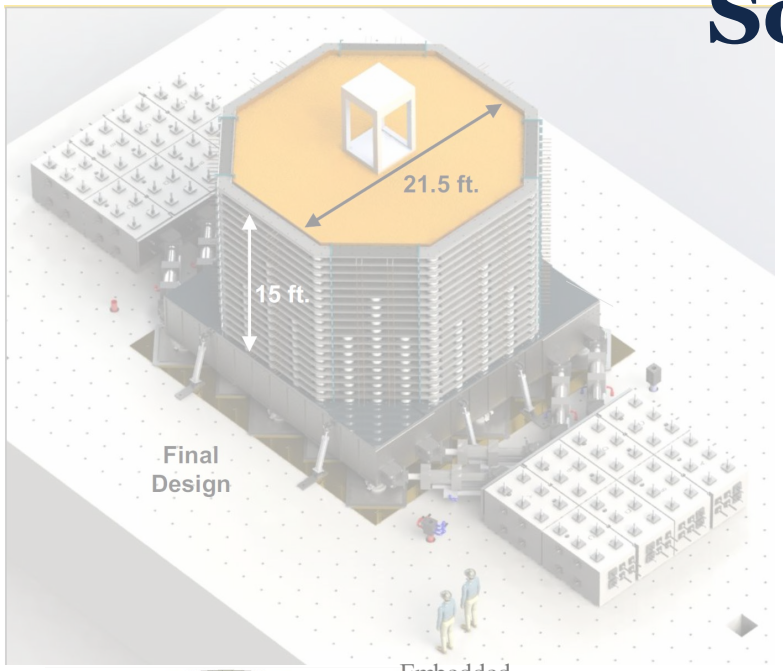
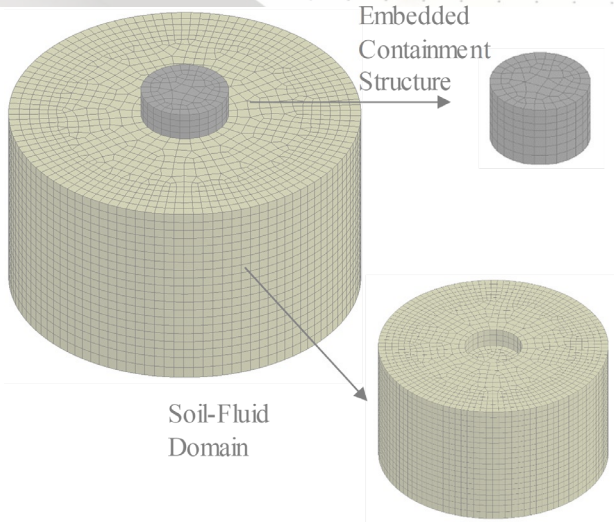
New Trends in Numerical Modeling of Seismic Soil-Structure Interaction -





Youssef M.A. Hashash, Ph.D., P.E.

May 17, 2021

DOE - PEER Workshop - Day 1".
Large-Scale Shake Table Testing for the Assessment of Soil-Foundation-Structure System Response for Seismic Safety of DOE Facilities.

Collaborators:

Yuamar I. Basarah **Ozgun Numanoglu, Ph.D.**

Guangchao Xing **Alvin P. Bayudanto**

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Department of Civil and Environmental Engineering

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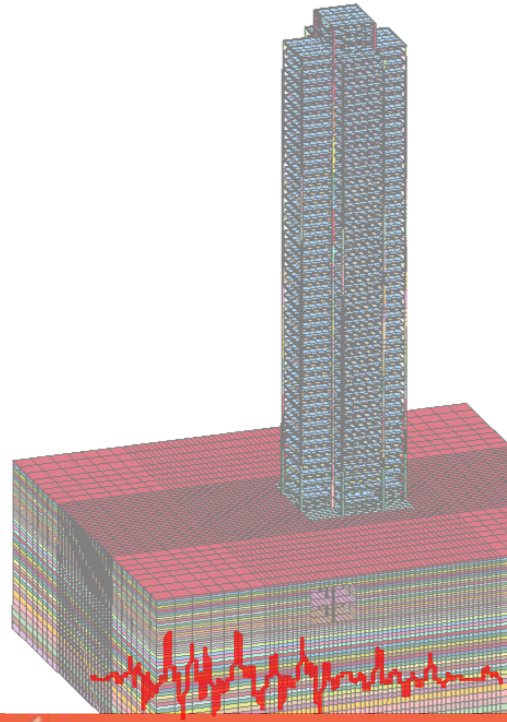


Outline

- Motivation
- State-of-the-practice modeling methods
- Considerations for seismic soil-structure interaction modeling
- Developments & applications
- Conclusions and engineering implications

Motivation: Physical infrastructure performance and resilience under extreme events – Earthquake Shaking

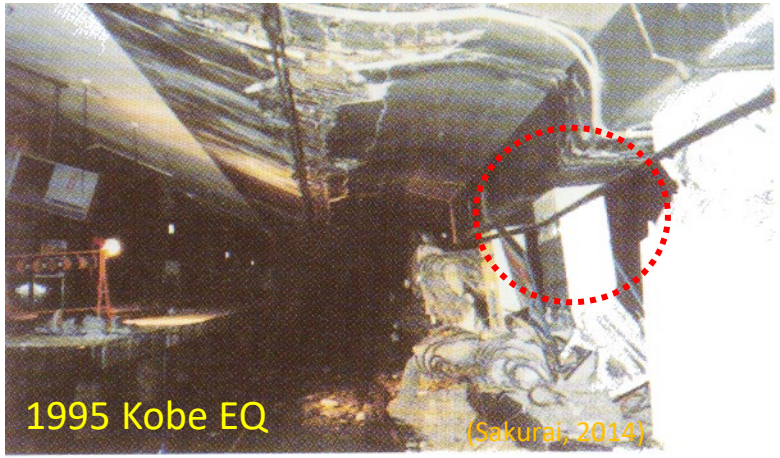
Motivation: Physical infrastructure performance and resilience under extreme events – Earthquake Shaking

- Settlement under nuclear power plant

- Liquefaction induced building movement

- Wall failure in buried reservoir

- Collapse of subway station



- Tall building-excavation

- Cracks in Concrete Face Rockfill Dam @ joints

Outline

- Motivation
- State-of-the-practice modeling methods
- Considerations for seismic soil-structure interaction modeling
- Developments & applications
- Conclusions and engineering implications

Simplified methods and Code-based Procedures for Seismic Soil-structure Interaction

ASCE 7-16 Chapter 19:

- SSI may be used with equivalent lateral force, linear dynamic, or nonlinear dynamic analysis.
- Site class C, D, E, or F
- Modified response spectrum to consider SSI

Needs to represent the soil and structure explicitly to understand the seismic behavior of SSI system

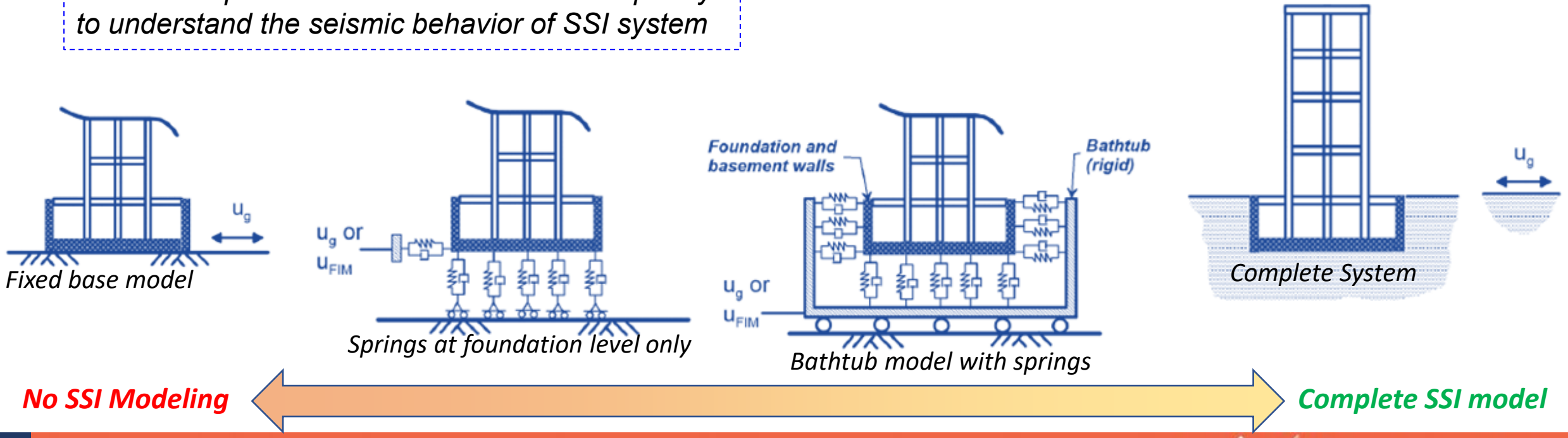
Tall Building Initiative (TBI, 2017):

Fixed base model:

Input motion applied directly at the base of the building (No SSI)

Bathtub model using springs to represent soil for flexible base

Complete SSI model where all components are modeled explicitly



Outline

- Motivation
- State-of-the-practice modeling methods
- Considerations for seismic soil-structure interaction modeling
  - Input: Site investigations and ground motions
  - Elements of seismic soil-structure interaction analysis
  - Structural modeling and soil-structure interface conditions
- Developments & applications
- Conclusions and engineering implications

Elements of Seismic Soil-structure Interaction Analysis

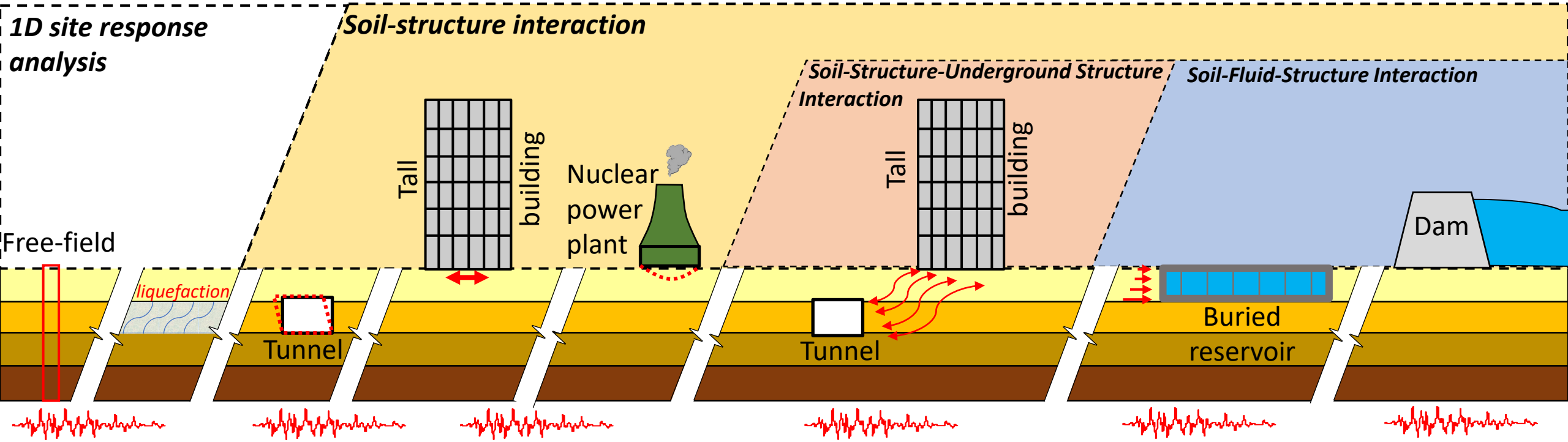
Free-field condition

- 1D site response analysis
  - DEEPSOIL, SHAKE, Strata Shear beam model
- Soil liquefaction assessment

