *broad-band* ground shaking scenario

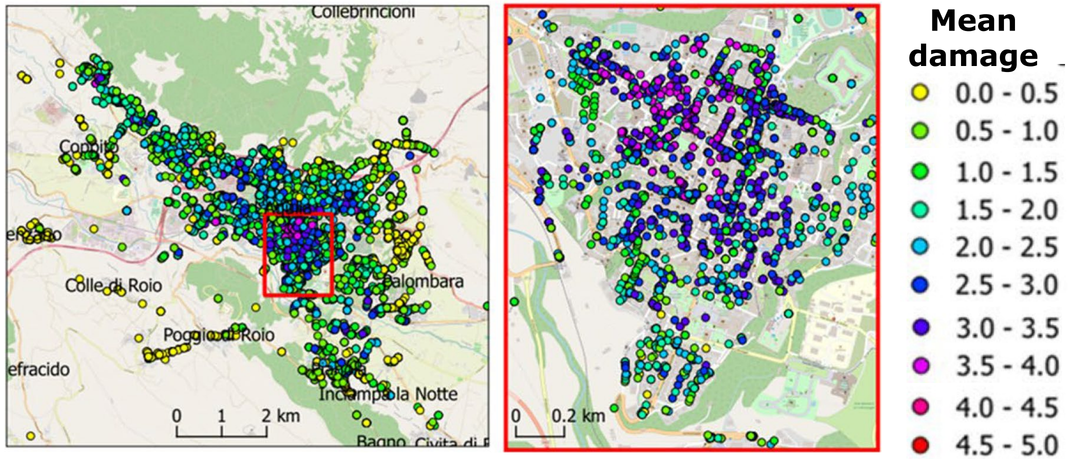


+ damage observations

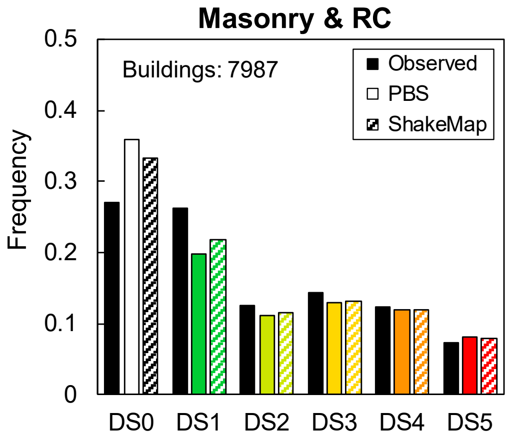
PBS-based fragility curve for PGA
(masonry & RC typologies)



Damage prediction

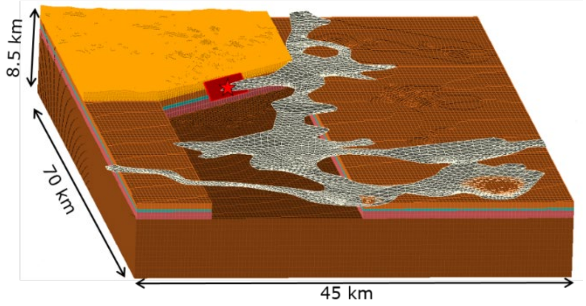


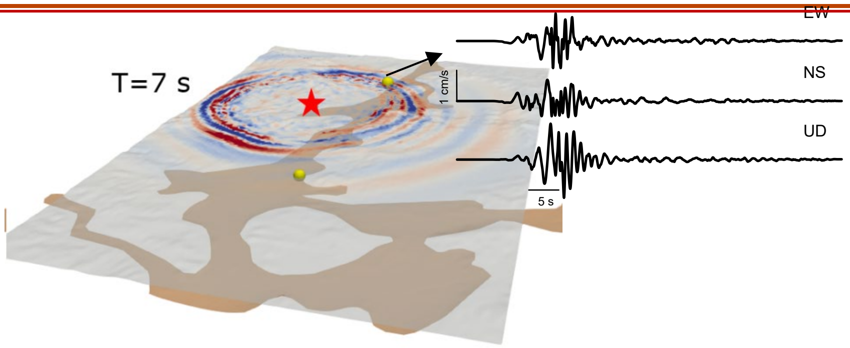
Comparison with damage observations



Exploring different approaches using physics-based numerical ground motion simulation

