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Rupture-to-Rafters: Scenario-Based Seismic Risk Assessment of Critical Infrastructure through Regional Earthquake Simulations

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Outline

- Preliminary results are presented.
- Ongoing study on effects of surface topography, and soil stratigraphy and nonlinearity on site (and civil infrastructure) responses for a region of Istanbul.
- Extremely large-scale linear and nonlinear physics-based 3D earthquake ground motion simulations using real site topography and soil stratigraphy data, and realistic fault rupture sources models are performed.
- A computational workflow for hi-res rupture-to-rafters simulation is developed.

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Rupture-to-Rafters *ingredients*

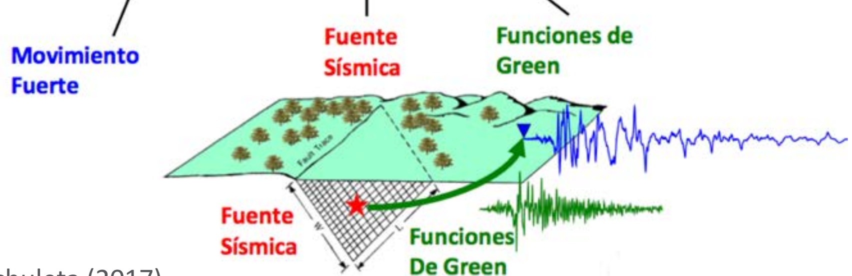
Source Modeling (Crempien)

Fault Rupture Simulations

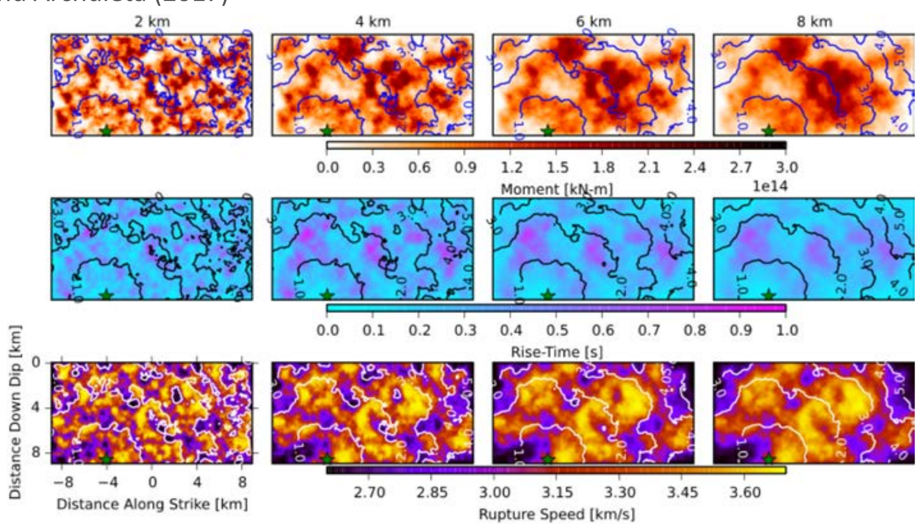
- Sudden slip on faults produce seismic waves
- With known crustal properties Green´s functions can be devised and convolved with the source, to produce input ground motions
- The figure shows different earthquake source parameters on each point on the fault, such as seismic moment, slip duration and rupture speed.

Representation Theorem

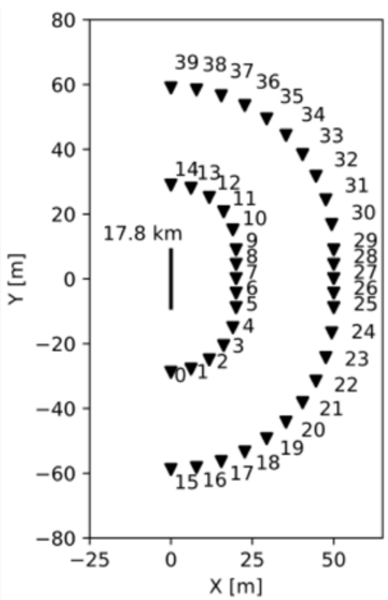
$$u_n(\mathbf{x},t) = \int_{-\infty}^{\infty} d\tau \iint_{\Sigma} s_i(\xi,\tau) c_{ijpq} \nu_j G_{np,q}(\mathbf{x}, t-\tau; \xi, 0) d\Sigma$$



Crempien and Archuleta (2017)



Verification



Crempien and Archuleta (2017)

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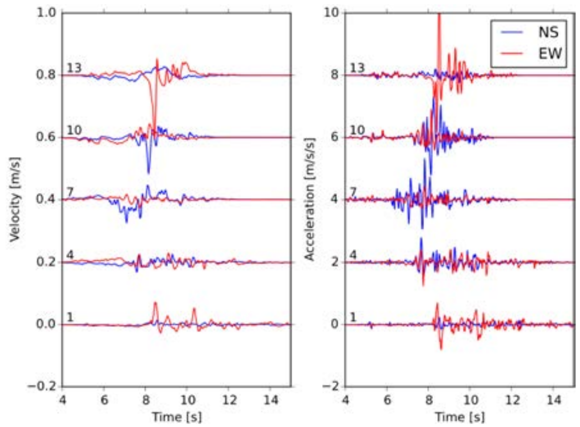
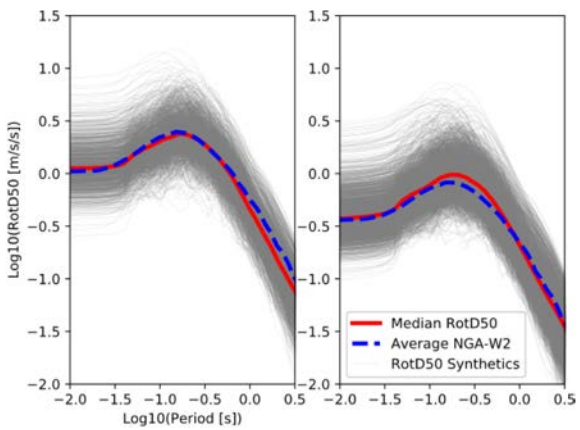
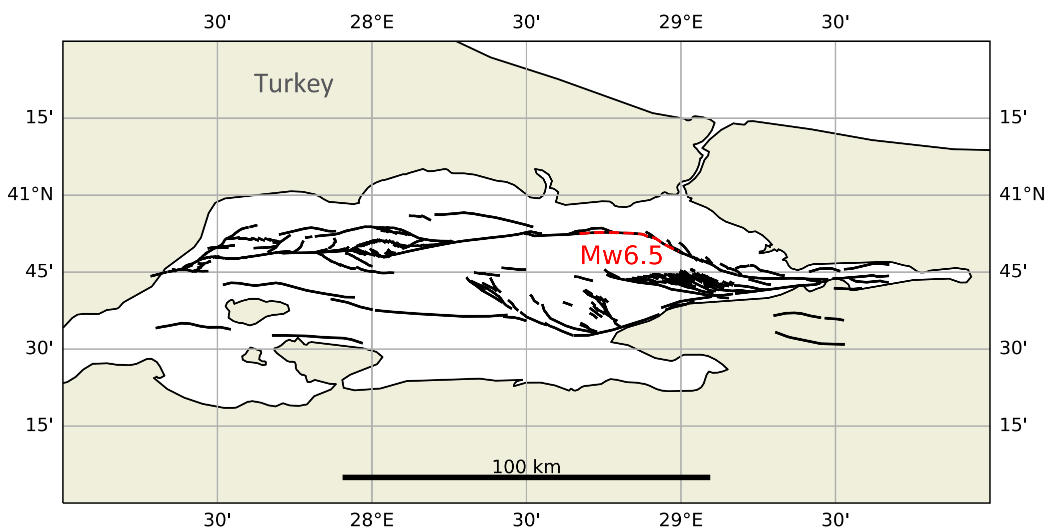


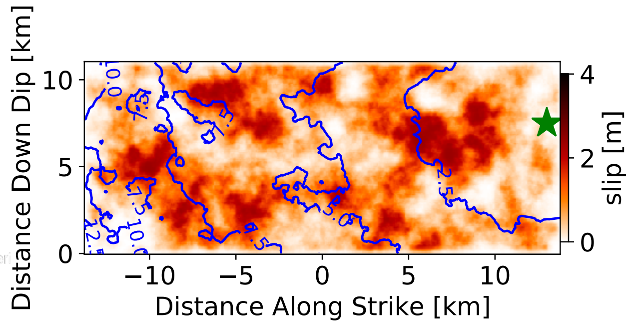


Synthetic ground velocity and acceleration at different virtual stations.

The red line shows the median response spectrum of synthetic simulations and the blue lines depicts the average NGA-W2 ground motion prediction equations.

Marmara region, Turkey (Crempien)





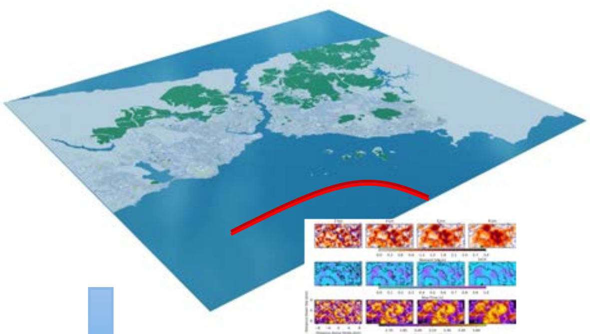
The black lines correspond to mapped fault traces by Pondard et al. (2007)

The red segmented line depicts the fault trace of a Mw6.5 strike-slip earthquake scenario.

The figure shows the amount of slip imposed on each sub-fault. The Kinematic rupture parameters are then convolved with Green's functions to generate strong ground motion.

