

Engineering Use of Recent Physics-based Ground Motion Simulations

Arben Pitarka

Lawrence Livermore National Laboratory



INGV-SECURE Project Meeting

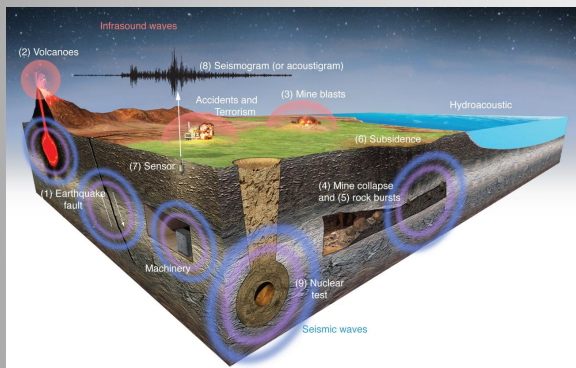
Rome Italy, March 11-12, 2026

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

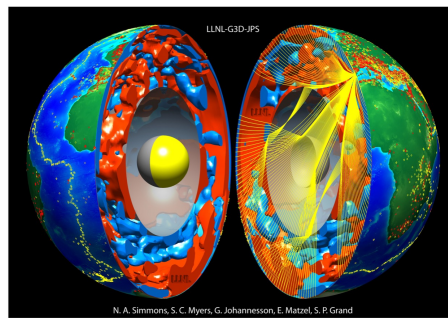


Waveform modeling is an important tool for seismic global monitoring and strong motion prediction using high performance computing

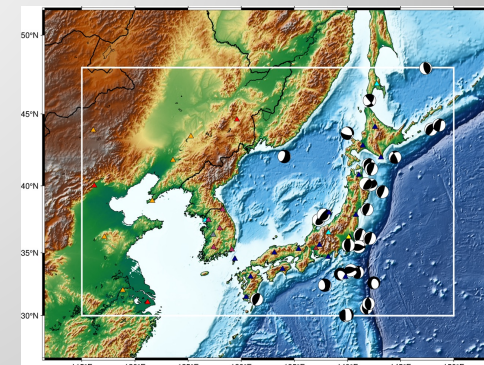
Global Monitoring and Source Discrimination



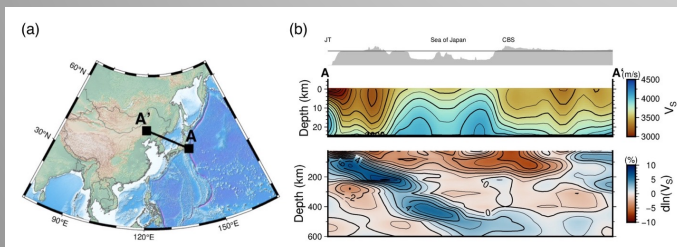
LLNL Global Tomographic Model



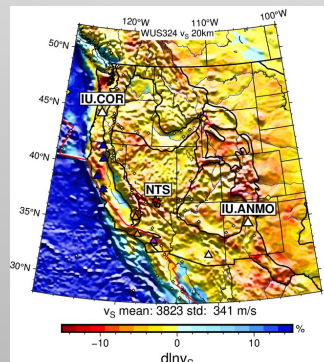
Global Seismicity and Source Characterization



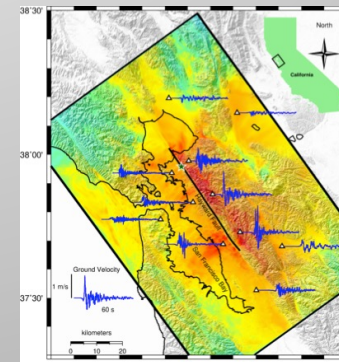
Full Waveform Inversion to Develop Regional Velocity Models



Adjoint Waveform Tomography



Broad-band Strong Motion Simulations



LIVERMORE COMPUTING CENTER
HIGH PERFORMANCE COMPUTING

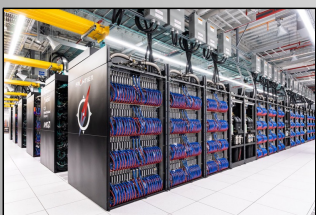


Major U.S. DOE efforts ramped up over the past seven years

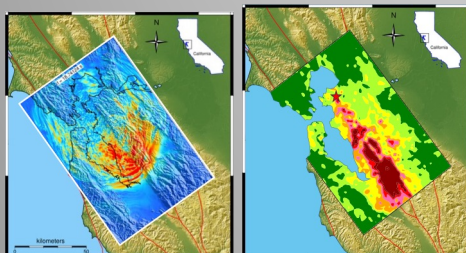
Computational R&D

DOE ushering in the era of exascale super computing

ECP (2017-2023)
EXASCALE COMPUTING PROJECT



Frontier – the world's first exaflop computer (ranked #1 in the world)



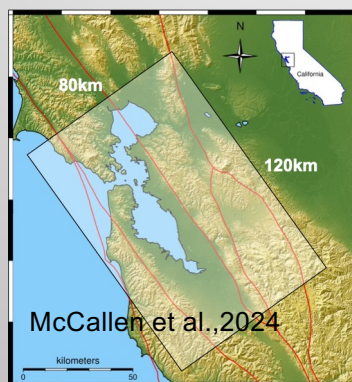
EQSIM – a computational framework for fault-to-structure simulations

Energy Mission Applications (2023-2024)

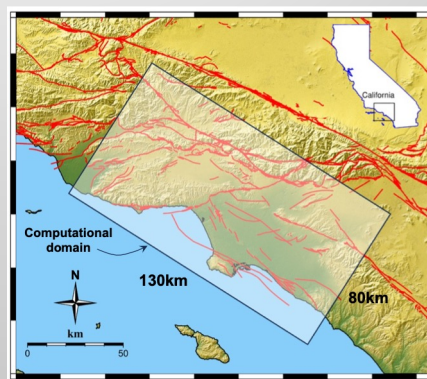
Generation of high-fidelity earthquake ground motions across key regions for engineering risk applications

U.S. DEPARTMENT OF
ENERGY

Office of
Cybersecurity, Energy Security,
and Emergency Response (2023-2025)



San Francisco region
computational domain

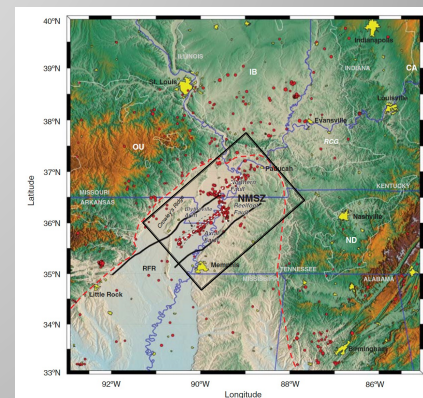


Los Angeles region
computational domain

NRC: Improved GMMs for CEUS

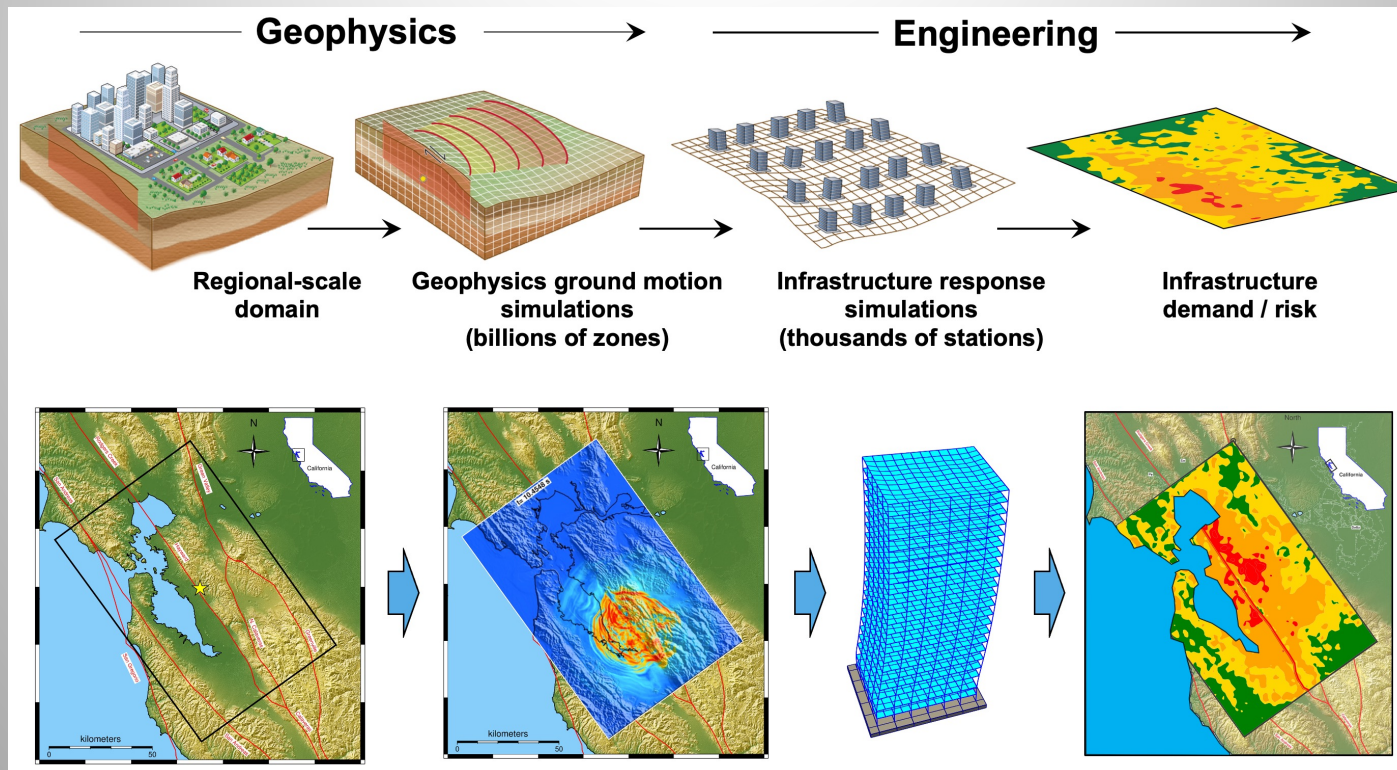
10Hz Mw7 Ground Motion
Simulations in CEUS

(2023-2025)



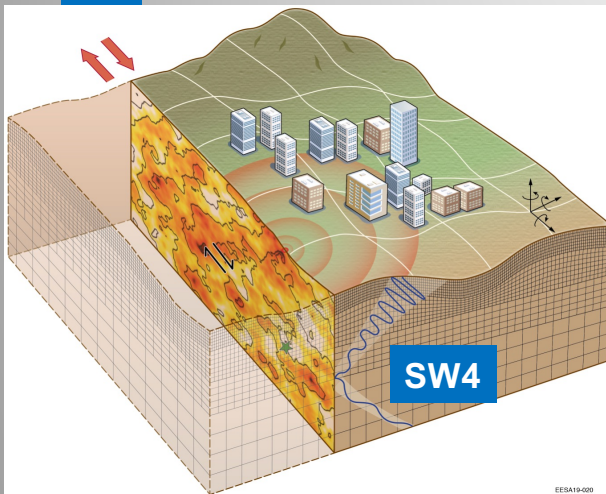
New Madrid Fault Zone
computational domain

EQSIM : Earthquake ground motion simulations in engineering applications



Important and uniqueness: advanced widely used physics-based earthquake rupture generator and highly efficient elastic wave propagation modeling code

GP



GP – Graves and Pitarka Rupture Generator

(Grave&Pitarka, BSSA 2016; Pitarka et al BSSA 2021)