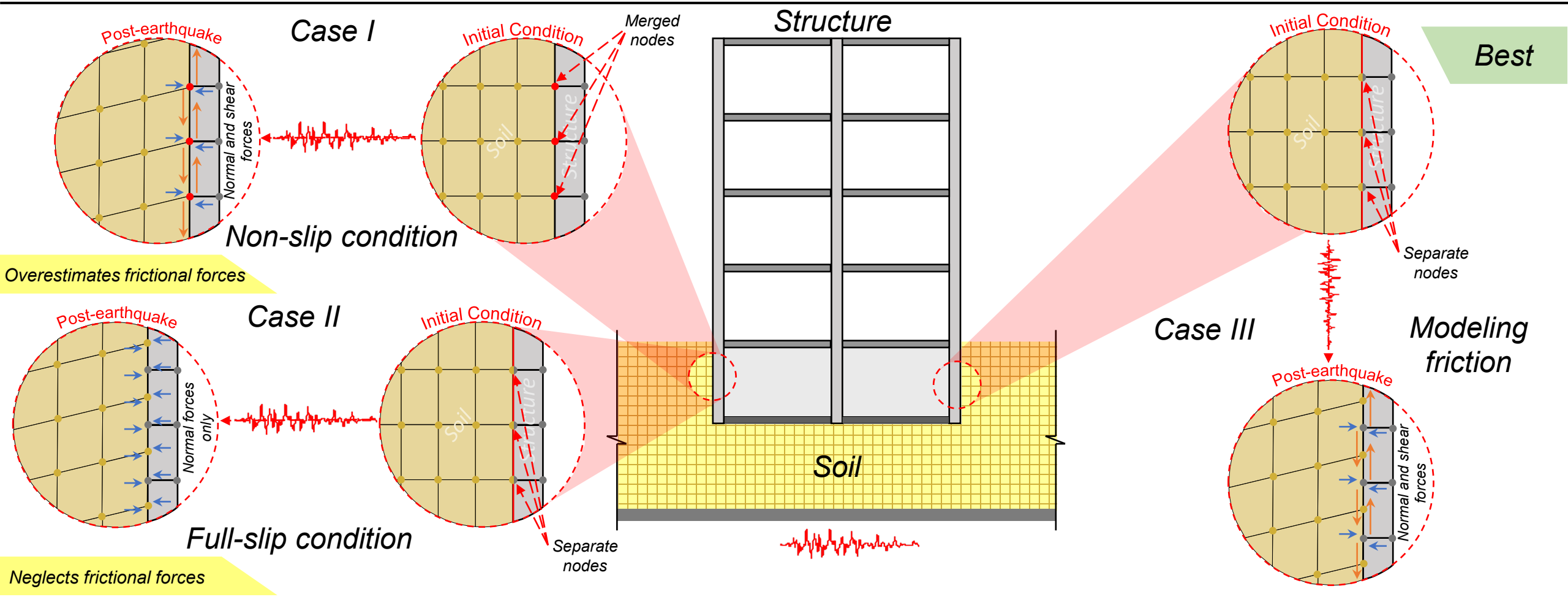
Soil-structure interaction

- Ex.: Tunnel, Tall building, Nuclear power plant on sand ...

- **Soil-structure-underground structure interaction:**
  - Tall building-tunnel system in urban area
- **Soil-fluid-structure interaction:**
  - Dam & buried reservoir



Soil-Structure Interface Conditions



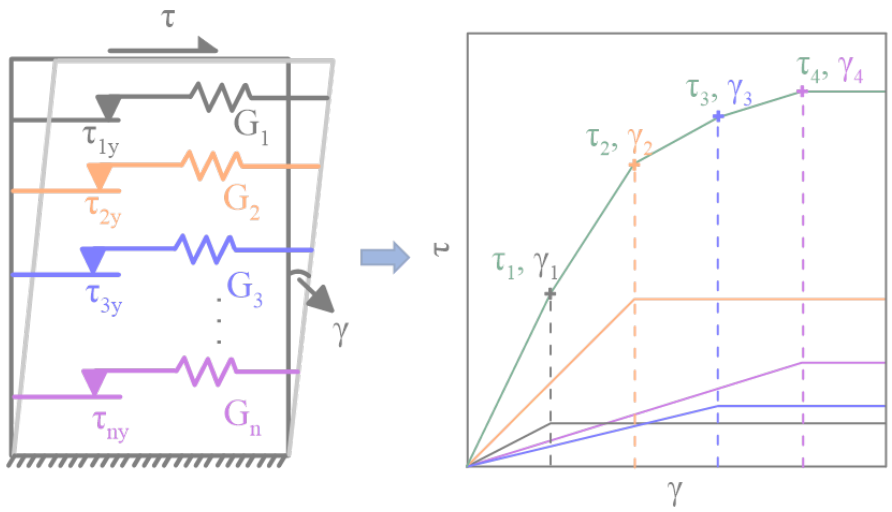
- The interface between soil and structure can be modeled as full-slip, non-slip, or something in between by modeling friction (reflecting real world conditions).

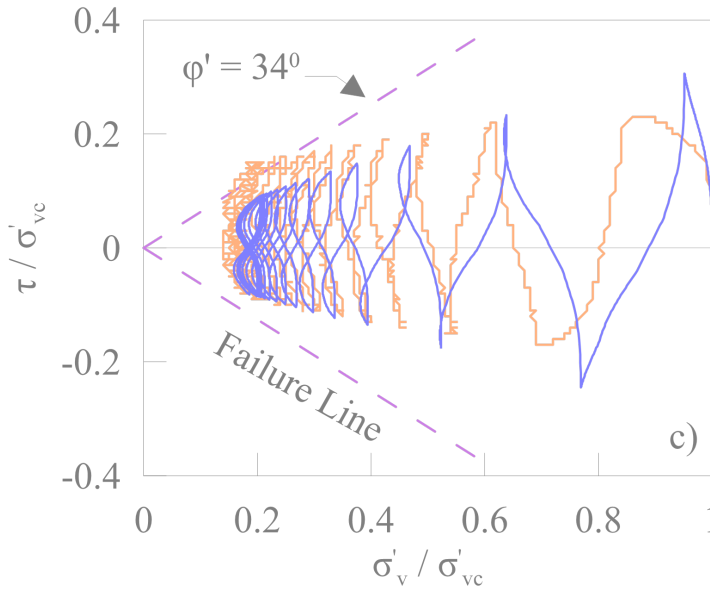
Gaps/Needs in Numerical and Material Constitutive Modeling

- Higher fidelity representation of both the structure and soil as well as interface interaction - friction, sliding, gapping.
- 3-D geometries and multi-directional base excitation.
- Simulation run times and need for representation of uncertainty – computational cost.

Outline

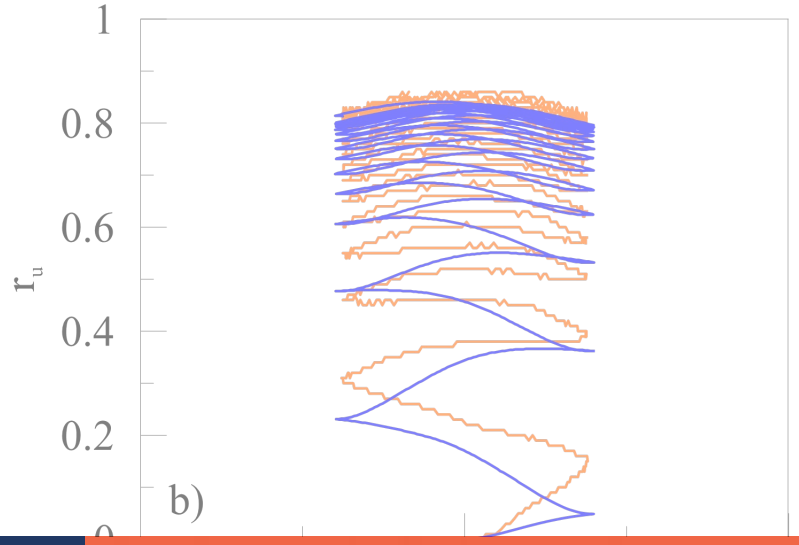
- Motivation
- State-of-the-practice modeling methods
- Considerations for seismic soil-structure interaction modeling
- Developments & applications
  - Advances in soil constitutive modeling (I-soil)
  - Seismic settlement of heavy structures on dense sands
  - Other problems
  - Computational considerations
- Conclusions and engineering implications





Advances in Soil Constitutive Modeling (I-soil)

Ozgun A. Numanoglu, Youssef M.A. Hashash



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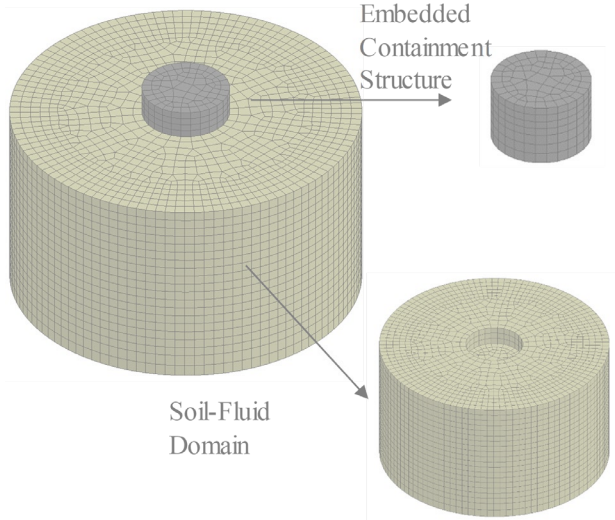
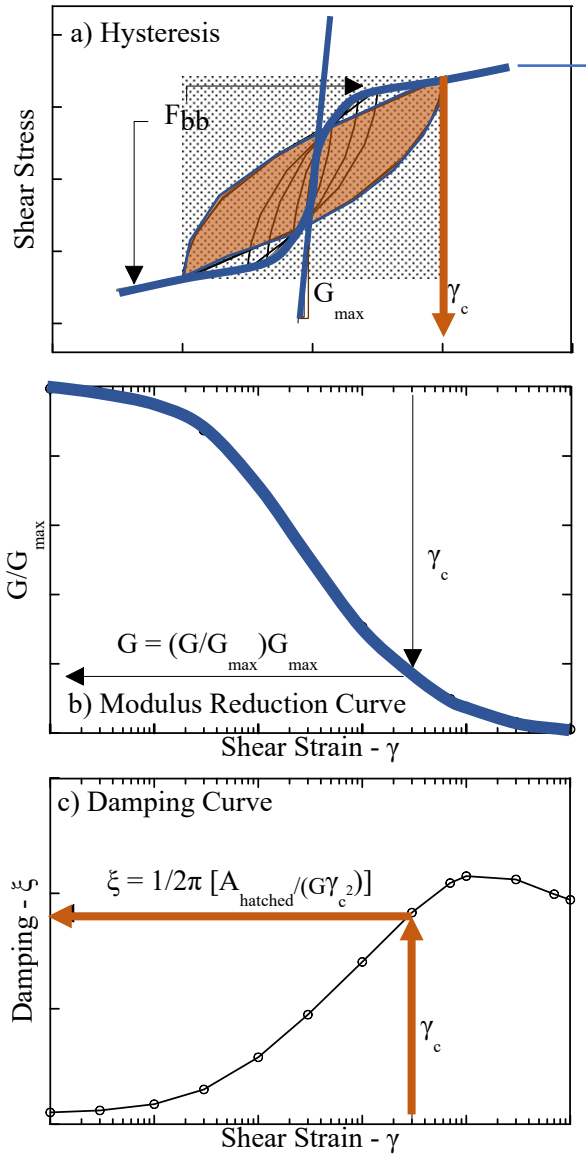
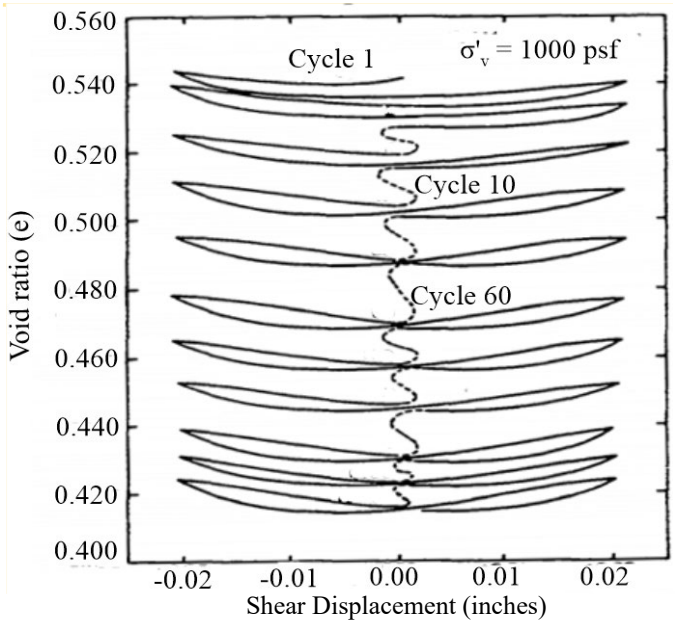


Conceptual Constitutive Model for Seismic Behavior of Sands



Small strain stiffness and normalized modulus reduction curve defines the backbone (F_{bb})



1. Small strain stiffness
2. Normalized Secant Modulus Reduction
3. Hysteretic Damping
   - *Non-Masing type*
4. Shear Induced Volumetric Response

Development of I-soil – A New Practical Soil Model

- Extension of MAT79 in LS-DYNA - A 3D, distributed element plasticity model introduced by Chiang and Beck (1994) based on Iwan (1969) distribution of elasto-plastic nested components.

- Model formulation
  - Piecewise-linearized, hysteretic, non-Masing type nonlinear model to represent modulus reduction and damping curves.
  - Models shear induced volumetric strains and excess porewater pressures.
  - Represents medium dense to very dense sand behavior. Promising for loose to medium sands. Easy to calibrate and use.