Regional scale PBS by the high-performance computer code SPEED





Coupling of PBS ground shaking scenarios with existing fragility curves

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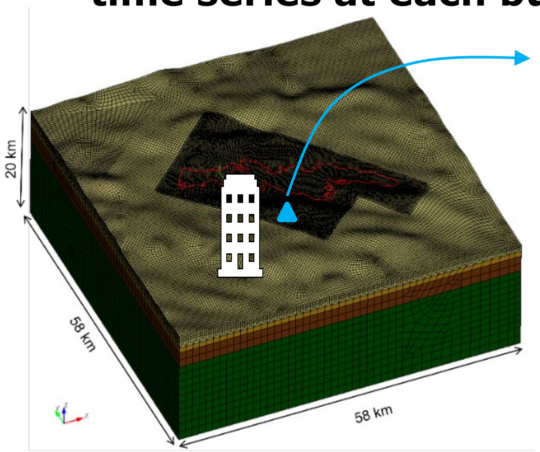
Fully coupled 3D numerical approach for the PBS of ground motion and structural response at city level

Increasing complexity

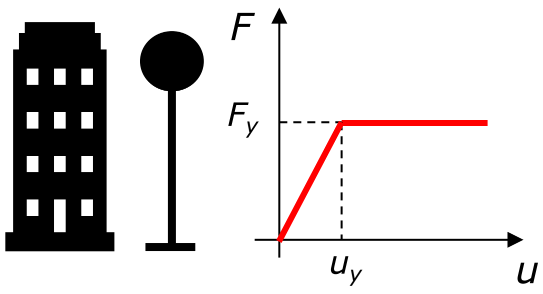
Coupling of PBS scenarios with mechanics-based models of structural response

PBS provides *broad-band* ground motion time series at each building sites

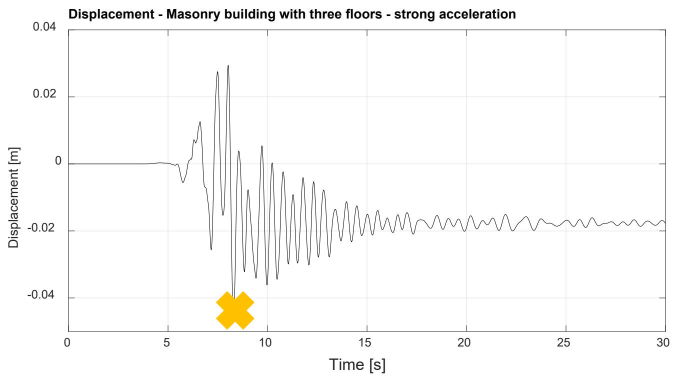


Case study:
2009 L'Aquila

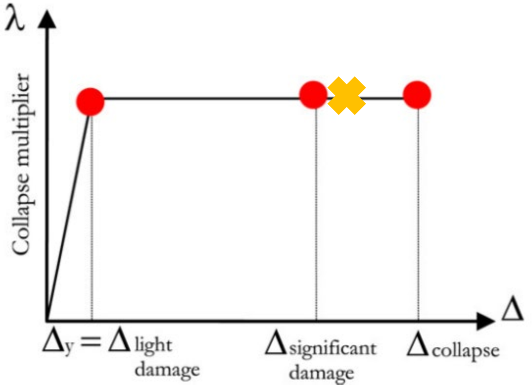
Building is modelled as an elasto-plastic SDOF with prescribed capacity curves



