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

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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:

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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
  - Significant settlement in Kashiwazaki NPP, 2007 Chuetsu EQ
  - Collapse of subway station
    - 1995 Kobe EQ
  - Wall failure in buried reservoir
    - Reservoir wall failure
  - Liquefaction induced building movement
    - 1999 Kocaeli EQ
  - Cracks in Concrete Face Rockfill Dam @ joints
    - Regional connector
  - Tall building-excavation
    - 2008 Wenchuan EQ
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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

**Fixed base model**

**Springs at foundation level only**

**Bathtub model with springs**

**Complete System**

No SSI Modeling → Complete SSI model
Outline

• Motivation

• State-of-the-practice modeling methods

• Considerations for seismic soil-structure interaction modeling
  o Input: Site investigations and ground motions
  o Elements of seismic soil-structure interaction analysis
  o 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
• 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
  o Advances in soil constitutive modeling (I-soil)
  o Seismic settlement of heavy structures on dense sands
  o Other problems
  o Computational considerations

• Conclusions and engineering implications
Advances in Soil Constitutive Modeling (I-soil)

Ozgun A. Numanoglu, Youssef M.A. Hashash

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United States Nuclear Regulatory Commission
Protecting People and the Environment
Conceptual Constitutive Model for Seismic Behavior of Sands

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


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

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

• Not included
  o Plasticity due to hydrostatic loading
  o Anisotropy
  o 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

- 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

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

\[
\tau(\gamma) = \sum_{c=1}^{m} \tau^c_y + \sum_{c=m+1}^{n} G^c \gamma
\]

\( i = 1:m \) non-yielded
\( i = m+1:n \) yielded components

Allows representation of normalized modulus reduction

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

Piece-wise linear backbone made of 4 user defined points
Volumetric Response Calibration: $\eta_{dsr}$

- Values between 0.4 – 0.8 with mean value of 0.51 for 10 – 1200 kPa, 40 – 95% $D_R$
- $\eta_{dsr} = 0.51 \Rightarrow \phi'_{dsr} = 31^0 \leq \phi'_{critical \ space} (or \ constant \ volume) = 30^0 - 32^0$
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

![Diagram showing constant volume cyDSS with measured and computed data for different cycles.](image)
For a given trial, the aim is to keep the residuals near zero value throughout shearing.
Input Parameters

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

- Uni-bi-directional broadband base excitations
- 95% relative density Ottawa 40/70 sand material
1-D to 3-D stepwise modeling approach

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

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

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

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

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)
Tokimatsu (2008)
3-D Soil-Structure Interaction Model (SSI) – Bidirectional Simulations

| | Unit 1 Reactor Building | Unit 3 Turbine and Transformer House |
|----------------------------|-------------------------------------|
| 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 |

May, 2021

Hashash et al (2021)
**3-D SSI Seismic Settlements – Measurement vs Numerical Simulations**

<table>
<thead>
<tr>
<th>Unit 1 Reactor Building</th>
<th>Unit 3 Turbine and Transformer House</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settlement of Structures</td>
<td>Negligible</td>
</tr>
<tr>
<td>Settlement of Soil Near Structures</td>
<td>17.5 cm</td>
</tr>
<tr>
<td>Findings</td>
<td>Numerical simulations agreed well with measurement</td>
</tr>
<tr>
<td></td>
<td>Numerical simulations captured the observed settlement</td>
</tr>
</tbody>
</table>

- **Settlements**: The settlements of the structures were negligible, while the soil near the structures showed measurable settlements.
- **Findings**: The numerical simulations matched well with the measured data. Numerical simulations accurately captured the observed settlements.
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 Simulation of a Concrete Faced Rock-fill Dam
Muhsin Acar, Ozgun A. Numanoglu, Youssef M.A. Hashash

Numerical Modeling of LEAP Centrifuge Test
Guangchao Xing, Ozgun A. Numanoglu,
Maria Kontari, 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=blkVuN6CVs](https://www.youtube.com/watch?v=blkVuN6CVs)
Example of runtime comparison (Tall building-tunnel)

Stampede vs Single server

For 32.7 s of simulation

<table>
<thead>
<tr>
<th>Machine</th>
<th>No of cores</th>
<th>Runtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single server</td>
<td>12</td>
<td>25 hr</td>
</tr>
<tr>
<td>HPC on Stampede</td>
<td>12</td>
<td>11 hr</td>
</tr>
</tbody>
</table>

Number of elements: 394,958

Number of layers: 51 layers

75 m (75 meters)
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?