- Hybrid slip distribution
- Depth dependent kinematic rupture parametrization
- SRF HDF5-based format

SW4 - GPU-CPU based (LBNL LLNL Computing Platforms)

(Peterson and Sjogreen, 2015)

- 4th order accuracy with curvilinear mesh refinement
- HDF5-based IO



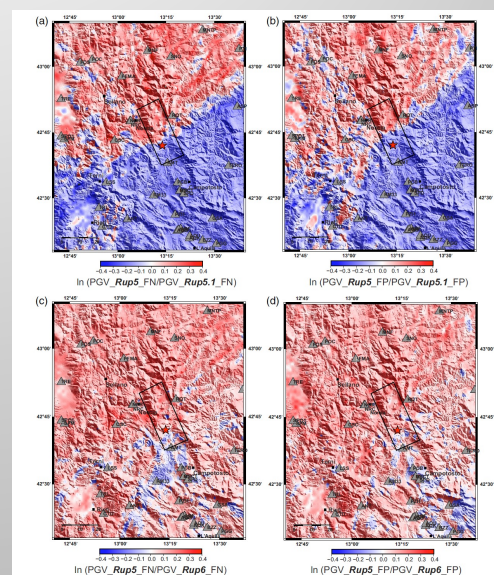
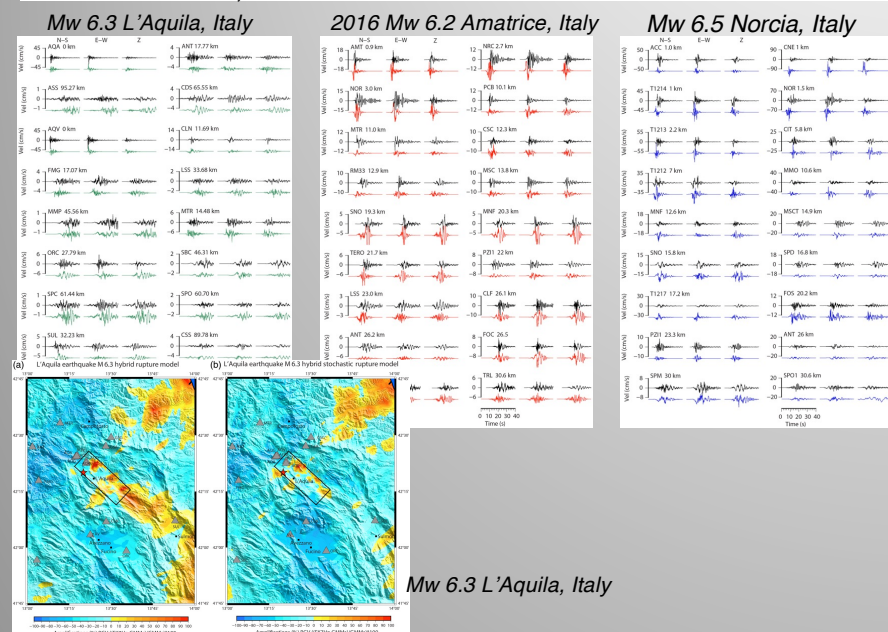
INGV-SECURE Project: Fast simulation of strong ground motion from earthquakes in Italy

Broadband Near-Fault Ground-Motion Simulations Using a Modified f - k Method in Central Italy

Pietro Artale Harris¹, Arben Pitarka², Aybige Akinci¹, and Arianna Cuius¹
Harris et al., 2026

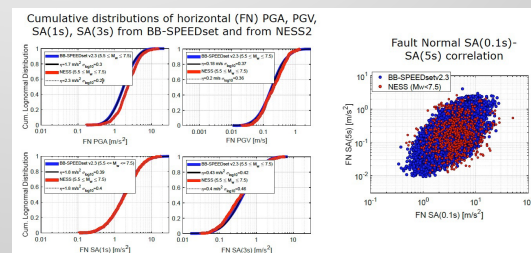
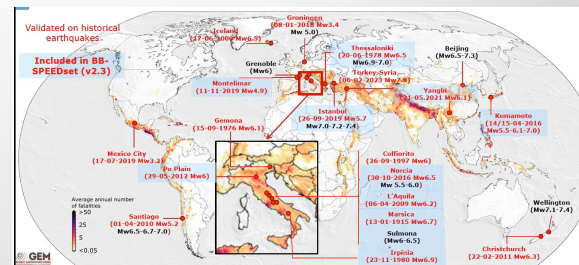
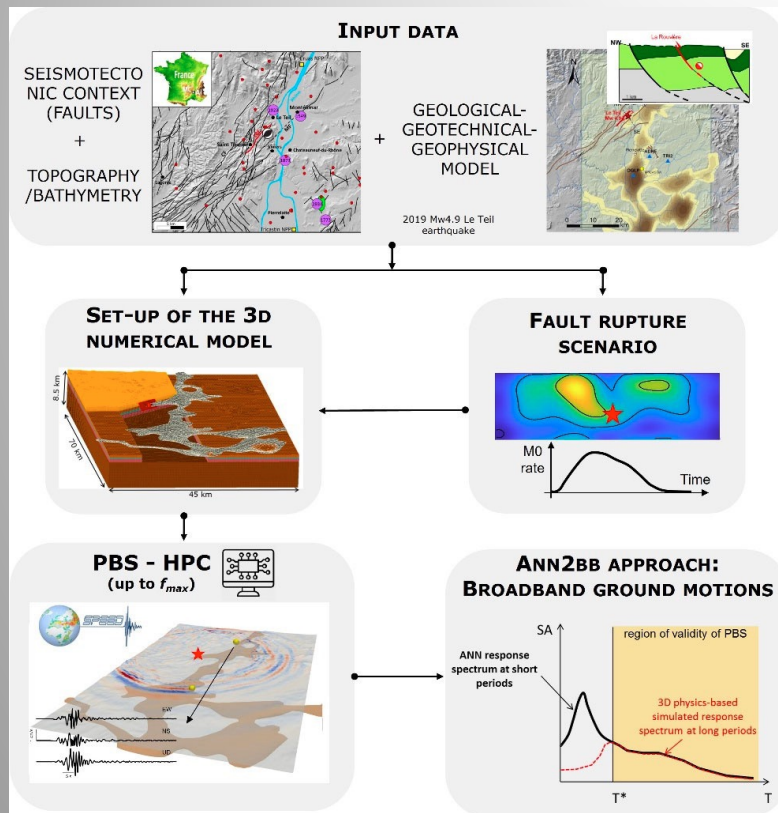
Impact of the Earthquake Rupture on Ground-Motion Variability of the 24 August 2016 M_w 6.2 Amatrice, Italy, Earthquake

Aybige Akinci¹, Arben Pitarka², Pietro Artale Harris¹, Pasquale De Gori¹, and Mauro Buttinelli¹
Akinci et al., 2025

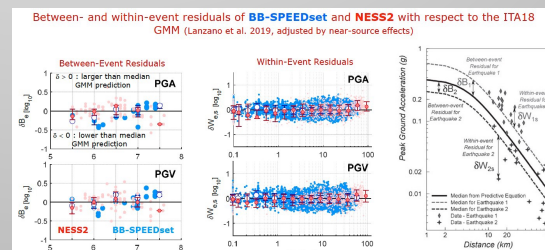


SPEED : A physics-based computing platform for generating broadband earthquake ground motions

From Paolucci and Smerzini, 2025

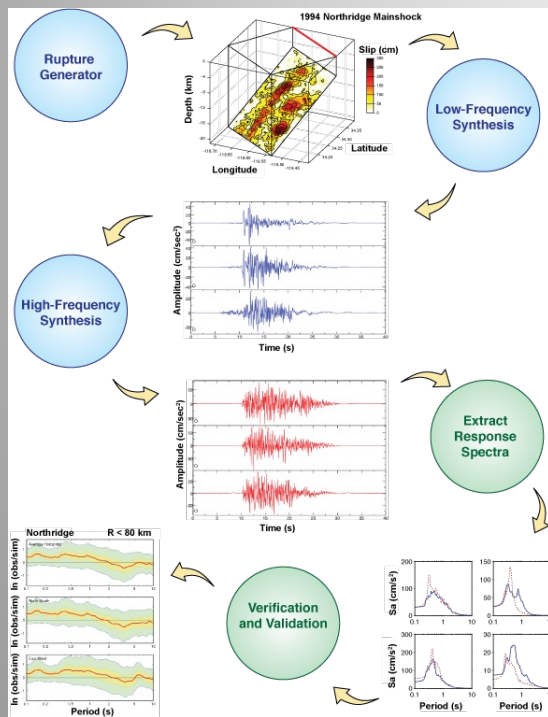


Consistency with
recorded data and
Empirical GMM

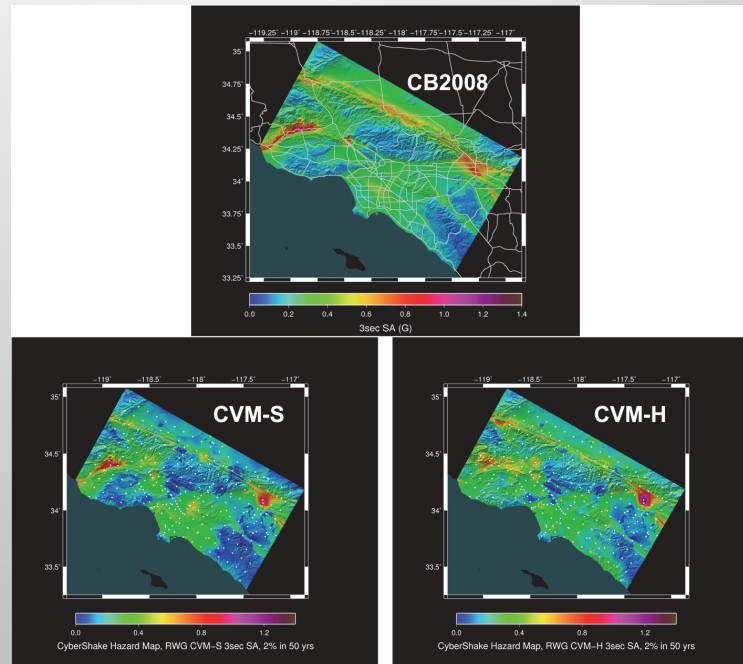


Engineering use of SCEC BB platform

SCEC BB Platform



Los Angeles region probabilistic seismic hazard maps constructed with GMM and CyberShake Platform using CVM-S and CVM-H



Baker et al., 2014

EQSIM Project: Examples of Kinematic Rupture Models Used in Simulations of Scenario Earthquakes on the Hayward Fault

Research Paper

**EARTHQUAKE
SPECTRA**

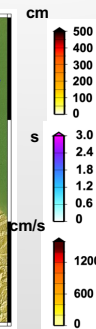
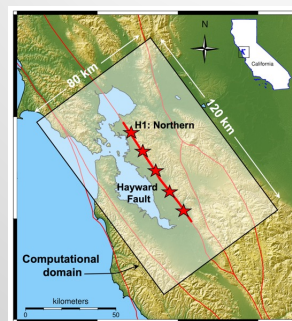
Earthquake Spectra
2024, Vol. 40(3) 1615–1652
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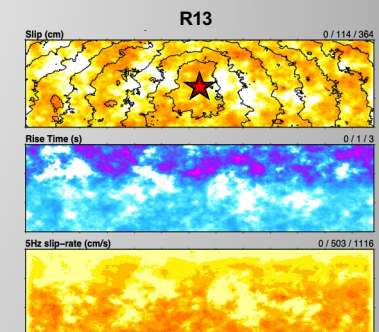
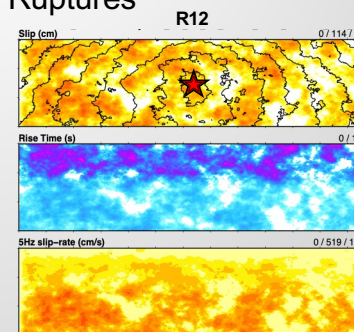
Sage