Building inelastic response under the PBS ground motion

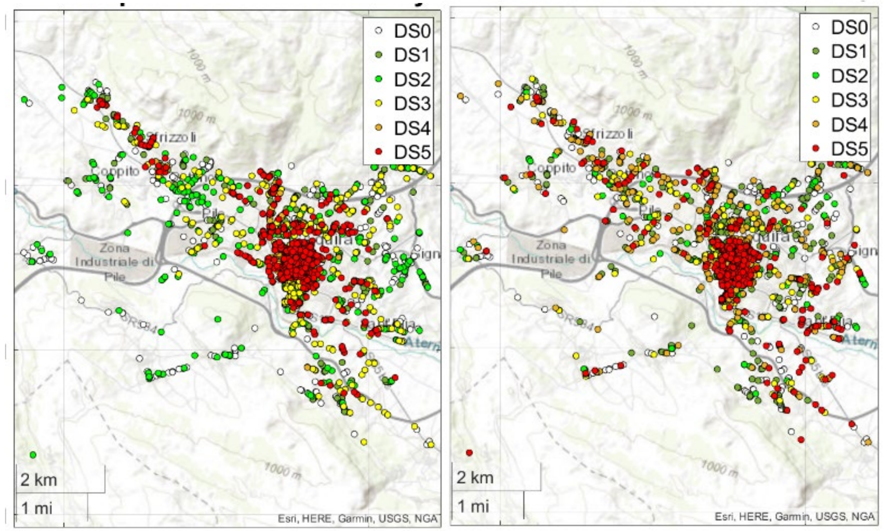


Damage level attribution based on maximum drifts



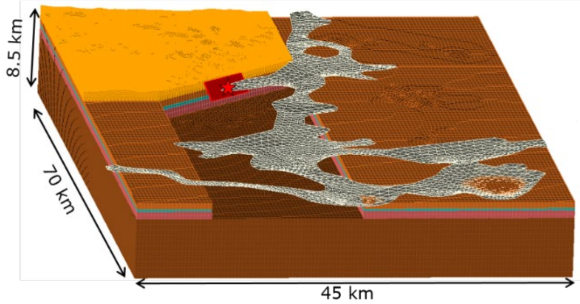
Damage scenario simulation, to be validated on post-earthquake damage observations

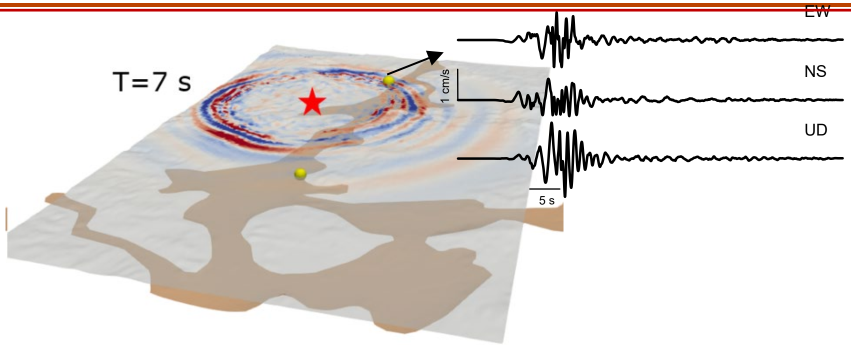
Simulated: MASONRY **Observed: MASONRY**



Exploring different approaches using physics-based numerical ground motion simulation

