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Nonlinear Soil Models in Regional Seismic Simulations

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PEER LBNL GM Sim Workshop – January 18-19, 2024

UCLA Samueli School of Engineering

Nonlinear Soil Models in Regional Seismic Simulations

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Clifford Yen, UCLA

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Outline

- the big picture
- a good model among many
    - some background
    - some formulation
    - verification & validation
- results form ongoing work
    - rupture to rafters in Istanbul
    - linear versus not

Big Picture

Why regional assessment?

- Hazards affect regions. The big picture is needed for
  - Actuarial plans (insurance companies)
  - Urban planning & public policy (government)
  - Emergency service planning (1st responders)

- Built environment is highly interconnected
  - Transportation networks
  - Lifelines (water, power, communications)
  - *even buildings*

Challenges

- Data ☞ metadata ☞ models
  - Diverse sample population (requires sophisticated data harvesting tools)
  - Access to detailed data may be not be possible (requires estimation missing data, machine learning)
  - Processing requires *large* computational resources (would break records for civil engineers)
- Models ☞ decision variables
  - Heterogeneous analysis tools need to be stitched in
    - {OpenSHA, SW4, Hercules}, OpenSees, R2D, PACT
  - New tech needs to be brought in (data analytics, Bayesian inference, etc.)

Objectives

Zeytinburnu District, Istanbul (Zhang et al. 2022)

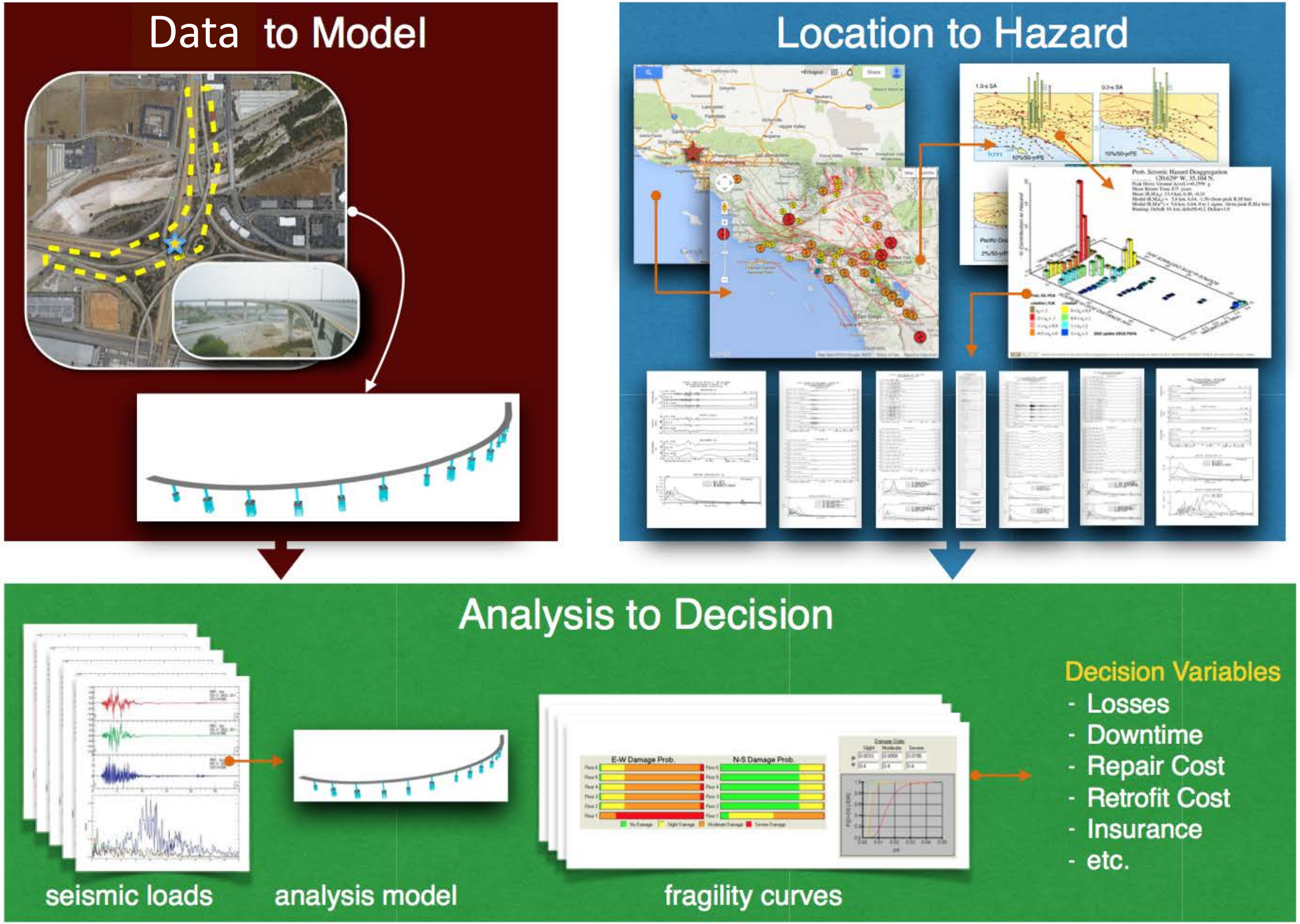
Develop (semi-) automated interactive platforms that can evaluate the hazard vulnerability of complex networks:

1. Generate predictive analysis models for civil infrastructure inventories using data harvested from various sources
2. Carry out site- and structure-specific {*seismic*, *wind*, *fire*} analyses
3. Evaluate the consequent economic losses at the network-level

Objectives

Zeytinburnu District, Istanbul (Zhang et al. 2022)

Existing predictive computational tools and IT capabilities allow unprecedented granularity for such seismic risk and loss assessment studies



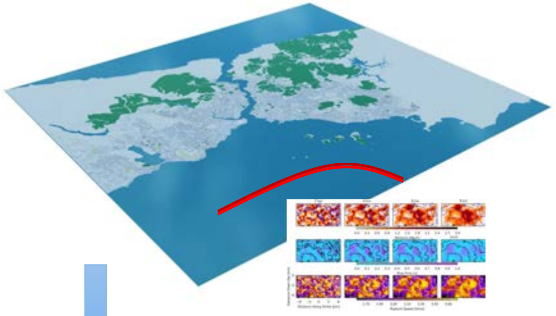
Data to Model
Location to Hazard
Analysis to Decision
seismic loads
analysis model
fragility curves
Decision Variables
- Losses
- Downtime
- Repair Cost
- Retrofit Cost
- Insurance
- etc.

rupture to rafters

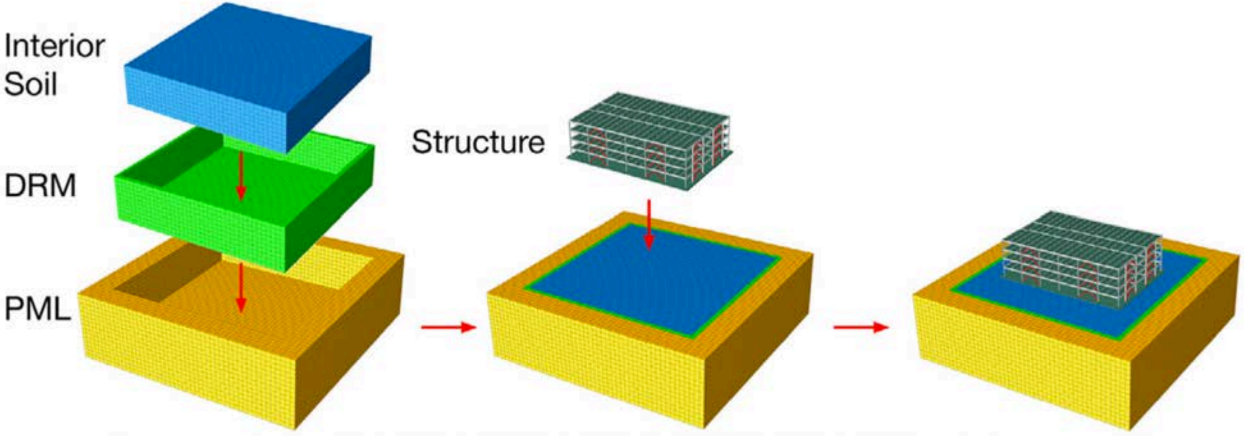
regional physics-based seismic simulations

Our Workflow

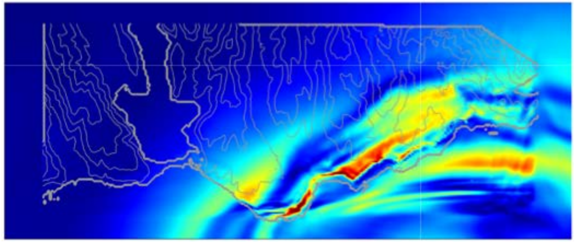
Regional-scale domain



Local analyses of critical infrastructure (ABAQUS, OpenSees)



Physics-based GM Sim (Hercules by Bielak & Co.)



Infrastructure inventories

Physics-based large-scale ground motion simulation

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

Model parameter	Linear	Linear + topography	Nonlinear	Nonlinear + topography
(Hz)	16.4	16.4	8.2	8.2
(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 (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

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

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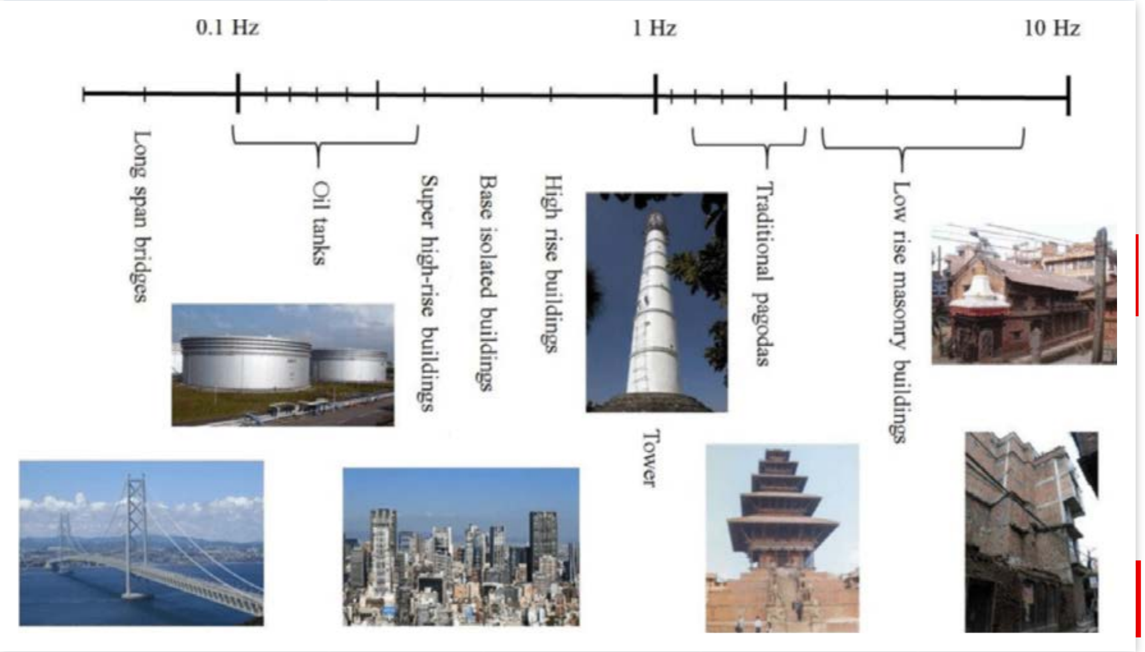

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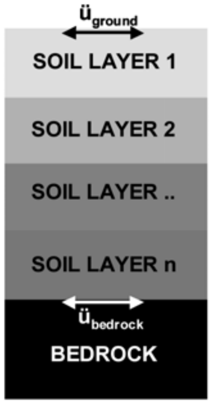
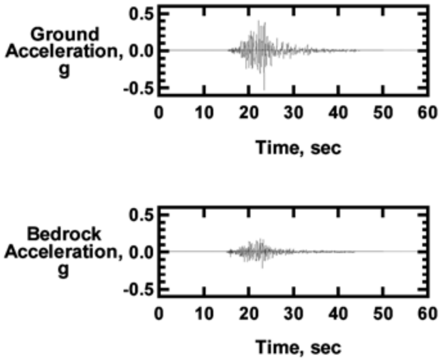
Nonlinear Behavior of Soils

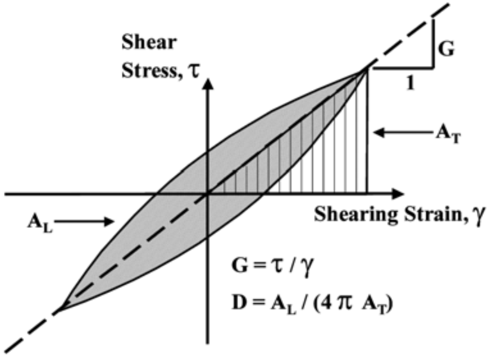
confined deep soils

Deep Soils

- High confinement
- Strains < %3
- Minimal permanent deformations (*except perhaps deep-layer liquefaction events*)
- Highly hysteretic
- Nonlinear backbone (strain-dependent moduli)







Hardin BO, DrnevichVP (1972). Shear modulus and damping in soils: design equations and curves. *ASCE J. Soil Mech. Found. Eng. Div.*, 98,667–692.
Seed HB, Idriss IM. Soil moduli and damping factors for dynamic analyses. EERC Report No. 10-10, University of California, Berkeley, CA, 1970.

