A Modern Computational Framework for the Nonlinear Seismic Analysis of Nuclear Systems

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The DOE owns an extensive inventory of unique, mission critical facilities.
For DOE, there is motivation for full realization of a performance based approach.
DOE was out front in developing the first performance based design standard

LLNL led development of the DOE standards for seismic design and evaluation

DOE Standard 1020

DOE Standard 1020 ASCE 43-05

Establishes Performance Goal (Risk) Based Seismic Design Criteria

Reg. Guide 1.208

1973

Reg. Guide 1.60

1994

Reg. Guide 1.165

2005

Reg. Guide 1.208

2007

These standards were adopted by the NRC
The overall methodology relies on a strong blend of science and engineering.

**Hazard (Science-based)**
- Forcing Function
- From empirical data
  - Define Earthquake Motions Based on Probabilistic Seismic Hazard Analysis

**Risk (Engineering-based)**
- System Demands
- System Capacities
- From relevant engineering codes and standards
  - Evaluate System Component Force Capacities
  - Determine System Allowable Deformations

If...

Then...
Quantitative Performance Goal is Met
(e.g. Annual probability of exceeding limit state < 1 x 10^-5)
The UC Labs have developed models for quantifying demands in complex systems.
But, we have not paid as much attention to coupled soil-structure systems.

![Diagram showing PSHA and reactor models with soil, near-surface, and at-depth motions.]

- **PSHA**
  - Zonation
  - Recurrence
  - Hazard Curve
  - Attenuation

- **Reactor**
  - Control motions
  - Site response model
  - Near-surface motions
  - At-depth motions

- **SASSI**
  - 1970’s developments

- **Professor Lysmer UCB**
Our project is pursuing a fully nonlinear framework for performance-based design.

**Equivalent Linear (frequency domain)**

- Enhanced understanding for beyond design basis events
- Full realization of performance-based design
- More realism for truly nonlinear systems

**Nonlinear (time domain)**

- Soil
  - Shear Modulus
  - Damping

- Structure

- Multi-D
We have assembled a multi-institution, multidisciplinary team

Dr. McCallen  Dr. Jeremic  Prof. Buckle  Dr. McKenna

Dr. Wong  Dr. Petrone  Dr. Rodgers  Dr. Pitarka

Dr. Levin  Dr. Goodwin
Project element #1
A state-of-the-art, HPC code

Combined with advanced nonlinear structural element technology

Start with strong geo-mechanics and robust nonlinear algorithms

To model fully coupled soil-structure systems
Project element #2
Systems analysis and V&V is crucial

Inter-code comparisons for verification

Comparison with data and analytical solutions for validation
Finite deformation, fiber-based nonlinear steel beam element

120 inches length
W 14 x 159 cross section

Comparison of multiple beam elements for an elasto-plastic problem with kinematic hardening
Steel system inter-code comparisons

Figure 1. Three Story Steel Moment Frame Building designed for UBC Zone 3

Taiwan 1 Nonlinear Response

Turkey Nonlinear Response

Taiwan 2 Nonlinear Response
Finite deformation, fiber-based nonlinear reinforced concrete beam element
Concrete system inter-code comparisons

Taiwan 1 Nonlinear Response

Taiwan 2 Nonlinear Response

Turkey Nonlinear Response
We are currently working on element technology for concrete shear walls

Four node shell of Dvorkin and Bathe

Data for Validation
Project element #3
Confront SSI system simulations with data

Create an experimental capability for SSI phenomenon and code validation
An experimental laminar soil box system

Vertically Propagating Shear Waves
We will build a *big* and *smart* soil box

**New Laminar Box**

- **24 ft. diameter**
- **20 ft. deep**
A fundamental requirement is the ability to induce nonlinear system behavior.

Amplitude-dependent response (Measured vs. linear simulation vs. nonlinear simulation)

The ability for the box to shake into the nonlinear regime is crucial to our overall objectives.
After extensive analysis and design our experimental system is converging.
We are evaluating a capability to perform measurements of dynamic soil properties.

3D simulations generating synthetic data to assess soil box tomography.

Volumetric Strain (P-waves)
Rotation (S-waves)
Radial Displacement [nm]
Vertical Displacement [nm]
Evaluate the significance of complex incident seismic waveforms (multi-dimensional wavefields)

Classical idealizations  Versus  Rigorous waveforms

3D Geophysics model provides 3D wavefield at surface “Pt A”
Assuming vertically propagating shear waves, deconvolve with 1D site response code to base at “B-B”
Utilize motions at “Pt B” as assumed vertically propagating shear wave input to NF SSI model

- 3D Geophysics model provides 3D wavefield at surface Γ for input to NF SSI model
A 3D parametric rock / basin model has been developed for SW4

Fault rupture model for $M_w=6.5$ earthquake

Rupture hypocenter
A 3D parametric rock / basin model has been developed for SW4
Our end-game objectives

- Increased understanding of the differences between…
  - Nonlinear vs. equivalent linear vs. linear response in an SSI setting

- A modern, validated computational tool for facility seismic analyses – available to the DOE enterprise
  - Element technology tailored to civil structures (both steel and concrete)
  - Moment frames, braced frames, shear walls
  - Soil library

- Increased understanding of the influence of complex, 3D incident seismic waveforms
We have assembled an External Advisory Board of eminent experts
We have developed a formal collaboration with the Japanese on advanced simulation

Technical Meeting of the Civil Nuclear Energy Research and Development Working Group

Tokyo, Japan
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