Regional-scale fault-to-structure earthquake simulations with the EQSIM framework: Workflow maturation and computational performance on GPU-accelerated exascale platforms

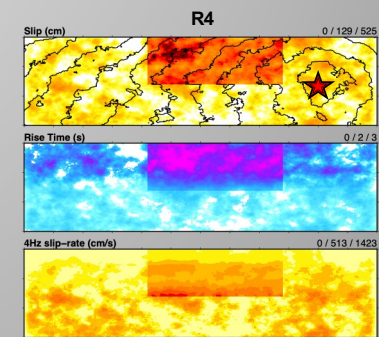
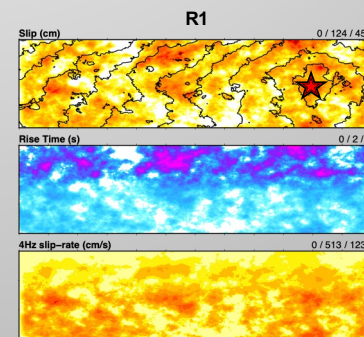
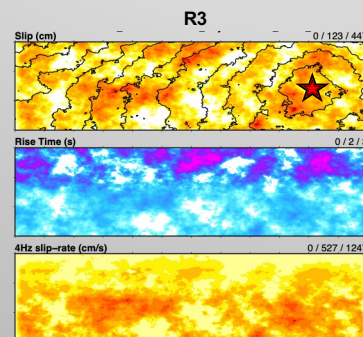
David McCallen, M.EERI¹, Arben Pitarka², Houjun Tang¹, Ramesh Pankajakshan², N Anders Petersson², Mamun Miah¹, and Junfei Huang³



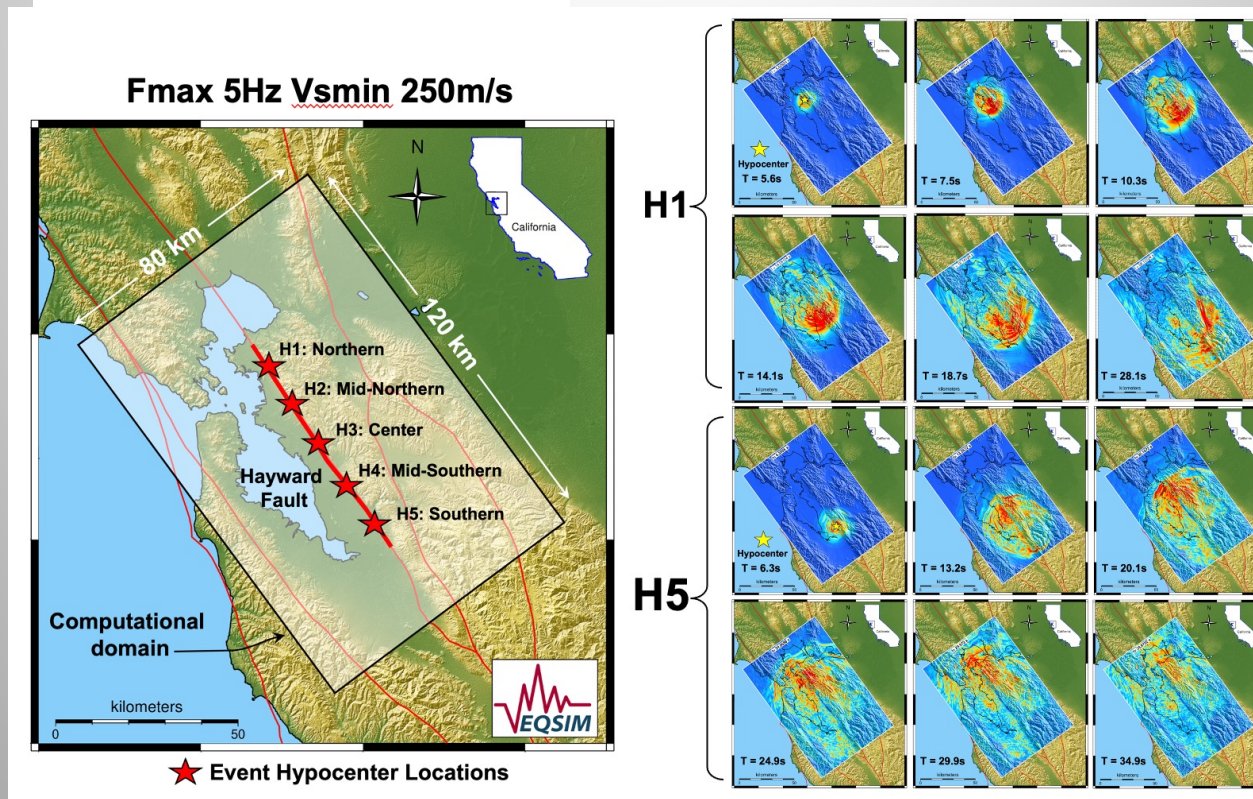
Bilateral Ruptures



Unilateral Ruptures



PEER Synthetic Ground Motion Database for Engineering Applications. Captures Source + Wave Propagation Effects



PEER-LBNL Simulated Ground Motion Database

Data Paper

EE EARTHQUAKE
RI SPECTRA

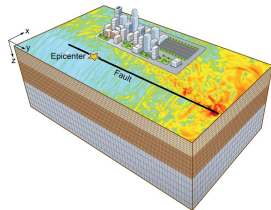
An open-access simulated earthquake ground-motion database for an M7 Hayward Fault earthquake in the San Francisco Bay Region

Earthquake Spectra
2025, Vol. 41(3) 2560–2597
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S Sage

David McCallen, M.EERI¹, Arben Pitarka²,
Houjun Tang¹, Rie Nakata¹,
Khalid M Mosalam, M.EERI³,
Floriana Petrone, M.EERI⁴,
Selim Günay³, and Claudio Perez³

PEER-LBNL Simulated Ground Motion Database

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The Pacific Earthquake Engineering Research Center (PEER) – Lawrence Berkeley National Laboratory (LBNL) Simulated Ground Motion Database (SGMD) includes a large set of simulated ground motions generated from physics-based, deterministic, broad-band earthquake simulations. These simulated ground motions in the database have undergone careful validation, including comparisons against recorded ground motions from actual earthquakes. The PEER-LBNL SGMD is one of the few simulated ground motion databases globally and is anticipated to enable engineers to utilize validated simulated ground motions in seismically active regions in the U.S. and around the world.

The development and maintenance of SGMD is supported by the Department of Energy (DOE) and LBNL under award number 056892.

Login

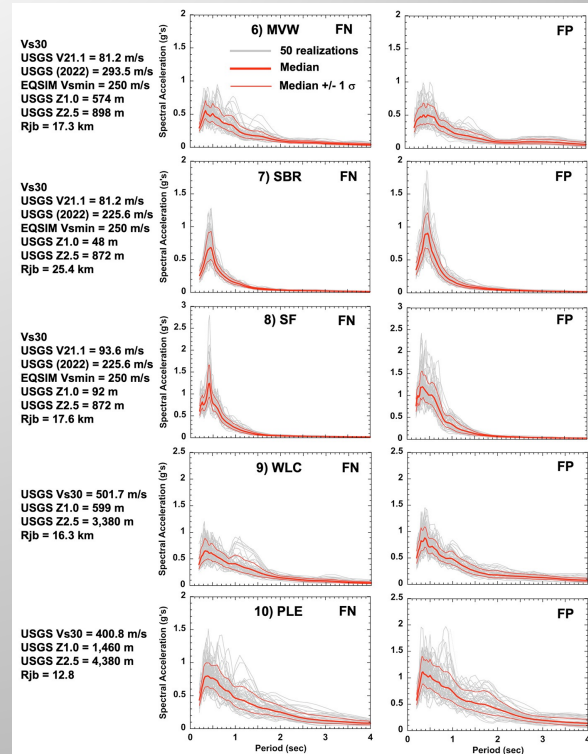
Signup

Number of ground motion time series in the SGMD = 1,021,500

Number of ground motion time series downloaded to date = 6,224,929

Number of registered users = 526

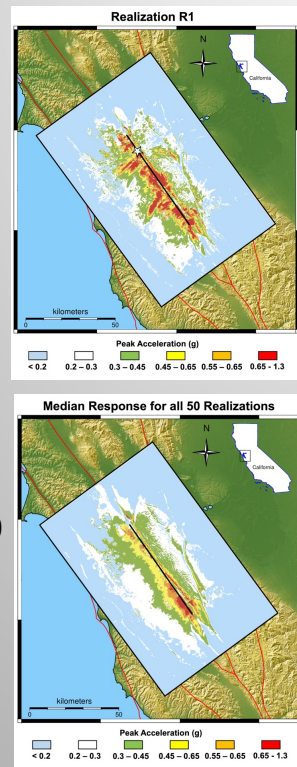
Synthetic Spectral Acceleration



Validations of Rupture Models and EQSIM Computing Platform Against M7 GMMs

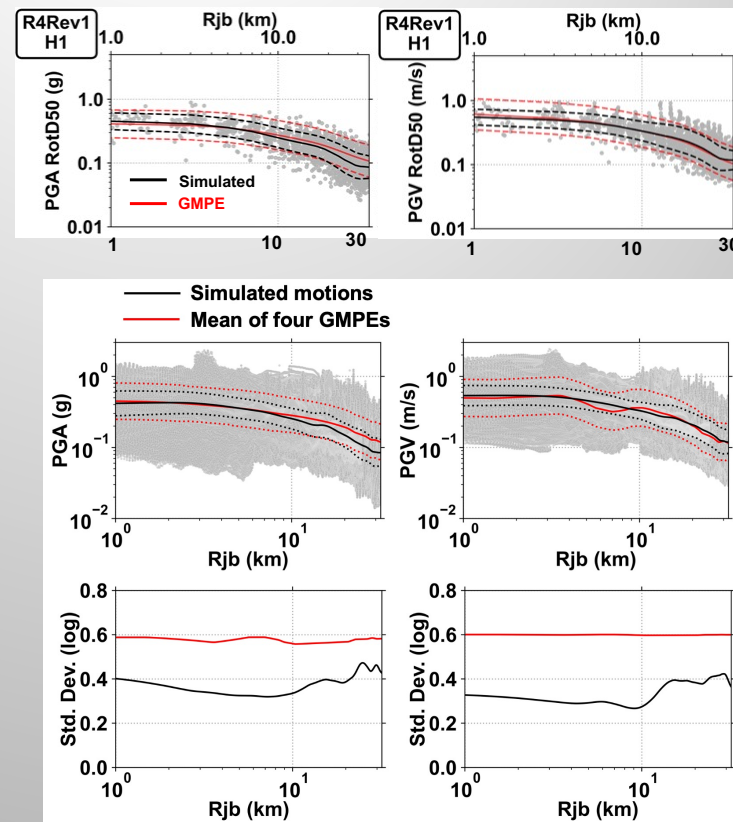
Single realization

Deterministic earthquake rupture and wave propagation effects are explicitly included in the ground motion response



