Fukushima NPP: Damage, Inelastic Behavior
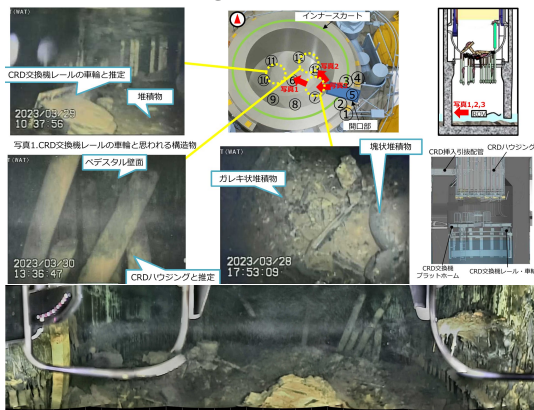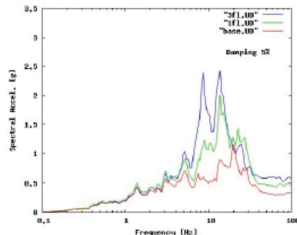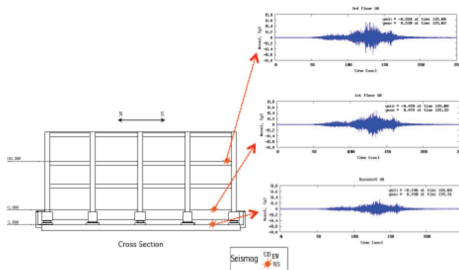

Control Rod Drive System <u>DAMAGE</u> [TEPCO, 2023]

+

Loss of Coolant Accident, <u>LOCA</u> [Japanese Diet NAIIC, 2012]

Fukushima NPP: Vertical Isolator Amplification +80%

Base isolation, VERTICAL amplification (!) [JAEE/LLNL, 2012]

Assessing and Increasing Resilience of Nuclear Energy Facilities for Dynamic, Seismic Loads

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Motivation

Improve static and dynamic analysis of Soil-Structure Interaction (SSI) for Nuclear Energy Facilities (NEF)

Inelastic behavior of NEF SSI systems is always present

Reduce modeling uncertainty

Improve analysis sophistication level

Analyze, propagate parametric uncertainty

Goal: Predict and Inform

Engineer needs to know all <u>what ifs!</u>

Dedication

Robert P. Kennedy, 1939-2018

"Response of a soil structure system is nonlinear, and I would really like to know what that response is!"

Nebojša Orbović, 1962-2021

"As an engineer, I have to know what are response sensitivities to modeling choices and model parameters."

Analysis of NEF Soil-Structure Systems

- Nonlinear, inelastic material behavior of SSI systems
    - Soil: always inelastic
    - Interfaces: always inelastic
    - Concrete: usually inelastic
    - Steel: sometimes inelastic

- Numerical analysis <u>has to</u> follow physics

- Numerical analysis programs to provide all necessary modeling (models, elements) and simulation (algorithms, methods) features

- Verification and Validation (QA) is really important
    - Quality of numerical discretization, algorithms (math.)
    - Quality of models (phys.)

Motivation
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Asses and Increase Resilience of NEF SSI
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Summary
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Resilient NEF SSI Systems

Stress Test Motions, Inclined Wave $\theta = 60^o$

Motivation
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Asses and Increase Resilience of NEF SSI
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Summary
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Resilient NEF SSI Systems

SMR ESSI, Variation in Input Frequency, $\theta = 60^{o}$

Seismic Energy Propagation in ESSI System

Energy input, forces/loads, static/dynamic

Energy dissipation outside SSI domain:
    SSI system oscillation radiation
    Reflected waves radiation

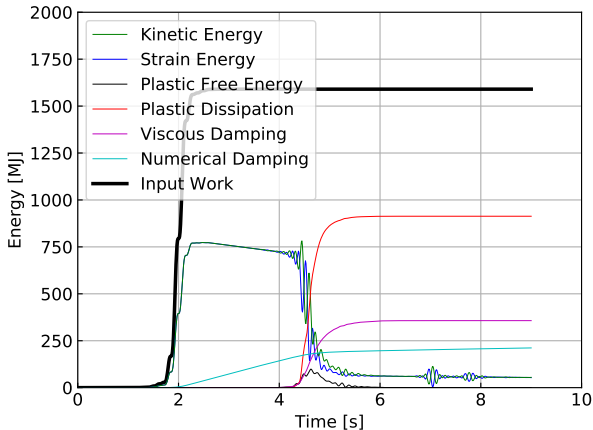Energy dissipation/conversion inside SSI domain:
    Inelasticity: soil/rock, interfaces, structure, dissipators
    Viscous coupling: internal, pore and external fluids
    Energy deflectors, meta-materials/meta-devices

Numerical energy dissipation/production

Motivation
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Asses and Increase Resilience of NEF SSI
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Summary
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Resilient NEF SSI Systems