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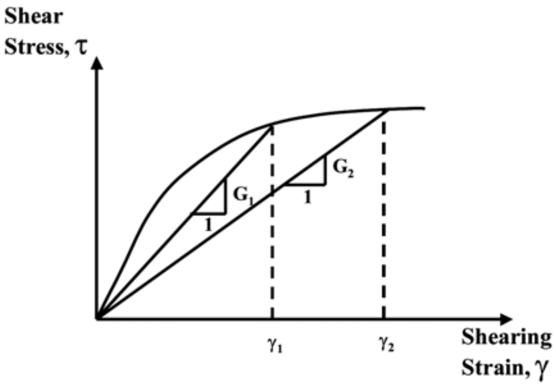

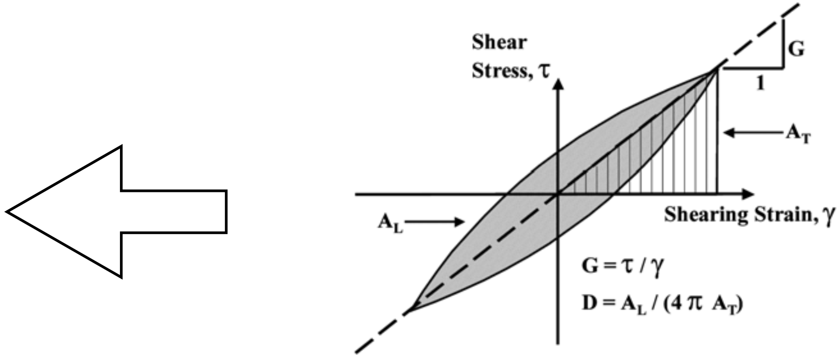

Darendeli MB (2001).Development of a new family of normalized modulus reduction and damping curves. PhD Dissertation, UT Austin.

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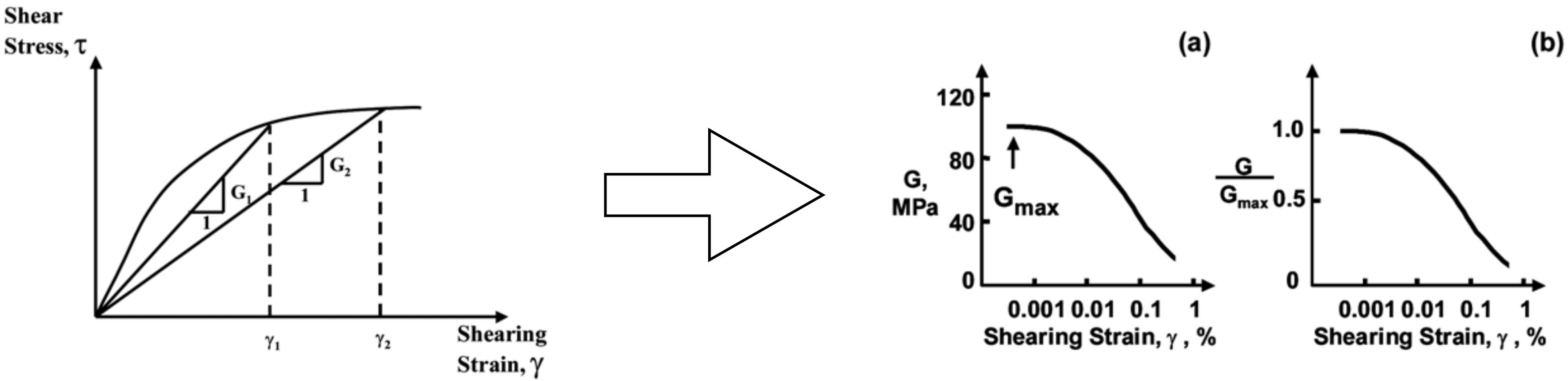

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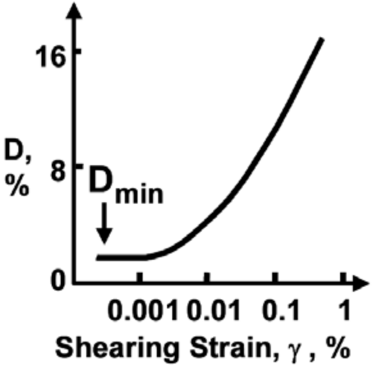

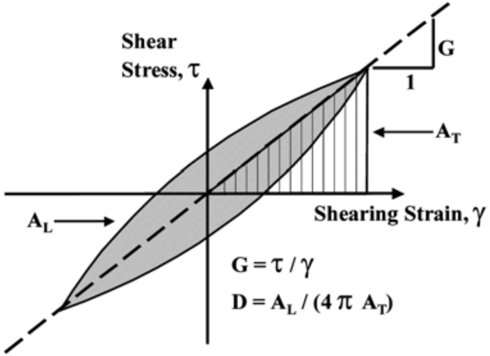

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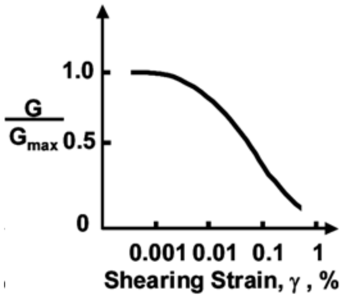

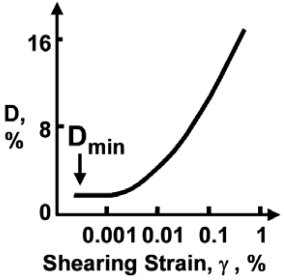

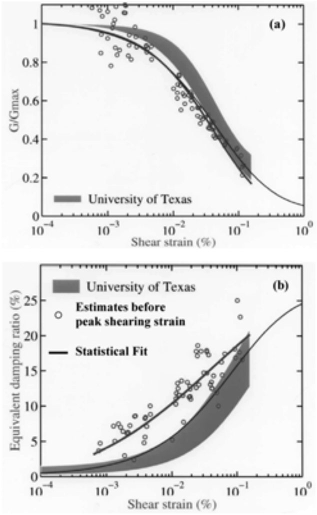

ROSRINE (Resolution of Site Response Issues from the Northridge Earthquake) Project

Darendeli MB (2001).Development of a new family of normalized modulus reduction and damping curves. PhD Dissertation, UT Austin.

Deep Soils

- Many nonlinear soil models offered
  - equivalent linear models (1D site response)
  - one-dimensional phenomenological nonlinear models (1D site response)
  - multi-surface plasticity models (pressure-dependent, larger strains, near surface)
  - minimalist multiaxial plasticity models (G/G_{max}, damping)

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Borja et al. (2000). Modelling non-linear ground response of nonliquefiable soils. *Eq. Eng. Struct. Dyn.*, 29, 63-83.

Lotung Large Scale Seismic Test

Tang HT, Tang YK, Stepp JC (1990). Lotung large-scale seismic experiment and soil-structure interaction method validation. *Nuclear Engrg. and Des.*, 123, 197–412.

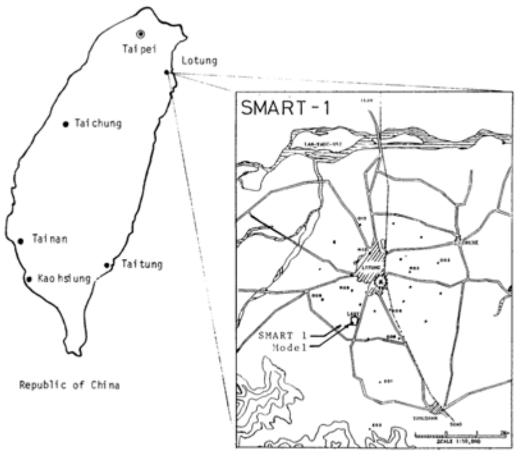

Fig. 1. Test site location.

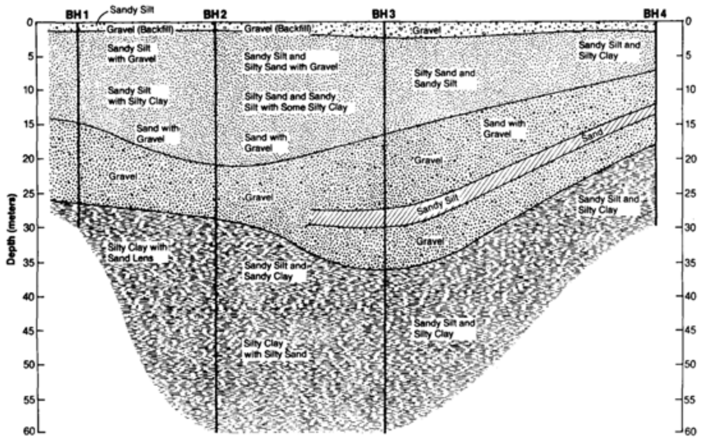

Fig. 2. Local geological profiles at test site.

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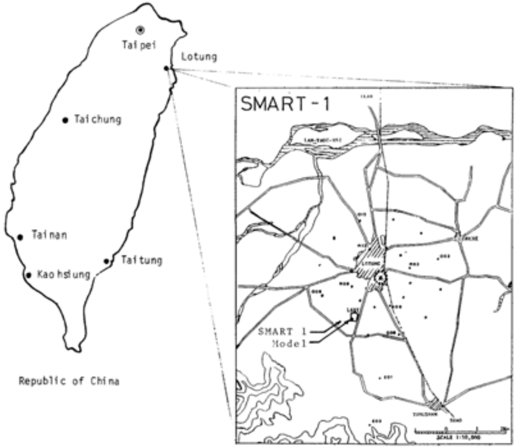

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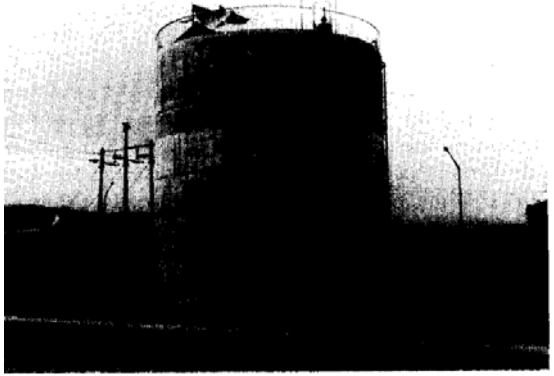


Fig. 4. The completed 1/4-scale model.

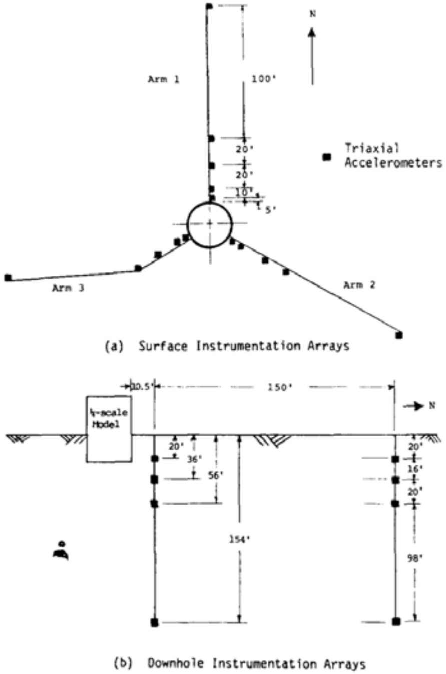
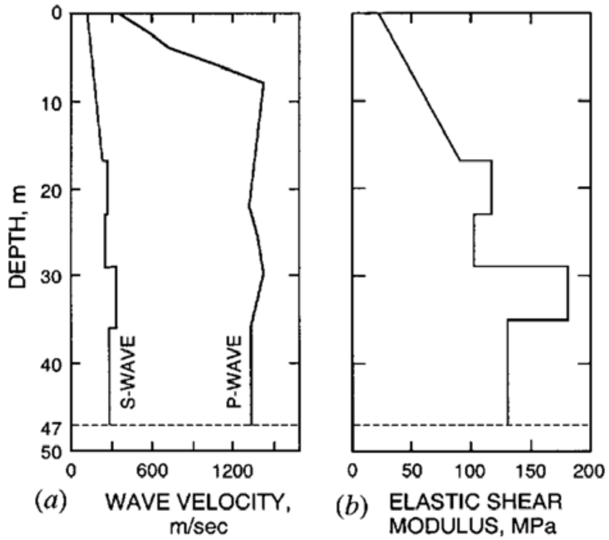
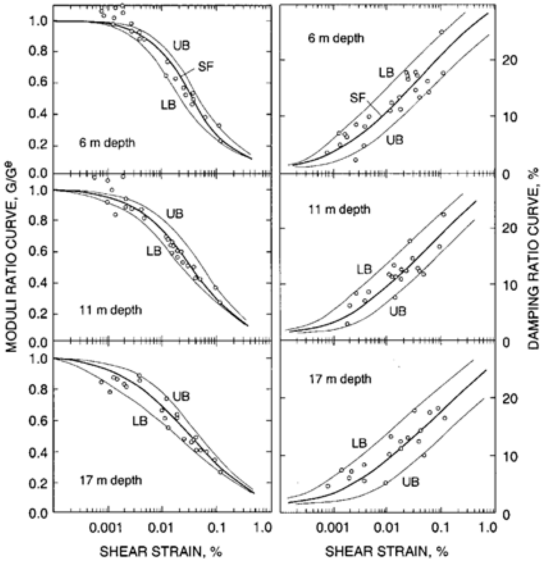


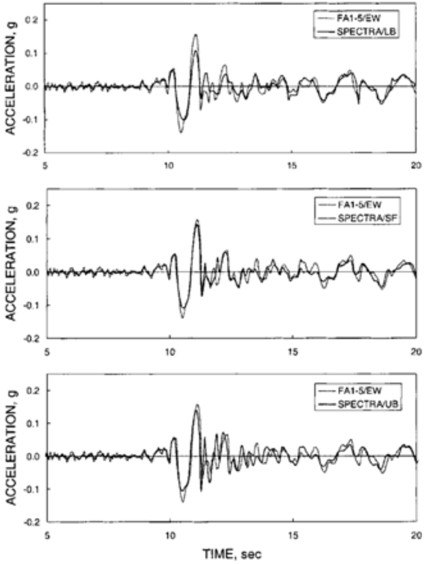
Fig. 5. Location of free-field instrumentations: (a) surface instrumentation arrays, (b) downhole instrumentation arrays.

Borja-Amies multi-axial nonlinear soil model

Borja et al. (2000). Modelling non-linear ground response of nonliquefiable soils. Eq. Eng. Struct. Dyn., 29, 63-83.