Regional scale PBS by the high-performance computer code SPEED





Coupling of PBS ground shaking scenarios with existing fragility curves

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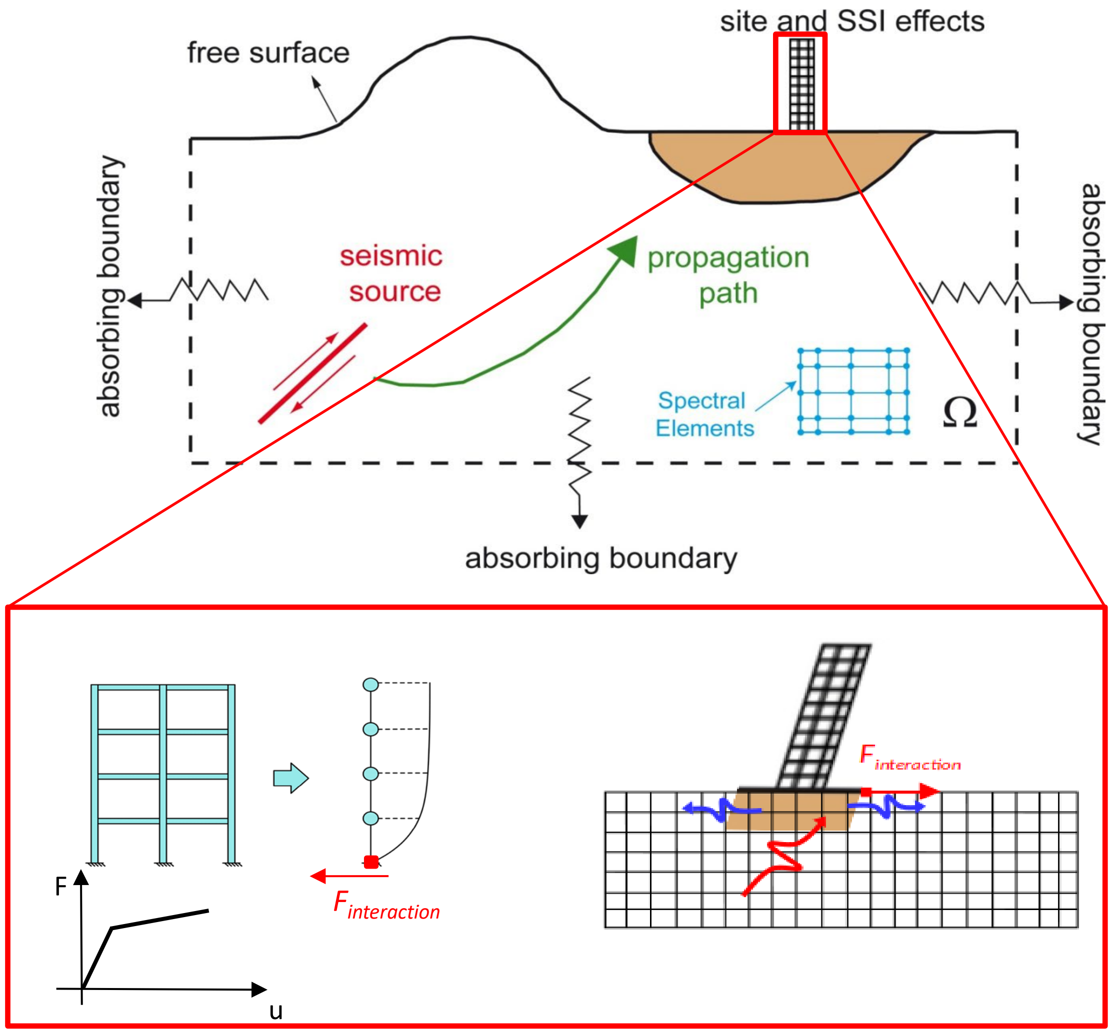
Fully coupled 3D numerical approach for the PBS of ground motion and structural response at city level

Increasing complexity

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



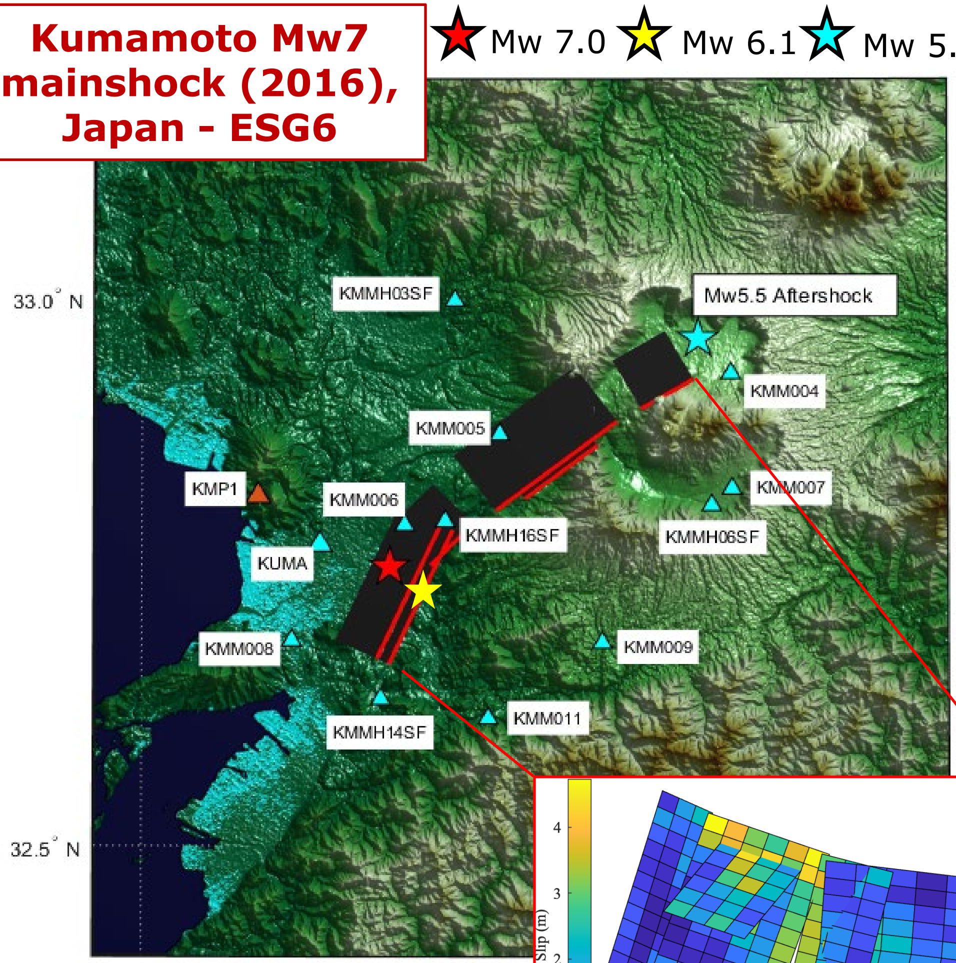
- ✓ Coupling algorithm embedded in SPEED kernel at each time step (without computational overload)
- ✓ Buildings are modelled as non-linear SDOF or MDOF systems
- ✓ Possibility to include building clusters to model urbanized environments
- ✓ Effects of soil-structure interaction (SSI) and site-city interaction (SCI) are accounted (albeit in a simplified manner)