Energy Dissipation Control, Analysis

Design Alternatives

Energy dissipation in structure   Energy dissipation in soil

More structural damage   Less structural damage

LWR NEF, Energy Dissipation

Resilient NEF SSI Systems

SMR NEF, Energy Dissipation

Forward and Bakward Uncertainty Propagation

Time Domain Stochastic Elastic-Plastic FEM
$M\ddot{u}_i + C\dot{u}_i + K^{ep}u_i = F(t)$

- Input random field and random process, non-Gaussian,
  heterogeneous/non-stationary: Multi-dimensional Hermite
  Polynomial Chaos (PC) with known coefficients

- Output response process: Multi-dimensional Hermite PC
  with unknown coefficients

<u>Results</u> $\rightarrow$ Probability Distribution Functions (PDF) ($u_i, \sigma_{ij}, \epsilon_{ij}$...)

<u>Sensitivities</u> $\leftarrow$ Sobol sensitivities to input uncertainties
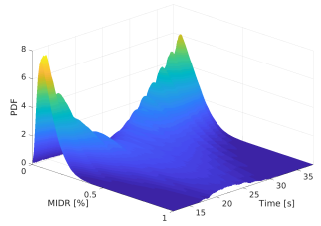
Sensitivity Example: Probabilistic SSI

- Uncertain material: uncertain random field, marginally lognormal distribution, exponential correlation length 10m

- Uncertain seismic rock motions: seismic scenario M=7, R=50km
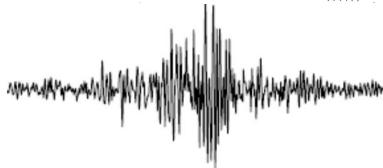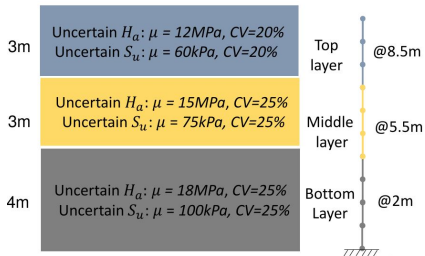
Seismic Risk Analysis

Engineering demand parameter (EDP): Maximum inter-story drift ratio (MIDR)

Resilient NEF SSI Systems
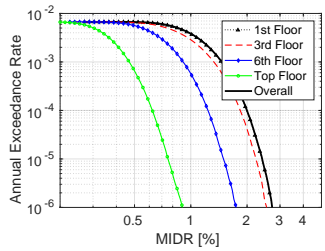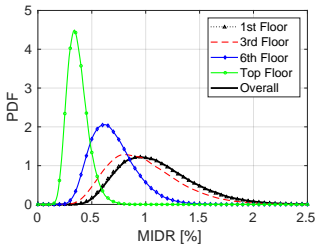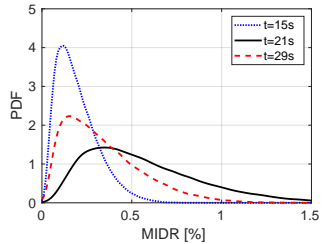
Sensitivity Analysis

Total variance in PGA, in this particular case (!), dominated by uncertain ground motions

49% from uncertain rock motions at depth

2% from uncertain soil

49% from interaction of uncertain rock motions and uncertain soil

Increase Resilience of NEF SSI Systems

1. Plasticity of soil, structure, and the soil-foundation interface

2. Energy dissipators, energy sinks

3. Viscous dampers and viscous coupling

4. External trenches

5. Meta-materials, meta-devices

UCDAVIS L·B·N·L
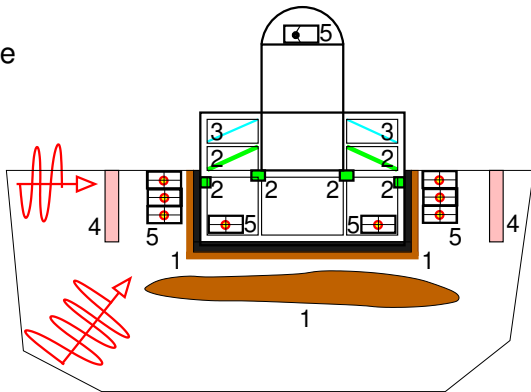
Summary

- Sophisticated, realistic analysis: improve design, safety

- Improved infrastructure economy, and (!) $CO_2 \downarrow$

- Education and Training is the Key !

- Analysis tool: Real-ESSI Simulator

- Students/PostDocs: Yang, Cheng, Tafazzoli, Feng, Yang, Sinha, Wang, Pisanó, Abell, Tafazzoli, Sett, Vilhar, Jeong, Jie, Preisig, Liu, Jain, Liao, Wu, Li, Tasiopoulou, Watanabe, Luo, Cheng, Yang, Kanellopoulos, Staszewska ...

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