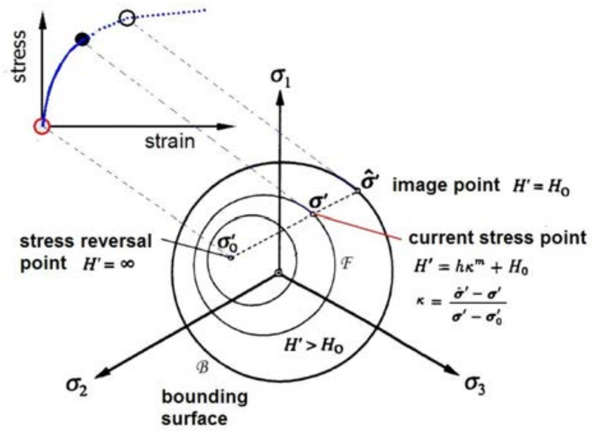






Borja-Amies multi-axial nonlinear soil model

Model	Category	Scope	Viscous effects	Number of parameters
Borja-Amies nonlinear soil model (Borja and Amies, 1994)	Elastic-plastic model with vanished elastic region	3D	Yes	4 (frictional only) 6 (frictional and viscous)



J₂ bounding surface plasticity
(Wang et al., 2006)

$$\sigma = \sigma^f + \sigma^v$$

$$B = s_{ij}^b s_{ij}^b - R^2 = 0$$

$$H' = h\kappa^m + H_0$$

$$\sigma_{ij}^v = D_{ijhk}^v \dot{\epsilon}_{hk}$$

$$D_{ijhk}^v = a_1 D_{ijhk}^e$$

$$a_1 = \frac{2\zeta_0}{\omega}$$

- 1D nonlinear site response analyses (Borja et al., 1999, 2000; Rodriguez-Marek, 2000)
- 2D numerical analysis of drilled piers (Wang et al., 2006)

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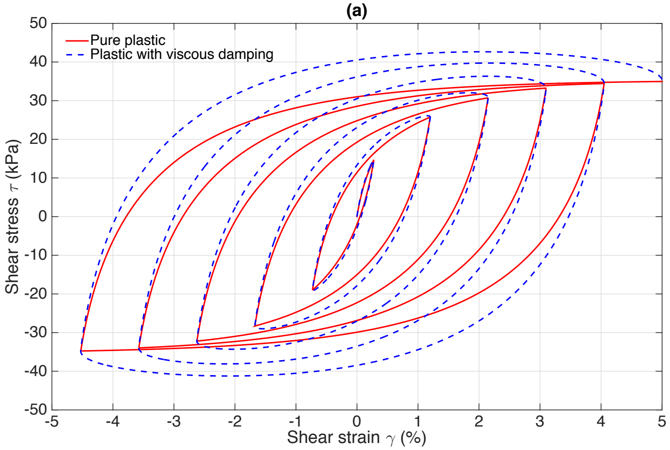
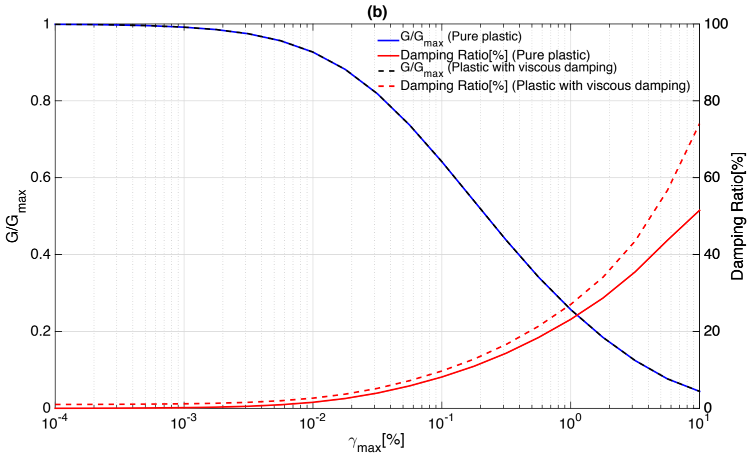


(a) hysteresis curve



(b) stiffness reduction and damping ratio curves.