Median 50 realization

McCallen et al., 2025

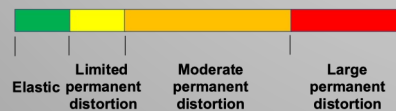
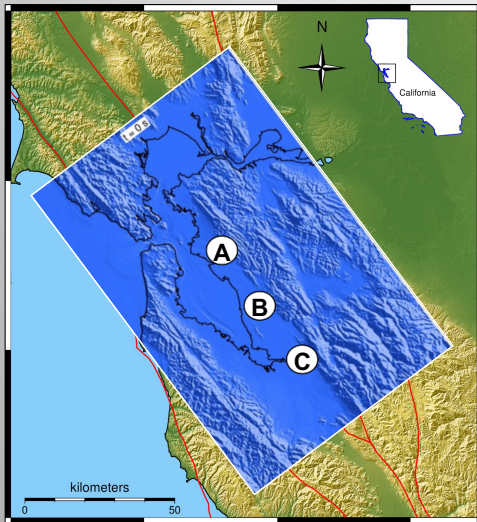


Hypocenter H1

All 50 Realizations

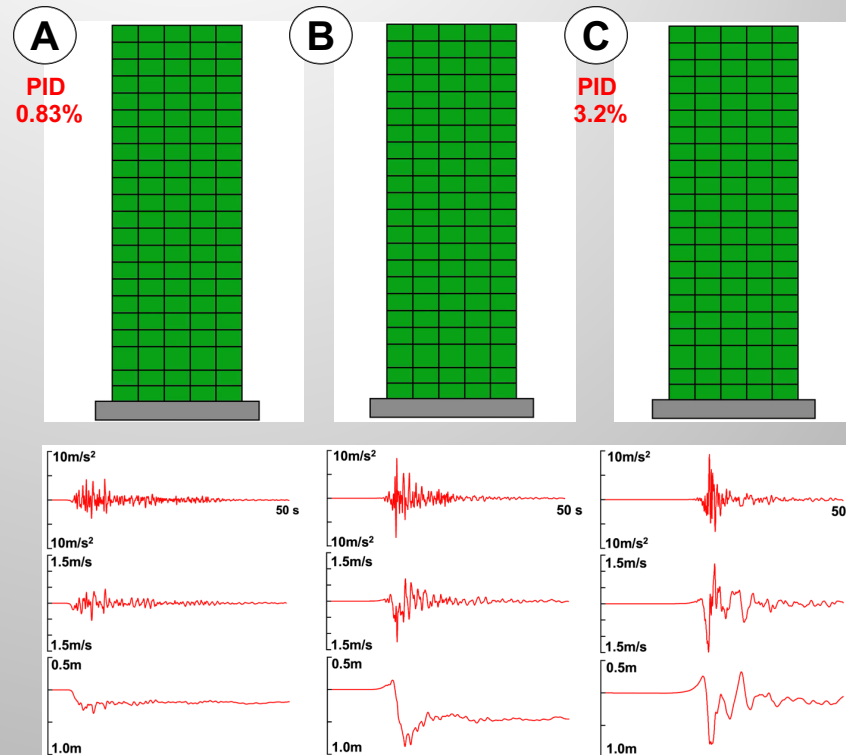
Site Specific Building Demand: Within Event Ground Motion Spatial Variability

Magnitude 7
Hayward fault
northern hypocenter



McCallen et al., 2024

20 story steel frame Nevada fiber model
Peak Interstory Drift (fault-normal motions)

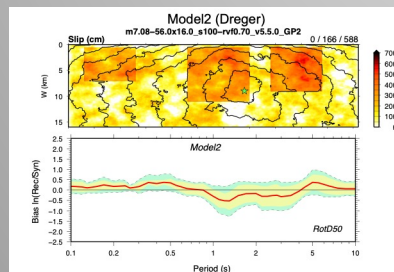
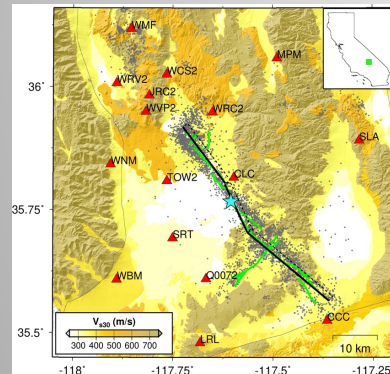


Building Confidence in Synthetic Ground Motion

Validation of GP Hybrid Rupture Model (Pitarka et al., 2022) in Deterministic Simulations of Recorded Crustal Earthquakes

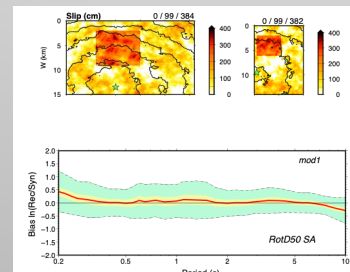
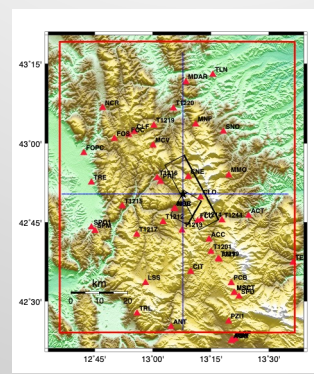
$M_w 7.1$ Ridgecrest, California
0-5Hz

Pitarka et al., BSSA 2021



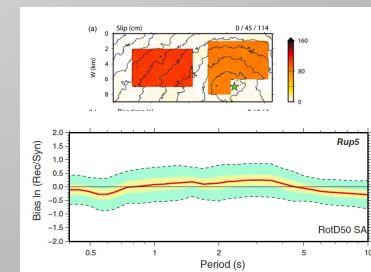
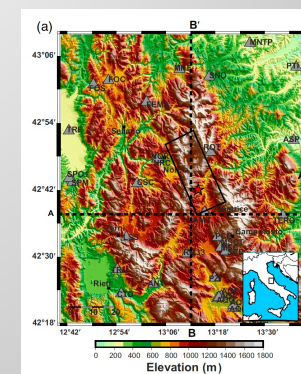
$M_w 6.5$ Norcia, Italy
0-5Hz

Pitarka et al., BSSA 2021



$M_w 6.2$ Amatrice, Italy
0-3Hz

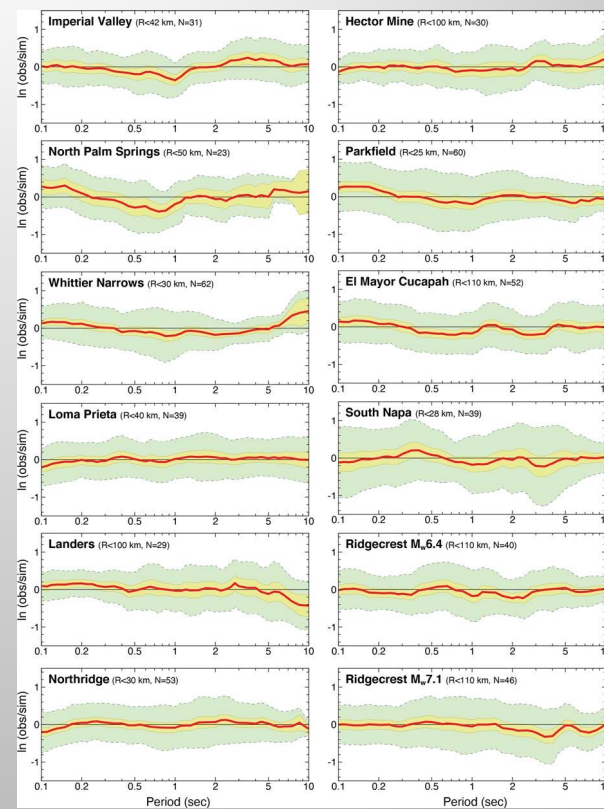
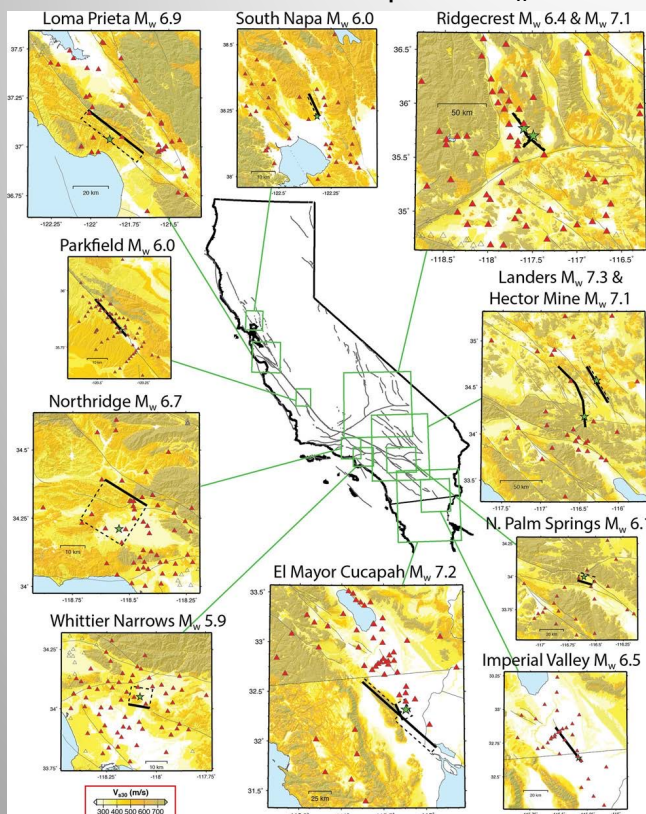
Akinci et al., BSSA 2024



Performance of the GP Rupture Model in BB Simulations Using Hybrid Approach (0-1 Hz Deterministic and 1-10 Hz Stochastic)

from: Graves, 2022

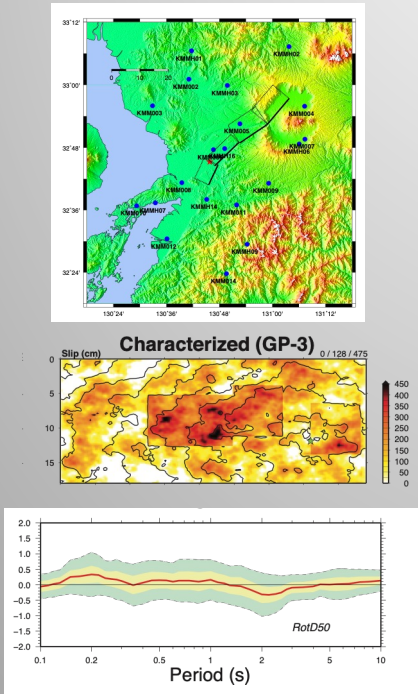
10 California Earthquakes M_w 5.9-7.2



Performance of the BB Hybrid Simulations in Japan and New Zealand Earthquakes (0-1 Hz Deterministic and 1-10Hz stochastic)