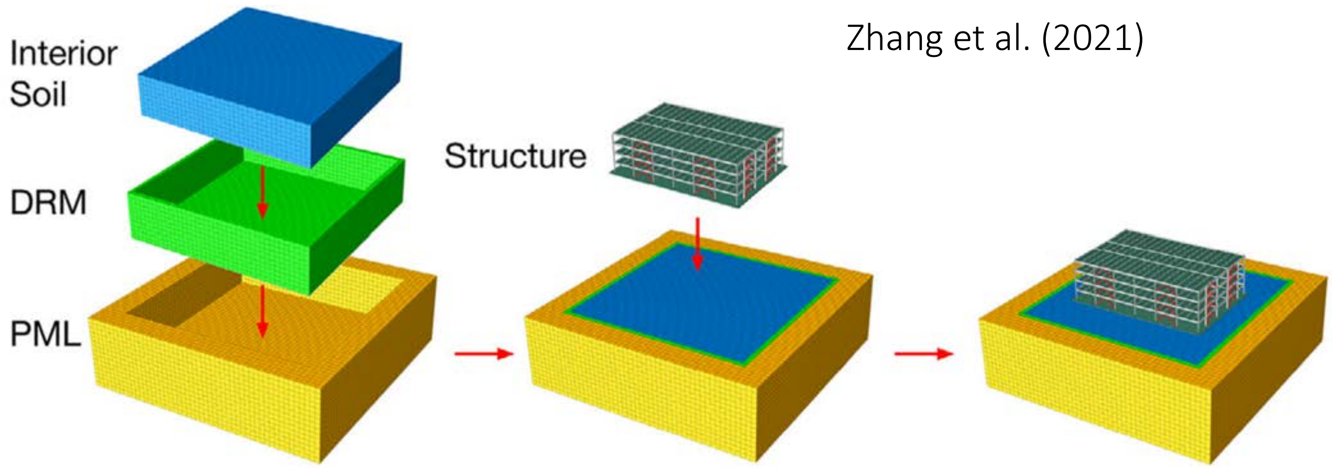
Main Components

Regional-scale domain (Crempien)

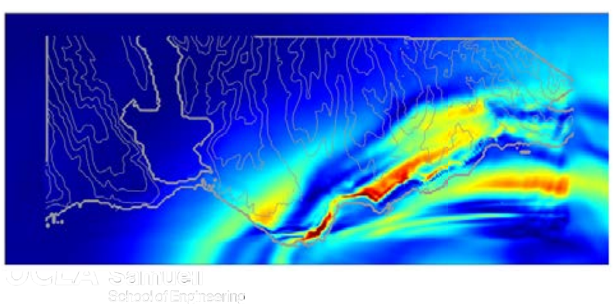


Local analyses of critical infrastructure (ABAQUS, OpenSees)

Zhang et al. (2021)



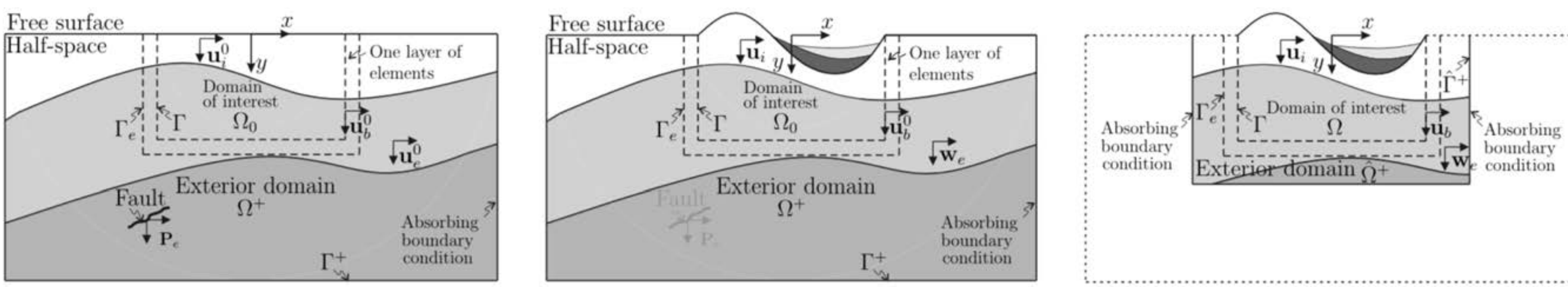
Physics-based ground motion simulation (Hercules)



Infrastructure inventories (UCLA & Tsinghua codes, ongoing)

Domain Reduction Method (DRM)

The Domain Reduction Method is a two-step technique proposed by Bielak et al. (2003), with a goal of reducing the computational cost by bringing the effects of seismic source closer to the domain of interest



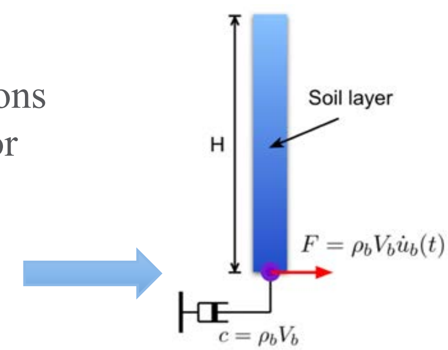
(a) (b) (c)

$$\mathbf{P}^{eff} = \begin{bmatrix} \mathbf{P}_i^{eff} \\ \mathbf{P}_b^{eff} \\ \mathbf{P}_e^{eff} \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ -\mathbf{M}_{be}^{\Omega+}\ddot{\mathbf{u}}_e^0 - \mathbf{C}_{be}^{\Omega+}\dot{\mathbf{u}}_e^0 - \mathbf{K}_{be}^{\Omega+}\mathbf{u}_e^0 \\ +\mathbf{M}_{eb}^{\Omega+}\ddot{\mathbf{u}}_b^0 + \mathbf{C}_{eb}^{\Omega+}\dot{\mathbf{u}}_b^0 + \mathbf{K}_{eb}^{\Omega+}\mathbf{u}_b^0 \end{bmatrix}$$

where the subscripts i, b and e refer to the nodes within the domain of interest, along the inside and outside boundary of the one layer of elements, respectively.

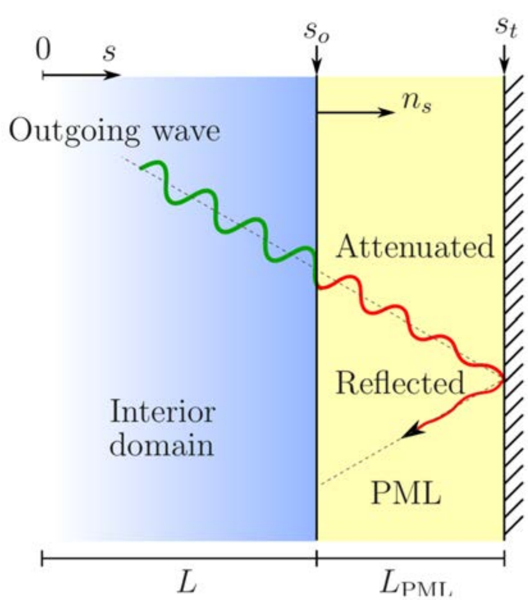
Free-field response:

- Analytical solutions (homogeneous for time domain)
- 1D site response analysis



Perfectly-Matched-Layer (PML) absorbing boundary condition

The key idea of the PML is to attach a high-attenuation zone to the truncation surface of the regular domain, as shown below, within which outgoing waves are forced to decay.



The complex stretching function

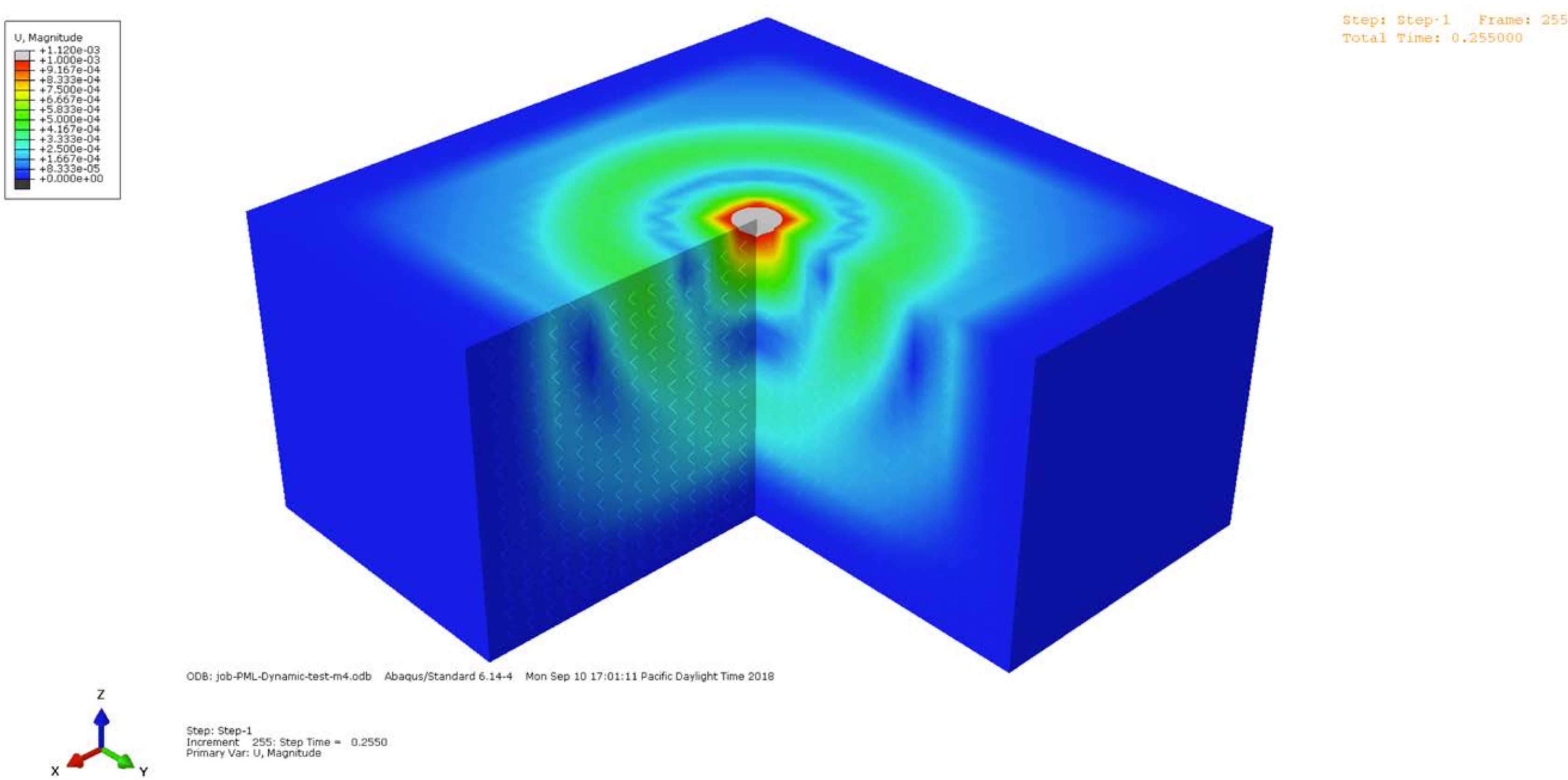
$$\lambda_i(x_i,\omega) = \alpha(x_i) + \frac{1}{j\omega}\beta(x_i)$$

The idea is to "stretch" the originally physical coordinates to the virtually infinite coordinates

The PML has been implemented in ABAQUS by writing a user-defined element subroutine (a.k.a., UEL) for both 2D and 3D versions.

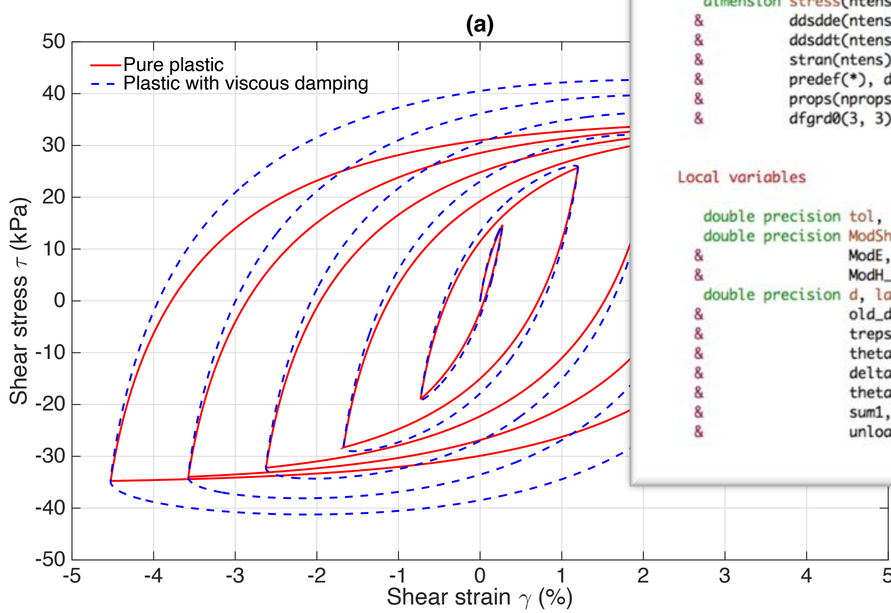
- It can be used for arbitrarily heterogeneous soil domain.
- It results in no reflections at the truncated near-field boundary (i.e., "perfect matches" it) for all non-zero-frequency impinging waves, irrespective of their angles of incidence.
- It attenuates the wave energy within itself.

