Use of Nonlinear, Time Domain Analysis for Design

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Outline

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Motivation

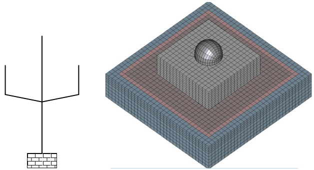
- Improve seismic design, safety and economy, of Nuclear Power Plants (NPPs)
- Follow seismic energy within NPP ESSI system
- Accurate, high fidelity numerical modeling and simulation of Nonlinear Earthquake Soil Structure Interaction (ESSI), in time and space, for realistic analysis of NPP response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

Predictive Capabilities

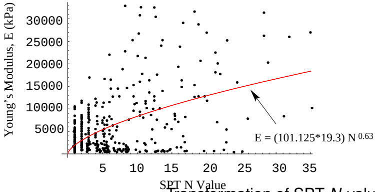
- High fidelity, accurate modeling and simulation: Verification and Validation
- Verification provides evidence that the model is solved correctly. Mathematics issue.
- Validation provides evidence that the correct model is solved. Physics issue.
- Verification and validation (V&V) require huge effort!
- 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)

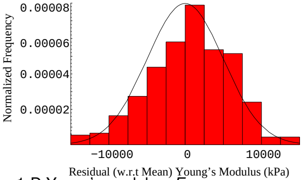
Uncertainties

- 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))

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
- Assesement of NPP designs using sweeps of earthquakes/motions and realistic nonlinear ESSI analysis

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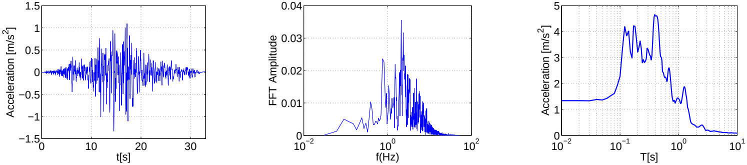
Earthquake Motions

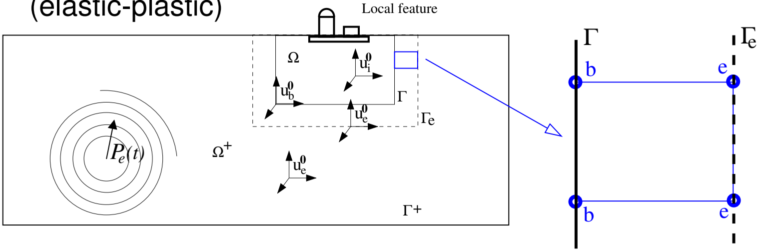
- Earthquake record: Taiwan SMART1(45), Time: 11/14/1986, Station:SMART1 E02.



- Horizontal #1: 100%, horizontal #2: 40%, vertical: 40%
- Full application of 3D motions, no superposition allowed (nonlinear analysis)

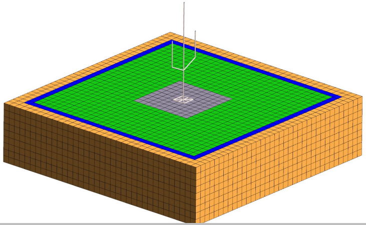
Earthquake Motion Input into FEM Model

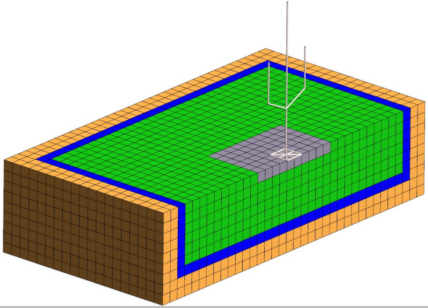
- Domain Reduction Method (Bielak et al.)
- Capable of accurately inputting all body (P, SV, SH) and surface (Rayleigh, Love, etc.) earthquake waves into a finite element model
- Free field motions needed for input effective forces
- Radiated waves from the structures leave the system
- Inside DRM finite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