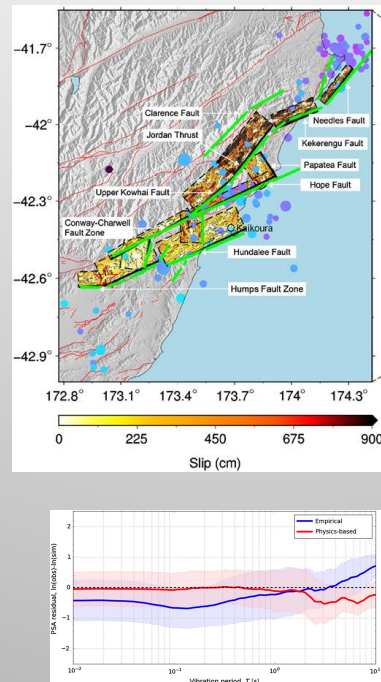
M_w7 2016 Kumamoto,
Japan

Pitarka et al., 2019



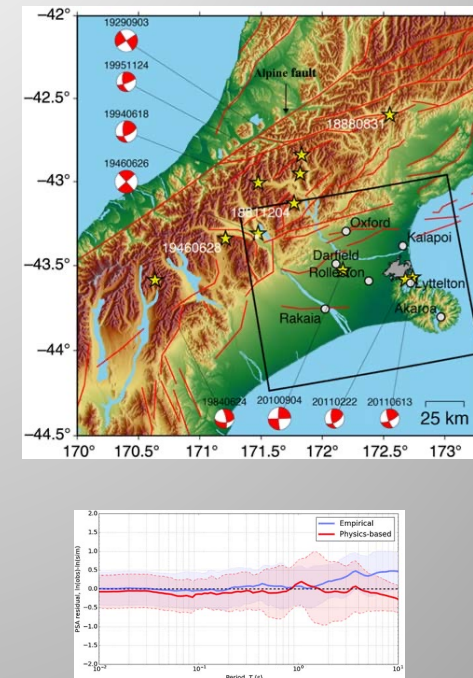
2016 Mw7.8 Kaikoura
New Zealand

Bradley et al., 2017



2011 Mw6.2 Christchurch
New Zealand

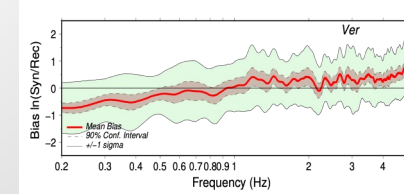
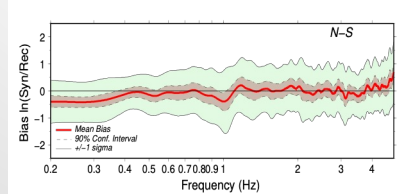
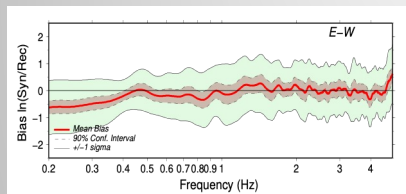
Razafindrakoto et al., 2018



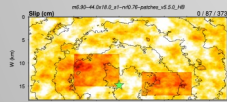
Performance of EQSIM in 5Hz physics-based ground motion simulations of the Mw6.9 Loma Prieta earthquake

$V_{\min}$: 250m/s $f_{\max}$: 5Hz

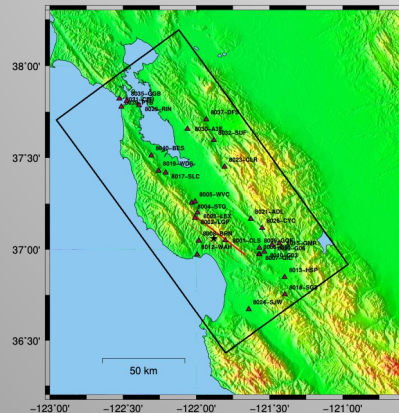
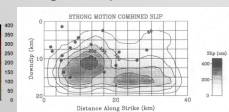
Fourier Amplitude Goodness-of-Fit



GP Rupture Model

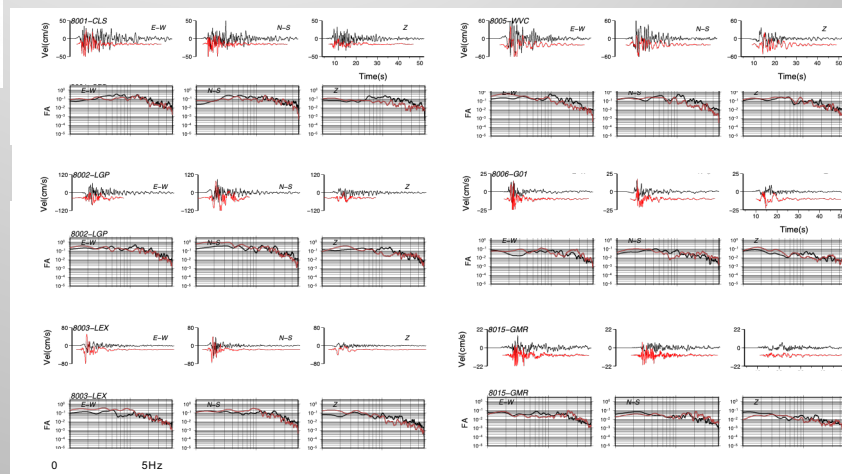


Target Slip Model



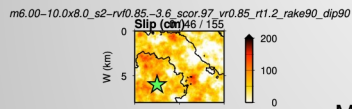
Velocity 0-5Hz 3D+Topo

___ synthetic ___ recorded



Applications of GM Simulations: Near-fault Saturation Refinements to GMMs for CEUS

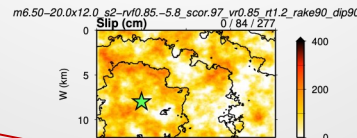
Pitarka and Graizer, 2024



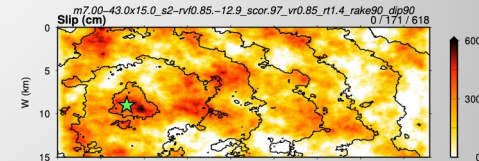
M6.0

Near-fault
saturation

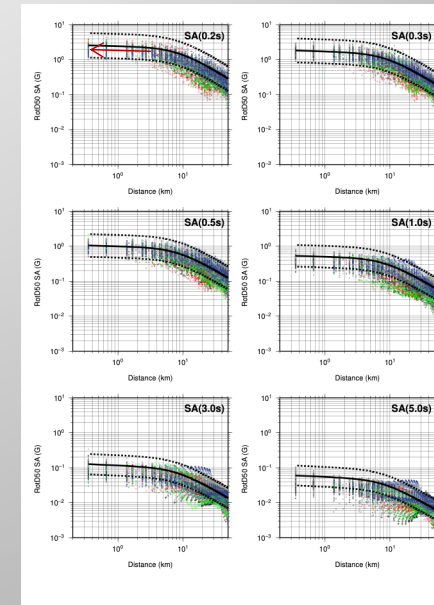
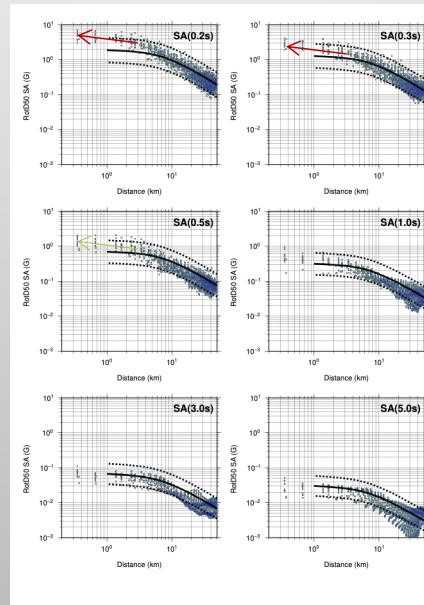
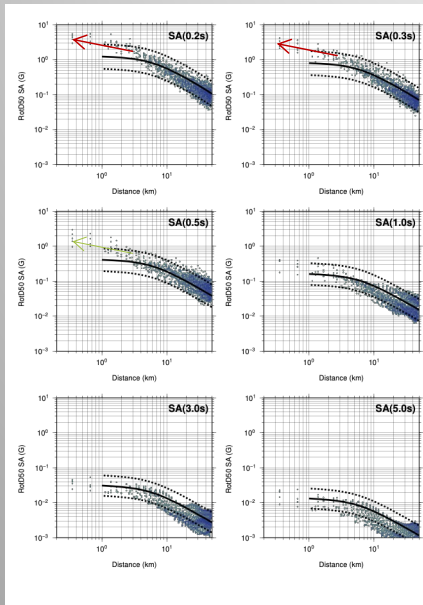
M6.0
M6.5
M7.0



M6.5



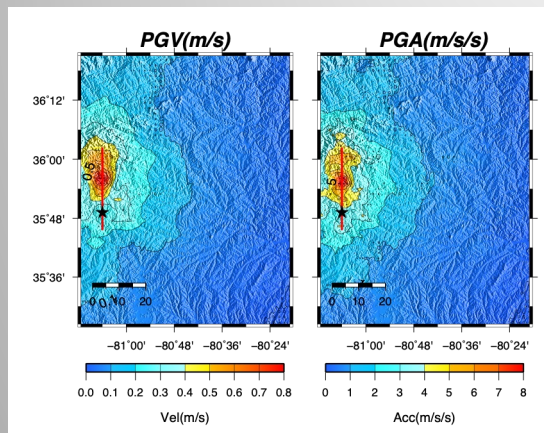
M7.0



NRC Project: Dependency of Near-fault Amplitude Saturation to Type of Faulting in CEUS GMMs

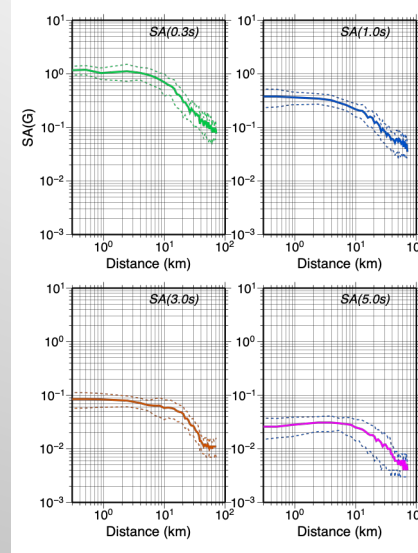
Pitarka and Graizer, 2024

0-10Hz 3D Simulations
for Central Eastern US

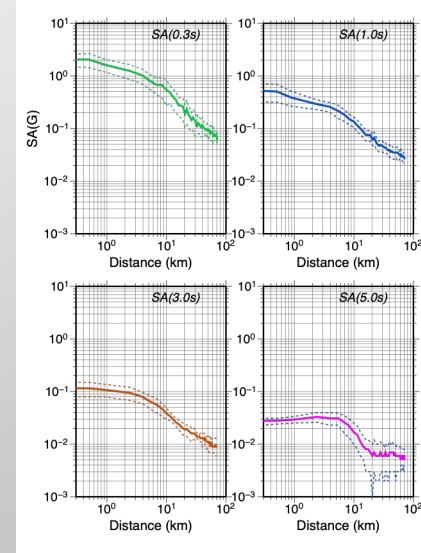


*Simulations performed on DANE
at Livermore Computing Center*

M7 Strike-Slip Faulting
(SA saturation)

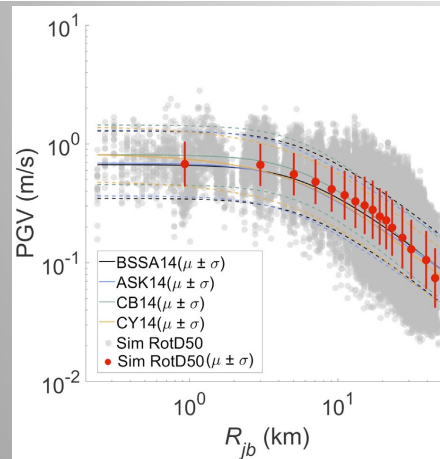
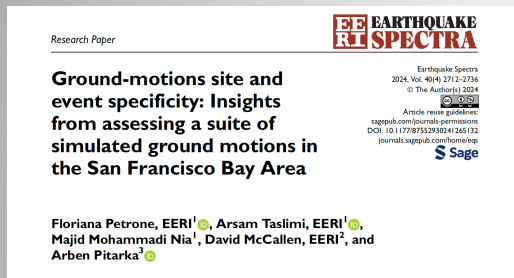