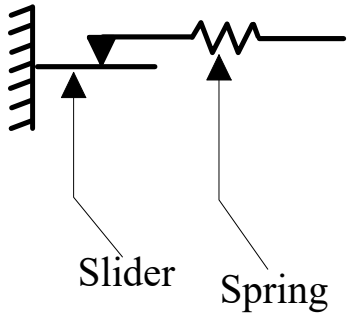
- Analysis platform:
  - Implemented in LS-DYNA (with solid-fluid coupled framework)

- Not included
  - Plasticity due to hydrostatic loading
  - Anisotropy
  - Critical state behavior

Why LS-DYNA?

- Designed to solve dynamic problems
- Detailed representation of structural components
- Fluid modeling capability
- Ease of use (e.g., GUI, pre- and post-processor)
- Computationally efficient
- Parallel computing capabilities
- Easy to automate/queue analyses

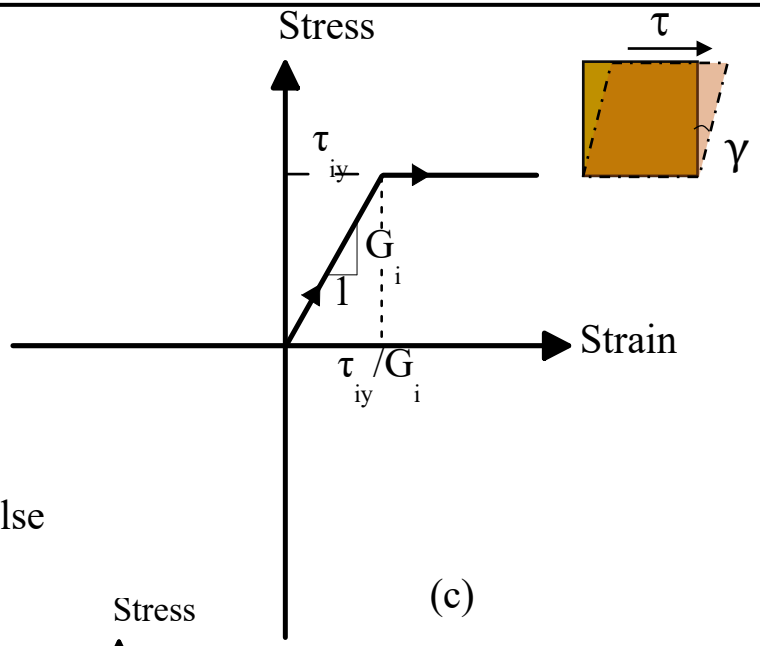
Model Formulation: One-dimensional Framework



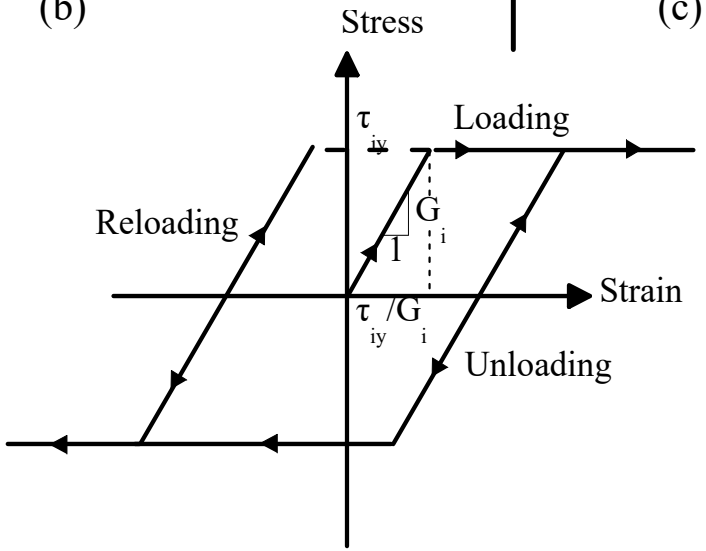
Elastic if $\tau < \tau_{iy}$

Perfectly plastic else

(b)



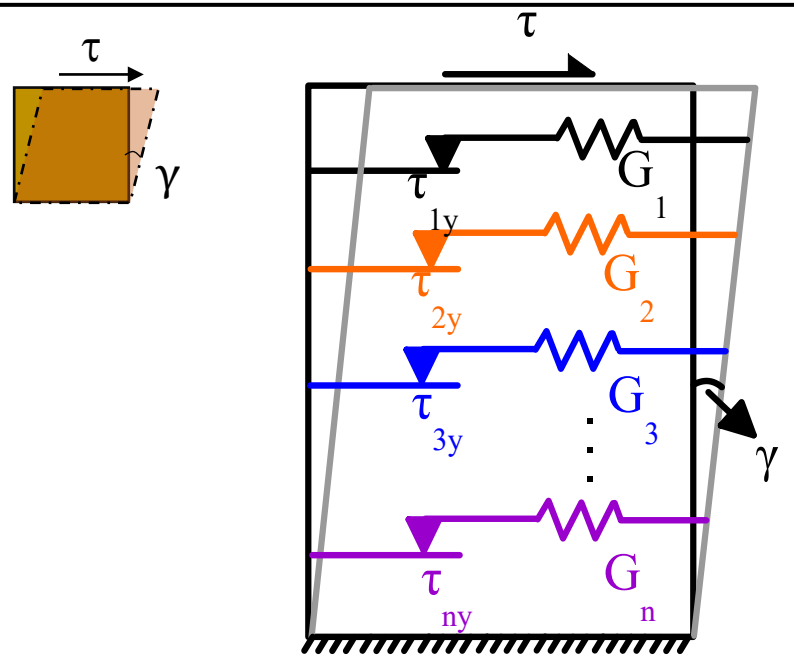
(c)



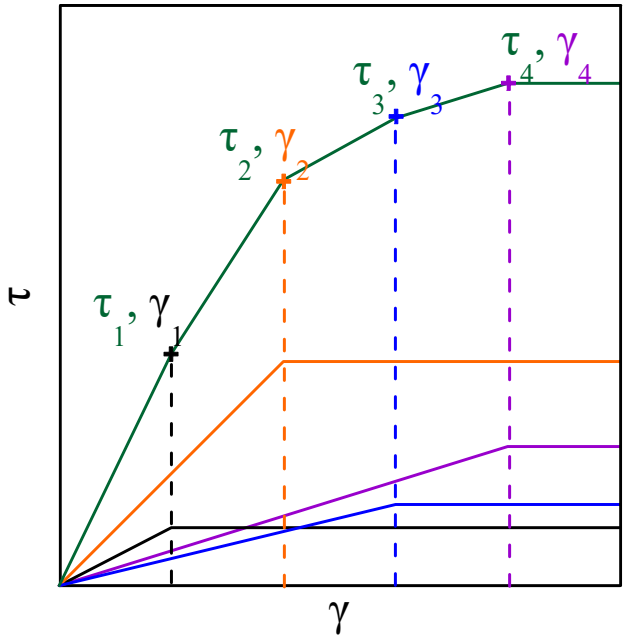
(d)

- Simple spring slider systems
- Elastic perfectly plastic behavior
- Produces Masing type hysteretic behavior upon un/reloading
- Extended to include non-Masing hysteretic behavior to avoid over-estimating damping during strong shaking

Model Formulation: One-dimensional Framework



(a)



(e)

Piece-wise linear backbone made of 4 user defined points

Components 1 to n (n = 4 for demonstration purposes)

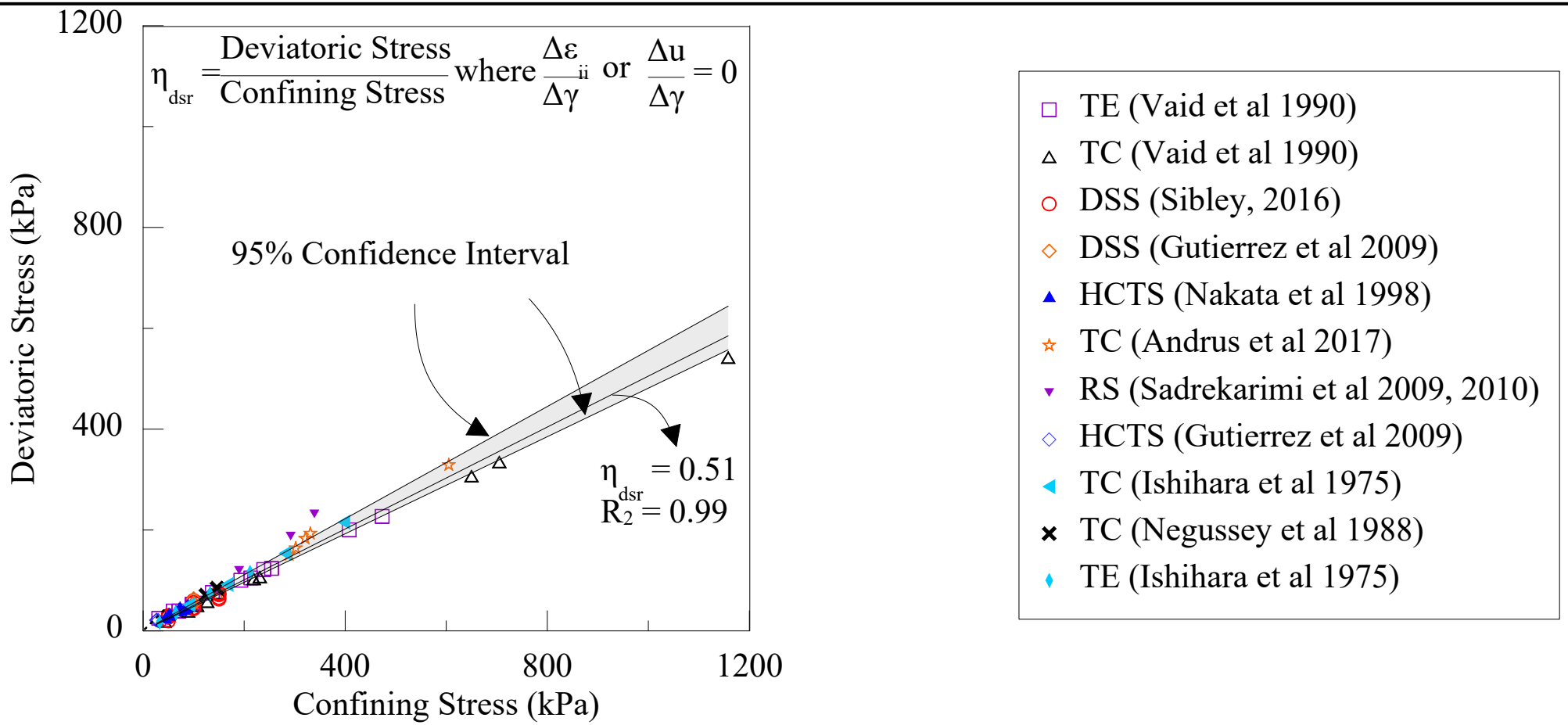
- Superposition of n number of spring and slider components distributed in parallel
- Simple summation formulation to model piecewise linearly nonlinear behavior

$$\tau(\gamma) = \sum_{c=1}^{m} \tau_y^c + \sum_{c=m+1}^{n} G^c \gamma$$

i = 1:m non-yielded components
i = m+1:n yielded components

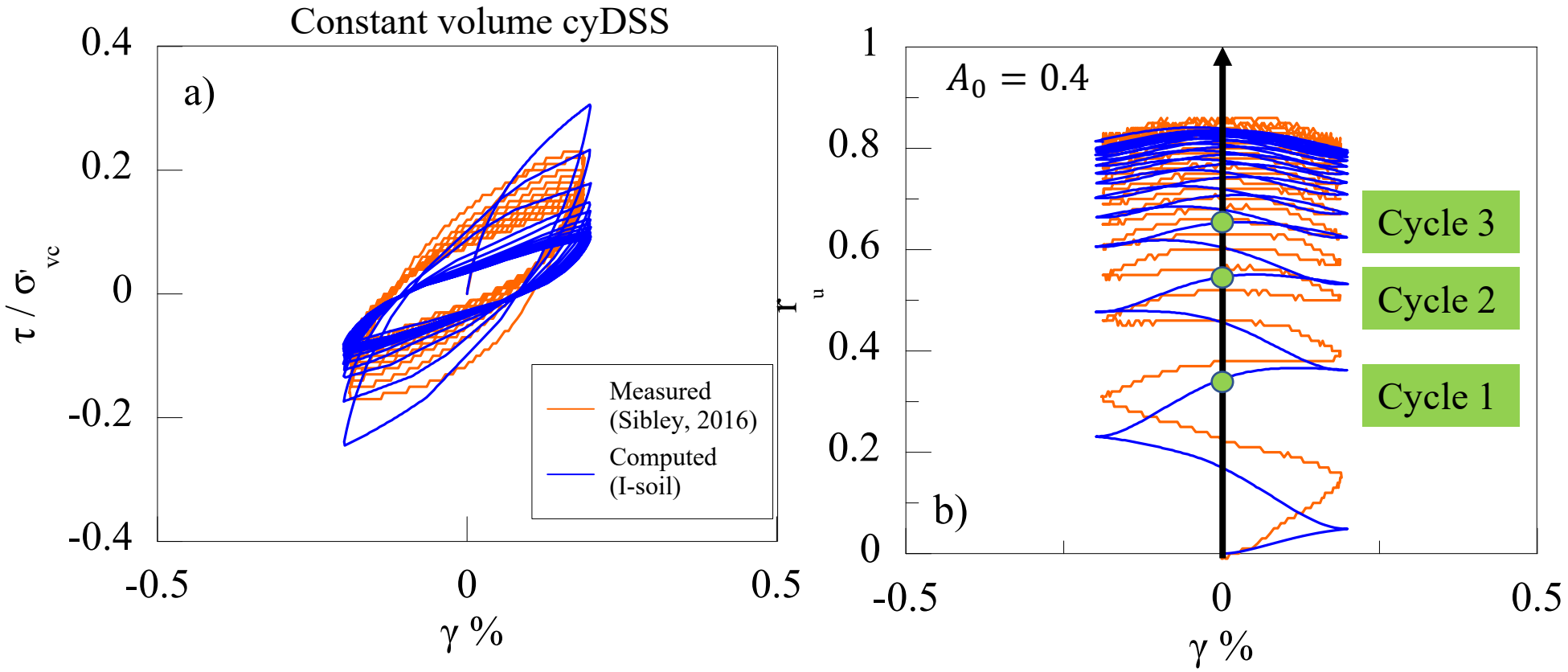
Allows representation of normalized modulus reduction