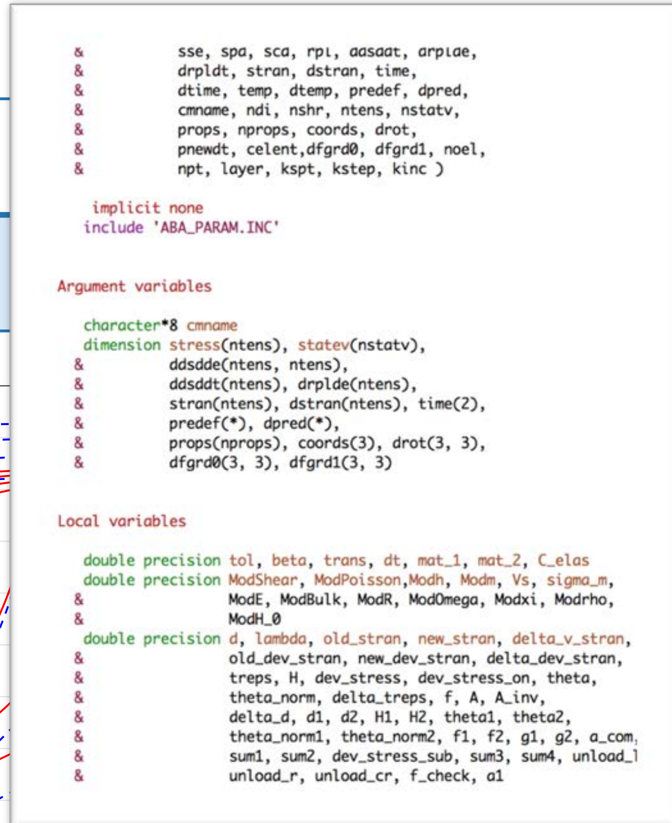
A vertical point load applied on three-layered half-space in 3D



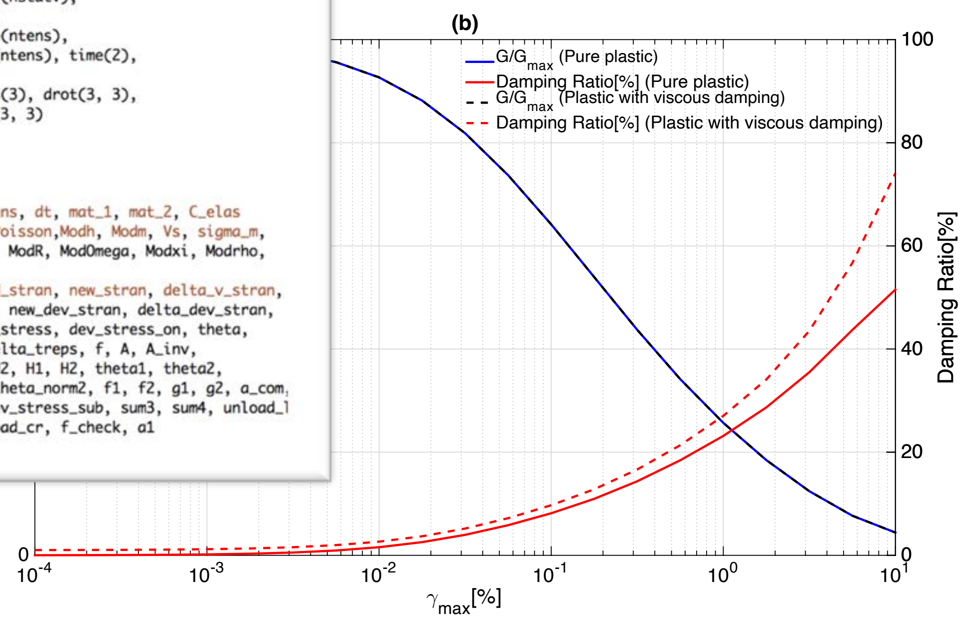
Borja-Amies multi-axial nonlinear soil model

Model		cous ects	Number of parameters
Borja-Amies nonlinear soil model (Borja and Amies, 1994)		'es	4 (frictional only) 6 (frictional and viscous)

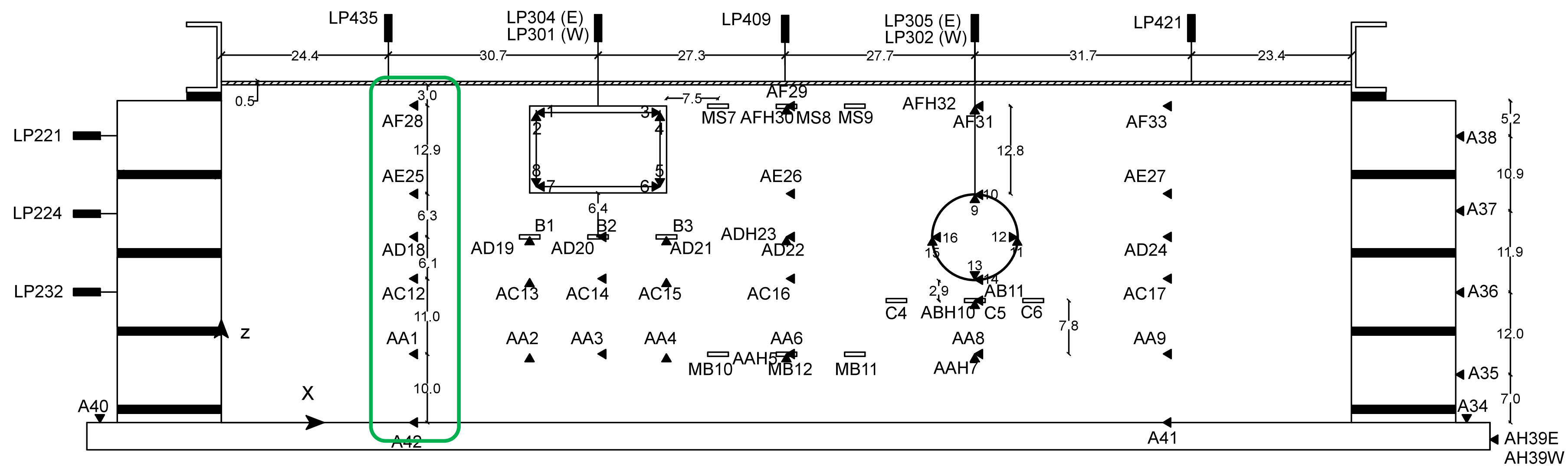




```
&        sse, spa, sca, rpl, ddsddt, drplde,
&        drpldt, stran, dstran, time,
&        dtime, temp, dtemp, predef, dpred,
&        cmname, ndi, nshr, ntens, nstatv,
&        props, nprops, coords, drot,
&        pnewdt, celent,dfgrd0, dfgrd1, noel,
&        npt, layer, kspt, kstep, kinc )

  implicit none
 include 'ABA_PARAM.INC'

Argument variables

 character*8 cmname
 dimension stress(ntens), statev(nstatv),
&        ddsdde(ntens, ntens),
&        ddsddt(ntens), drplde(ntens),
&        stran(ntens), dstran(ntens), time(2),
&        predef(*), dpred(*),
&        props(nprops), coords(3), drot(3, 3),
&        dfgrd0(3, 3), dfgrd1(3, 3)

Local variables

 double precision tol, beta, trans, dt, mat_1, mat_2, C_elas
 double precision ModShear, ModPoisson,Modh, Modm, Vs, sigma_m,
&                 ModE, ModBulk, ModR, ModOmega, Modxi, Modrho,
&                 ModH_0
 double precision d, lambda, old_stran, new_stran, delta_v_stran,
&                 old_dev_stran, new_dev_stran, delta_dev_stran,
&                 treps, H, dev_stress, dev_stress_on, theta,
&                 theta_norm, delta_treps, f, A, A_inv,
&                 delta_d, d1, d2, H1, H2, theta1, theta2,
&                 theta_norm1, theta_norm2, f1, f2, g1, g2, a_com,
&                 sum1, sum2, dev_stress_sub, sum3, sum4, unload_l
&                 unload_r, unload_cr, f_check, a1
```



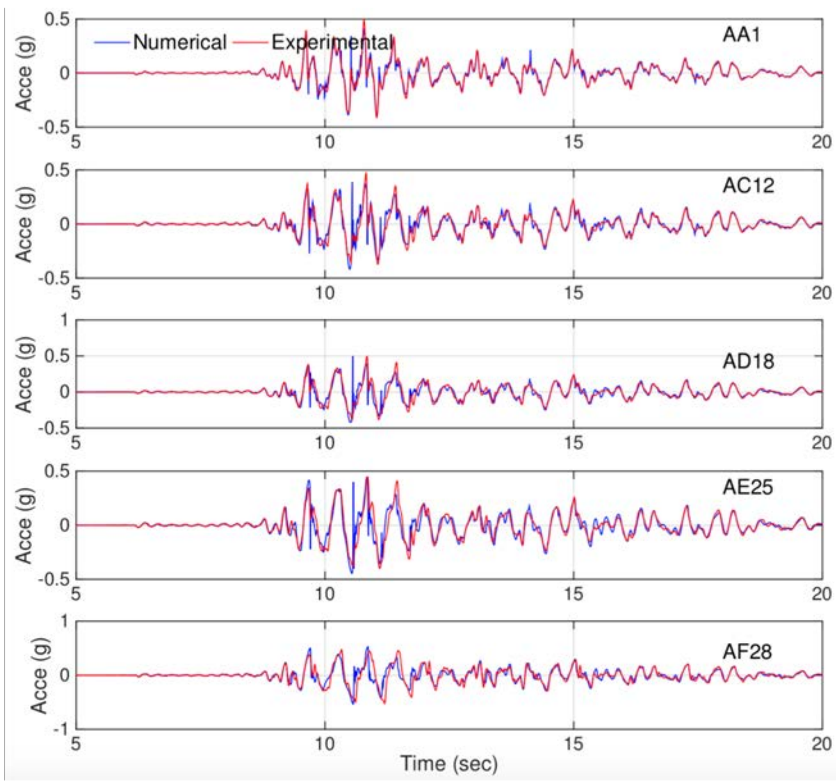
Centrifuge experiments @ UC Davis (Seylabi et al., 2015)