M7 Thrust Faulting
(SA under saturation)



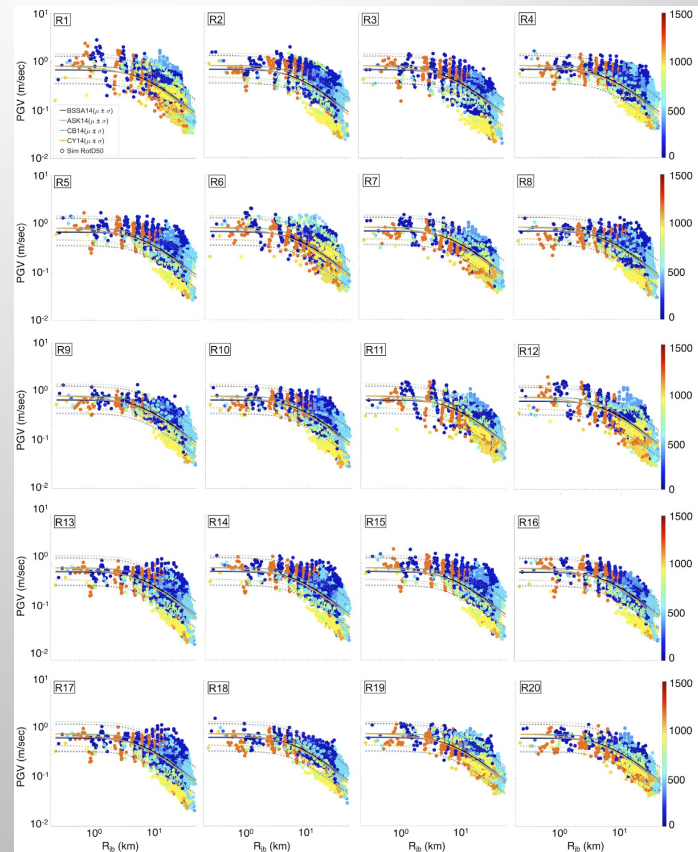
Strike-slip faulting: ground motion saturates at short distances
Thrust faulting: ground motion under saturates at short distances

BB Simulations are used to identify areas where ergodic NGA-W2 GMMs may underpredict the seismic hazard in the SF Bay Area



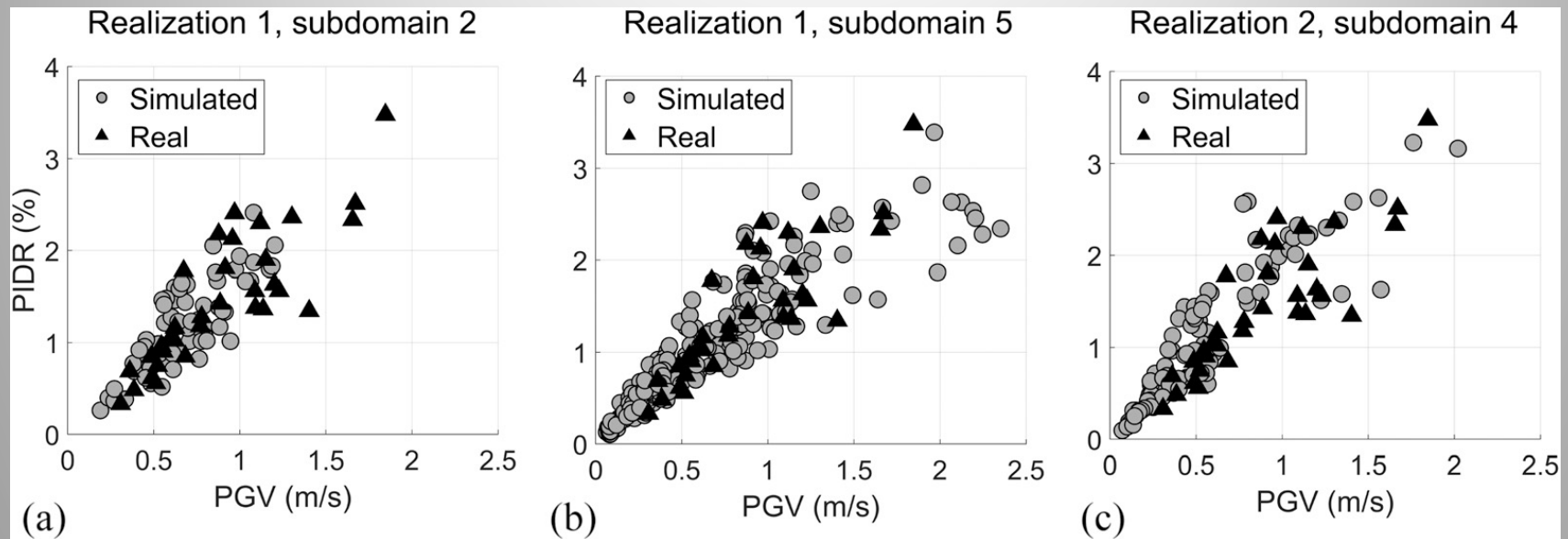
Existing regional hazard models may underestimate ground-motion intensities in selected regions in the San Francisco Bay Area, highlighting the importance of correctly estimating the concurrent effects of rupture directivity and local basin amplification. This information is key to improving our understanding of regional risk.

Comparison of simulated PGV and NGA-W2 GMMs' predictions.



Realistic character of simulated ground motion generated with the GP rupture generator in the SF Bay Area.

Recorded and simulated **twenty-story** steel moment-resisting frame building model building: PIDR vs PGV-FN.



Sensitivity of tall structures to long-period velocity pulses that characterize forward-directivity ground motions, the periods of the fundamental and higher modes of vibration of the considered structure are fully resolved by the considered ground-motion simulations, which is crucial to ensure reliability of the obtained structural response.

Effects of site conditions on building response

Research Paper

**EE EARTHQUAKE
RI SPECTRA**

Earthquake Spectra

1–25

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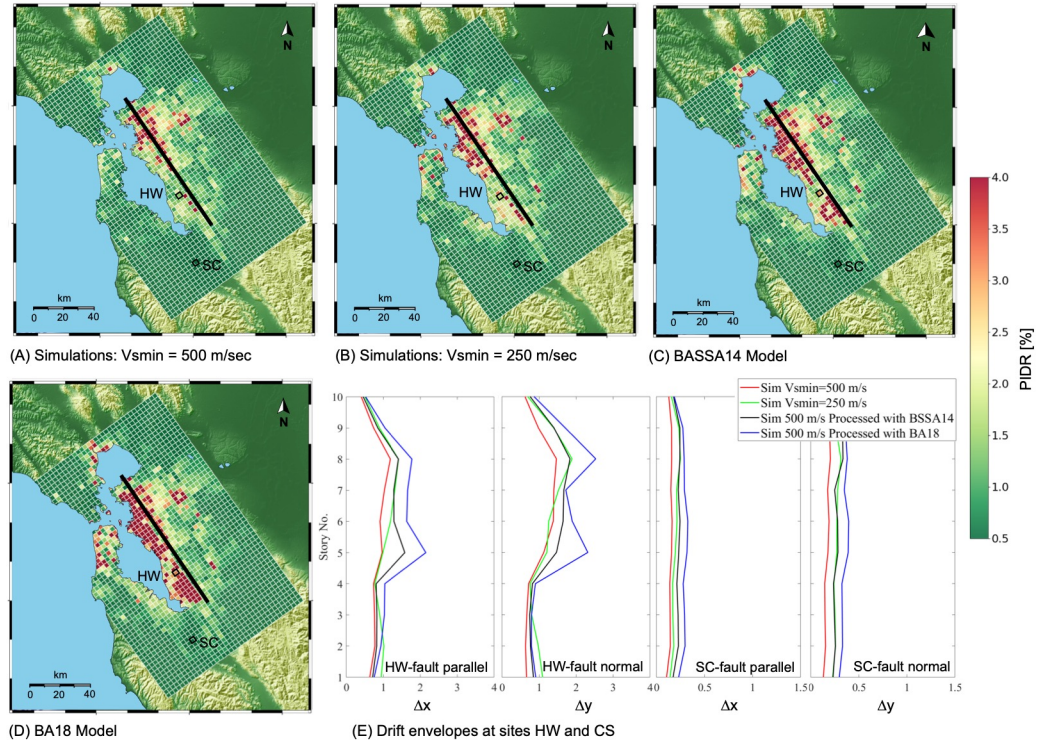
Effect of soft sediments modeling on the seismic response of a 3D mid-rise RC building: high-resolution physics-based ground-motion simulations and empirical factors

Pezhman Matinrad M.EERI,
and Floriana Petrone, M.EERI

The objective is to assess the effectiveness of hybrid methods in providing ground motions that can be reliably utilized by engineers in seismic analyses and offer insights into the misestimates introduced by empirical factors and their interpretation in relation with local geology.

The findings reveal significant disparities in the prediction of ground-motion intensity measures and building responses, at both soft soil sites and stiff sites in their vicinity. Analyses conducted at selected locations attribute these differences to the concurrent effects of wave-propagation and topographic effects, which are adequately captured only by the simulation-based model with low shear-wave velocity, and the geological specificity of the chosen region.

Ten-story building response maps. PIDR obtained from the different methods to model the soft soil.



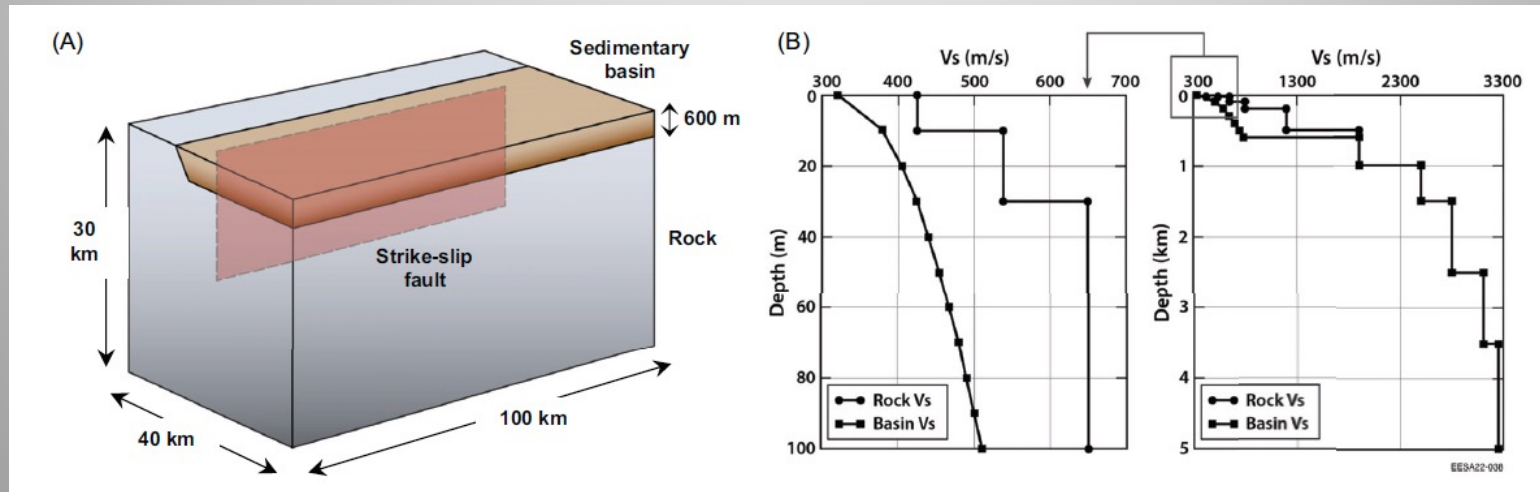
The use of empirical factors for regions with geological structures not well represented in the databases of historical records should be informed by considerations on the specificity of the domain under consideration, particularly if the intent is to examine long-period structures.