Volumetric Response Calibration: η_{dsr}



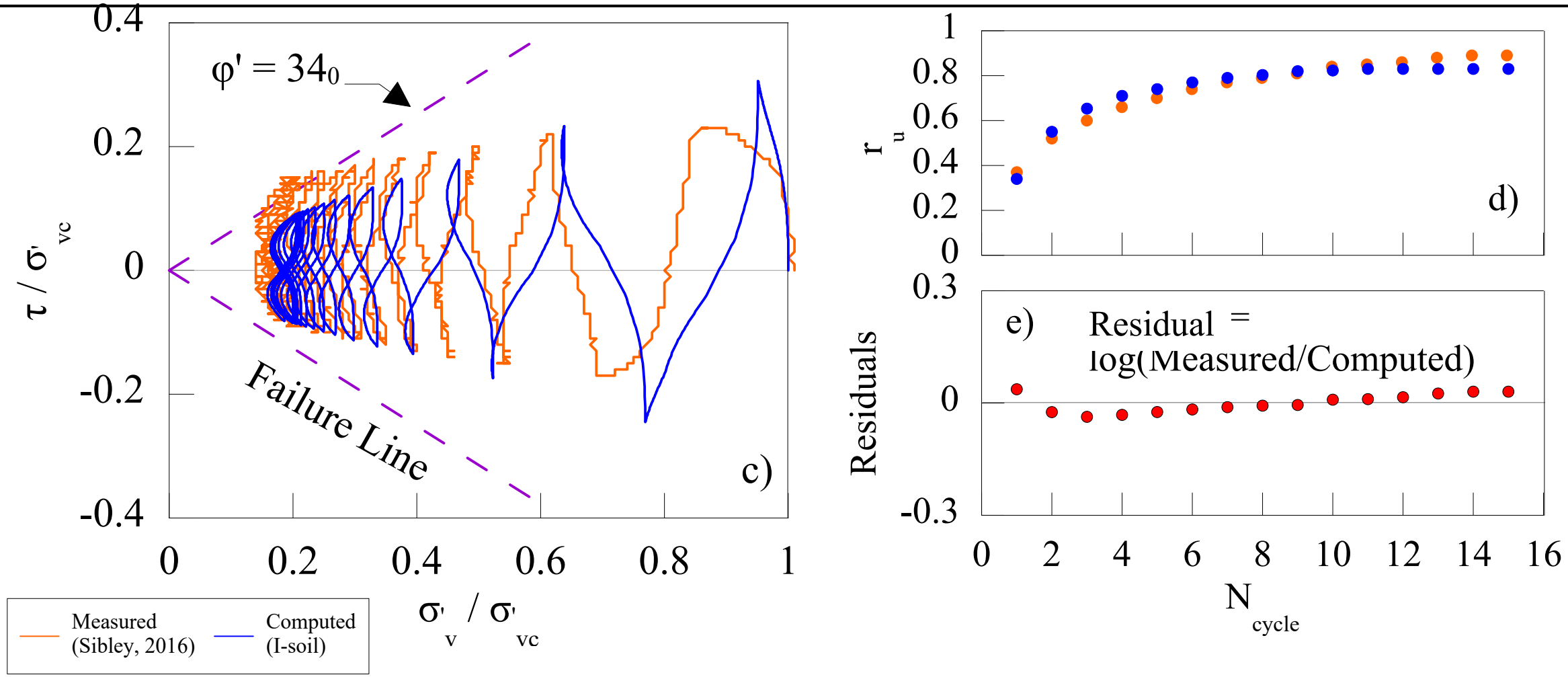
- Values between 0.4 – 0.8 with mean value of 0.51 for 10 – 1200 kPa, 40 – 95% D_R
- η_{dsr} = 0.51 => $\phi'_{dsr} = 31^0 \leq \phi'_{critical\ state\ (or\ constant\ volume)} = 30^0 - 32^0$
- Negussey et al. 1988, Vaid et al. 1990, Sadrekarimi and Olson, 2011

Volumetric Response Calibration : A_0



- A trial-and-error procedure to obtain good estimation of hysteretic and volumetric response
- e.g., A_0 = 0.4 captures both behavior well for a given sand specimen

Volumetric Response Calibration : A_0



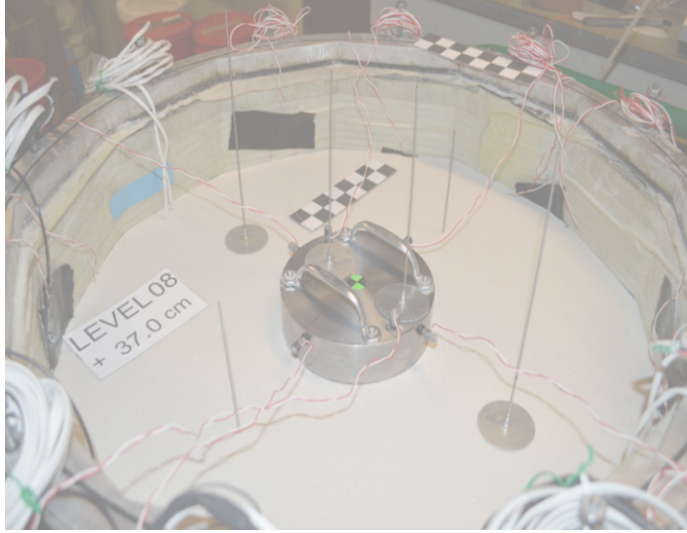
- For a given trial, the aim is to keep the residuals near zero value throughout shearing.

Input Parameters

Source	Parameters/ Symbol	Physical Contribution/Meaning	Dense Sand
	σ'_{ref}	Reference effective mean stress at which the parameters are defined	kPa
Normalized modulus reduction curve (MR) and shear wave velocity (Vs)	n number of τ -γ pairs	Curve fitted n point discretized backbone curve at σ'ref that matches Vs at very small strains and MR at different shear strain levels	MR: Darendeli (2001) Vs: Field Measurement (Alternatively Menq (2003) correlation
MR curves at different confining pressures	b	Power law coefficient defining the effective mean stress dependency characteristics of stiffness	0.5 (Arulmori et al. 1992)

In simple terms, I-soil input:

- Modulus reduction and damping curves commonly used for 1D nonlinear site response analysis
- Two volumetric response parameters (A_0 and η_{dsr}) calibrated using cyDSS or empirical correlations.



Seismic settlement of heavy structures on dense sands

Ozgun A. Numanoglu, Youssef M.A. Hashash, Scott M. Olson, Alfonso Cerna Diaz, Cassandra J. Rutherford, Thomas Weaver, Lopamudra Bhaumik

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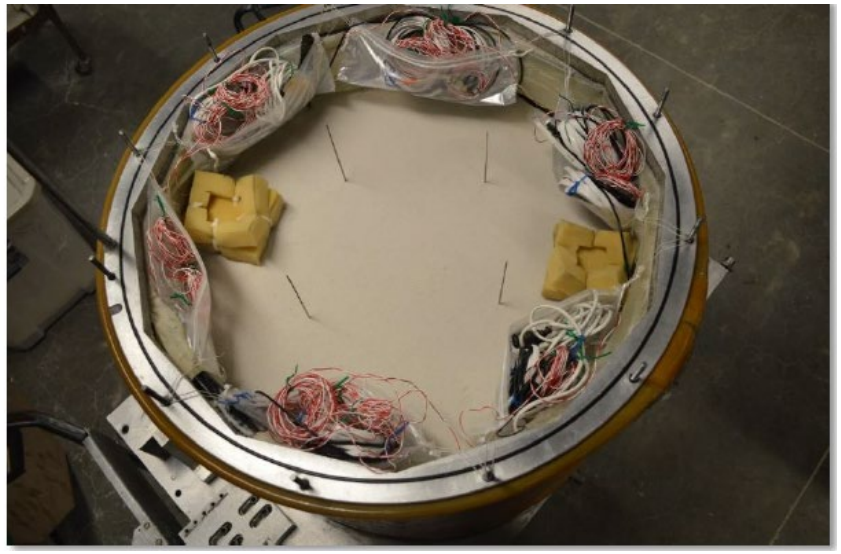
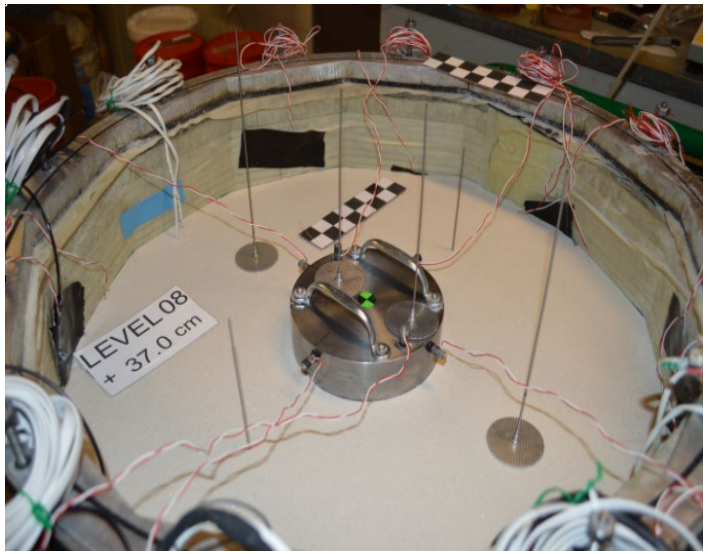
WHERE DISCOVERIES BEGIN