Borja-Amies multi-axial nonlinear soil model

Model		…ous …cts	Number of parameters
Borja-Amies nonlinear soil model (Borja and Amies, 1994)	F…	…es	4 (frictional only) 6 (frictional and viscous)

```
&            sse, spd, scd, 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
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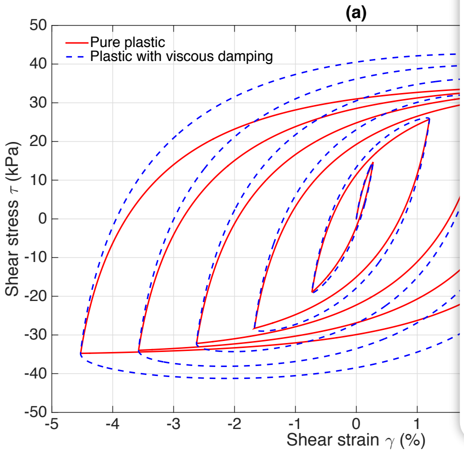

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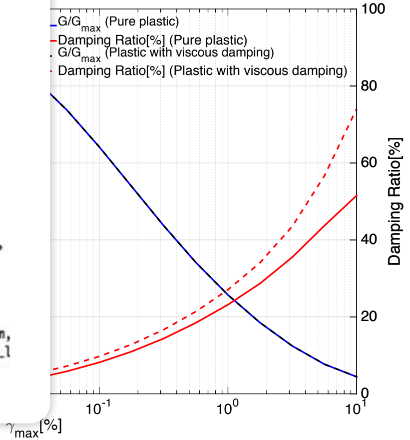
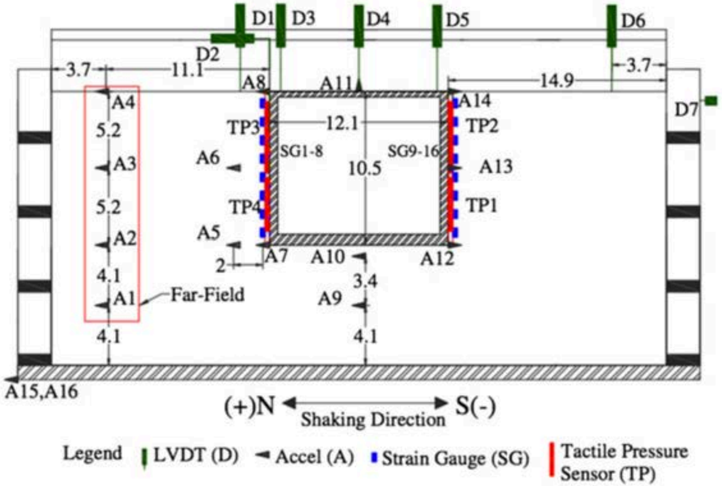


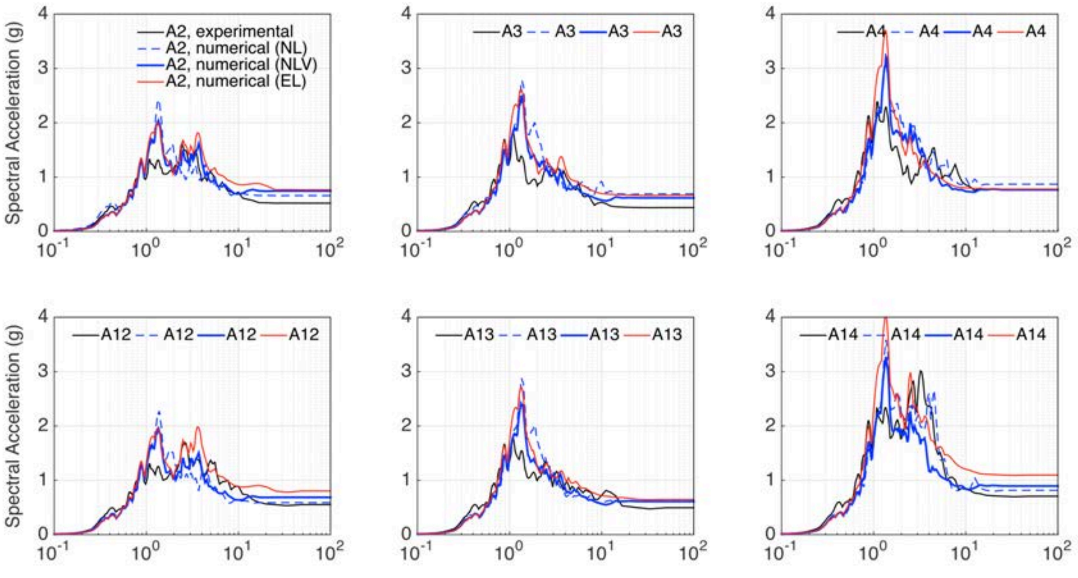
(b) stiffness reduction and damping ratio curves.

Validation of the Borja-Amies model

Centrifuge data by Hushmand et al. (2016) @CU Boulder



Free-field accelerations



(C) T-Flexible-AH

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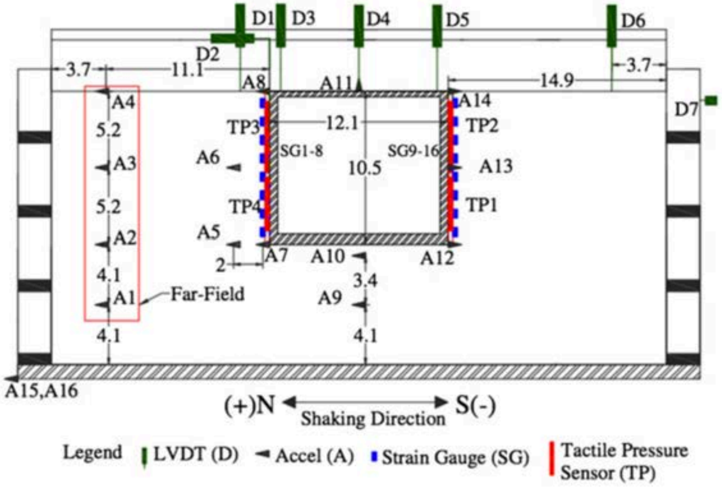
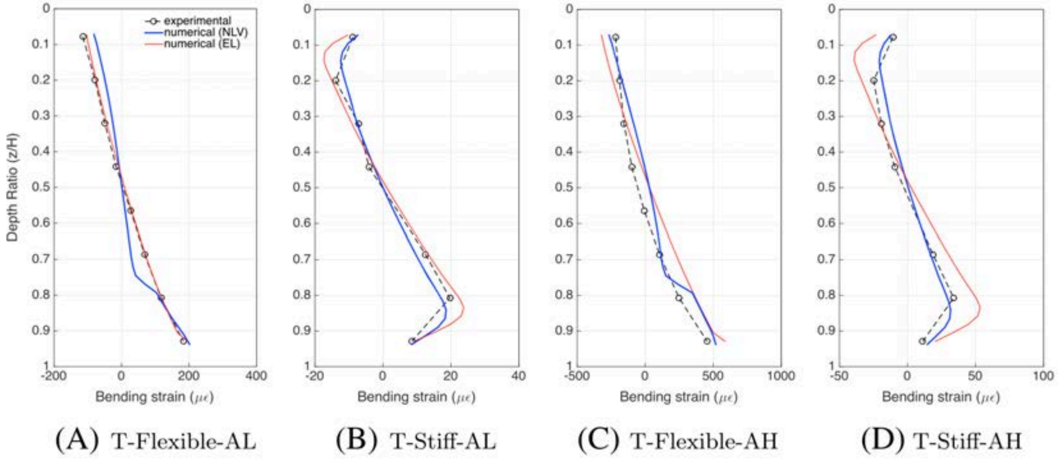


Bending Strains on Specimen



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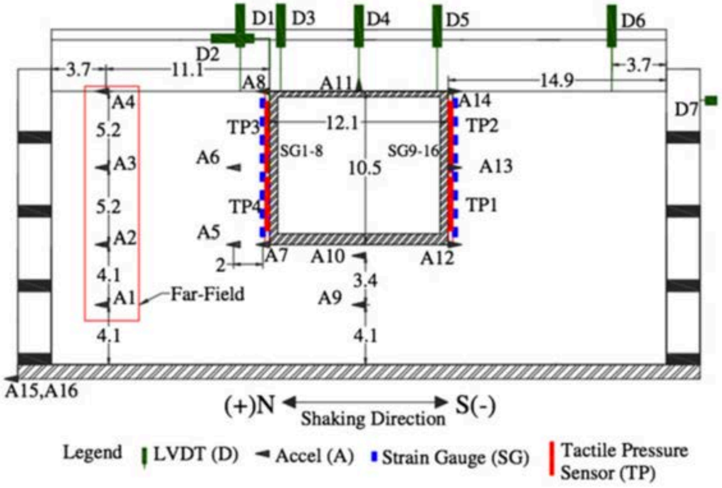
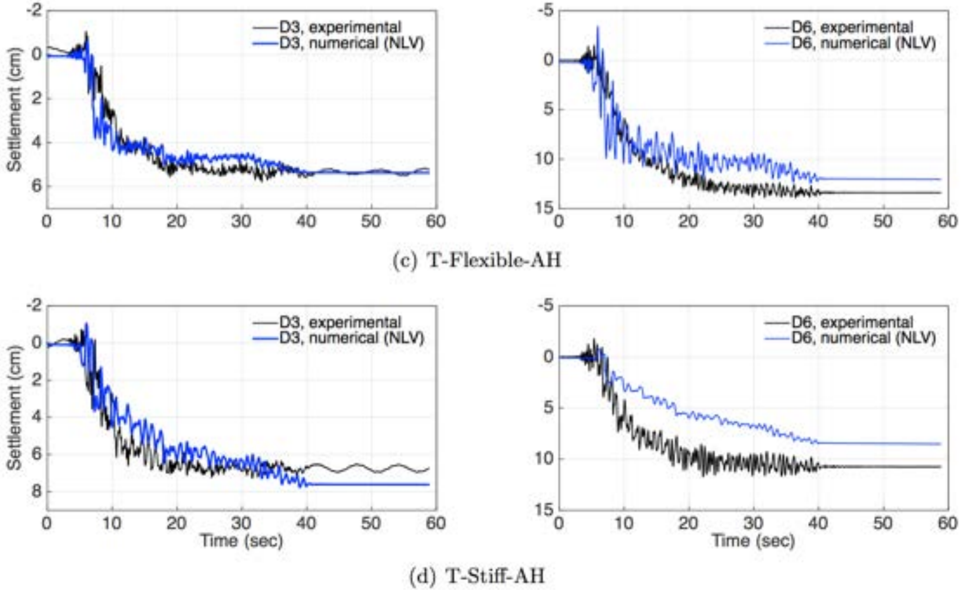


Surface settlements



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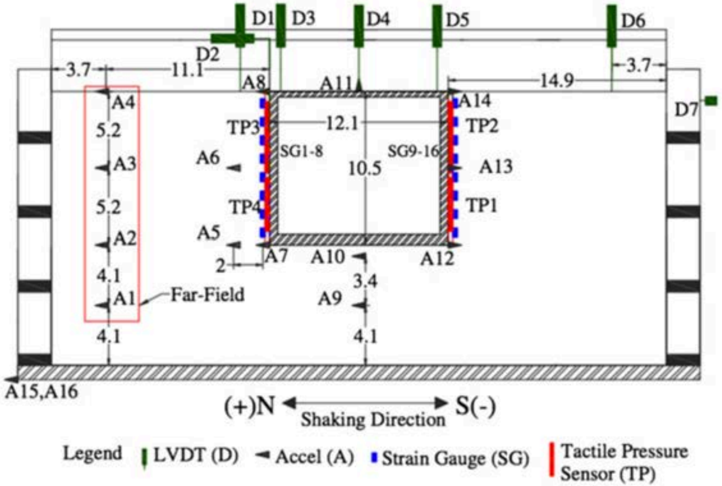

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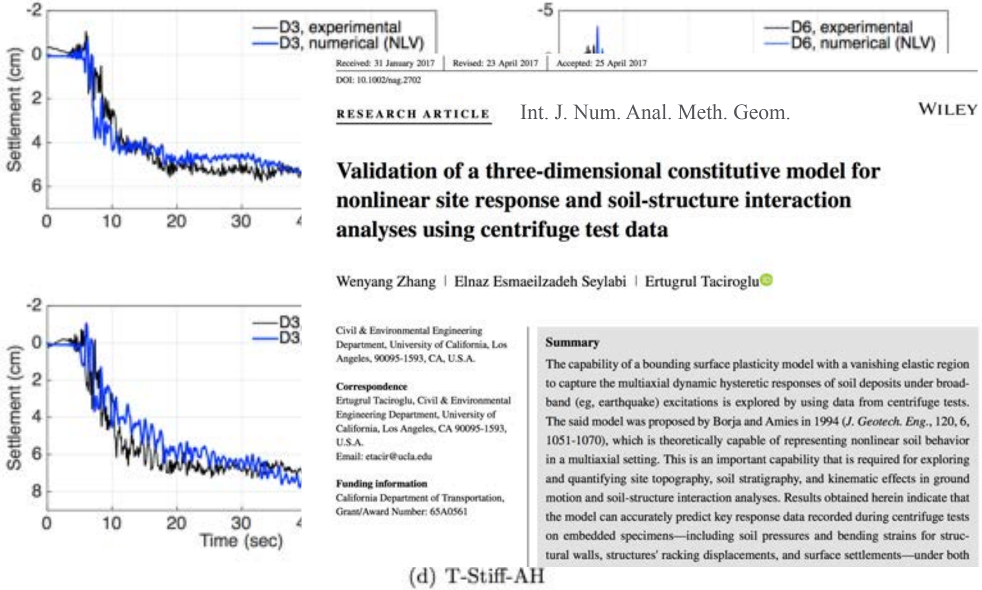

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Validation of a three-dimensional constitutive model for nonlinear site response and soil-structure interaction analyses using centrifuge test data

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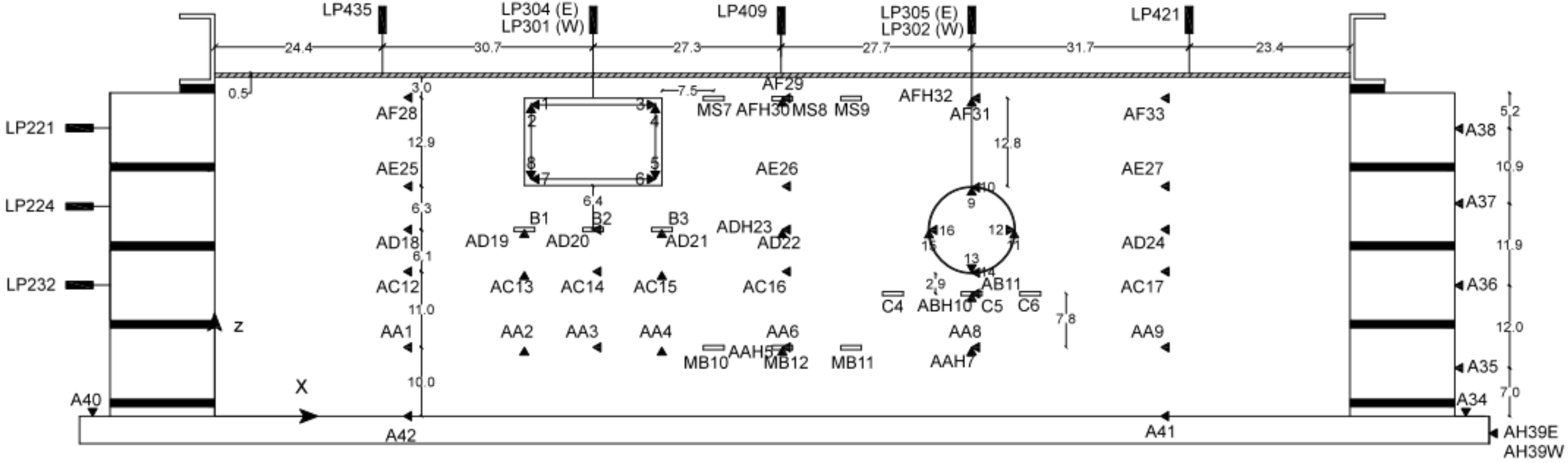
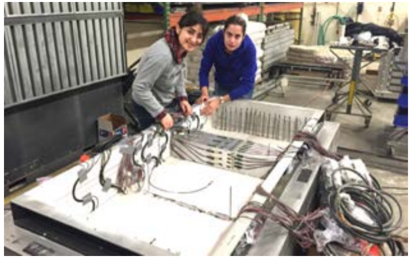
California Department of Transportation, Grant/Award Number: 65A0561

Summary
The capability of a bounding surface plasticity model with a vanishing elastic region to capture the multiaxial dynamic hysteretic responses of soil deposits under broad-band (eg, earthquake) excitations is explored by using data from centrifuge tests. The said model was proposed by Borja and Amies in 1994 (*J. Geotech. Eng.