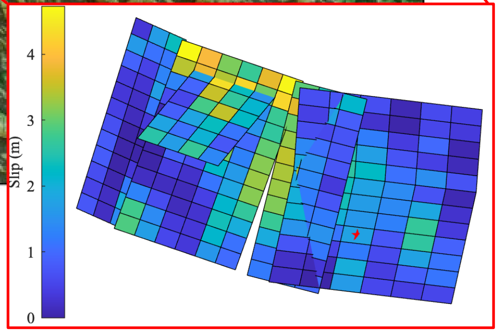
Srihari Sangaraju, PhD thesis (2025)

URBASIS-EU

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

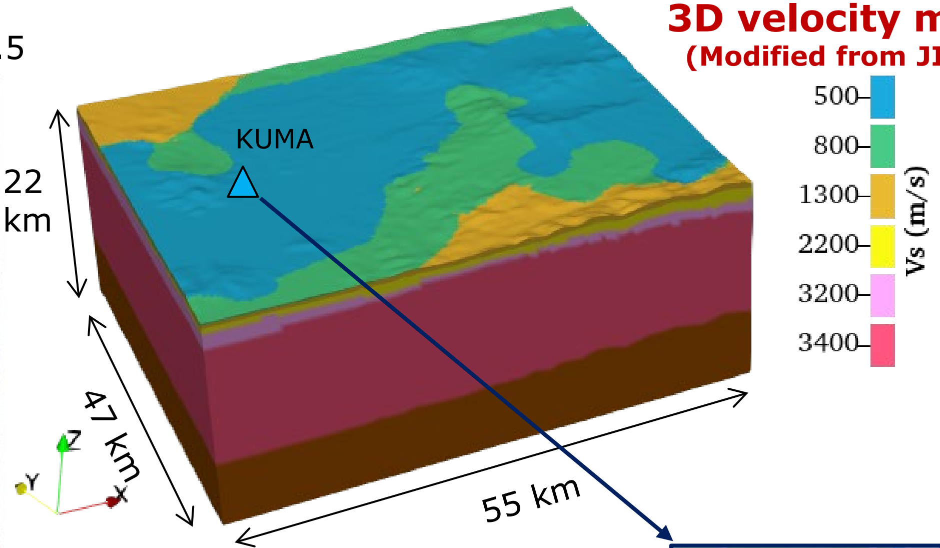
Kumamoto Mw7 mainshock (2016), Japan - ESG6





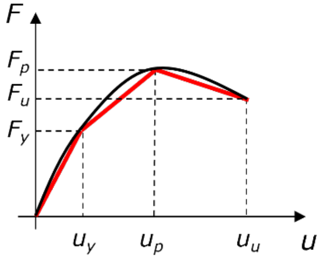
Mw7.0 multi-segment finite fault source (from Kobayashi et al. 2017)