Seismic Settlement of Dense Sand

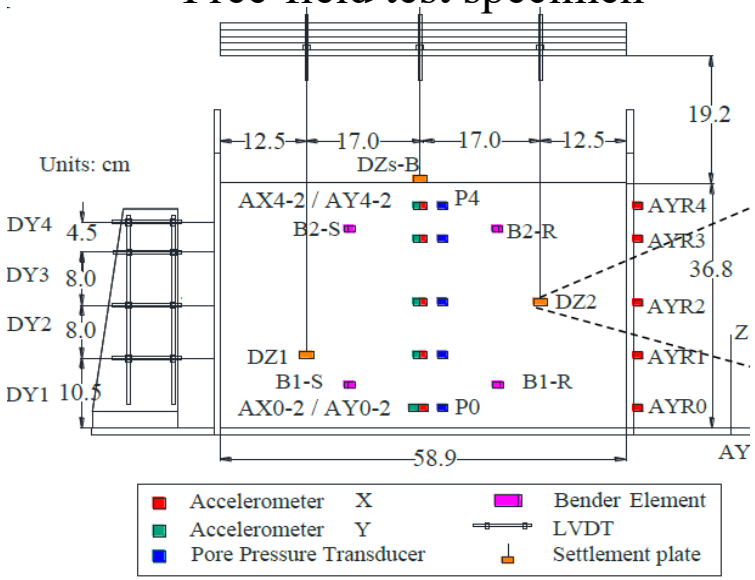


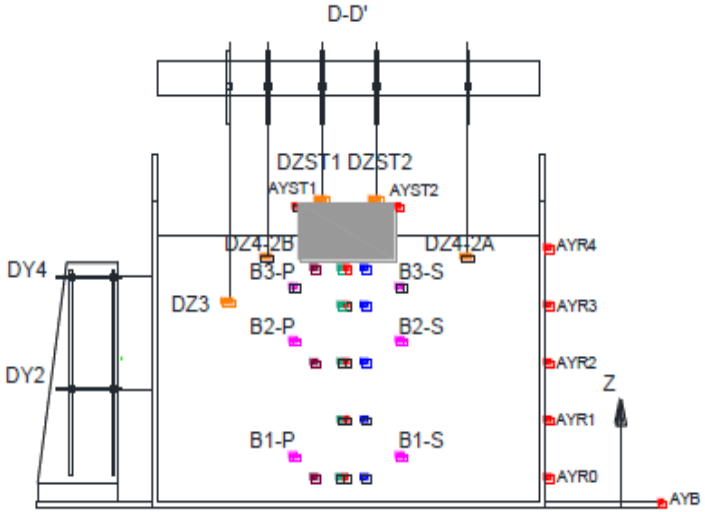
Free-field test specimen



SSI test specimen

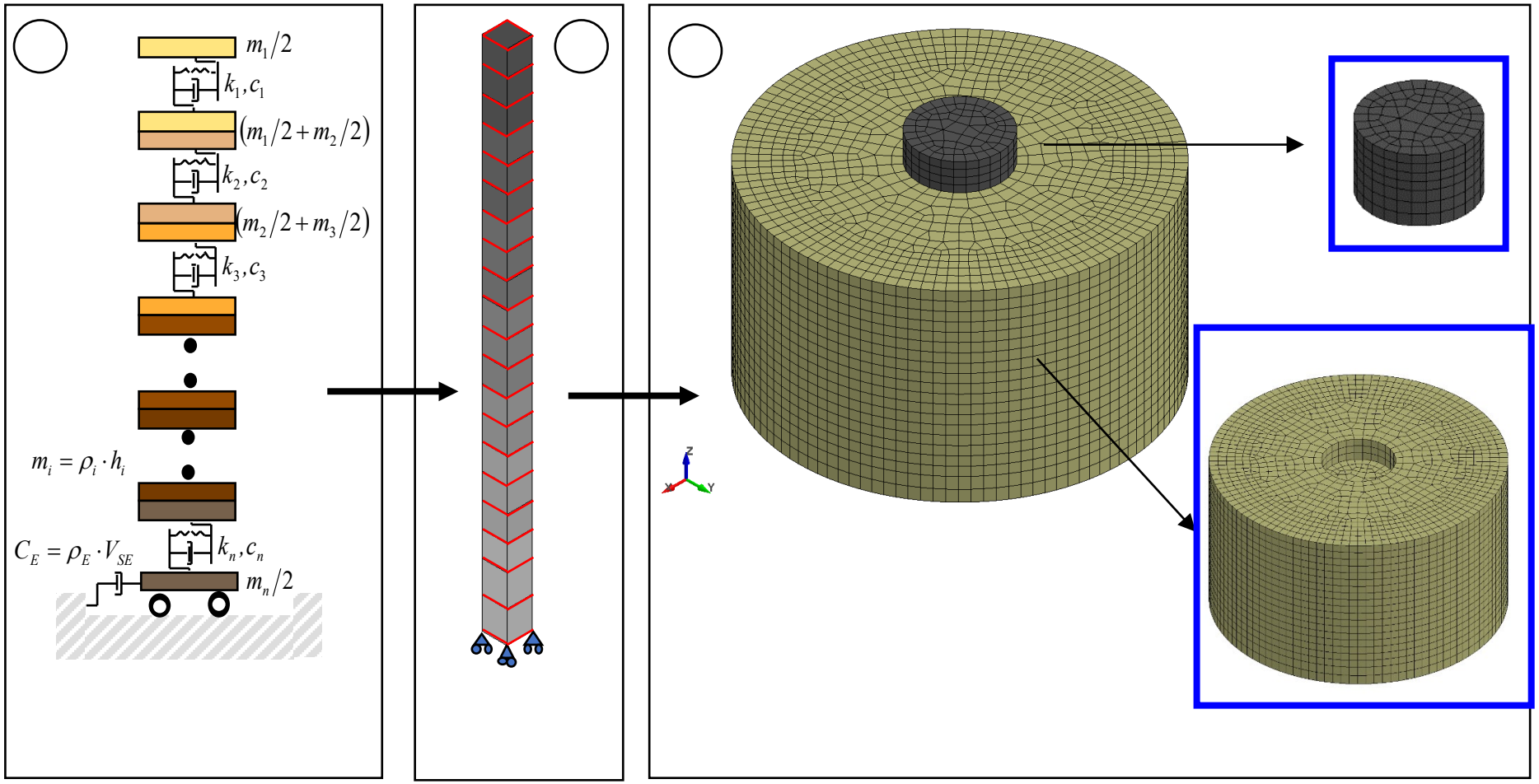
2D Laminar Container





- Uni-bi-directional broadband base excitations
- 95% relative density Ottawa 40/70 sand material

1-D to 3-D stepwise modeling approach



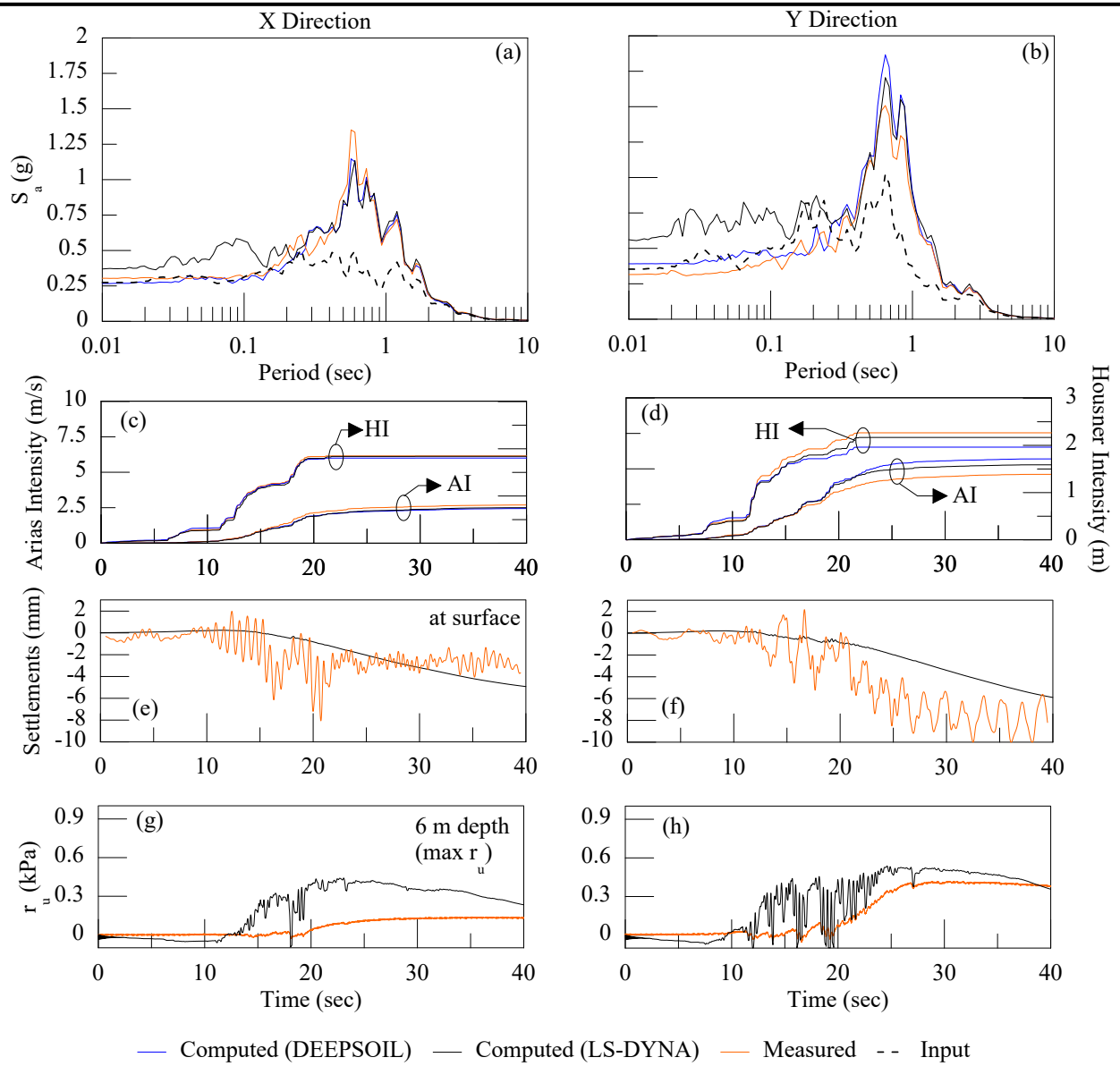
Rigid Steel Box with
YM: 200 GPa
Poisson's ratio : 0.3

- Profile from shear beam simulations
- Pressure dependency of constitutive model handles the effect of increase in confining pressure