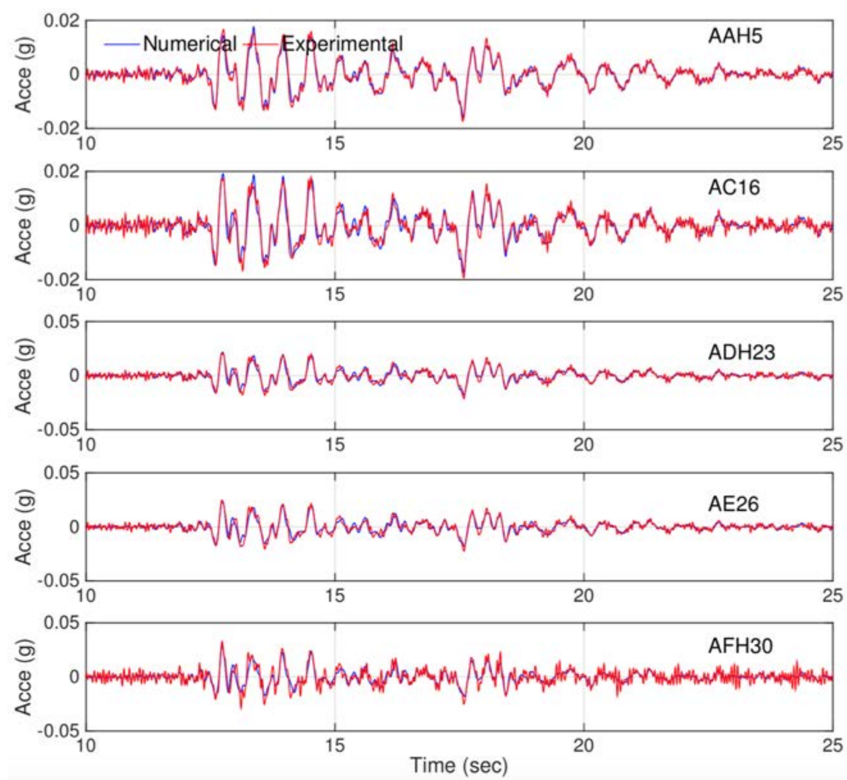
Box	Width (m)	Height (m)	Thickness (m)
	2.667	4.267	0.2
Pipe	Inside diameter (m)		Thickness (m)
	2.6		0.034

Horizontal accelerations (soil)

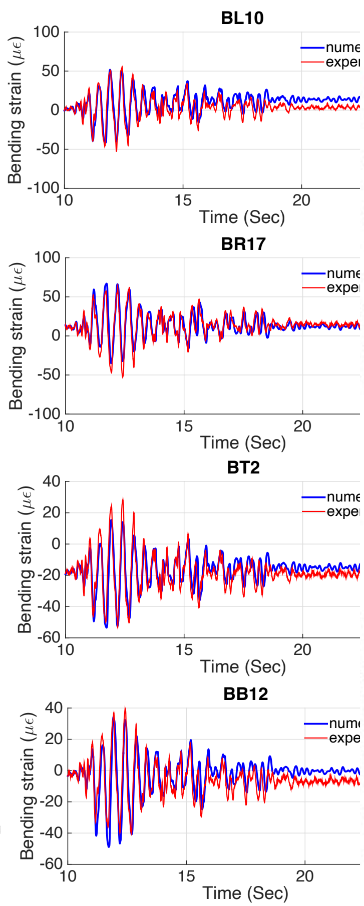
Motion #09 (left array)

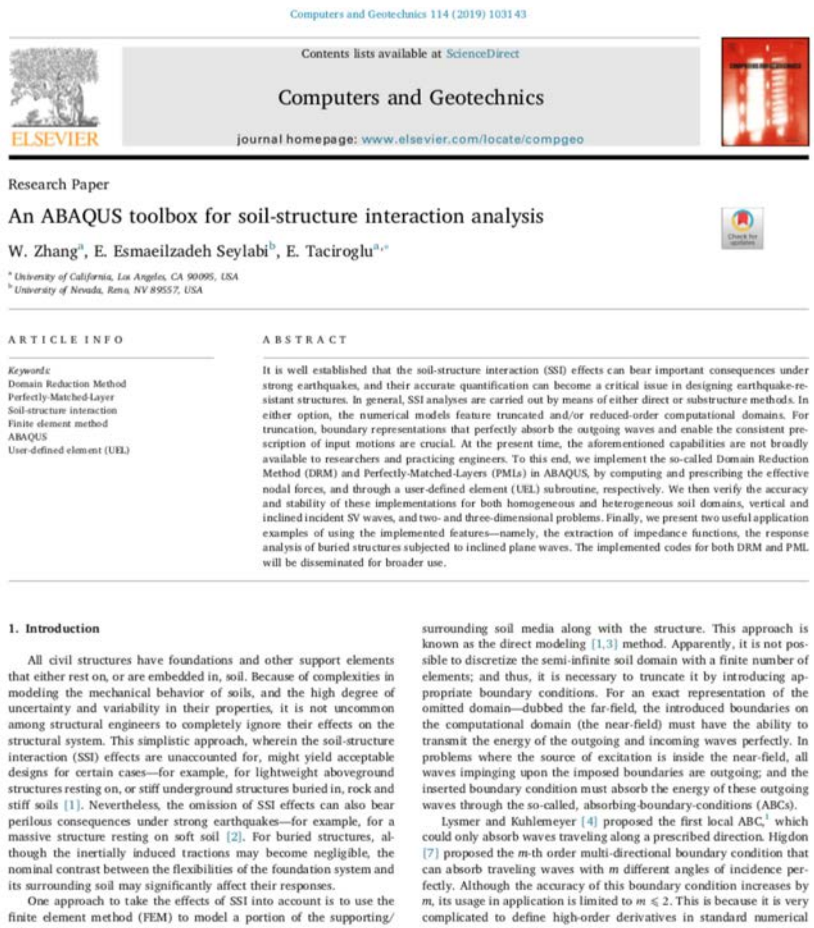


Motion #03 (middle array)



Bending strain (rectangular structure motion #09)





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Research Paper

An ABAQUS toolbox for soil-structure interaction analysis

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Soil-structure interaction
Finite element method
ABAQUS
User-defined element (UEL)

ABSTRACT

It is well established that the soil-structure interaction (SSI) effects can bear important consequences under strong earthquakes, and their accurate quantification can become a critical issue in designing earthquake-resistant structures. In general, SSI analyses are carried out by means of either direct or substructure methods. In either option, the numerical models feature truncated and/or reduced-order computational domains. For truncation, boundary representations that perfectly absorb the outgoing waves and enable the consistent prescription of input motions are crucial. At the present time, the aforementioned capabilities are not broadly available to researchers and practicing engineers. To this end, we implement the so-called Domain Reduction Method (DRM) and Perfectly-Matched-Layers (PMLs) in ABAQUS, by computing and prescribing the effective nodal forces, and through a user-defined element (UEL) subroutine, respectively. We then verify the accuracy and stability of these implementations for both homogeneous and heterogeneous soil domains, vertical and inclined incident SV waves, and two- and three-dimensional problems. Finally, we present two useful application examples of using the implemented features—namely, the extraction of impedance functions, the response analysis of buried structures subjected to inclined plane waves. The implemented codes for both DRM and PML will be disseminated for broader use.

1. Introduction

All civil structures have foundations and other support elements that either rest on, or are embedded in, soil. Because of complexities in modeling the mechanical behavior of soils, and the high degree of uncertainty and variability in their properties, it is not uncommon among structural engineers to completely ignore their effects on the structural system. This simplistic approach, wherein the soil-structure interaction (SSI) effects are unaccounted for, might yield acceptable designs for certain cases—for example, for lightweight aboveground structures resting on, or stiff underground structures buried in, rock and stiff soils [1]. Nevertheless, the omission of SSI effects can also bear perilous consequences under strong earthquakes—for example, for a massive structure resting on soft soil [2]. For buried structures, although the inertially induced tractions may become negligible, the nominal contrast between the flexibilities of the foundation system and its surrounding soil may significantly affect their responses.

One approach to take the effects of SSI into account is to use the finite element method (FEM) to model a portion of the supporting/surrounding soil media along with the structure. This approach is known as the direct modeling [1,3] method. Apparently, it is not possible to discretize the semi-infinite soil domain with a finite number of elements; and thus, it is necessary to truncate it by introducing appropriate boundary conditions. For an exact representation of the omitted domain—dubbed the far-field, the introduced boundaries on the computational domain (the near-field) must have the ability to transmit the energy of the outgoing and incoming waves perfectly. In problems where the source of excitation is inside the near-field, all waves impinging upon the imposed boundaries are outgoing; and the inserted boundary condition must absorb the energy of these outgoing waves through the so-called, absorbing-boundary-conditions (ABCs).

Lysmer and Kuhlemeyer [4] proposed the first local ABC,[1] which could only absorb waves traveling along a prescribed direction. Higdon [7] proposed the m-th order multi-directional boundary condition that can absorb traveling waves with m different angles of incidence perfectly. Although the accuracy of this boundary condition increases by m, its usage in application is limited to $m \leqslant 2$. This is because it is very complicated to define high-order derivatives in standard numerical

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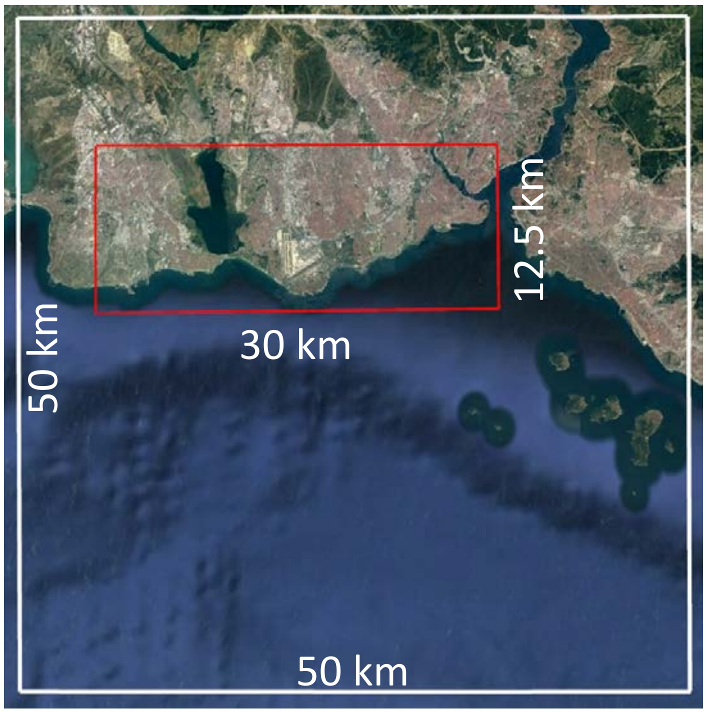
Preliminary Results from Istanbul

Physics-based large-scale ground motion simulation

Istanbul model: 50 km by 50 km by 25 km (depth)