*, 120, 6, 1051-1070), which is theoretically capable of representing nonlinear soil behavior in a multiaxial setting. This is an important capability that is required for exploring site topography, soil stratigraphy, and kinematic effects in ground motion and soil-structure interaction analyses. Results obtained herein indicate that the model can accurately predict key response data recorded during centrifuge tests on embedded specimens—including soil pressures and bending strains for structural walls, structures' racking displacements, and surface settlements—under both

Centrifuge experiments @ UC Davis (Seylabi et al., 2018)



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



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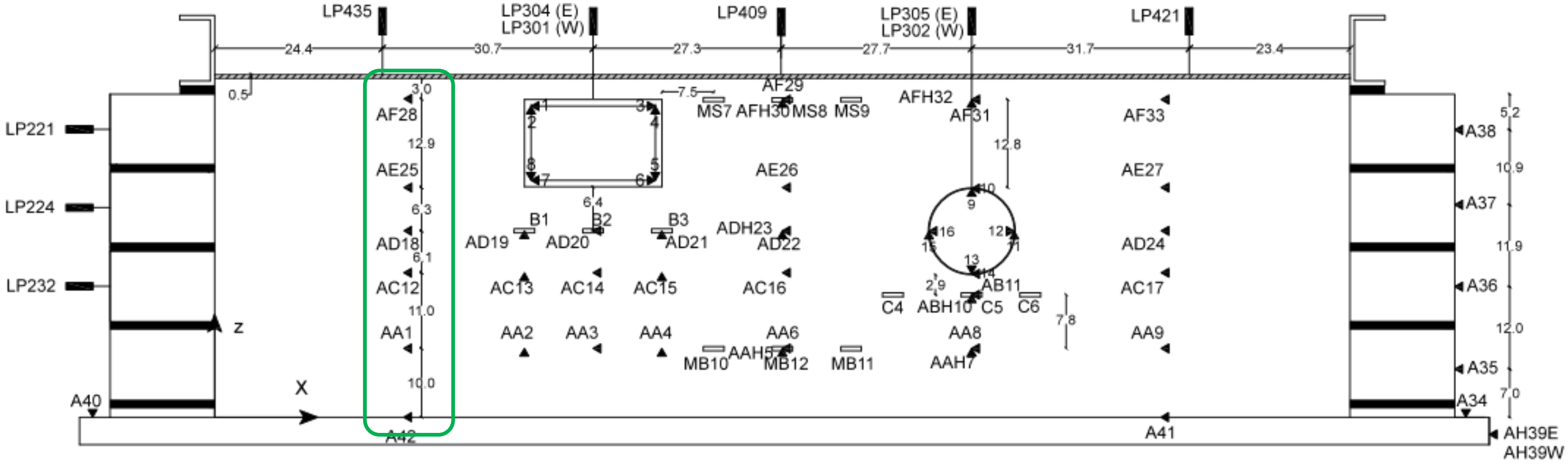
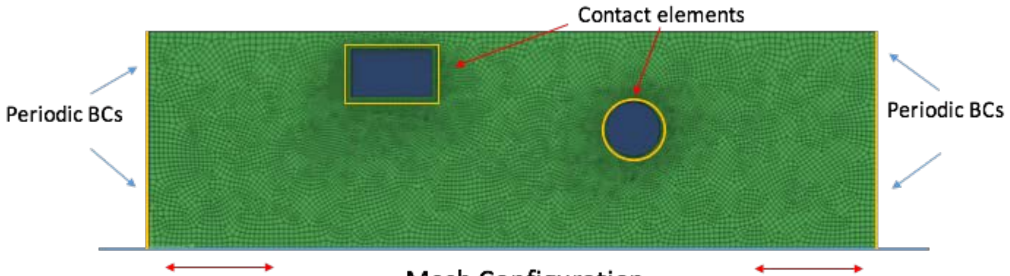
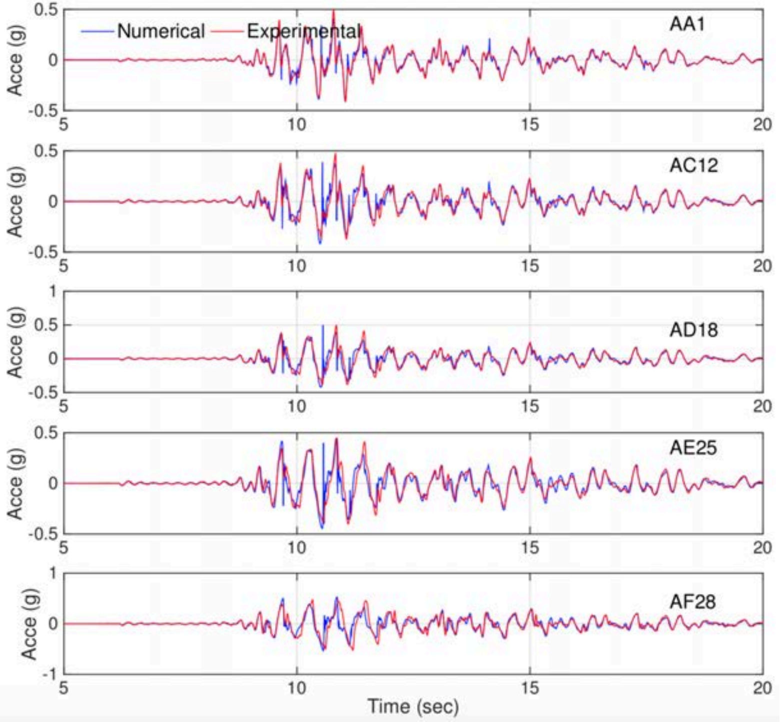




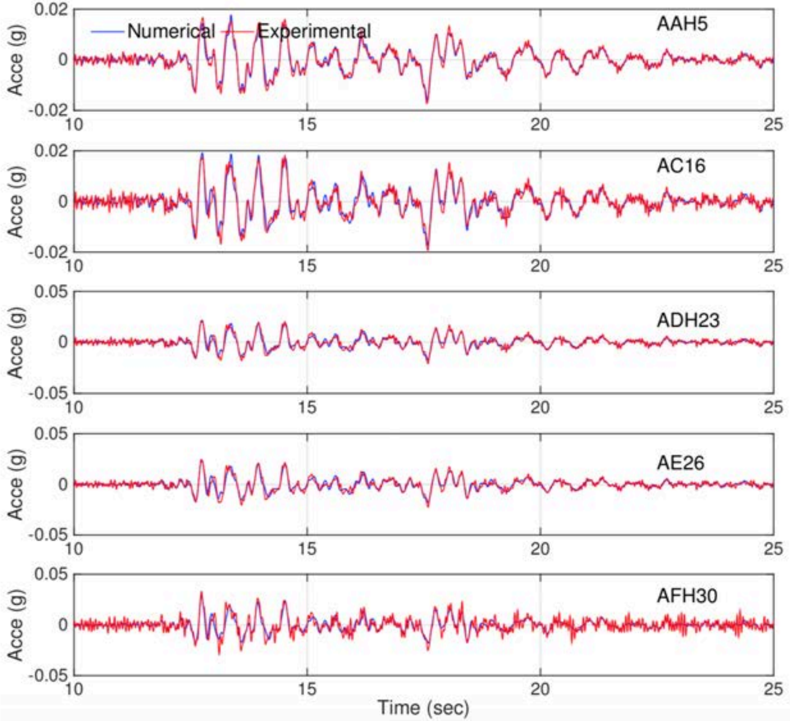
Mesh Configuration

Horizontal accelerations (soil)

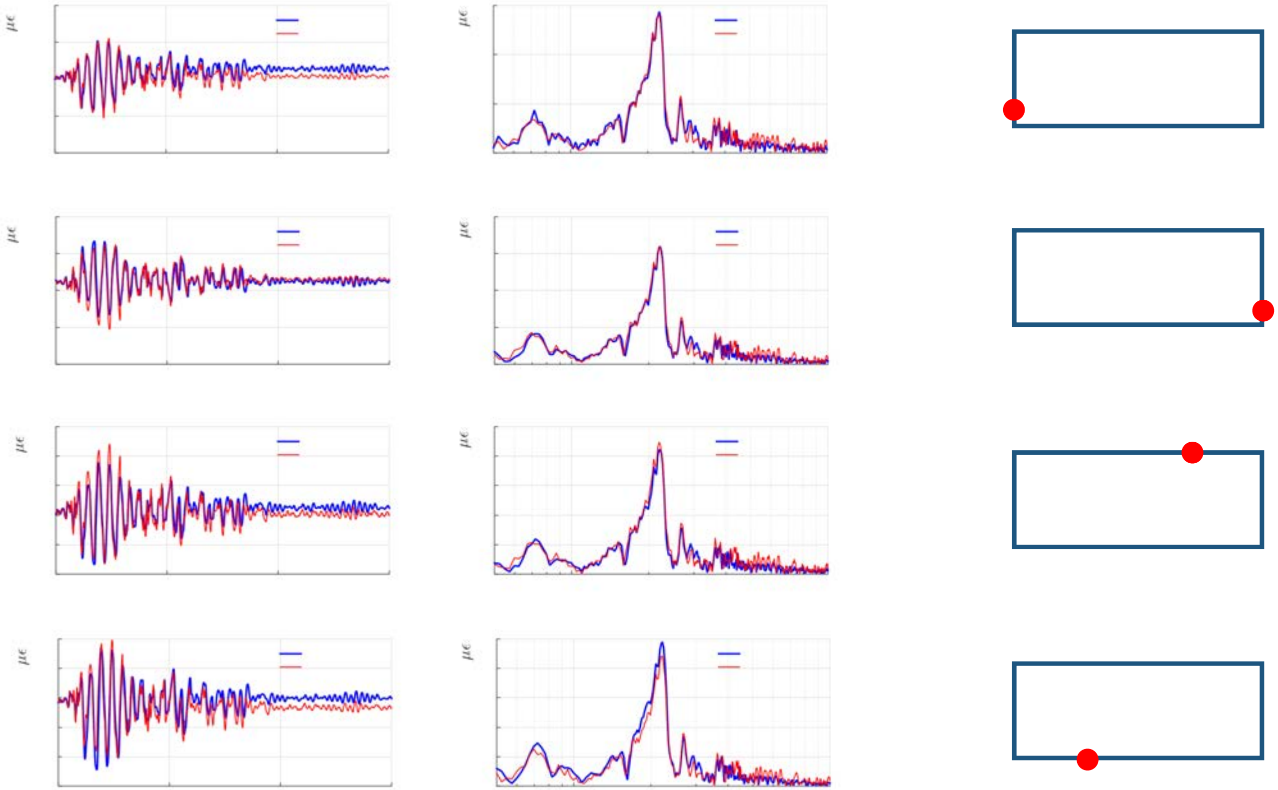
Motion #09 (left array)



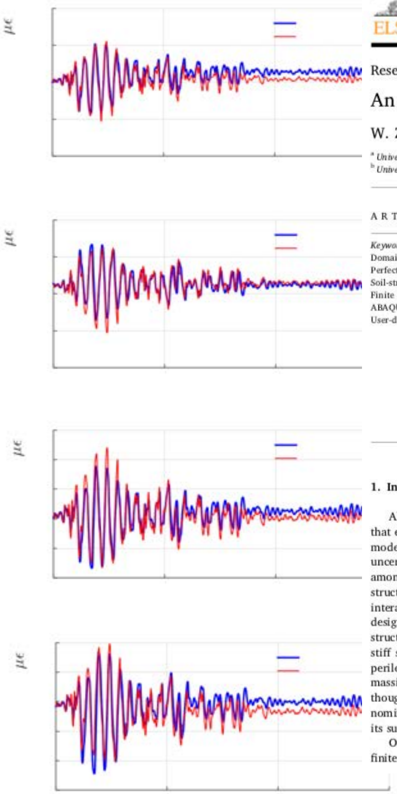
Motion #03 (middle array)



Bending strain (rectangular structure motion #09)



Bending strain (rectangular structure motion #09)



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journal homepage: www.elsevier.com/locate/compgeo

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Research Paper

An ABAQUS toolbox for soil-structure interaction analysis

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Domain Reduction Method
Perfectly-Matched-Layer
Soil-structure interaction
Finite element method
ABAQUS
User-defined element (UEL)

ABSTRACT

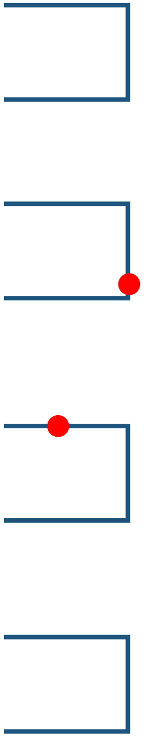
It is well established that the soil-structure interaction (SSI) effects can bear important consequences under strong earthquakes, and their accurate quantification can become a critical issue in designing earthquake-resistant structures. In general, SSI analyses are carried out by means of either direct 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).