- 1D Nonlinear site response => Shear beam => Three dimensional SSI

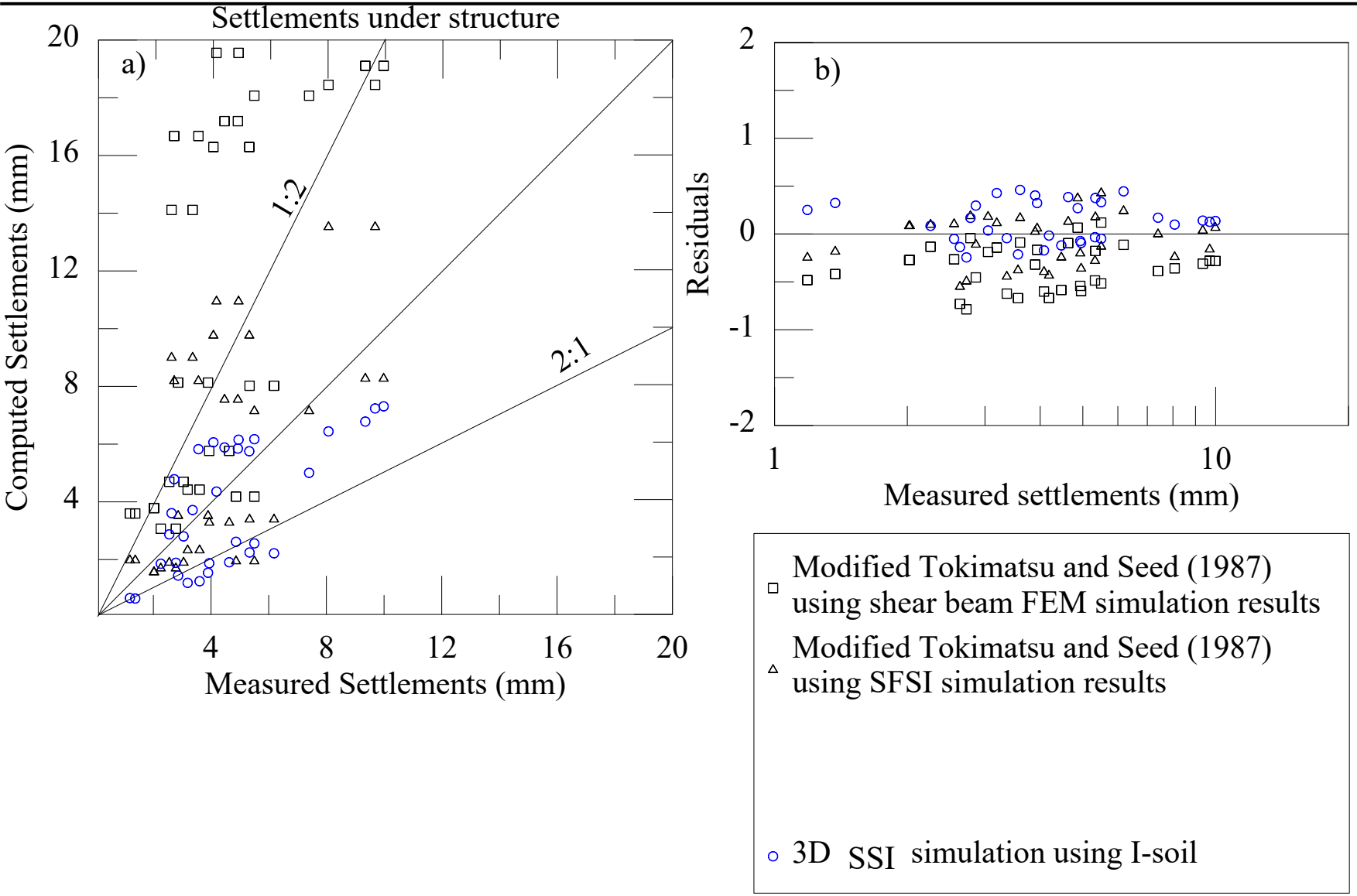
DEEPSOIL LS-DYNA LS-DYNA

Representative model- experiment comparisons
Seismic Settlement of Dense Sand

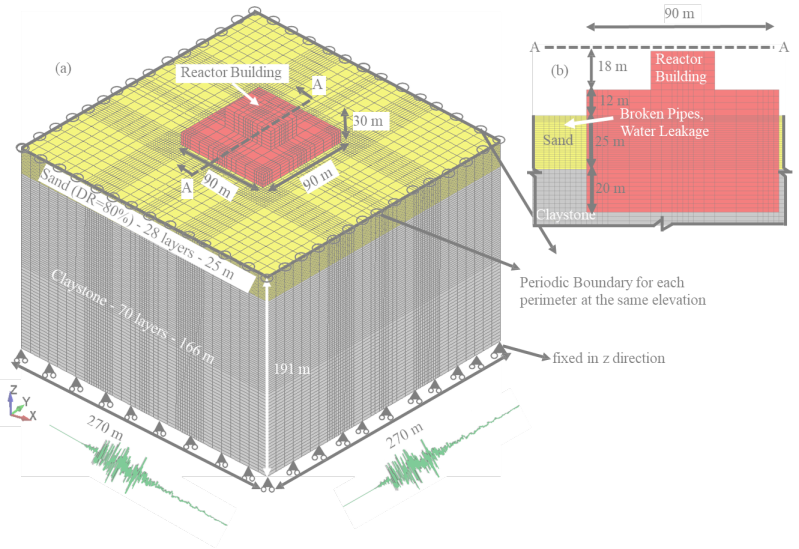


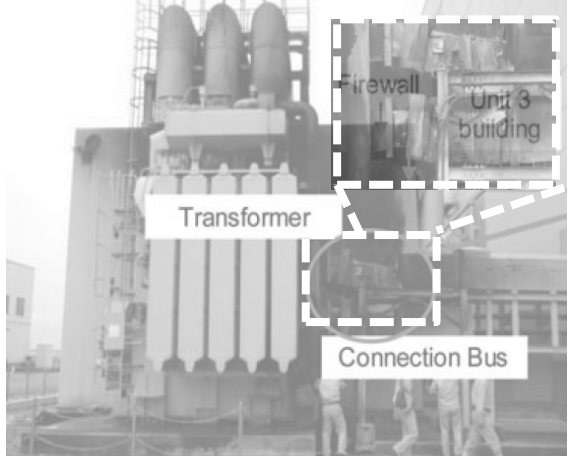
- Spectral response
- Housner and Arias intensities
- Seismic settlements
- Normalized excess porewater pressures
- Representative results for Landers event

Structure settlements: Modified Tokimatsu and Seed (1987) method + multi-dimensional SSI simulations



- With the help of FEM and I-soil on estimation of the effects of structure on soil behavior (increased confinement), much better empirical estimations were achieved.
- Strains were extracted from central array under the structure

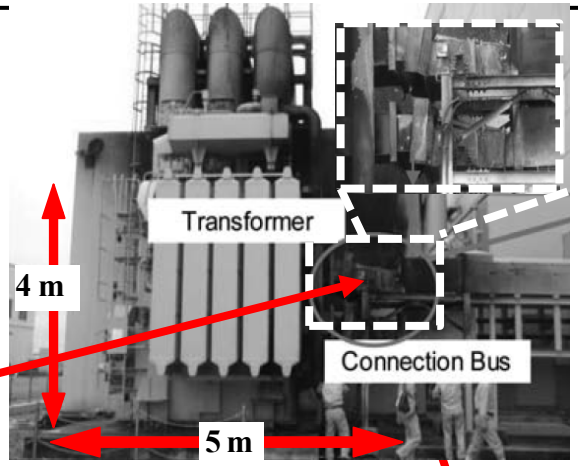




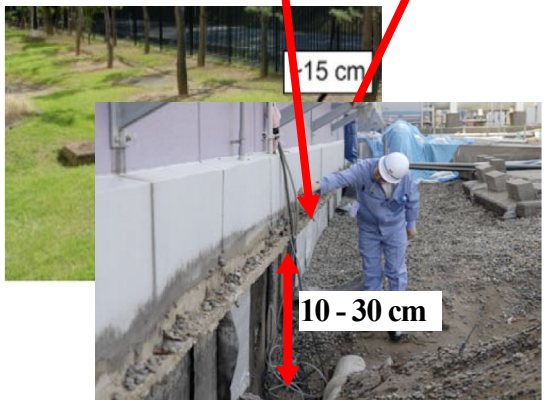
Numerical Simulations of Kashiwazaki-Kariwa Nuclear Power Plant, Japan

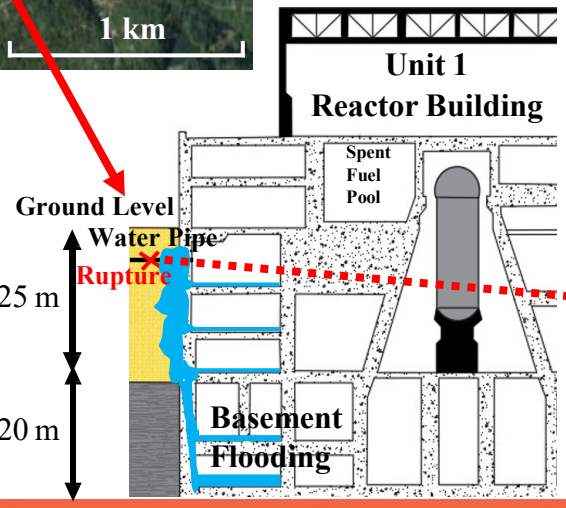
Alvin Bayudanto, Ozgun A. Numanoglu, Youssef M.A. Hashash

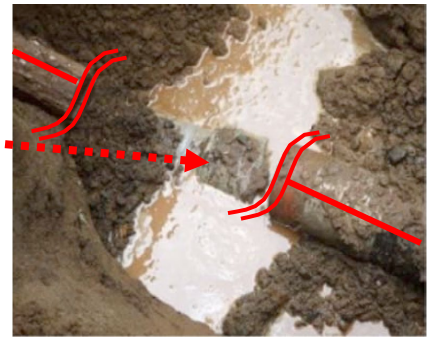
Summary of Geotechnical Problems and Objective of Study



SEISMIC SETTLEMENTS at KKNPP







Problems:

- Free-field ground subsidence at Service Hall
- Differential settlements at Unit 1 Reactor Building that caused broken water pipes and flooding
- Differential settlements at Unit 3 Turbine Building and Transformer House that caused displaced duct, oil leakage, and fire
- Temporary shut down for survey and maintenance

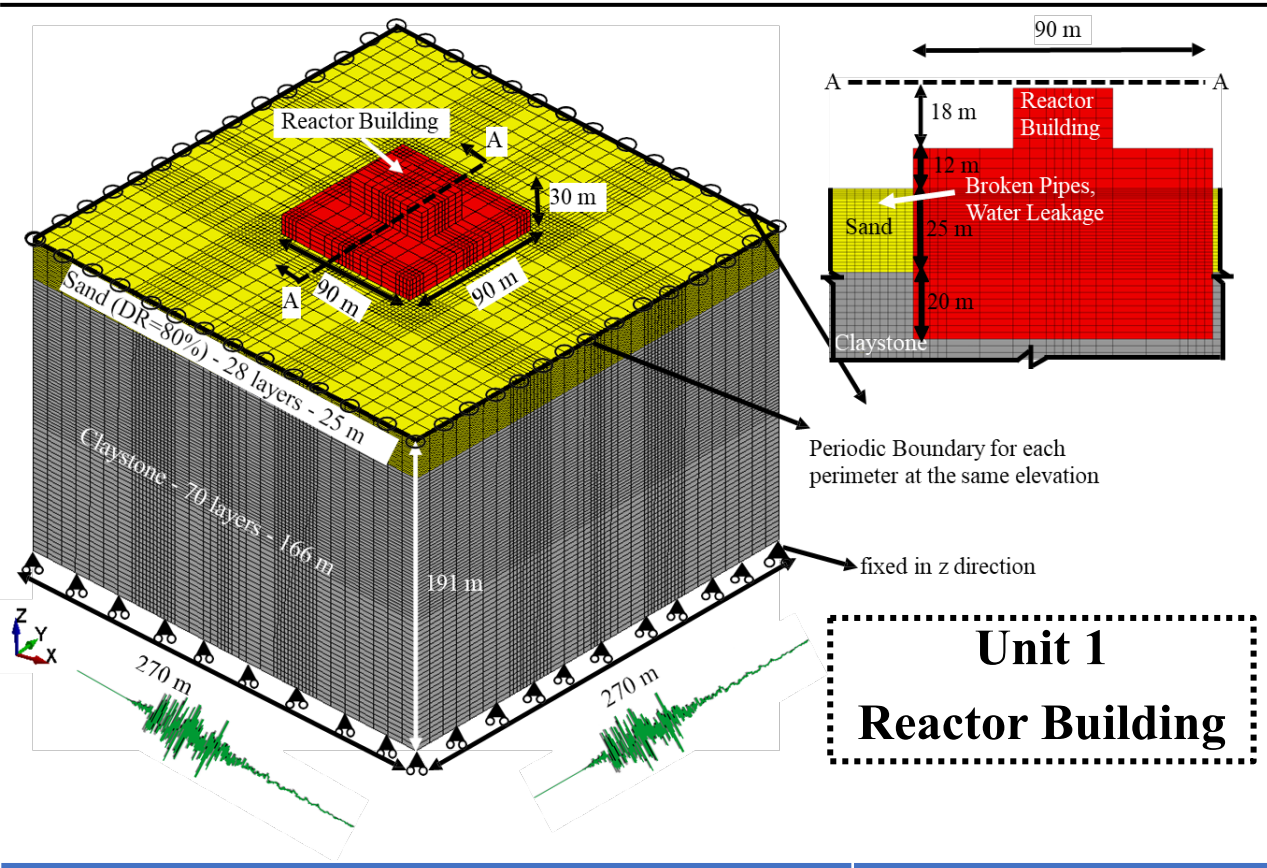
Objective of Study:

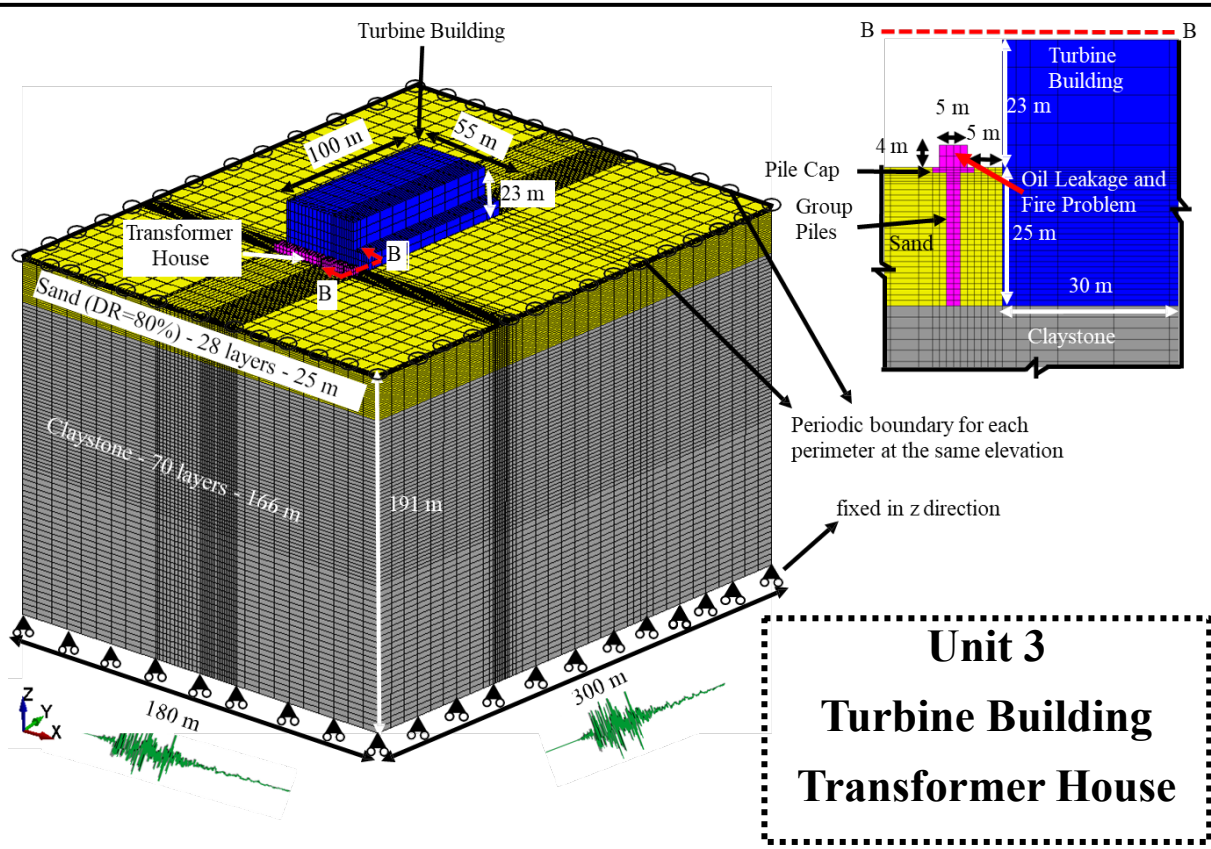
Utilizing I-soil in LS-DYNA to evaluate seismic settlements of nuclear power plant structures.