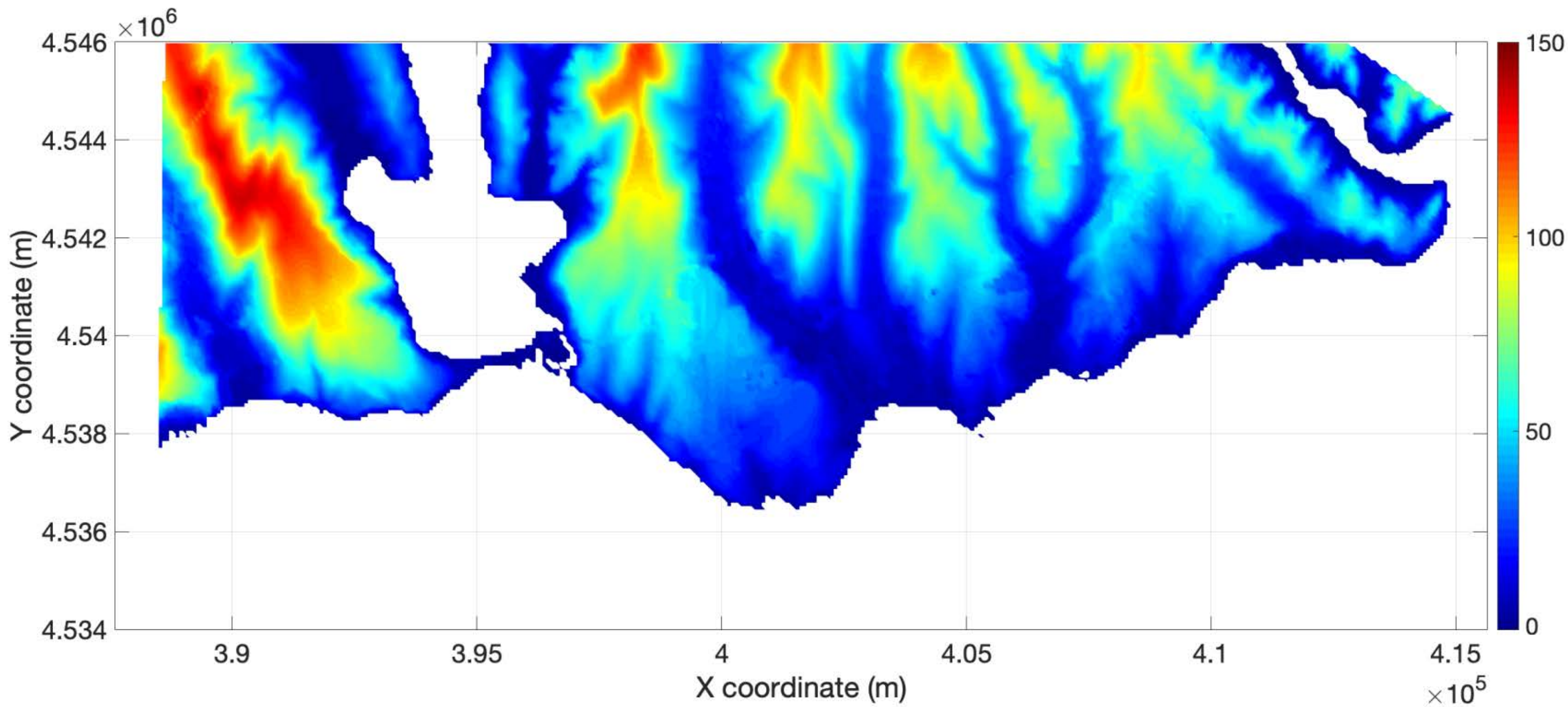


Simulations were performed using Hercules on Frontera / Stampede (TACC)

Model parameter	**Linear**	**Linear + topography**	**Nonlinear**	**Nonlinear + topography**
$f_{\max}$ (Hz)	16.4	16.4	8.2	8.2
$V_{s_{\min}}$ (m/s)	250			
Points per wavelength	10			
Min element size (m)	~1.5	~1.5	~3	~3
Number of elements (billions)	8.4	11.1	5.4	7.2
Number of nodes (billions)	8.48	11.60	5.48	7.48
Time-step Δt (s)	0.0004	0.0004	0.0004	0.0004
Simulated duration (s)	30			
Number of cores	8400	8400	22400	28000
Core usage time (hours)	11.1	16.6	33.5	47.5

Elevation data

High-resolution topography is taken into account in large-scale earthquake ground motion simulations

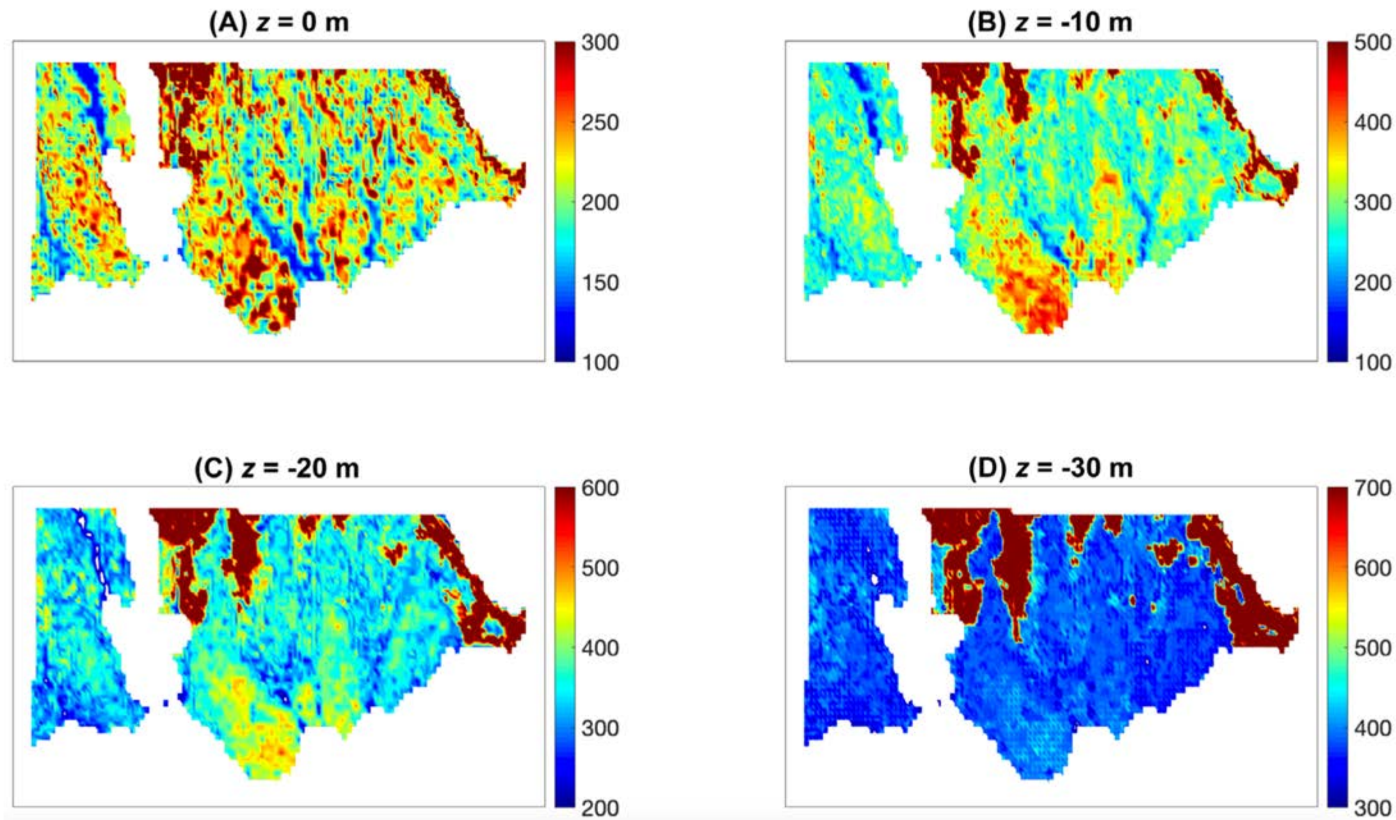


Elevation model (m)

Shear wave velocity (V_s) profiles

Detailed 3D velocity and density models are constructed given a total of 2912 boreholes distributed in 250 m × 250 m cells from prior large-scale micro-zonation studies

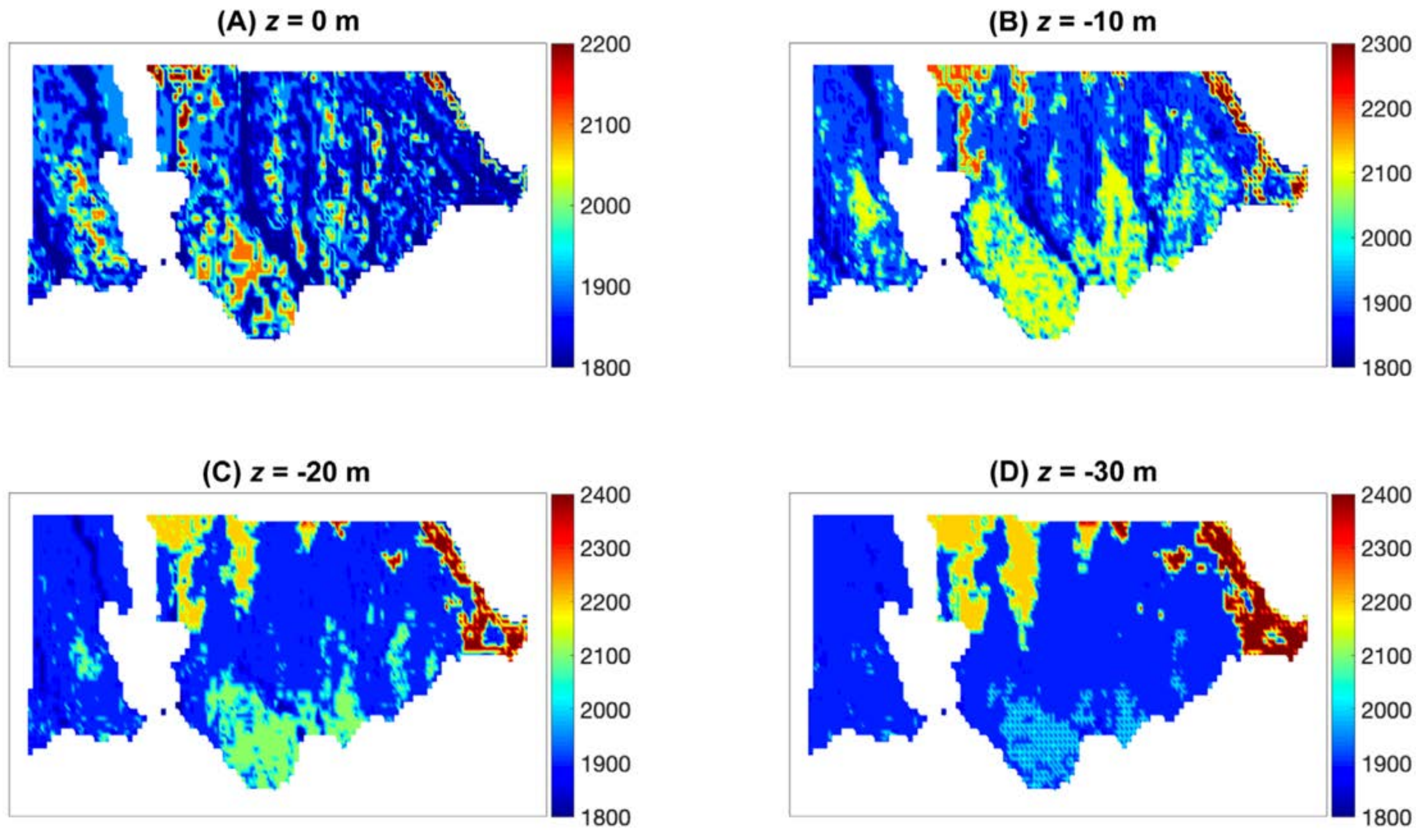
Velocity model (m/s)