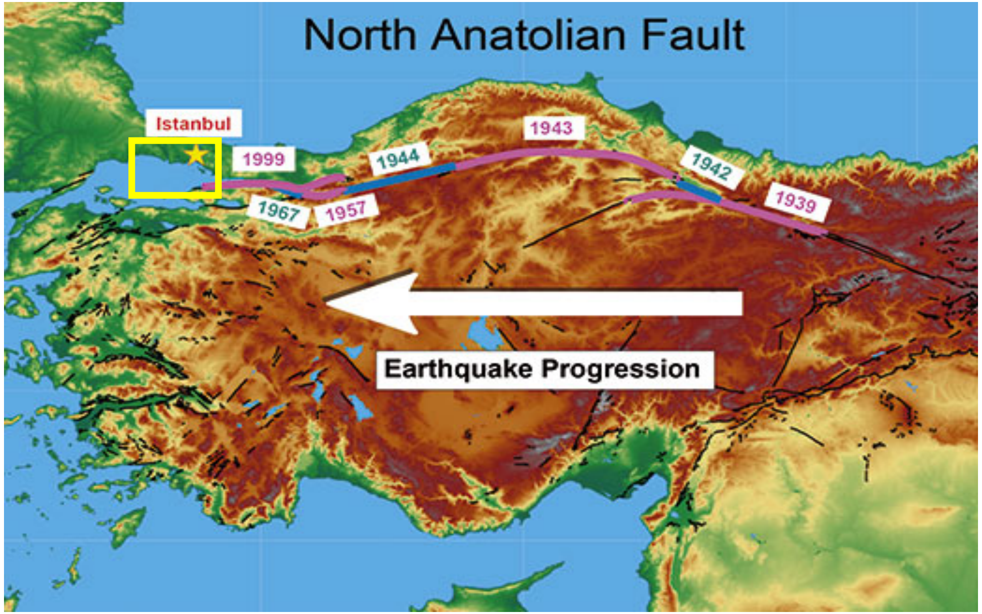
Lysmer and Kuhlemeyer [4] proposed the first local ABC,[1] which could only absorb waves traveling along a prescribed direction. Higdon [7] proposed the m-th order multi-directional boundary condition that can absorb traveling waves with m different angles of incidence perfectly. Although the accuracy 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



UCLA

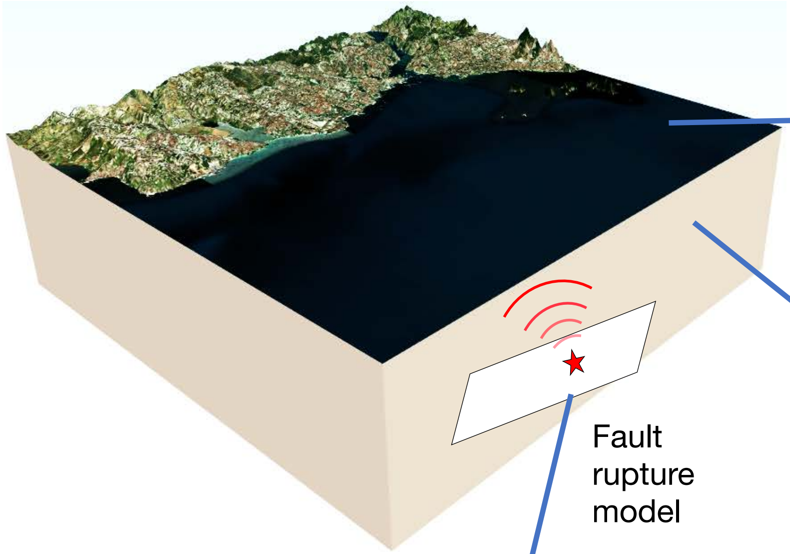
Application to Istanbul

Overview

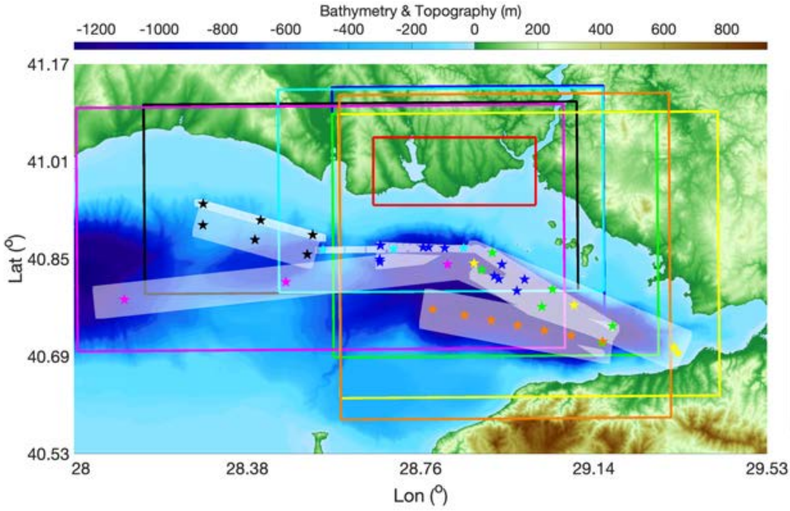


- Not enough historical earthquake data is available for the city of Istanbul
- Large-scale physics-based 3D earthquake ground motion simulations are performed for the south European side of Istanbul
- Regional-scale seismic loss assessment of buildings and infrastructure systems are being performed

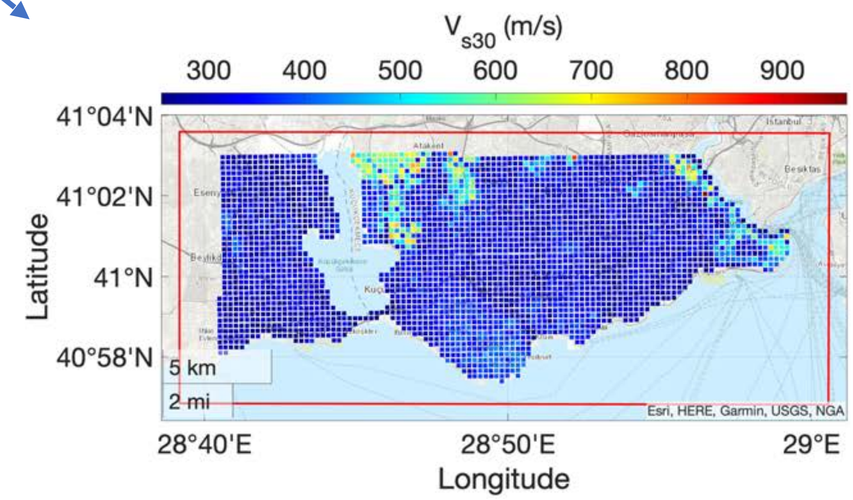
PhyGMS: an Application to Istanbul



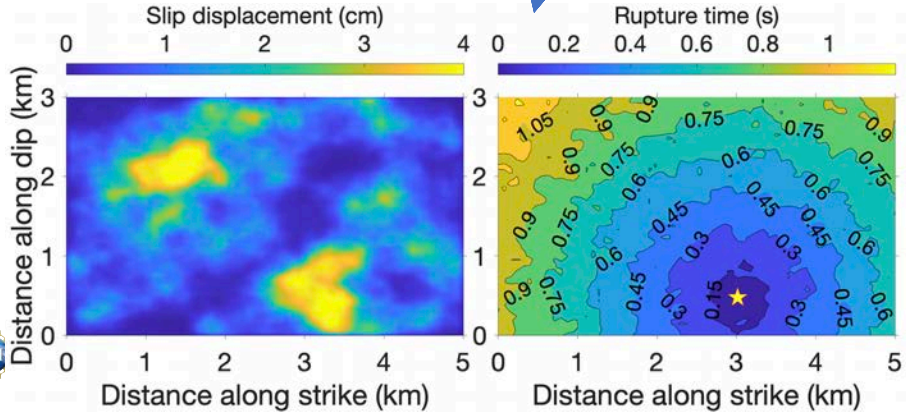
Topography & bathymetry



V_{s30} profile

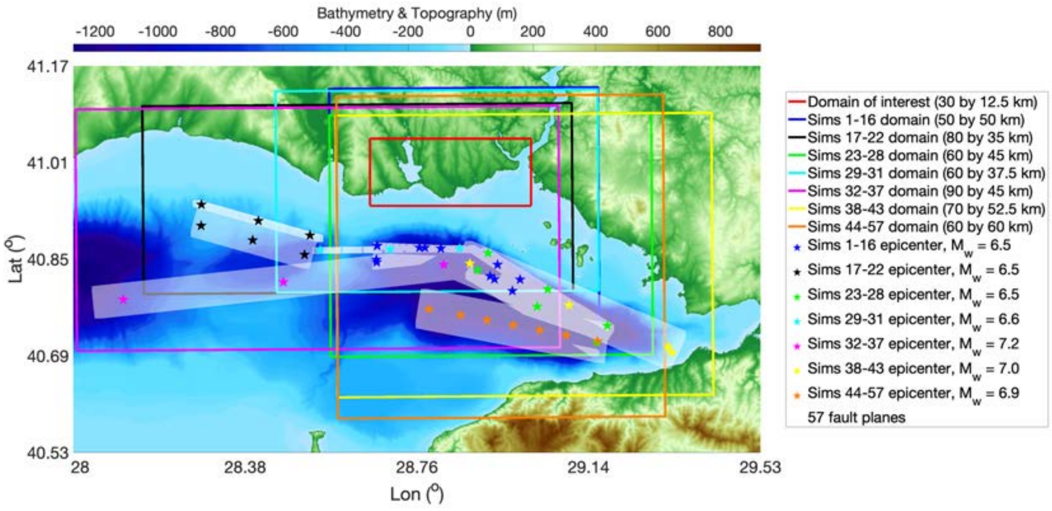


Fault rupture model



2,912 instrumented borehole arrays!

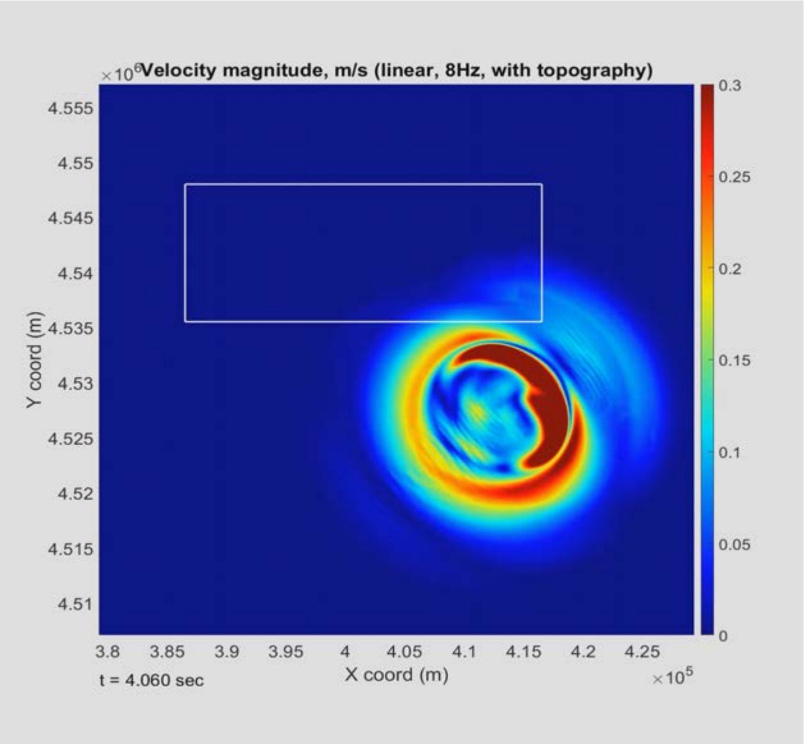
57 broadband **(8~12 Hz)** physics-based GMS



Simulation	Dimensions: L×W×H (km)	Number of compute nodes	Number of finite element nodes (×10⁹)	Minimum element size (m)	Average wall clock time (h)
1 - 16	50 × 50 × 18.75	400	7.39	3.05	4.43
17 - 22	80 × 35 × 20	400	14.36	2.44	8.60
23 - 28	60 × 45 × 22.5	400	16.15	1.83	9.63
29 - 31	60 × 37.5 × 18.75	500	23.78	1.83	18.33
32 - 37	90 × 45 × 22.5	400	15.33	2.74	9.20
38 - 43	70 × 52.5 × 21.875	500	28.52	2.14	22.73
44 - 57	60 × 60 × 18.75	400	20.88	1.83	14.96

All simulations are performed using Hercules on Frontera

Horizontal velocity magnitude



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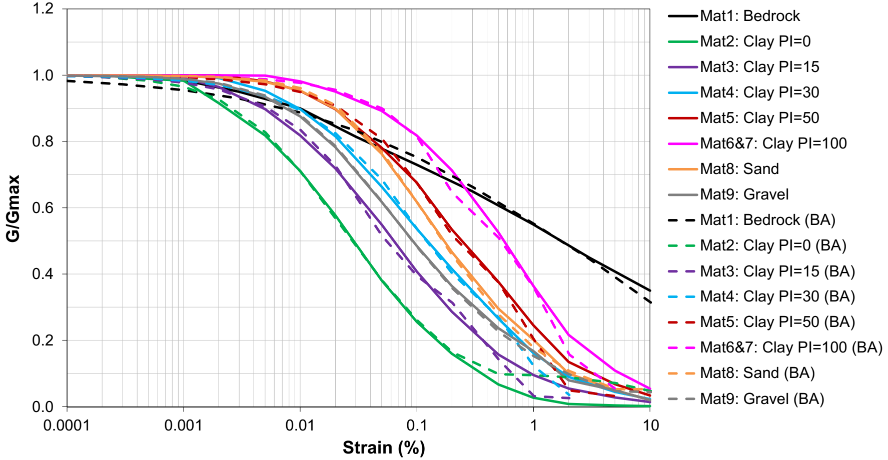
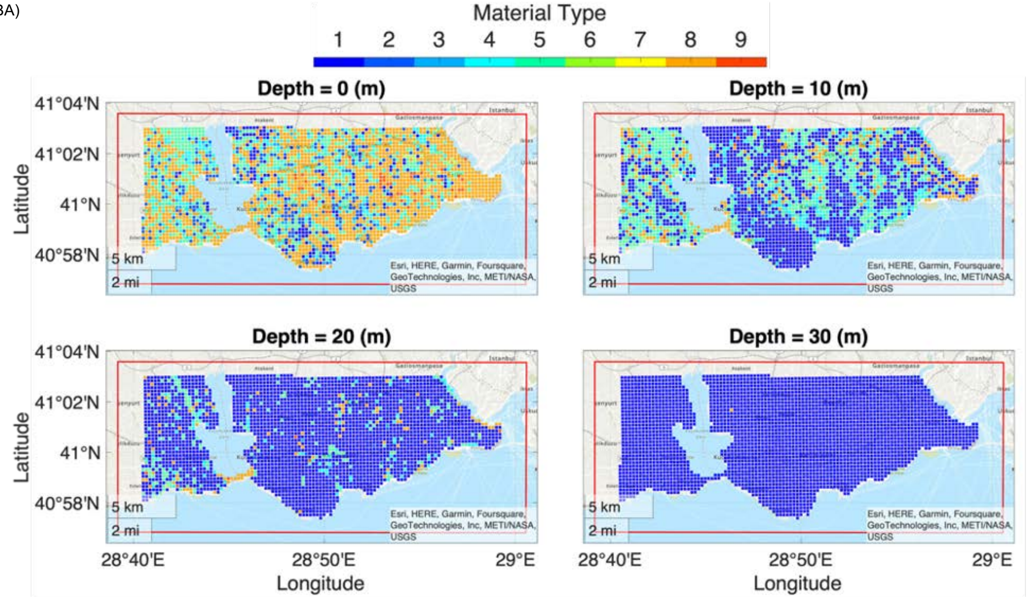
Soils



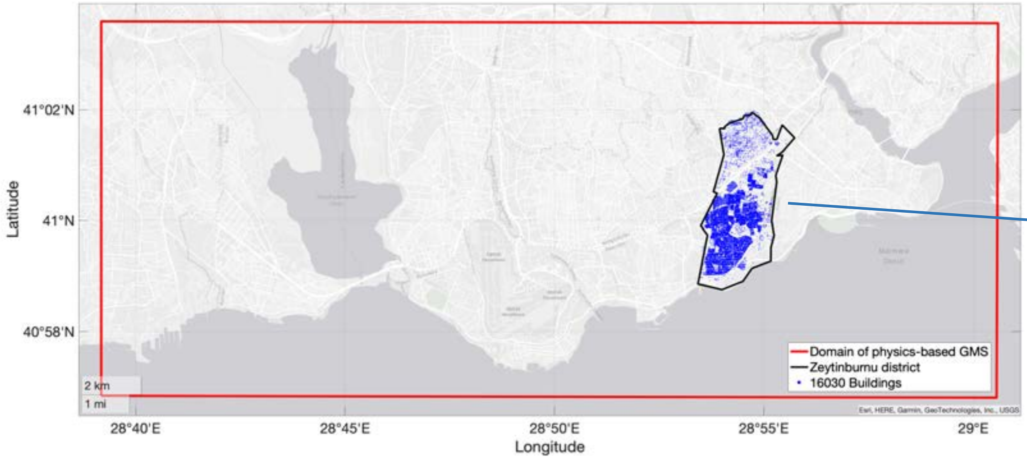
G/Gmax
Strain (%)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0001