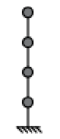
3D velocity model
(Modified from JIVSM)



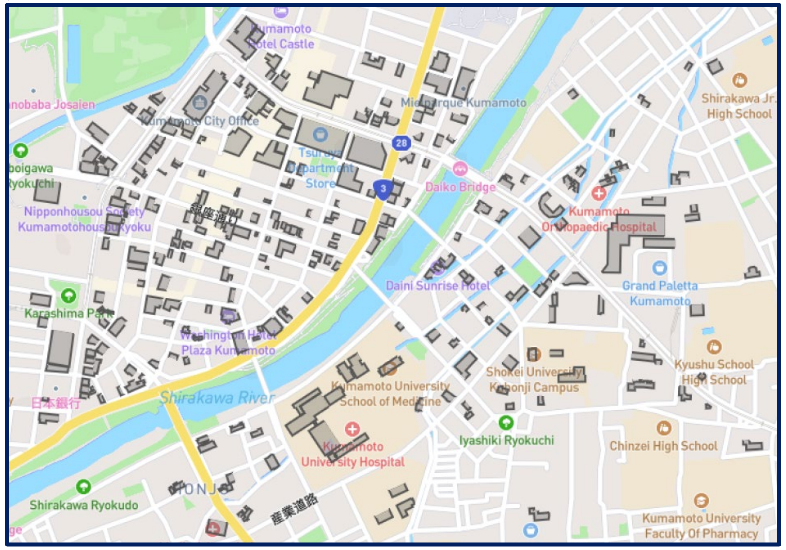
- Domain size : 55 km x 47 km x 22 km. Smallest size 100m.
- 1.4 Million Elements (**36M nodes**) with SD=3.
- Simulation Time : 4 Hours on 380 compute cores.

Modeling of Kumamoto urban district (~ 300 buildings) as clustered MDOF systems with prescribed capacity curves
(buildings taller than 25 m)





MDOF shear model



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

Movie of city response under the Mw7 scenario with indication of building damage levels

Concluding remarks

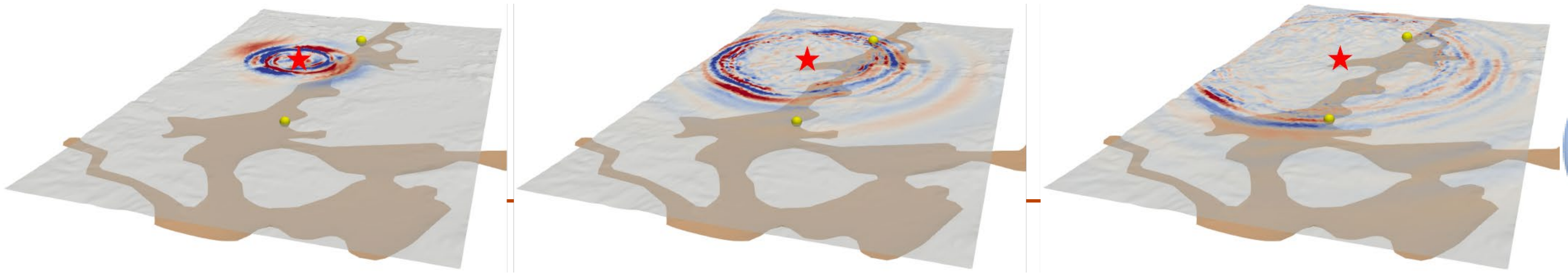
- In this study, different approaches for generating seismic damage scenarios in urban areas are explored and investigated by using physics-based numerical simulations for an enhanced characterization of earthquake ground motion

- Results offer insights into the potential advantages of PBS, in relation to:

  - Providing region- and site-specific ground shaking scenarios when ShakeMaps are poorly constrained due to the lack of recordings (e.g. historical earthquakes or peculiar geologic contexts)

  - Providing the entire ground motion time history at the building site to be used as input for mechanics-based non-linear models of structural response

  - Fully coupled (single-step) numerical approaches embedding, in the same computational domain, the seismic wave propagation from the seismic source to the structure, accounting for soil-structure and site-city interaction effects



Thank you

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