Density profiles

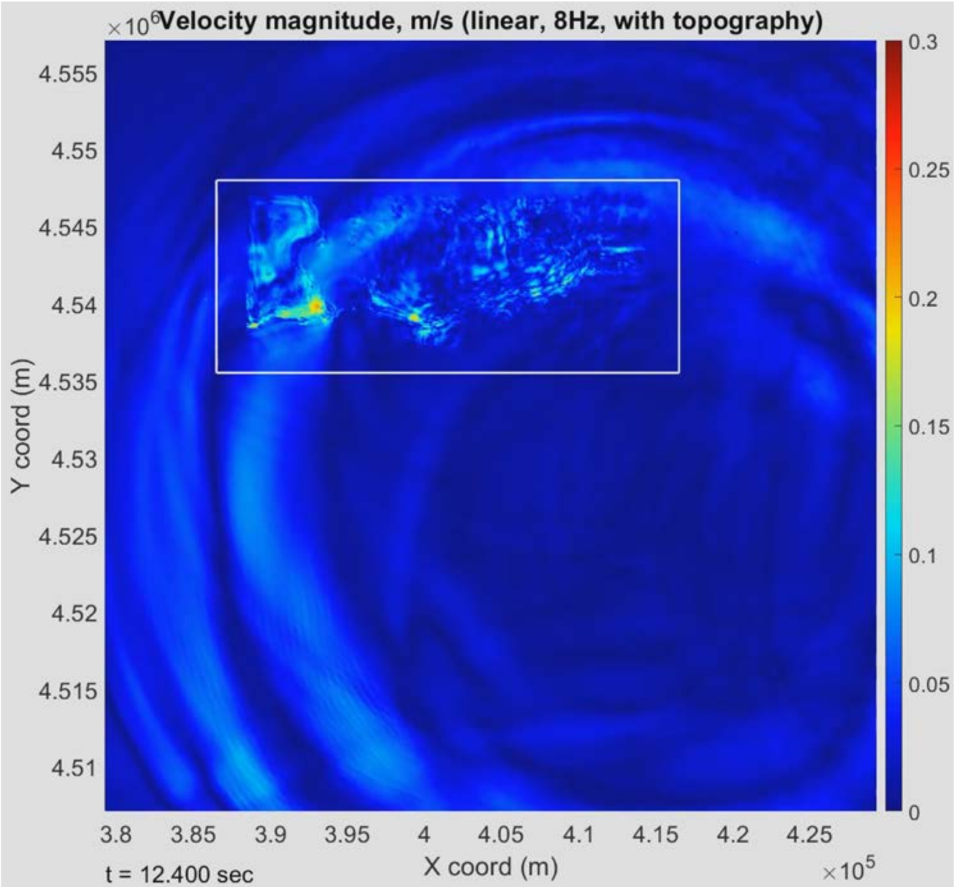
Detailed 3D velocity and density models are constructed given a total of 2912 boreholes distributed in 250 m × 250 m cells from prior large-scale micro-zonation studies

Density model (kg/m^3)



Physics-based large-scale ground motion simulation

A scenario earthquake with a magnitude of 6.5 is simulated



Physics-based large-scale ground motion simulation

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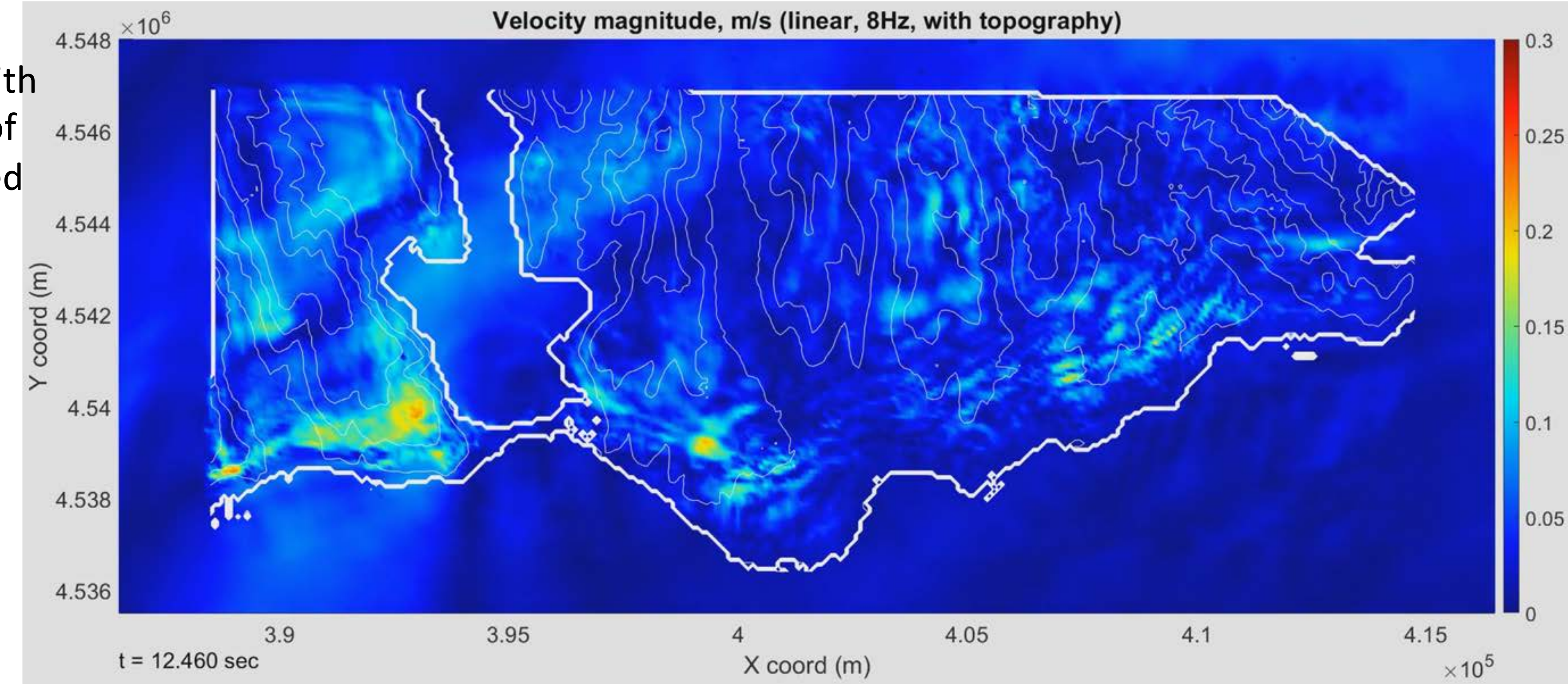
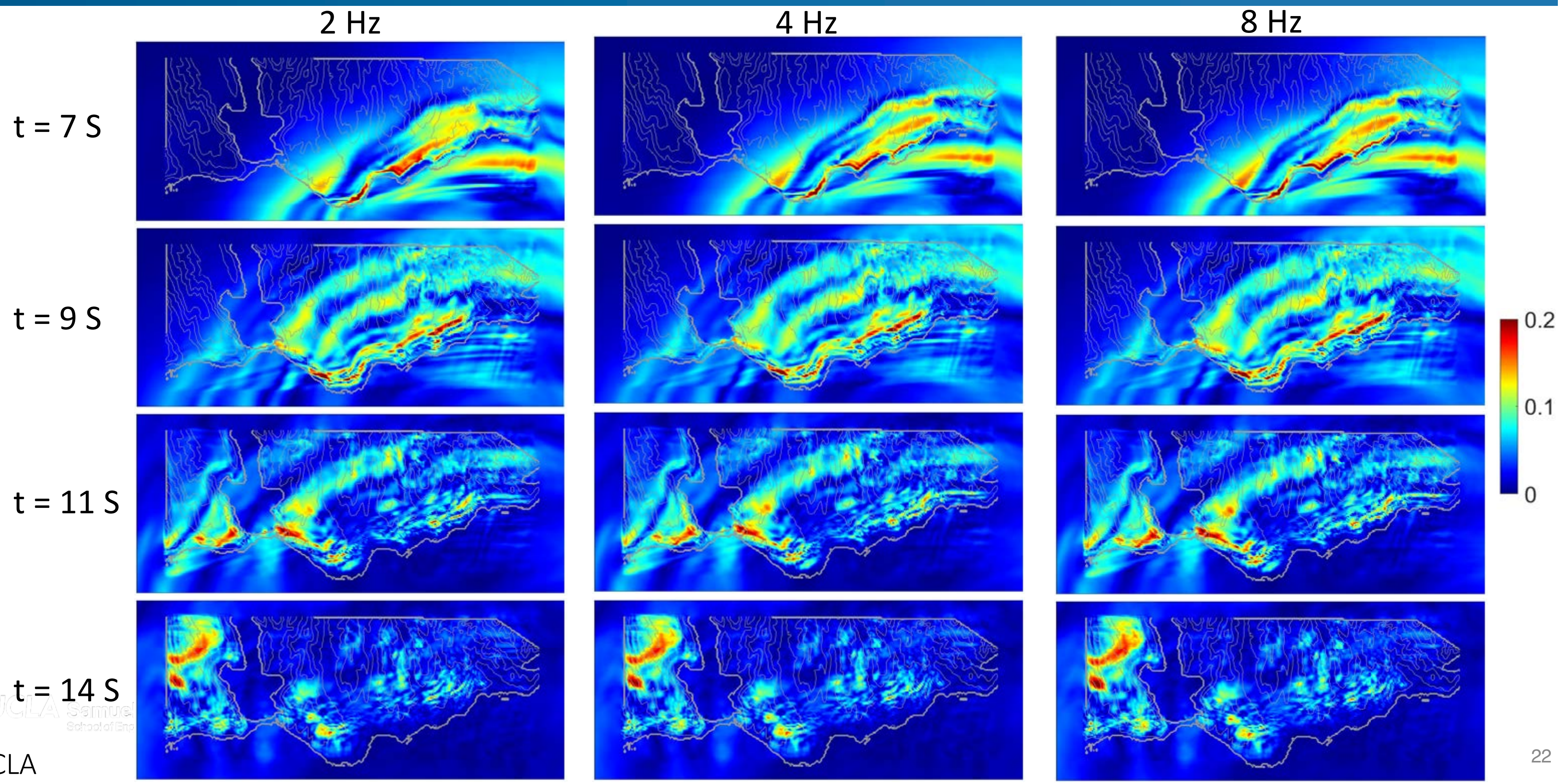


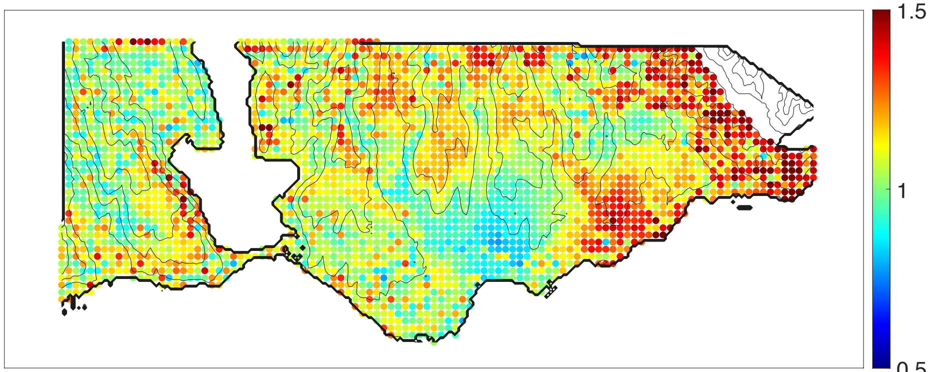
Effects of simulation resolution (velocity)