Simulation-based characterization of the variability of earthquake risk to buildings in the near-field

M. Miah, D. McCallen, A. Pitarka F. Petrone
(2023). Simulation-based characterization of
the variability of earthquake risk to buildings in
the near-field, Earthquake Eng. Struct Dyn.

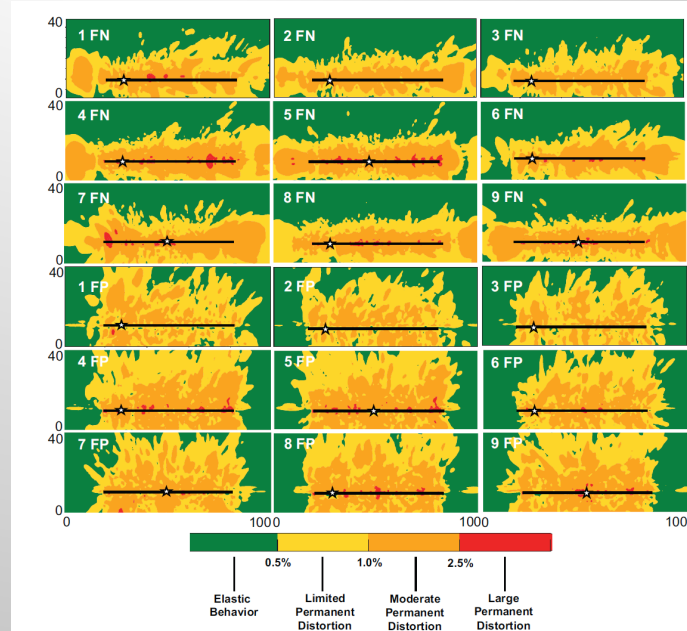
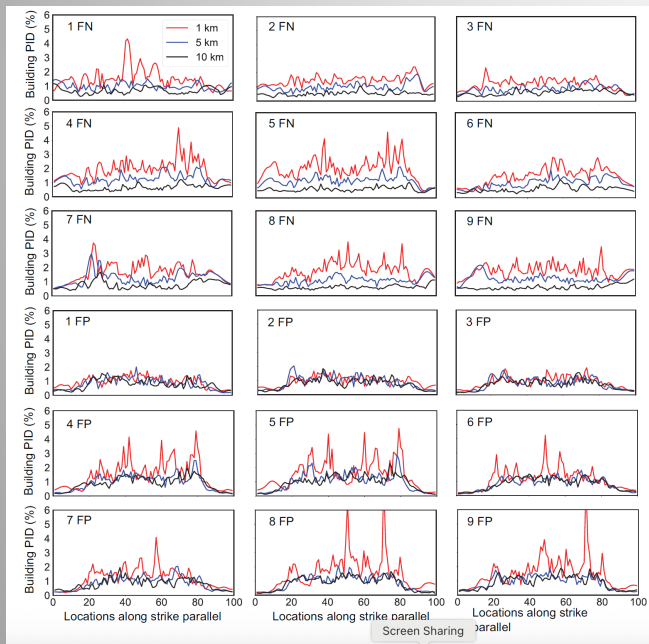
*18 fault rupture realizations and approximately 280,000 nonlinear dynamic building simulations for 3-story and 40-story building.
The simulations provide deeper insight into the relationship between fault rupture model parameterization and building response, which is essential information for developing a representative suite of rupture realizations for specific earthquake scenarios.*

Canonical Basin Model



Simulation-based characterization of the variability of earthquake risk to buildings in the near-field

Sit-to-site PID demands for different fault distances



- 1-A building could experience significantly different PID demands due to two different rupture characterizations of the same scenario earthquake.
- 2- Identical buildings, located at two adjacent sites, might also experience dramatically different seismic demands (intra-event variability)
- 3-story building undergoes higher median seismic demand and significantly greater variability of demand at a given site than the forty-story building,

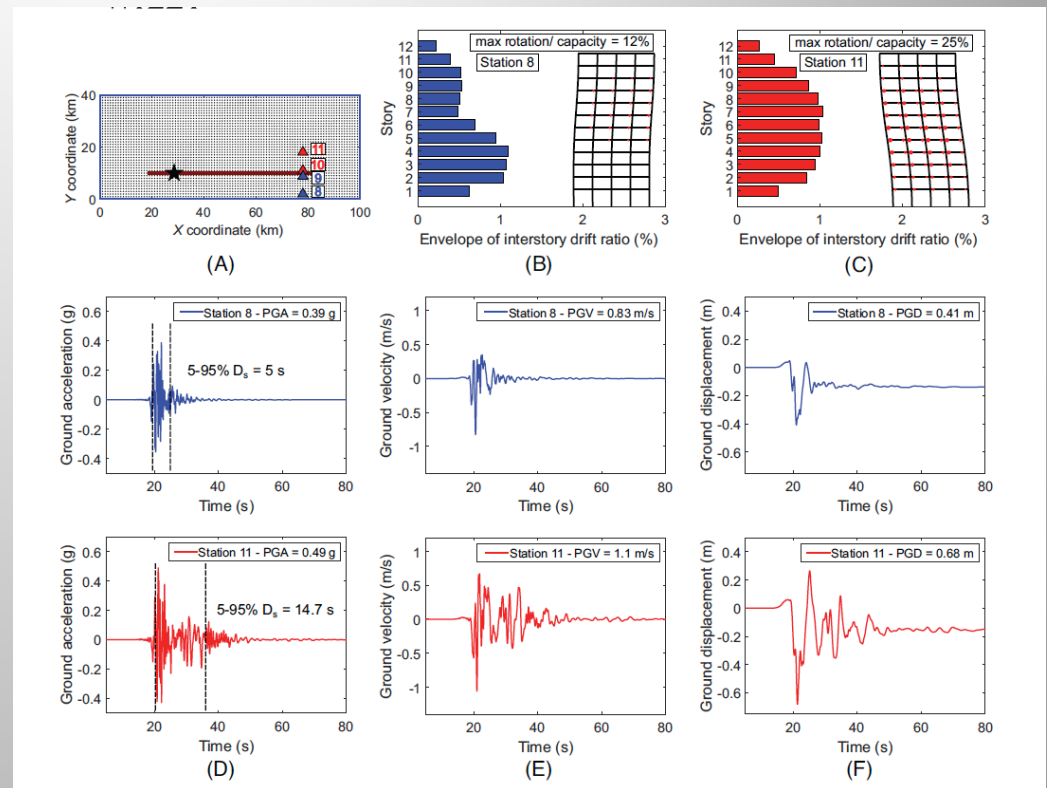
Simulated broadband earthquake ground motions to characterize the regional-scale variation of the seismic risk to RC structures for a M7 unilateral strike-slip earthquake

Kenawi, M., et al (2021). Variability of near-fault seismic risk to reinforced concrete buildings based on high-resolution physics-based ground motion simulations, *Earthq. Eng. Strukt. Dyn.*
DOI: 10.1002/eqe.3413

1-The amplification of the ground motion components normal to the rupturing fault caused by the forward rupture directivity effect is predominantly concentrated within a 10-km normal distance to the fault and may lead to extreme MIDR and member rotation demands within that region

2-The presence of localized high-slip patches along the fault consistently leads to higher ground motion intensity and structural demands over regions of the domain that are near the patches.

These findings could have major implications for the assurance of adequate building seismic response and needs further investigations



Effect of the co-seismic fault-parallel static offset (fling step) on structural response

Research Paper

EE **EARTHQUAKE**
RI **SPECTRA**

Performance assessment of near-fault buildings subjected to physics-based simulated earthquake ground motions with fling step

Maha Kenawy^{1,2} , and Arben Pitarka³ 

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The effects of fling step and associated velocity pulses on civil structures have been difficult to study because the static offset is typically removed during the processing of earthquake ground motion records.

Recorded and simulated maximum permanent offset

Kenawy and Pitarka

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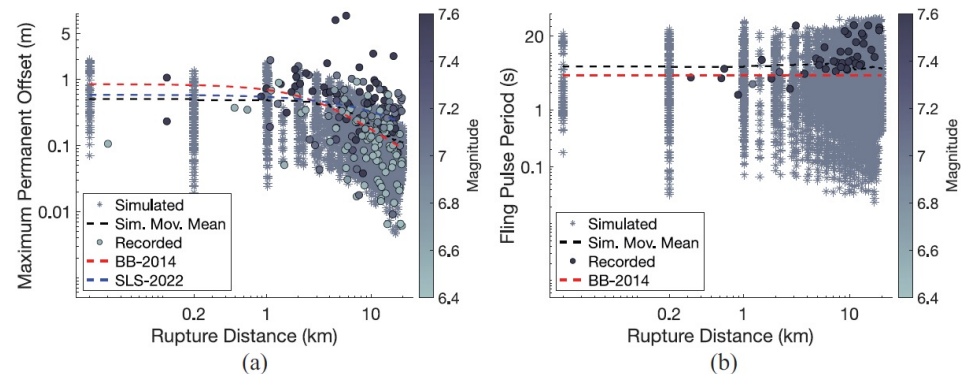


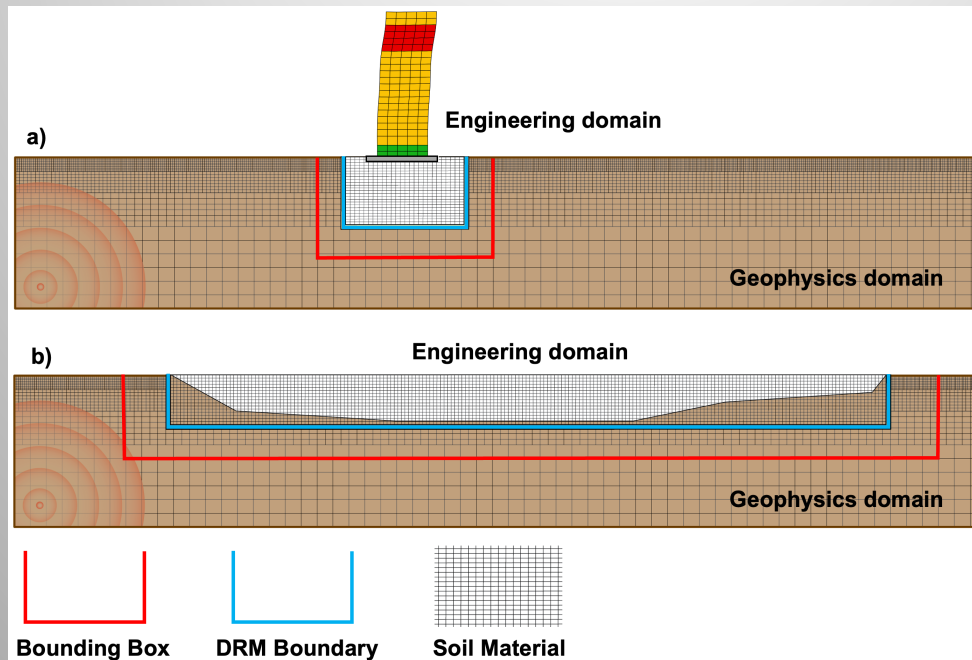
Figure 3. (a) Maximum permanent offset in simulated and recorded ground motions; (b) period of the fling pulse in the direction of the maximum offset extracted from simulated and recorded ground motions. The dashed black line represents the kernel moving mean of the simulated ground motions, the dashed red line represents the predictive model by Burks and Baker (2014b), and the dashed blue line represents the predictive model of Schiappapietra et al. (2022).