0.001
0.01
0.1
1
10
Mat1: Bedrock
Mat2: Clay PI=0
Mat3: Clay PI=15
Mat4: Clay PI=30
Mat5: Clay PI=50
Mat6&7: Clay PI=100
Mat8: Sand
Mat9: Gravel
Mat1: Bedrock (BA)
Mat2: Clay PI=0 (BA)
Mat3: Clay PI=15 (BA)
Mat4: Clay PI=30 (BA)
Mat5: Clay PI=50 (BA)
Mat6&7: Clay PI=100 (BA)
Mat8: Sand (BA)
Mat9: Gravel (BA)

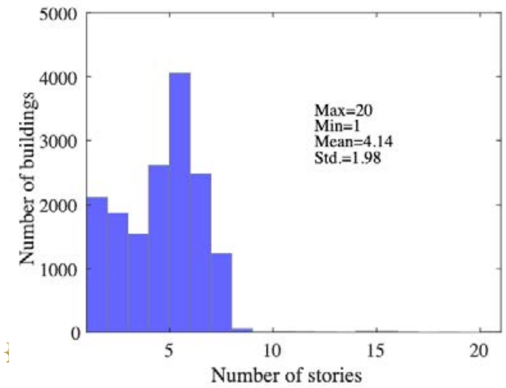


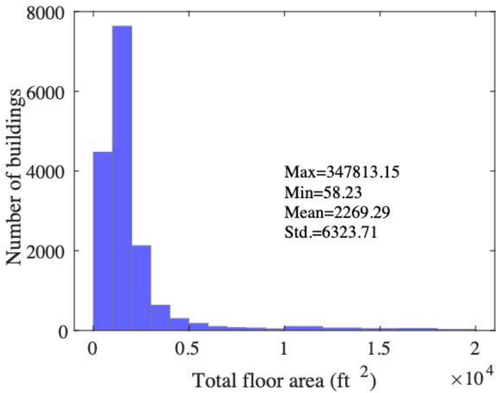
Material Type
1
2
3
4
5
6
7
8
9
Depth = 0 (m)
Depth = 10 (m)
Depth = 20 (m)
Depth = 30 (m)
41°04'N
41°02'N
41°N
40°58'N
Latitude
28°40'E
28°50'E
29°E
Longitude
5 km
2 mi
Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

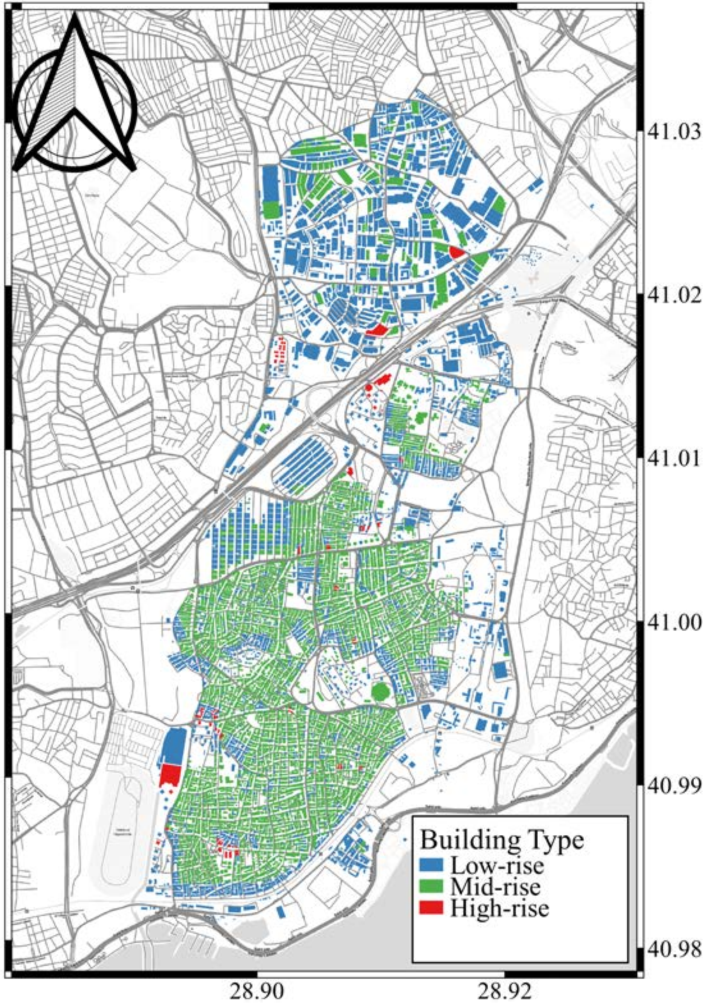
Building inventory for Zeytinburnu district

16,030 reinforced concrete buildings



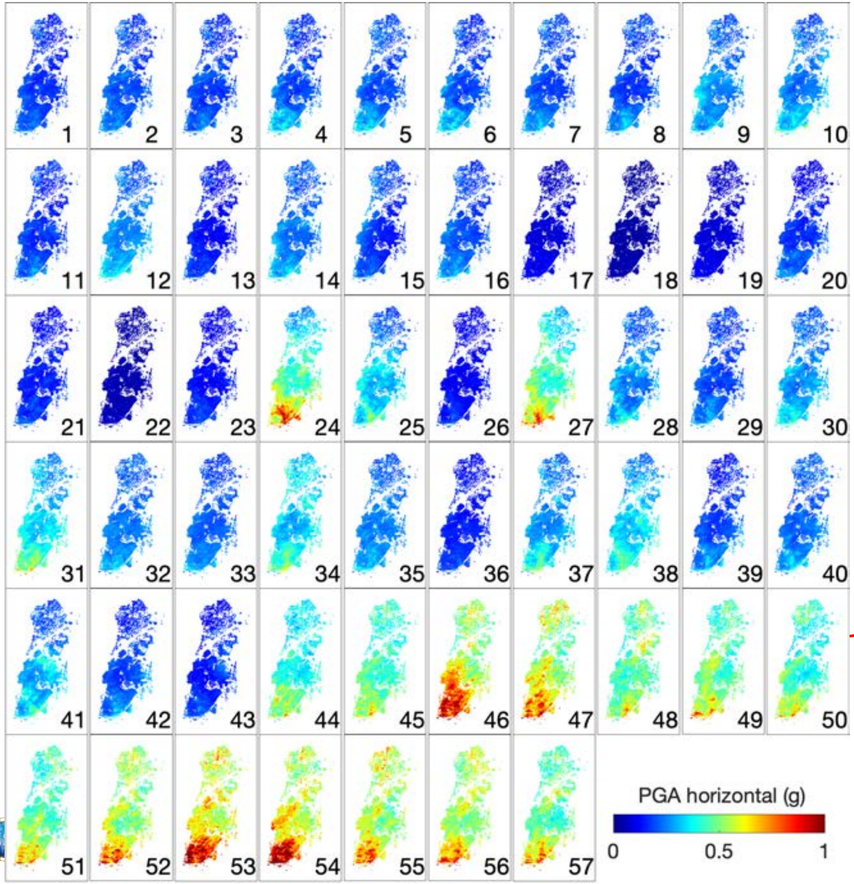




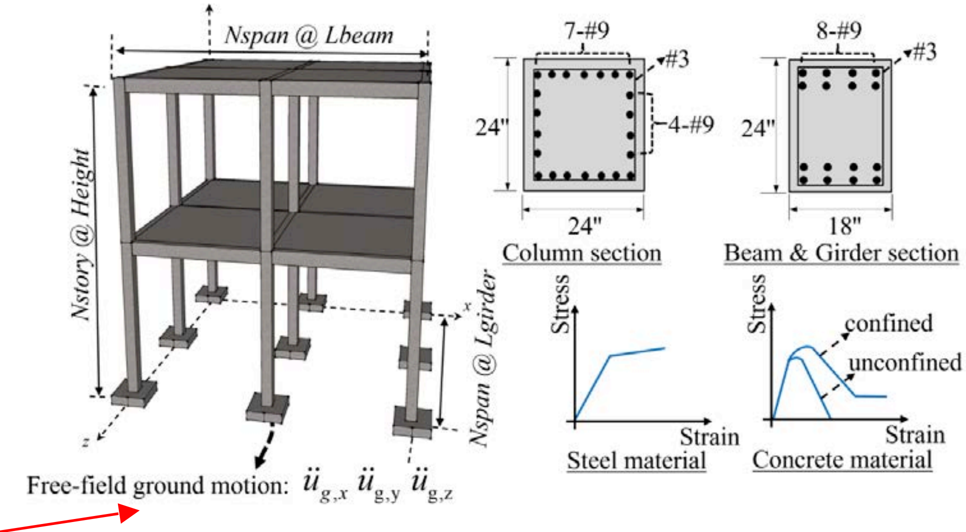


3D nonlinear time history analysis using OpenSees

Horizontal PGA of simulated ground motions

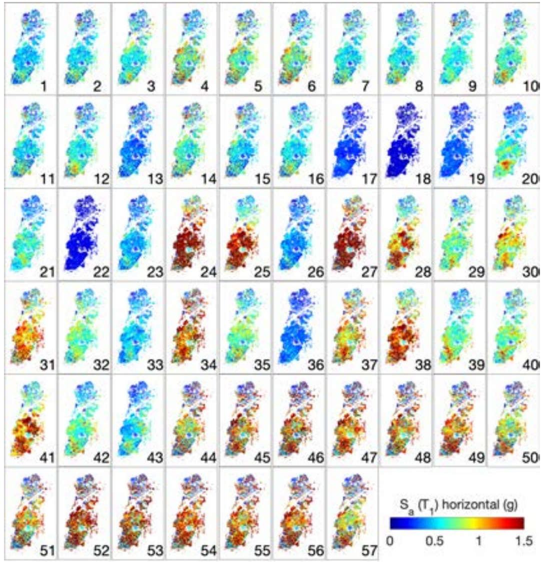


16,030*57 = 913,710 FEAs

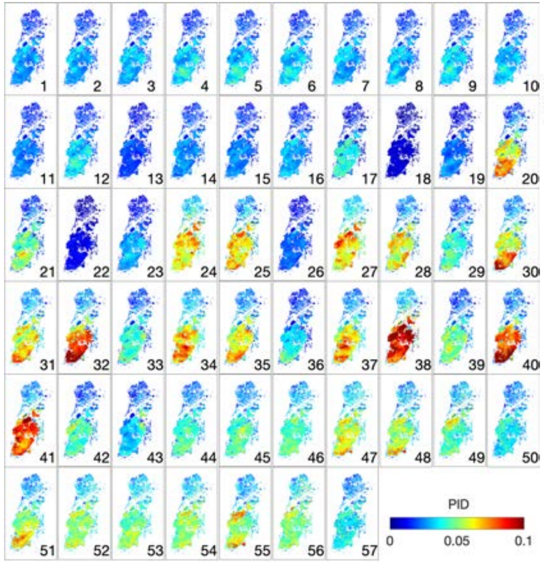


Seismic fragility analysis

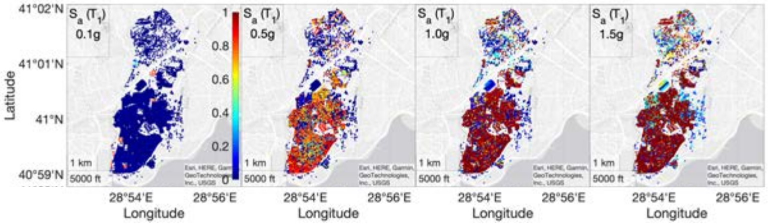
IM: Sa (T_1)



EDP: Story drift ratio



Probability of collapse



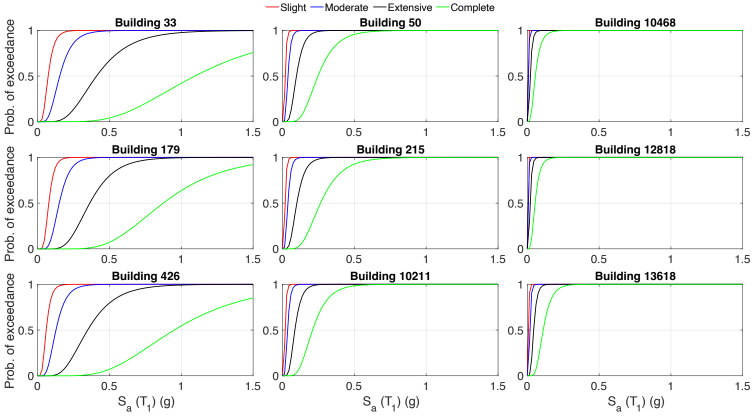
Sa (T_1) 0.1g

Sa (T_1) 0.5g

Sa (T_1) 1.0g

Sa (T_1) 1.5g

Fragility curves



Probabilistic seismic demand analysis

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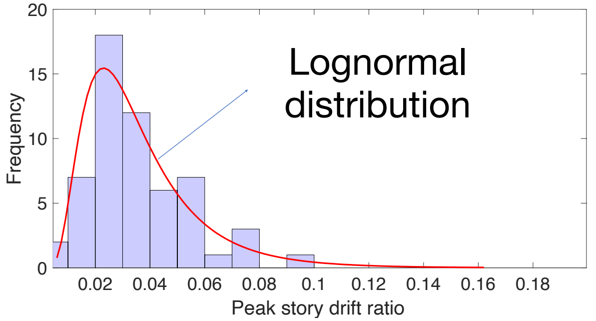
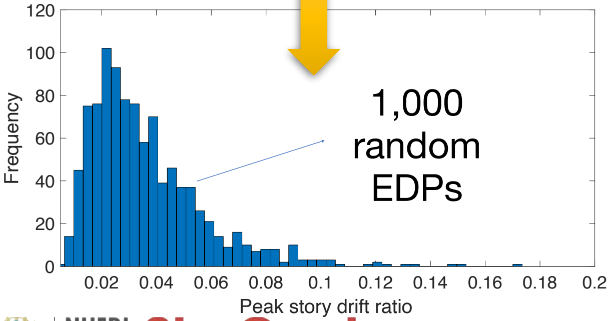
Seismic loss assessment

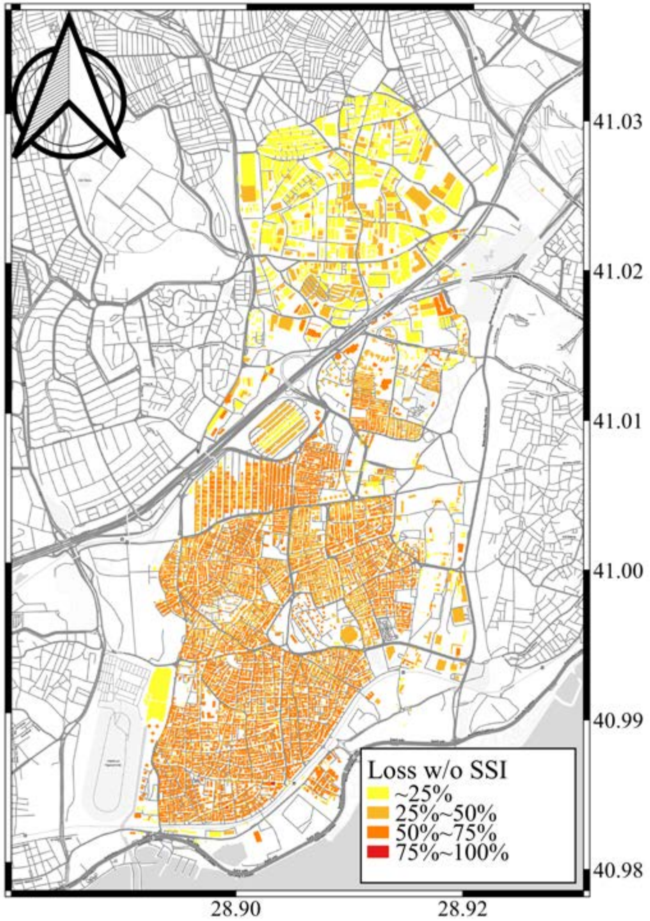
Pelicun is used to estimate the seismic losses of all 16,030 buildings in the Zeytinburnu district.





$$\textbf{Loss} = \frac{\text{Mean(damage+repair costs)}}{\text{Originial building cost}}$$

Loss assessment

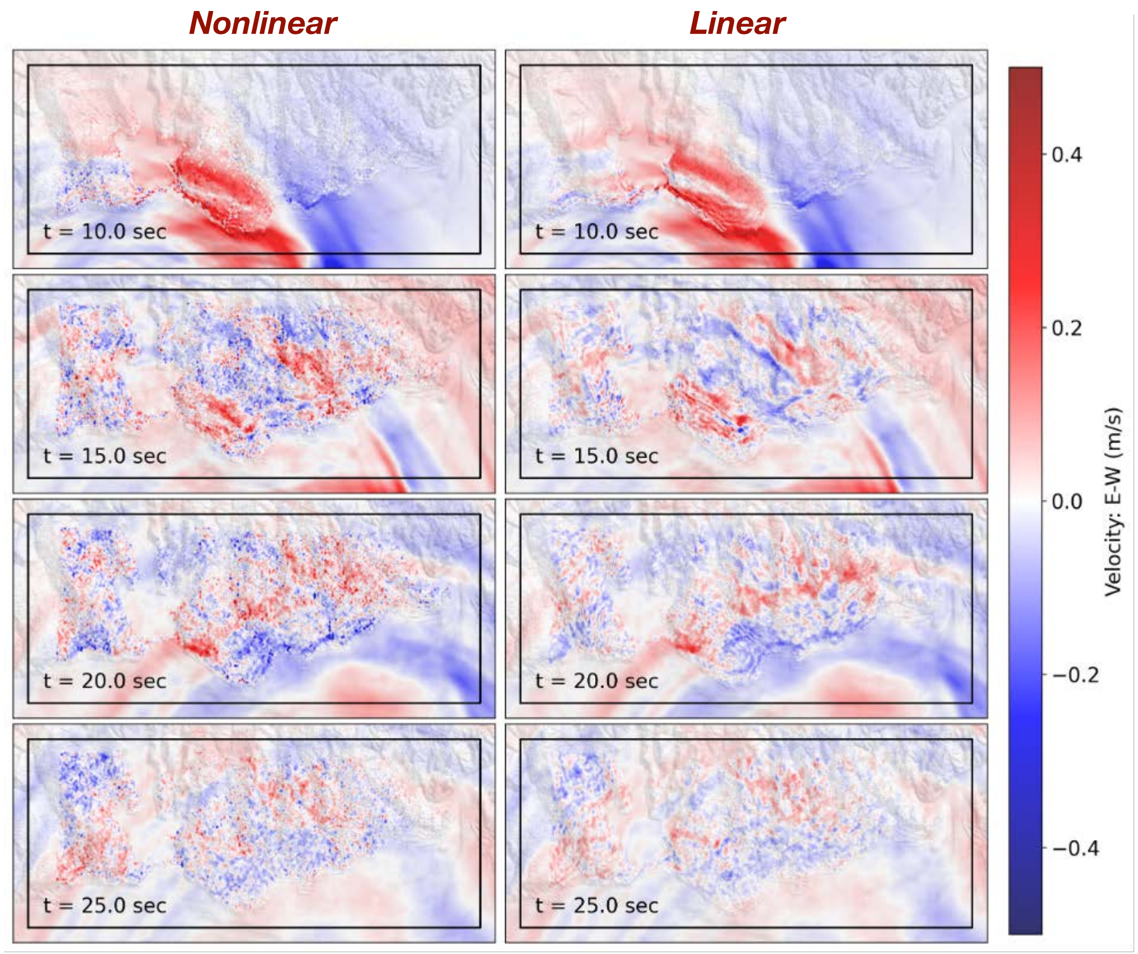


Linear v. Nonlinear Soils

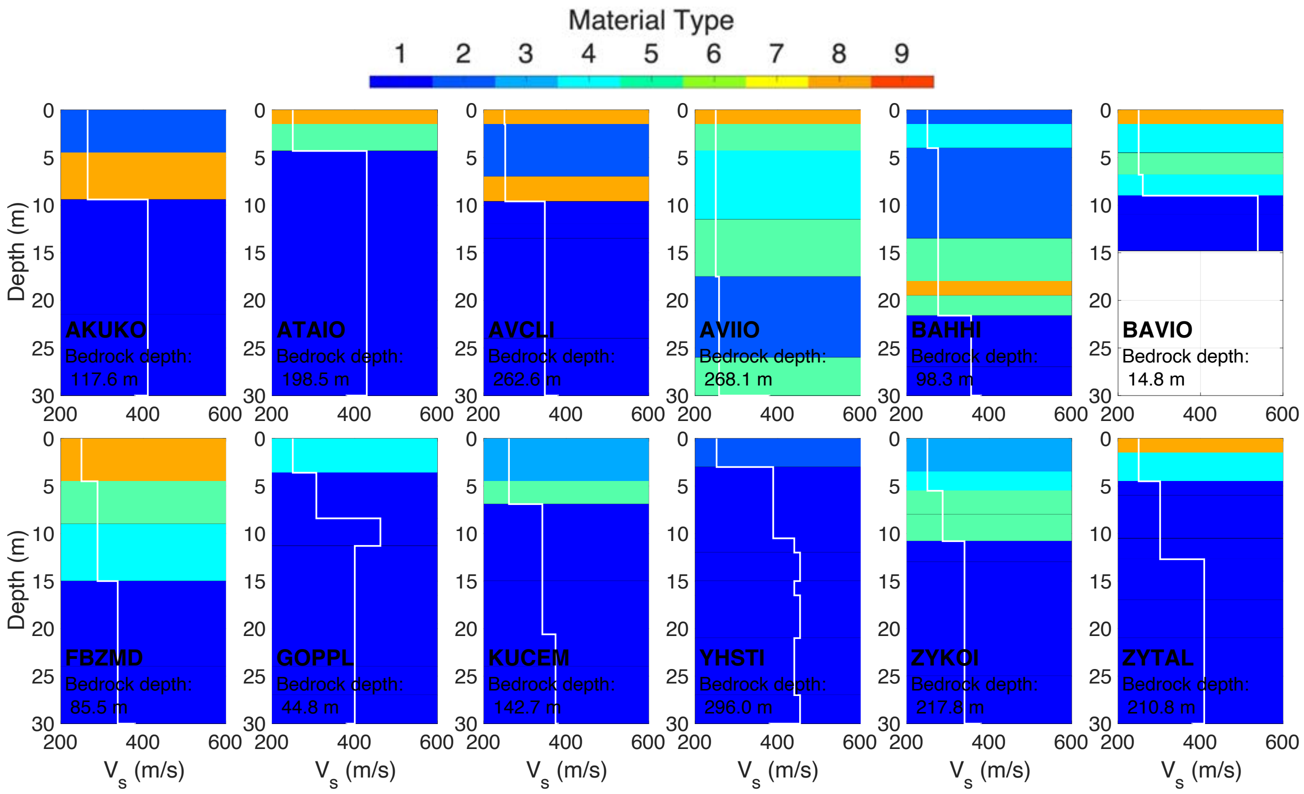
Metadata for simulations @ FRONTERA

Simulation type	Linear	Nonlinear
Maximum frequency (Hz)	8	8
Simulation time (sec)	30	30