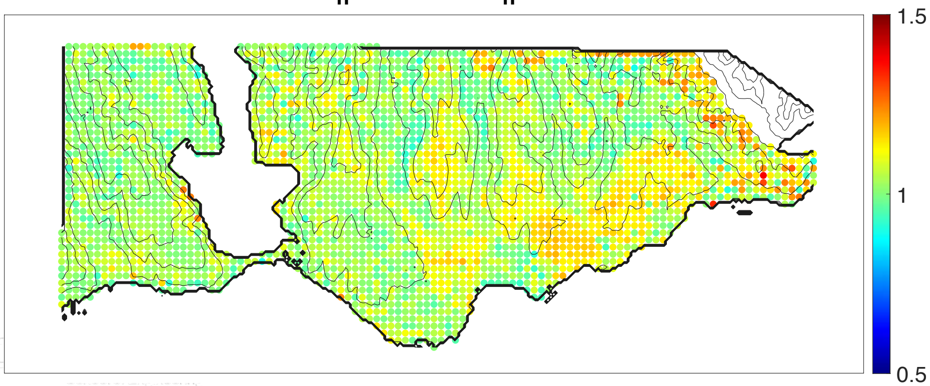
Effects of simulation resolution (PGA)

Horizontal

PGA_h (8Hz) / PGA_h (2Hz)

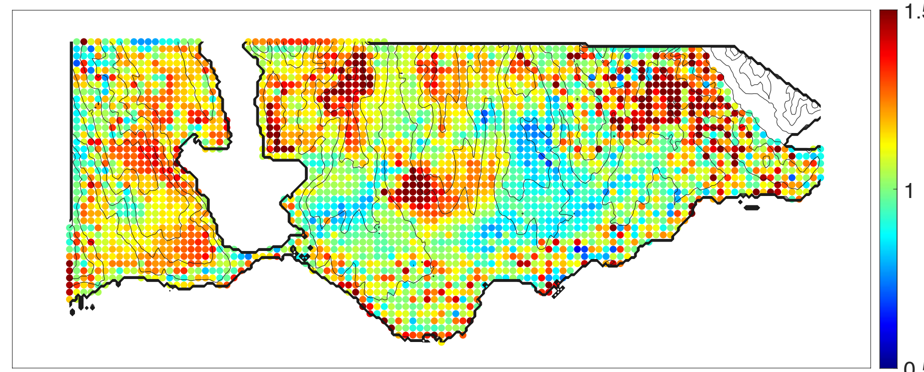


PGA_h (8Hz) / PGA_h (4Hz)

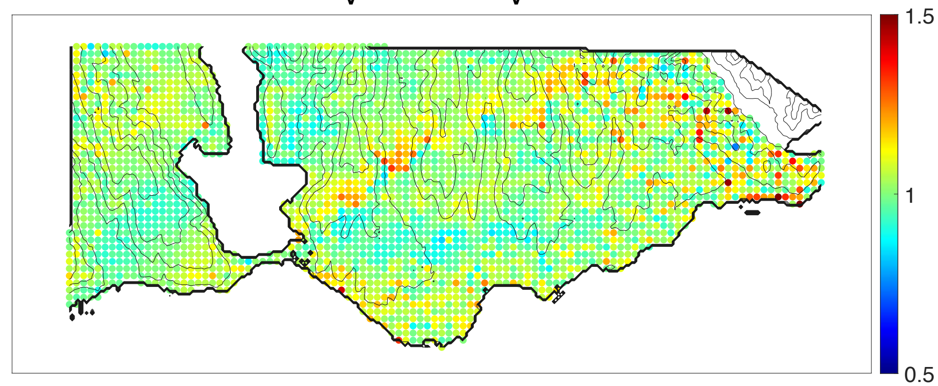


Vertical

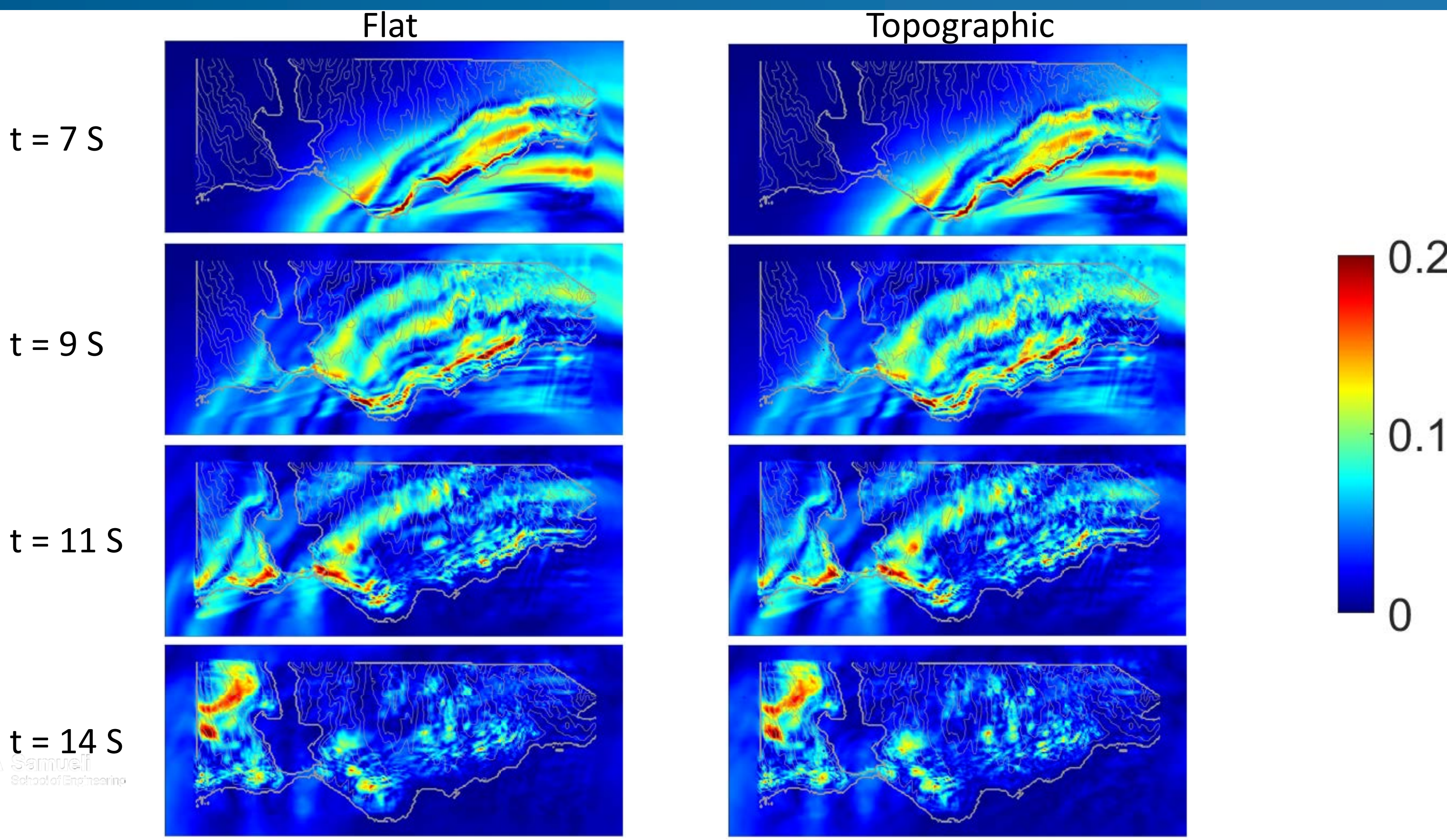
PGA_v (8Hz) / PGA_v (2Hz)



PGA_v (8Hz) / PGA_v (4Hz)

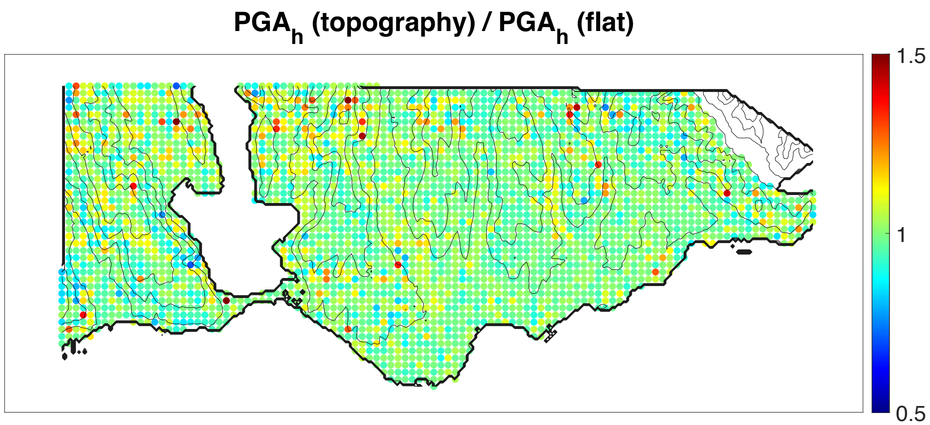


Effects of surface topography (velocity)

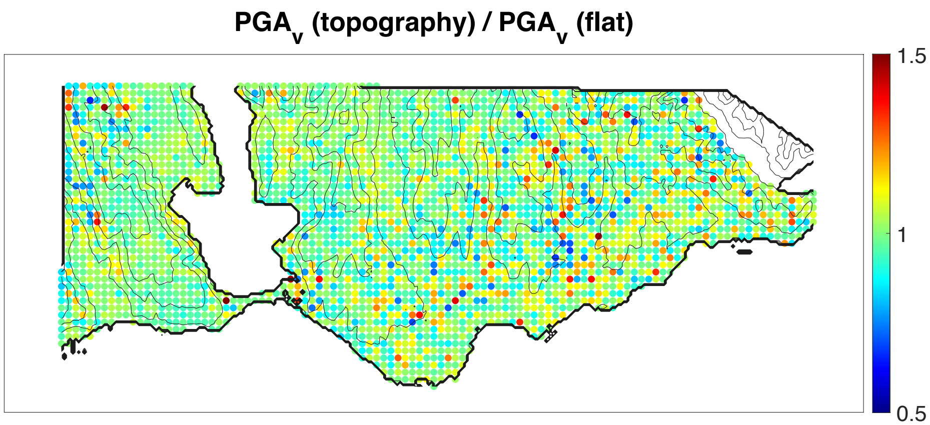


Effects of surface topography (PGA)