Finite Element Model

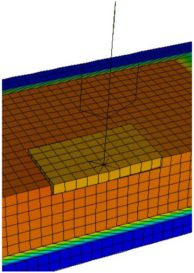
- Soil/Rock, solids, linear elastic (can be fully elastic-plastic)
- Contact (soil/rock – foundation slab) fully nonlinear, Coulomb friction (friction coefficient $\mu = 0.5$, taking into account plastic sheets beneath foundation) and gaping
- Structure (stick model) linear elastic (can use a far more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

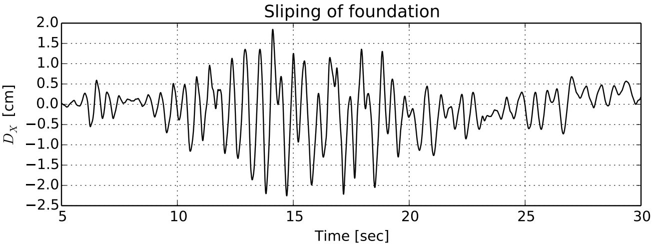




Foundation – Soil/Rock Slip

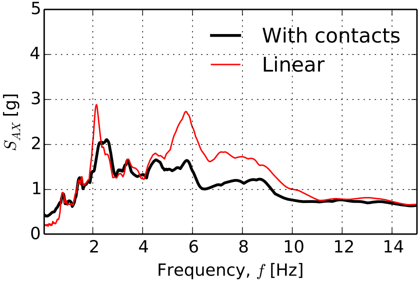
- Foundation slab slips significantly during an earthquake
- Base isolation (?!) and energy dissipation
- Soil on the side restricts movements
- Minimal gaping as contact sleeps before slab lifts-off



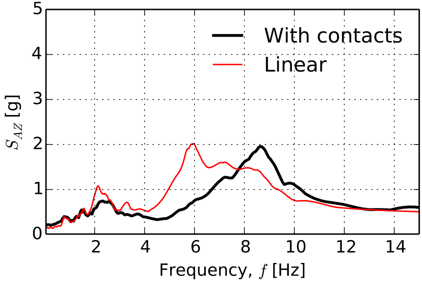


Nonlinear vs Linear Response, Top of Soil

- 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



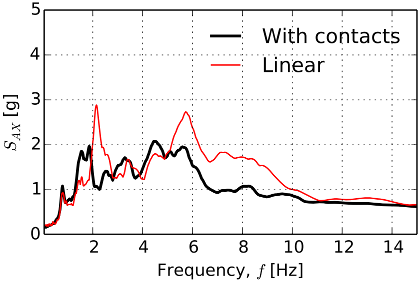
horizontal



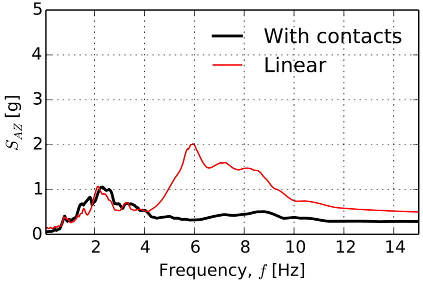
vertical

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



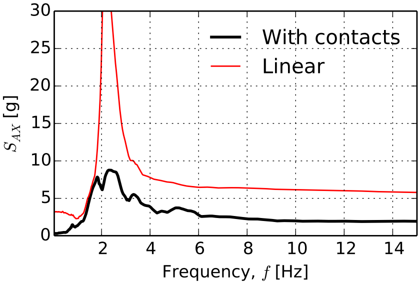
horizontal



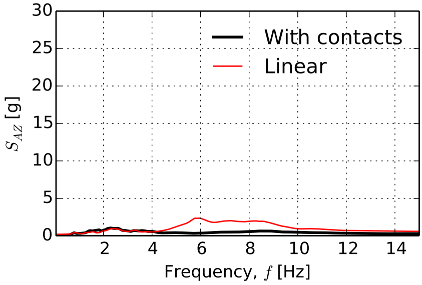
vertical

Nonlinear vs Linear Response, Top of Containment

- Significant reduction of horizontal motions
- Reduction of vertical motions



horizontal



vertical

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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Concluding Remarks

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