Use of Nonlinear, Time Domain Analysis for Design

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Outline

Introduction

Nonlinear ESSI in Design

Summary
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Nonlinear ESSI in Design

Summary

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Nonlinear ESSI for Design
Motivation

- Improve seismic design, safety and economy, of Nuclear Power Plants (NPPs)
- Follow seismic energy within NPP ESSI system
- Accurate, high fidelity numerical modeling and simulation of Nonlinear Earthquake Soil Structure Interaction (ESSI), in time and space, for realistic analysis of NPP response
- Use realistic nonlinear ESSI for design!
Predictive Capabilities

► High fidelity, accurate modeling and simulation: Verification and Validation

► Verification provides evidence that the model is solved correctly. Mathematics issue.

► Validation provides evidence that the correct model is solved. Physics issue.

► Verification and validation (V&V) require huge effort!

► Verification procedures in development

► Validation almost non-existent (new U.S. DOE project will add significantly to ESSI validation data base)

► Modeling and Parametric Uncertainties (sensitivity studies are very important)
Uncertainties

- **Modeling Uncertainty**: important features are neglected (6D ground motions, inelasticity), unrealistic and unnecessary modeling simplifications

- **Parametric Uncertainty**: spatial variability, measuring and transformation errors

Transformation of SPT $N$-value: 1-D Young’s modulus, $E$
(cf. Phoon and Kulhawy (1999B))

$E = (101.125 \times 19.3) \times N^{0.63}$
Realistic, Nonlinear ESSI Modeling

- Nonlinear behavior
  - Nonlinear, inelastic (saturated or dry) soil/rock
  - Nonlinear, inelastic (saturated or dry) contact
  - Nonlinear, inelastic structures, systems and components
  - Buoyant (nonlinear) forces

- Full 3D (6D) Earthquake motions

- Uncertain material and loads

- Verification and validation for accurate numerical simulations

- Real ESSI Simulator (developed in collaboration and with the support of NRC, CNSC, DOE)
Realistic, nonlinear ESSI for Design

- Design standards require structure to be elastic
- Anything below foundation can be modeled as nonlinear
- Possible reduction of demand due to nonlinearities in soil/rock and contact zone
- Assessment of NPP designs using sweeps of earthquakes/motions and realistic nonlinear ESSI analysis
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Earthquake Motions

- Earthquake record: Taiwan SMART1(45), Time: 11/14/1986, Station: SMART1 E02.

- Horizontal #1: 100%, horizontal #2: 40%, vertical: 40%

- Full application of 3D motions, no superposition allowed (nonlinear analysis)
Earthquake Motion Input into FEM Model

- Domain Reduction Method (Bielak et al.)
- Capable of accurately inputting all body (P, SV, SH) and surface (Rayleigh, Love, etc.) earthquake waves into a finite element model
- Free field motions needed for input effective forces
- Radiated waves from the structures leave the system
- Inside DRM finite element layer can be fully nonlinear (elastic-plastic)
Finite Element Model

- Soil/Rock, solids, linear elastic (can be fully elastic-plastic)
- Contact (soil/rock – foundation slab) fully nonlinear, Coulomb friction (friction coefficient $\mu = 0.5$, taking into account plastic sheets beneath foundation) and gaping
- Structure (stick model) linear elastic (can use a far more sophisticated structural model, however this is a demonstration)
- Seismic input using DRM
Foundation – Soil/Rock Slip

- Foundation slab slips significantly during an earthquake
- Base isolation (?!?) and energy dissipation
- Soil on the side restricts movements
- Minimal gaping as contact sleeps before slab lifts-off

Sliping of foundation

\[ D_x \text{ [cm]} \]

Time [sec]

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Nonlinear ESSI for Design
Nonlinear vs Linear Response, Top of Soil

- Reduction in soil horizontal demand
- Amplification of vertical due to pounding upon contact
- Soil horizontal and vertical peaks at the same frequency, hence vertical motions are from a Rayleigh surface wave
Nonlinear vs Linear Response, Foundation Slab

- Horizontal reduced at high frequency, due to slip,
- Horizontal slightly increased at low frequency, due to slip,
- Vertical reduced
Nonlinear vs Linear Response, Top of Containment

- Significant reduction of horizontal motions
- Reduction of vertical motions
Nonlinear vs Linear Response, Comments

- In general, significant reductions in motions for nonlinear response, both horizontally and vertically.

- Larger horizontal slip, low frequency response.

- Structure is still linear elastic (by modeling) and hence satisfies standard design.
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Nonlinear ESSI for Design
Concluding Remarks

- Nonlinear analysis can be used for design
- Potential for reduction of demand with realistic nonlinear analysis
- Assessment of NPP SSI systems using fully nonlinear, realistic ESSI analysis