Sources:

PEER REPORT (2011)
Sakai et al. (2009)
TEPCO Report (2007)
Tokimatsu (2008)

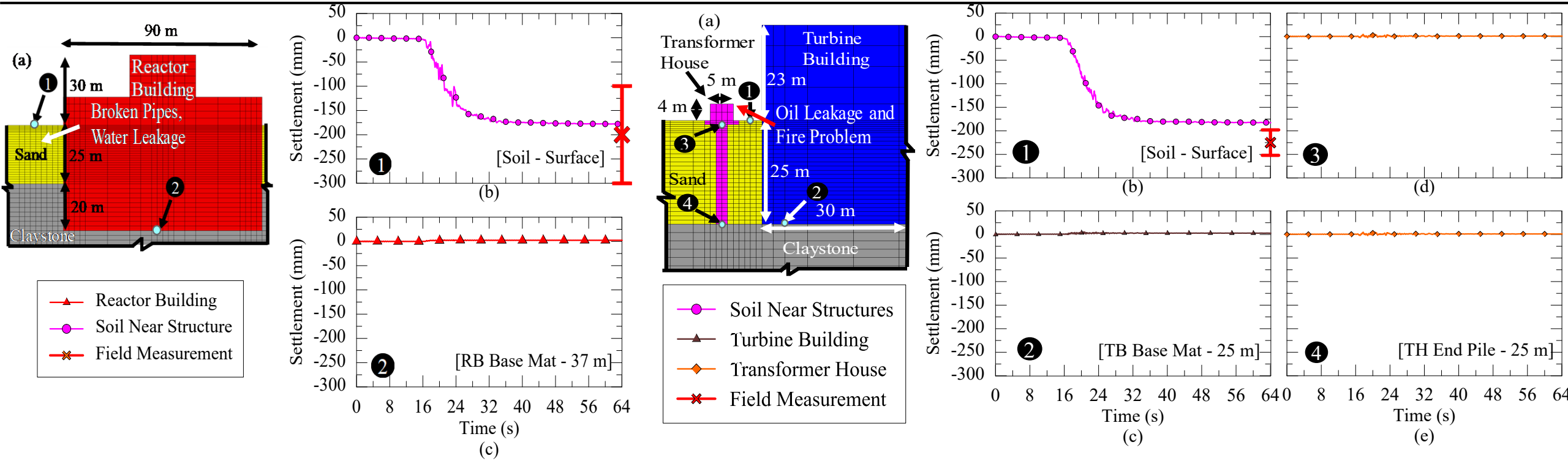
3-D Soil-Structure Interaction Model (SSI) – Bidirectional Simulations





	Unit 1 Reactor Building	Unit 3 Turbine and Transformer House
Computational Platform	I-soil (Numanoglu, 2019) in LS-DYNA	I-soil (Numanoglu, 2019) in LS-DYNA
Number of Solid Elements	247,080	226,257
Number of Cores	4 physical and 4 logical cores	4 physical and 4 logical cores
Computational Time (64 seconds motion duration)	15 hours 9 minutes 57 seconds	23 hours 12 minutes 44 seconds

3-D SSI Seismic Settlements – Measurement vs Numerical Simulations



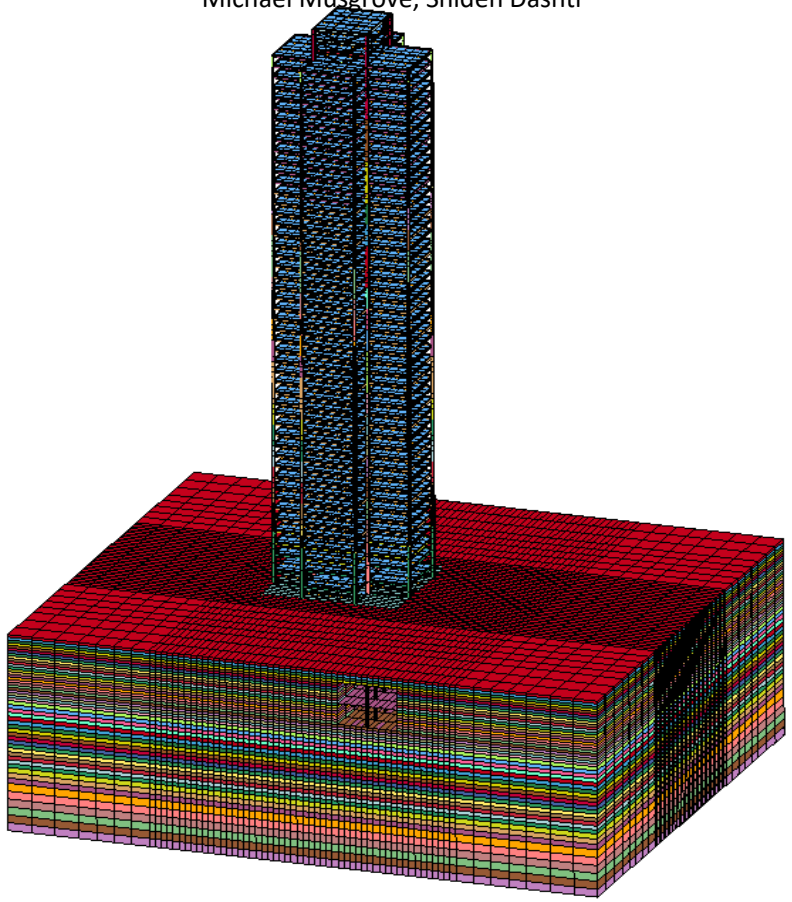
	Unit 1 Reactor Building	Unit 3 Turbine and Transformer House
Settlement of Structures	Negligible	Negligible
Settlement of Soil Near Structures	17.5 cm	18 cm
Findings	Numerical simulations agreed well with measurement	Numerical simulations captured the observed settlement

Other problems – simulations calibrated with centrifuge experiments

Simulation of Soil-Structure-Underground Structure Interaction

Yuamar Basarah, Ozgun A. Numanoglu, Youssef M.A. Hashash,

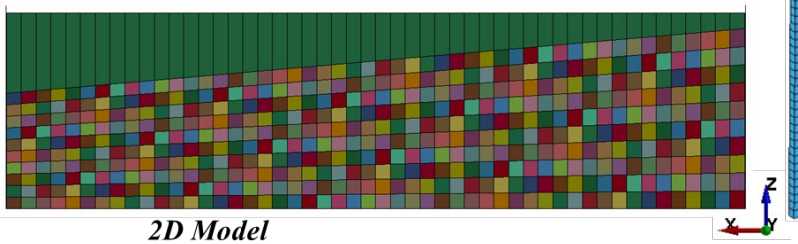
Michael Musgrove, Shideh Dashti



Numerical Modeling of LEAP Centrifuge Test

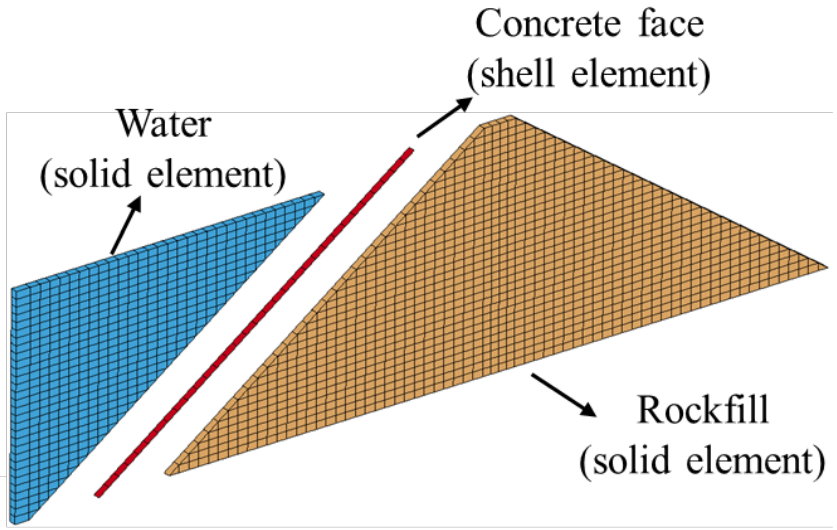
Guangchao Xing, Ozgun A. Numanoglu,

Maria Kontari, Youssef M.A. Hashash



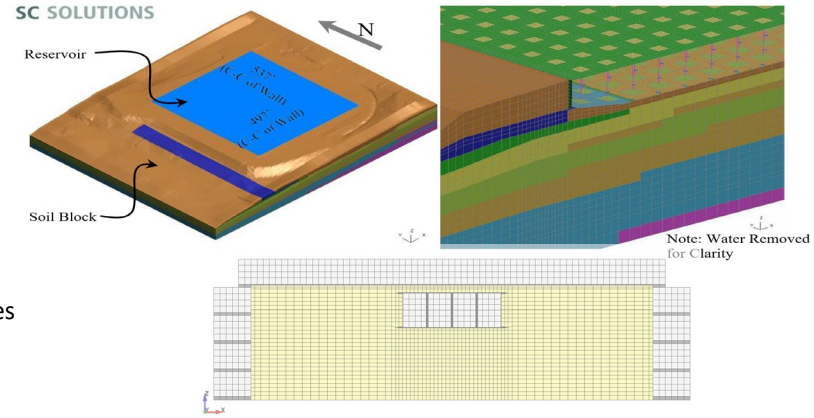
Numerical Simulation of a Concrete Faced Rock-fill Dam

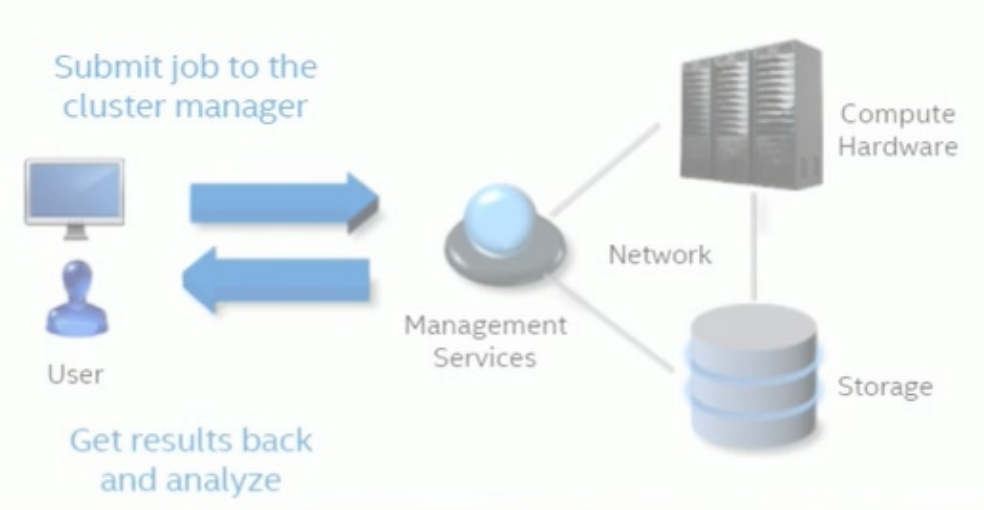
Muhsin Acar, Ozgun A. Numanoglu, Youssef M.A. Hashash



Seismic Fluid-structure-soil Interaction of Buried Water Reservoirs

Karim AlKhatib, Youssef M.A. Hashash, Katerina Ziotopoulou, James Heins, Brian Morales