Minimum element size (m)	3.1	3.1
Number of elements (billions)	6.6	6.6
Time increments (sec)	0.0005	0.0005
Number of cores	22400	28672
Wall clock (h)	4.7	33.3

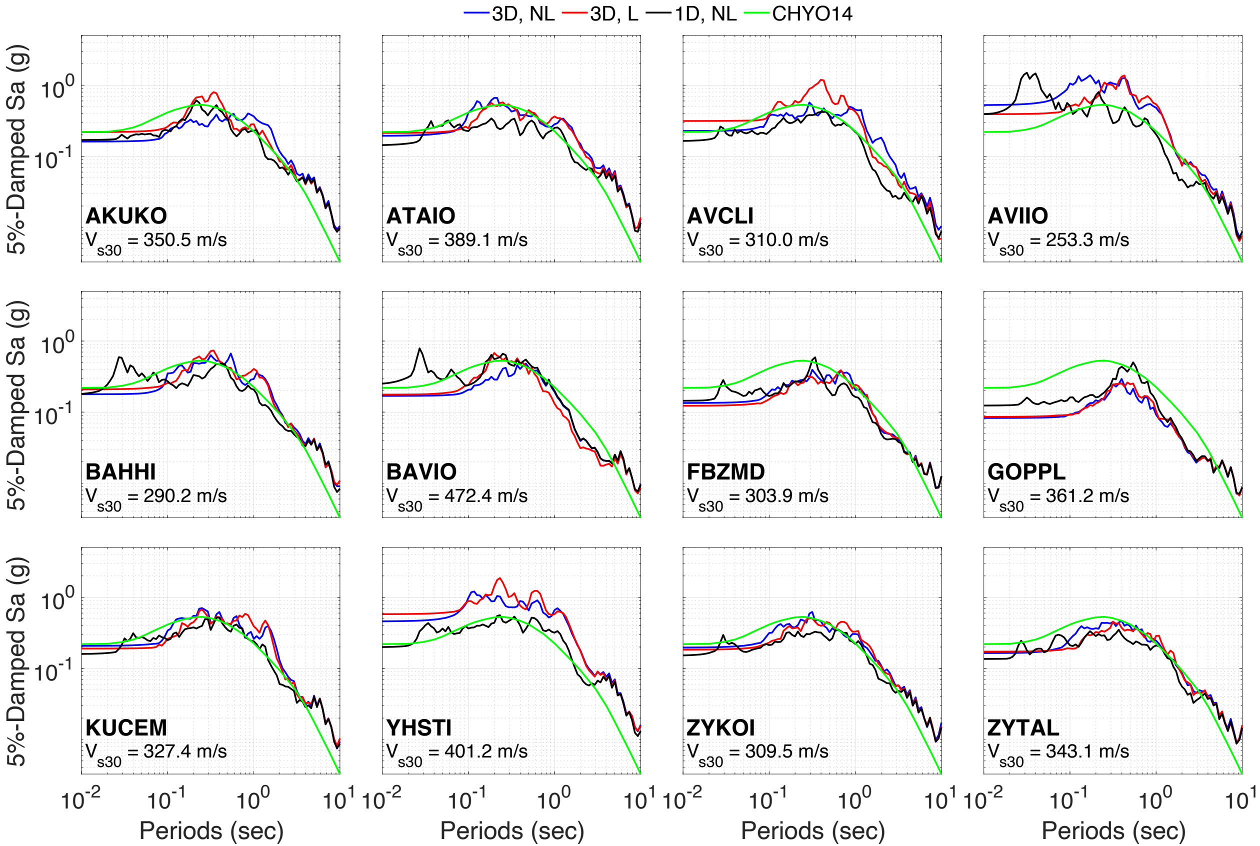
PGV


Nonlinear
Linear
t = 10.0 sec
t = 15.0 sec
t = 20.0 sec
t = 25.0 sec
t = 10.0 sec
t = 15.0 sec
t = 20.0 sec
t = 25.0 sec
0.4
0.2
0.0
−0.2
−0.4
Velocity: E-W (m/s)

S_a @ several stations



S_a @ several stations



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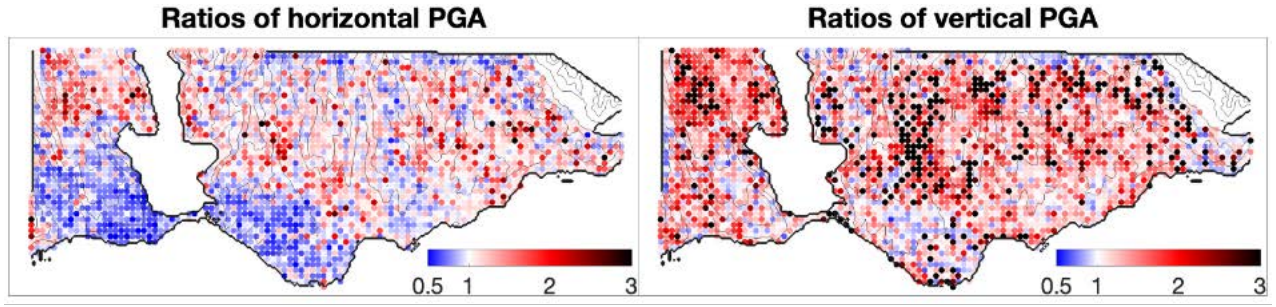
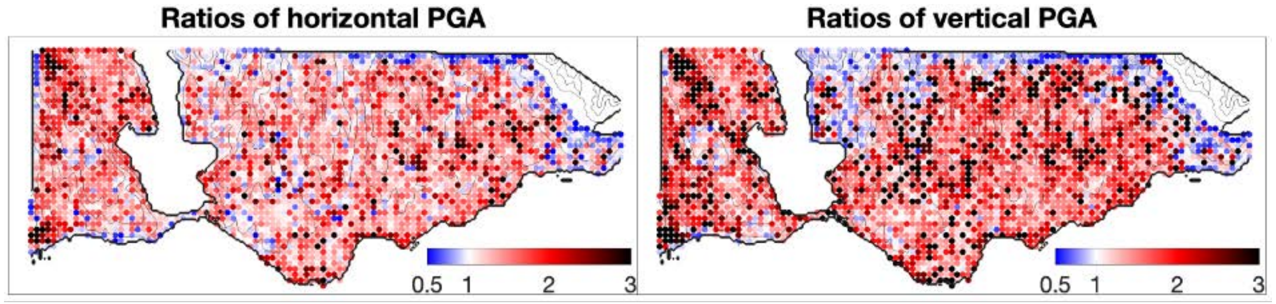
Chiou BS-J, Youngs RR (2014). Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra*, 30(3), pp. 1117–1153.

PGX_a / PGX_b

a = 3D Nonlinear GMSim, b = 3D Linear GMSim

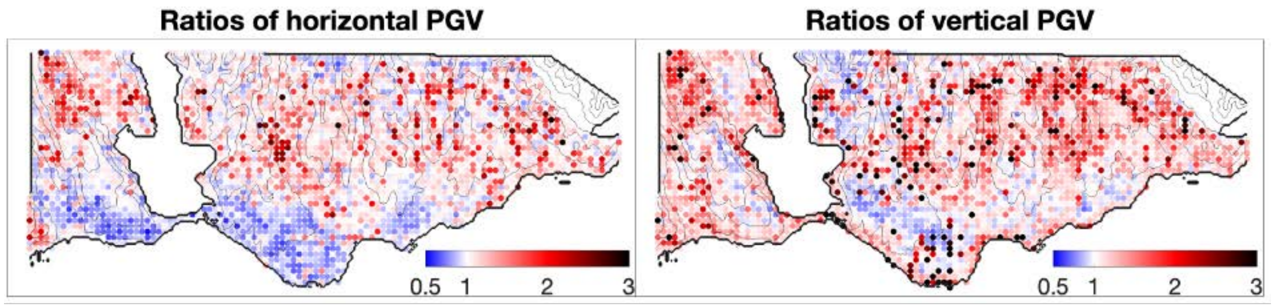


a = 3D Nonlinear GMSim, b = 1D Nonlinear SRA

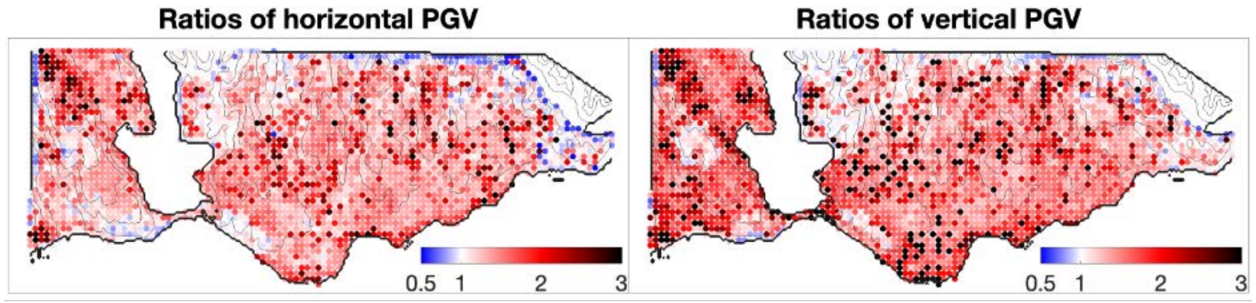


PGX_a / PGX_b

a = 3D Nonlinear GMSim, b = 3D Linear GMSim



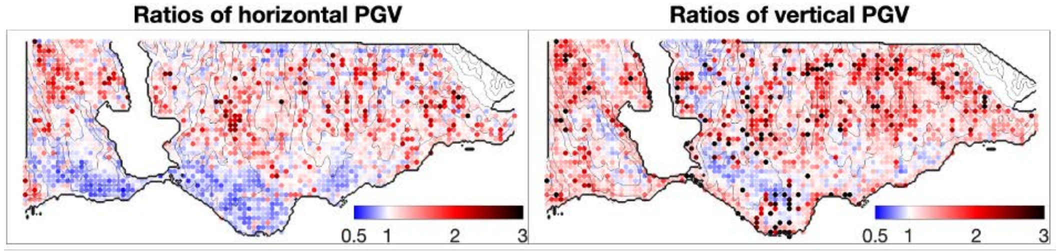
a = 3D Nonlinear GMSim, b = 1D Nonlinear SRA



Observations

- Soil nonlinearity can both amplify and de-amplify seismic intensity measures relative to linear
- Nonlinearity should be incorporated into simulations pending research
    - *regional soil metadata*
    - *parametric studies for specific applications*

a = 3D Nonlinear GMSim, b = 3D Linear GMSim



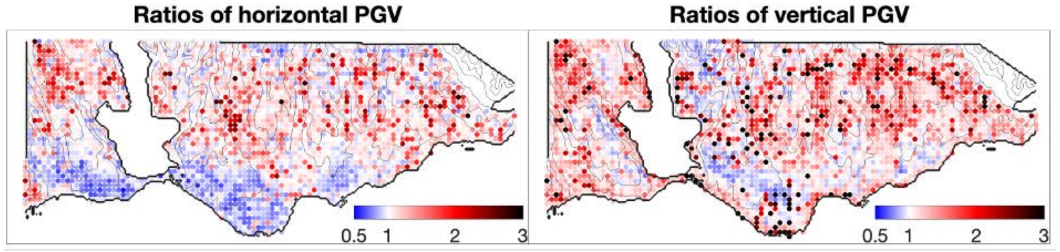
NHERI SimCenter

Observations

- Soil nonlinearity can both amplify and de-amplify seismic intensity measures relative to linear
- Nonlinearity should be incorporated into simulations pending research
    - *regional soil metadata*
    - *parametric studies for specific applications*
- Nonlinearity *can* be incorporated into simulations

Simulation type	Linear	Nonlinear
Maximum frequency (Hz)	8	8
Simulation time (sec)	30	30
Minimum element size (m)	3.1	3.1
Number of elements (billions)	6.6	6.6
Time increments (sec)	0.0005	0.0005
Number of cores	22400	28672
Wall clock (h)	4.7	33.3

a = 3D Nonlinear GMSim, b = 3D Linear GMSim




thank you
TRG @ UCLA