Applications of Domain Reduced Method coupled with SW4 code in the EQSIM framework

Use cases for the DRM :

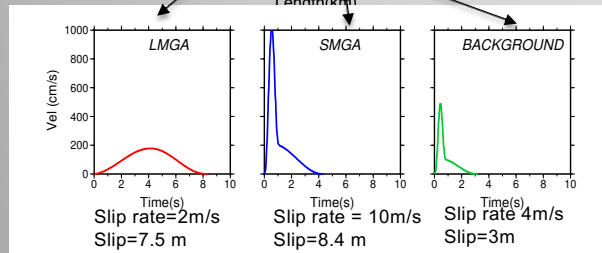
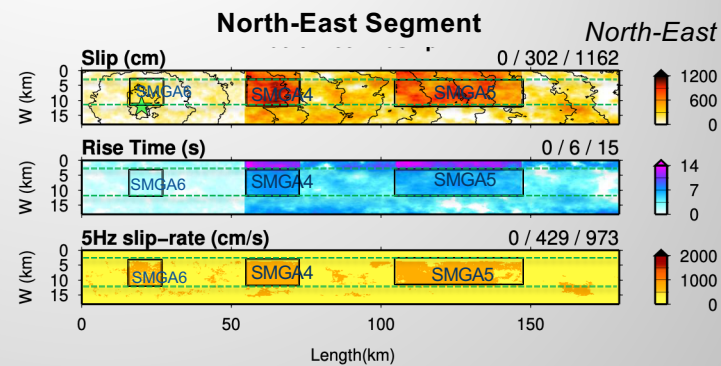
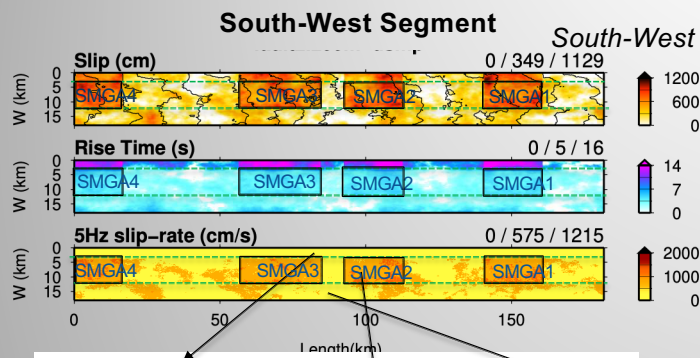
- a) coupling regional geophysics and local soil/structure island models
- b) representation of a near-surface nonlinear geotechnical layer

McCallen et al., 2025



Hybrid rupture model parameterization for Türkiye earthquake IM+GP (Irikura and Miyake +Graves and Pitarka Model)

Pitarka et al. 2026



Average Rupture Speed:
 $V_r = 0.90 V_s$

LMGA

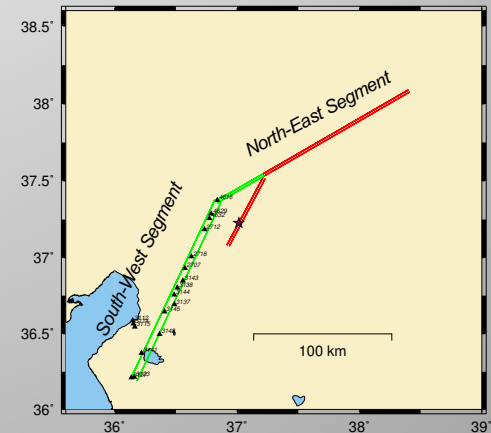
Depth range : 0-4km
Rup speed : $V_{LMGA} = 0.6 \cdot V_r$
STF : Bell shape
Rise time: 2 x aver rise time
Slip Contrast : 2.0

SMGA

Depth range : 4-12km
Rup speed : $V_{SMGA} = 1.1 \cdot V_r$
STF : Liu type
Rise time: correl. with slip
Slip contrast: 2.8

Background

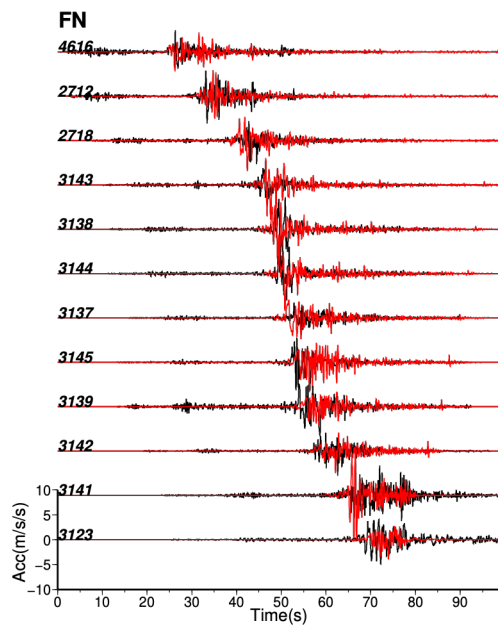
Depth range : 4-15km
Rup speed : $V = V_r$
STF: Liu type
Rise time = correl. with slip



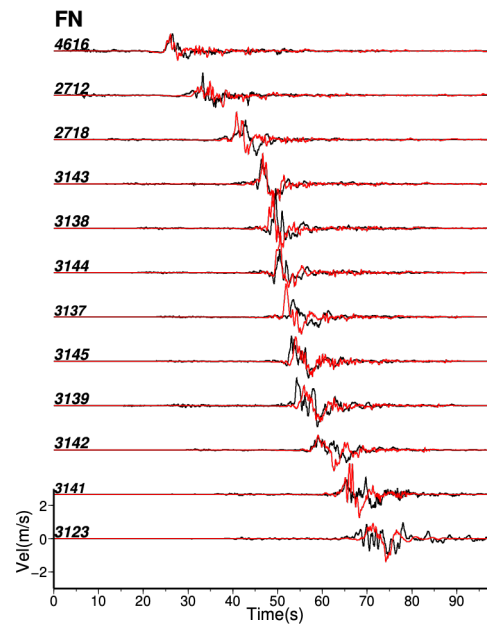
Comparison of recorded and simulated ground motion for the IM+GP rupture model

— Rec — Syn

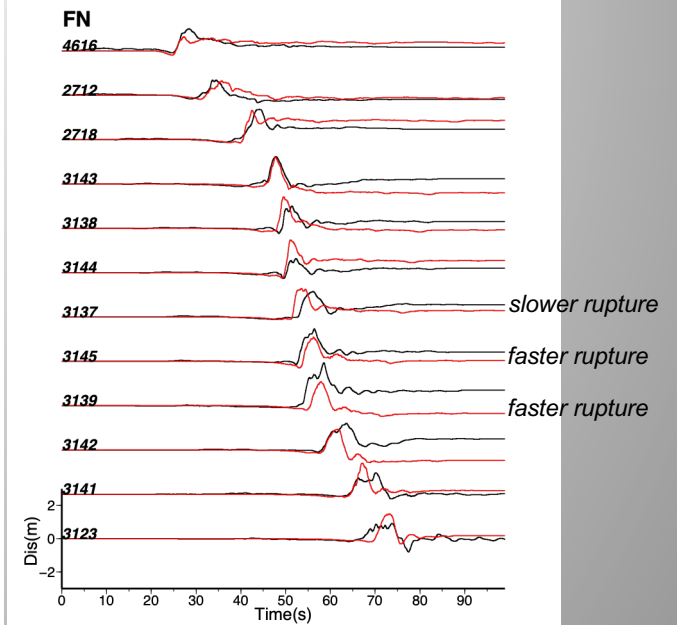
FN- Acceleration



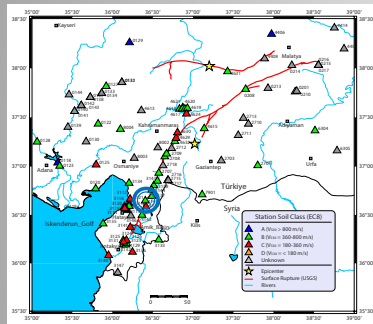
FN- Velocity



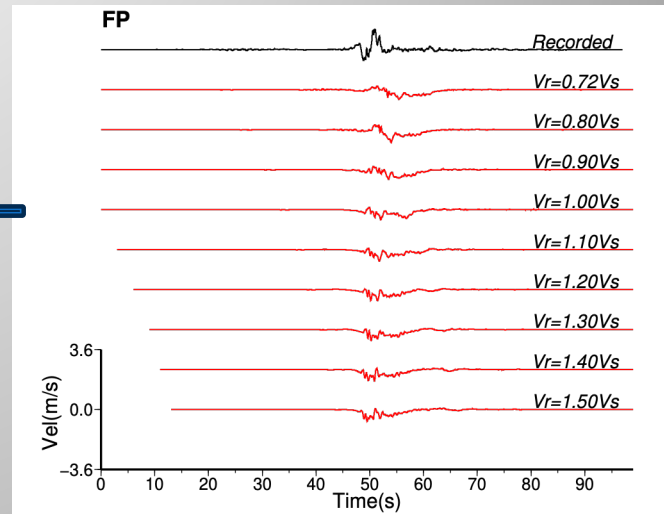
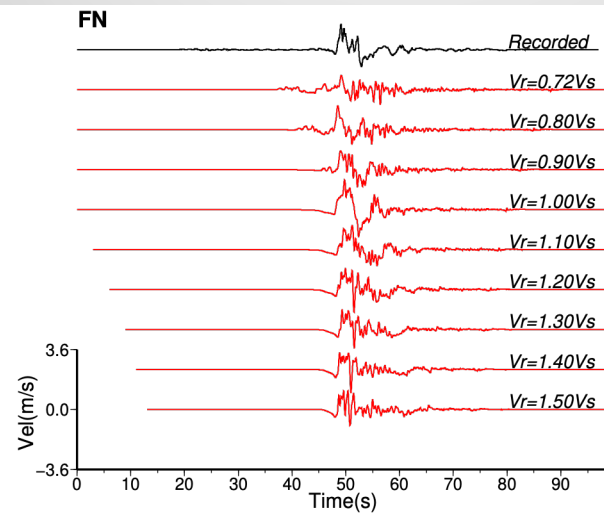
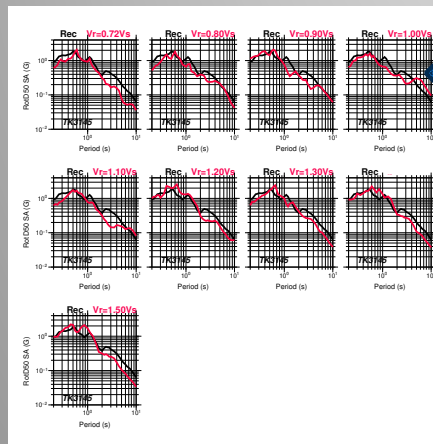
FN- Displacement



Effects of rupture velocity on near-fault ground motion



Station 3145



Conclusions

- Physics-based simulation platforms that are well suited to high performance computing are capable of producing high quality synthetic ground motion with engineering applications.
- Broad band ground motion simulations techniques such as the ones used in the INGV-Secure project are shown to be an excellent tool for seismic hazard assessment for scenario earthquakes.
- Quality checked synthetic ground motion offer opportunities for engineering applications aiming at reducing the uncertainty in building response estimates due to unknown input motion characteristics

Thank You !

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- Department of Energy, USA
- Nuclear Regulatory Commission, USA
- INGV, Italy
- Nuclear Regulatory Authority, Japan