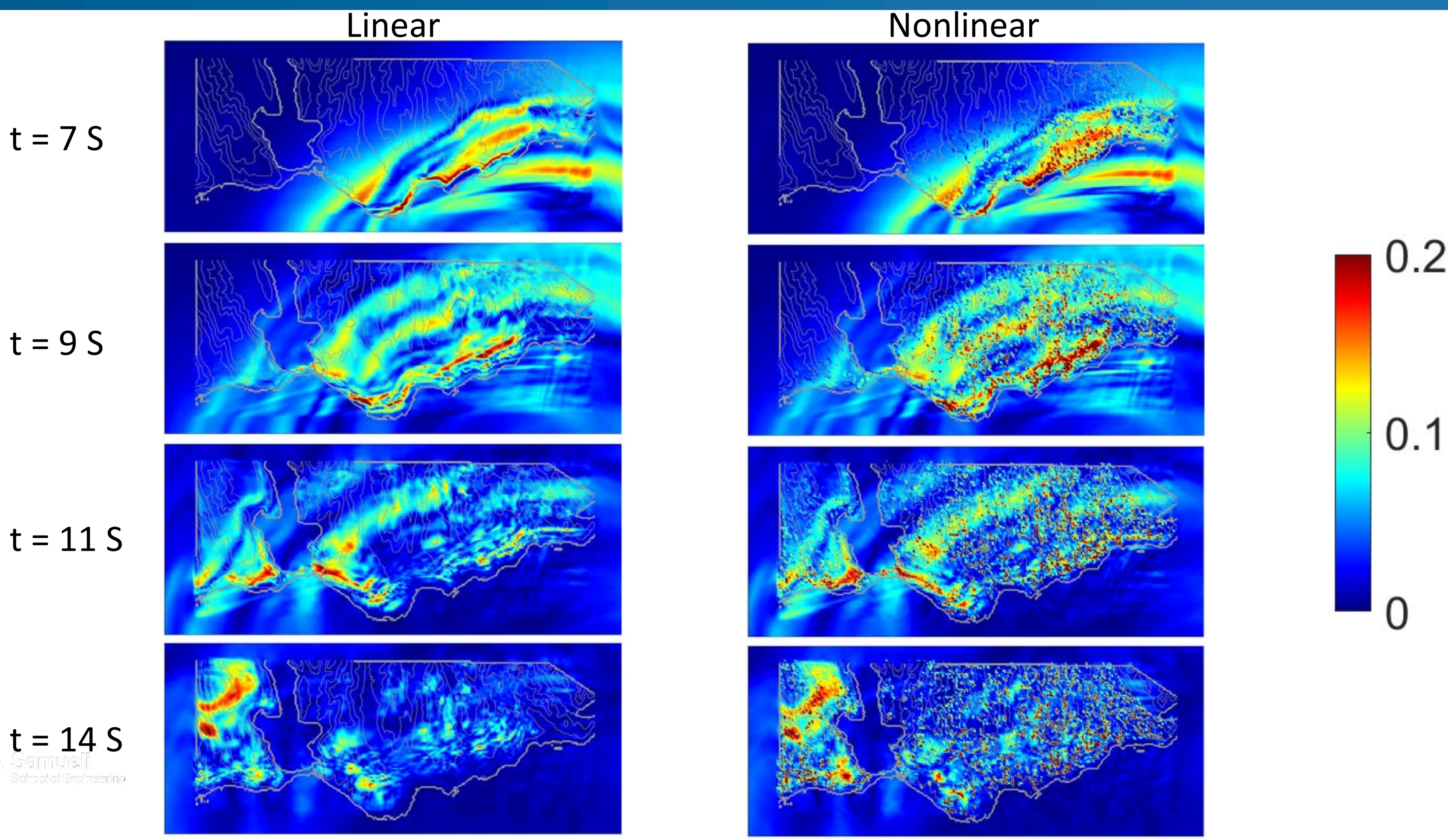
Horizontal



Vertical

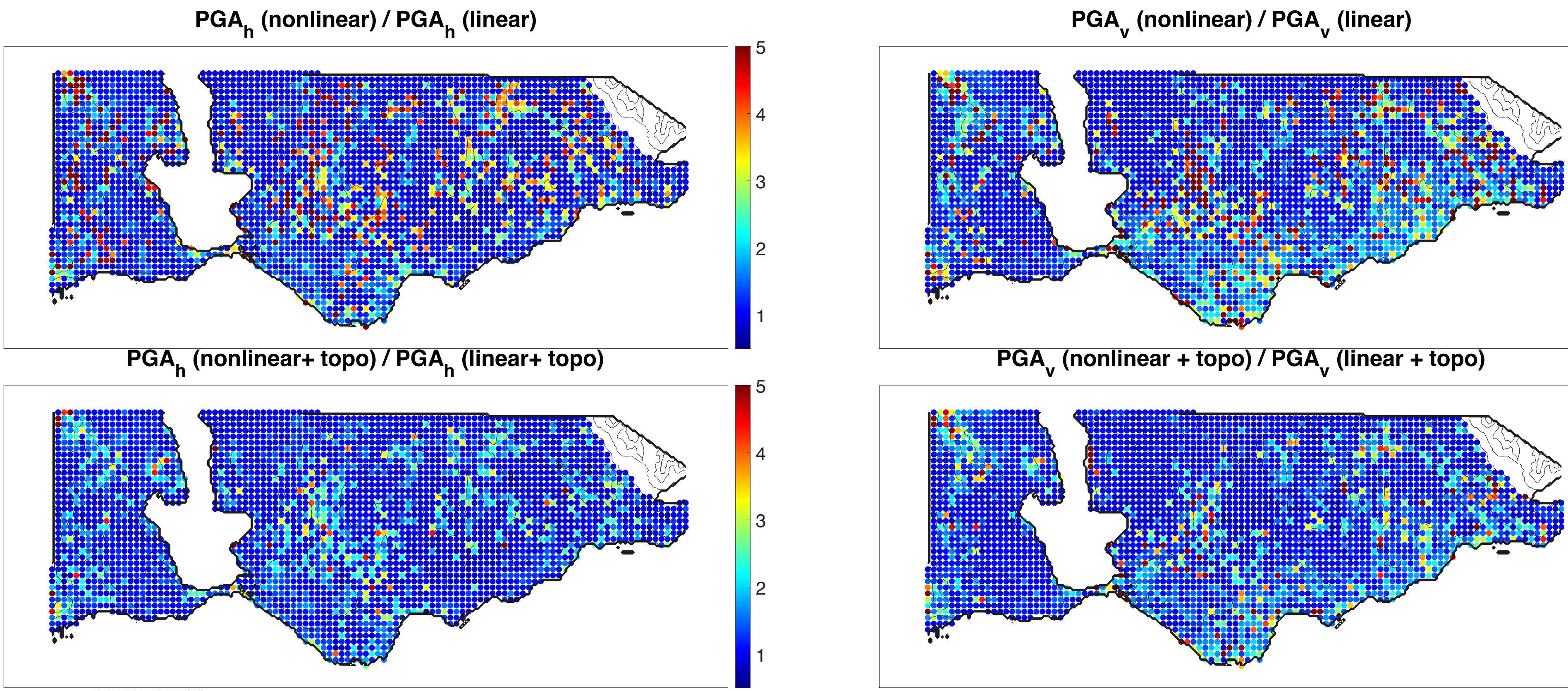


Effects of soil nonlinearity (velocity)

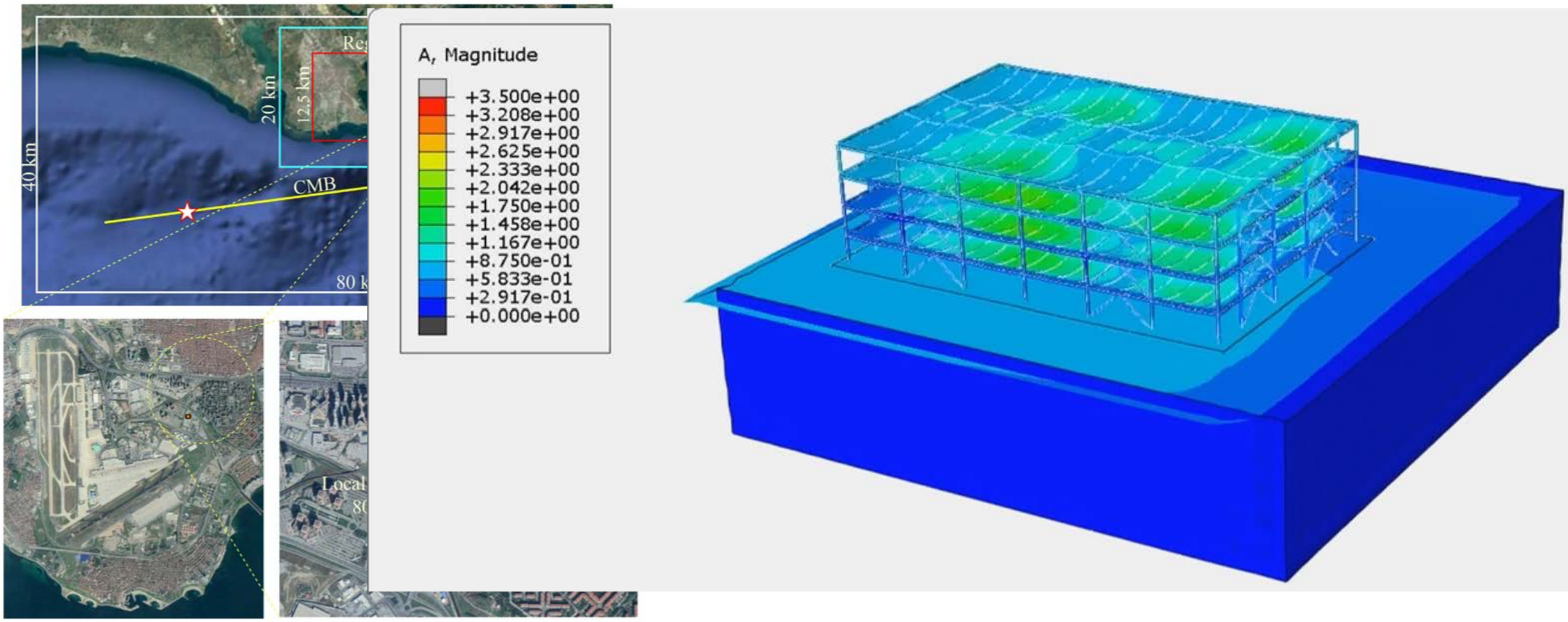


Effects of soil nonlinearity (PGA)

Horizontal | **Vertical**



Advanced SSI analyses using DRM-PML system

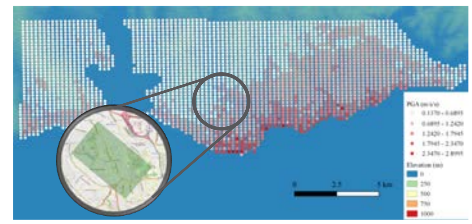


Collaborative Payload Studies

Collaborative Payload Studies

Tsinghua University (Xinzheng Lu’s Group)

- Use simulated GMs to examine/improve methods for estimating acceleration time-histories and GM intensity measures at non-instrumented locations
- Quantify seismic instrumentation requirements (spatial density, sensor quality) for rapid post-event assessment of civil infrastructure



McGill University (Yazhou Xie’s Group)

- Damage to Istanbul’s Bridges along the Trans-European Motorway

Gebze Technical University (Yasin Fahjan’s Group)

- Damage to historically significant structures (Hagia Sofia, etc.)

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thank you!

Scientific and Technological Research Council of Turkey

Istanbul Metropolitan Municipality

State Department of Transportation, Turkey

NHERI DesignSafe (Rathje et al.)

Texas Advanced Computing Center (Cockerill et al.)

Southern California Earthquake Center (Taborda et al.)

Pacific Earthquake Engineering Research Center