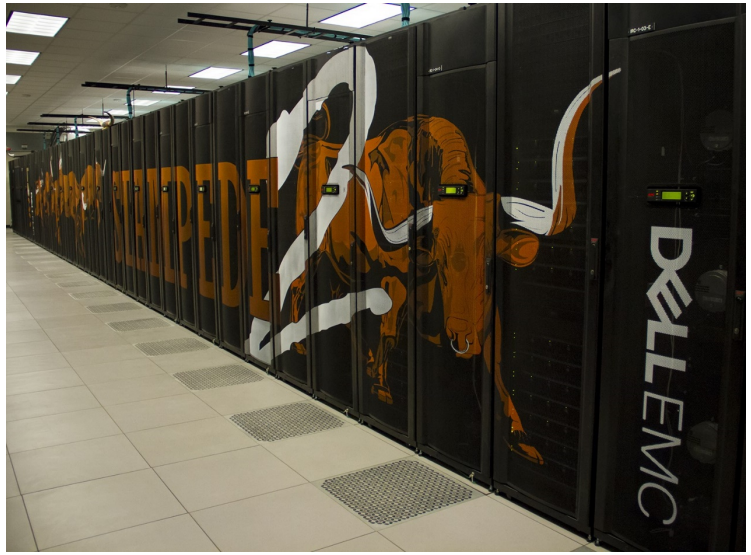




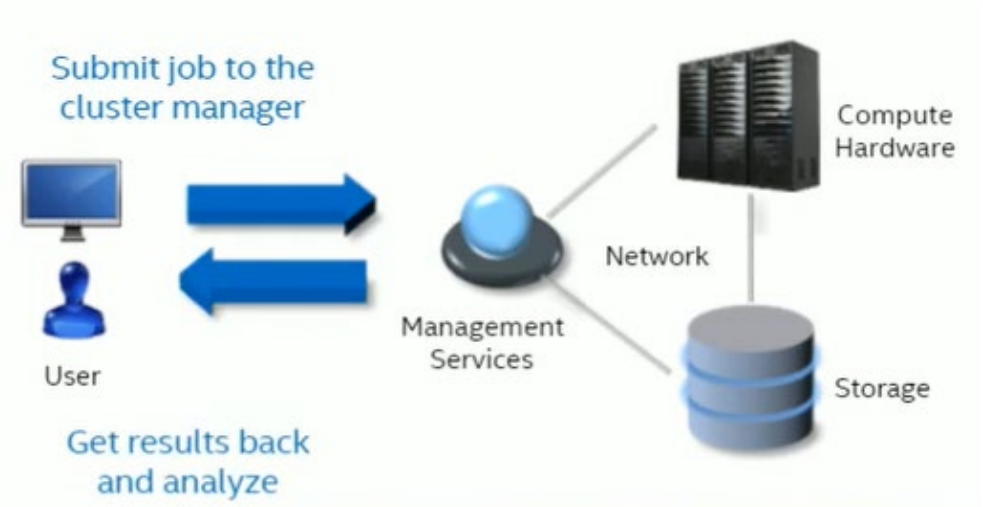
High Performance Computing (HPC)

Computational Platform for Large-scale Simulations

- Running large scale of simulations to evaluate the uncertainties
- Needs more powerful computer resources
- Using high performance computing (HPC) or supercomputer
  - Contains thousands of compute nodes (servers) that work together to complete tasks faster (parallel processing)
  - Submit a single job up to 6,144 cores with 128 nodes at one time
  - Max durations: 48 hrs/job
  - Max jobs in queue : 25 jobs



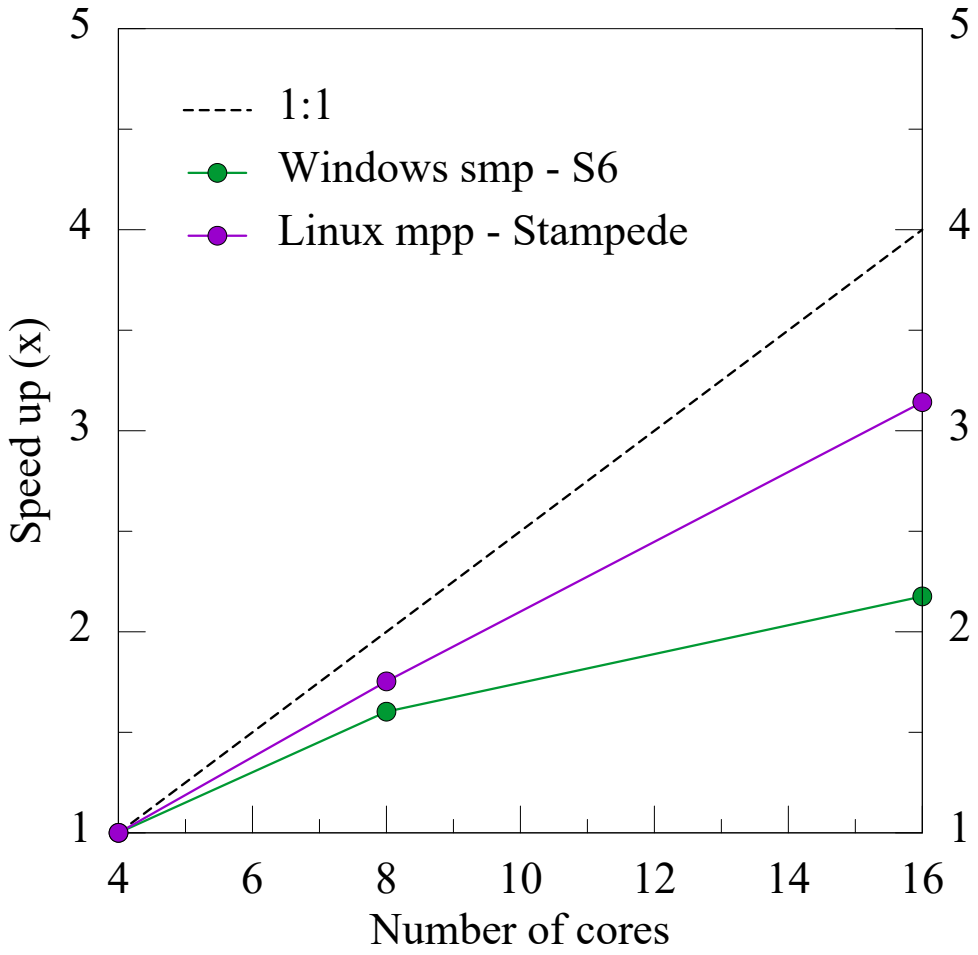
HPC Stampede in Texas Advanced Computing Center

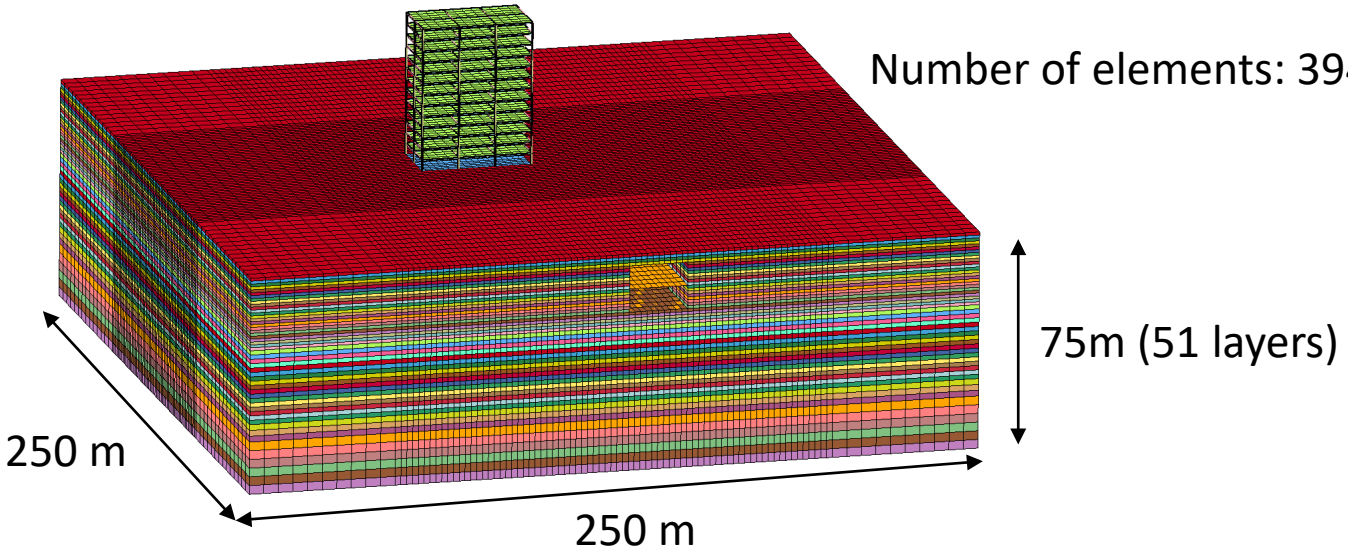


Source: Introduction to HPC https://www.youtube.com/watch?v=bkLVuNfiCVs

Example of runtime comparison (Tall building-tunnel)

Stampede vs Single server





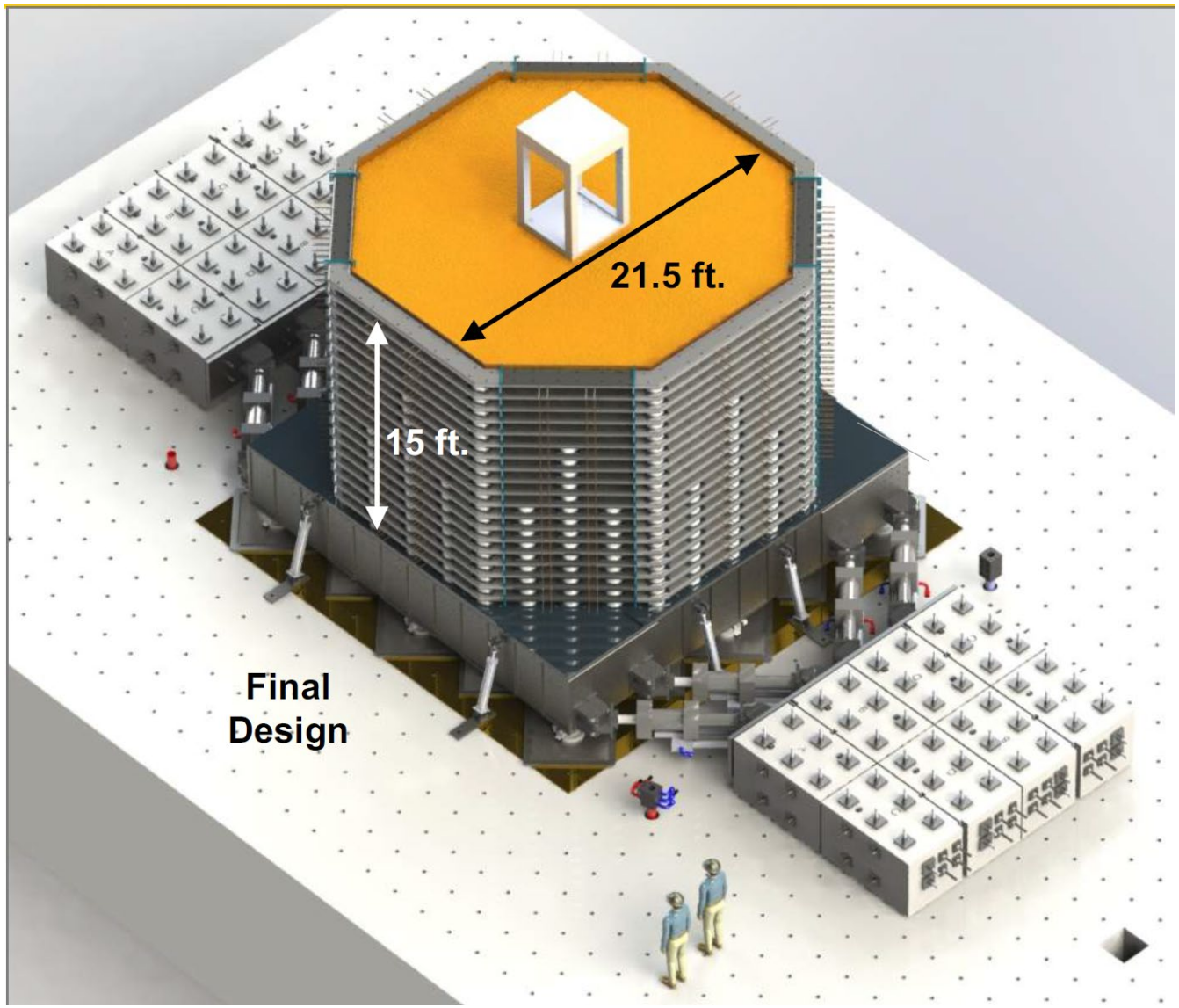
Number of elements: 394,958

For 32.7 s of simulation

Machine	No of cores	Runtime
Single server	12	25 hr
HPC on Stampede	12	11 hr

Role of large scale testing facilities

- All the considered simulations based on centrifuge experiments or field performance studies.
- Large scale testing facilities will provide importance additional capabilities to further enhance fidelity of simulations.
- Experimental cost and time considerations.
- In-place soil characterization
- Reproduce selected existing centrifuge experiments?
- Interface behavior?



Conclusions and Engineering Implications

- Advances in analysis software, computing hardware, and big data management tools has enabled a new era in the analysis of complex nonlinear seismic soil-structure interactions (SSSI) in three dimensions (3D). Multiple available platforms.

- Three-Dimensional SSSI modeling, with relatively simplified soil models, was successfully employed in analysis of complex engineering problems including: (a) settlement of heavy structures on dense sand, (b) tall building-tunnel interaction, (c) soil liquefaction, (c) concrete-face rock fill dams, (e) buried water supply reservoirs.

- Large scale testing facilities provide important data for further validation of SSI simulations.

- *If interested:* The presented new constitutive model (I-soil) that is calibrated, tested, and implemented in the numerical analysis platform LS-DYNA is computationally efficient and easy to use *and available upon request – Contact: hashash@illinois.edu* .

- Expanded presentation (KGS 2021 Lecture):
  - https://www.youtube.com/watch?v=sQZHOxe_p-Q

Thank you

Questions?