Probabilistic Soil-Structure Interaction (SSI) Analysis of Nuclear Power Plant Structures for Seismic Probabilistic Risk Assessment (SPRA)

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DOE Natural Phenomena Hazards Workshop

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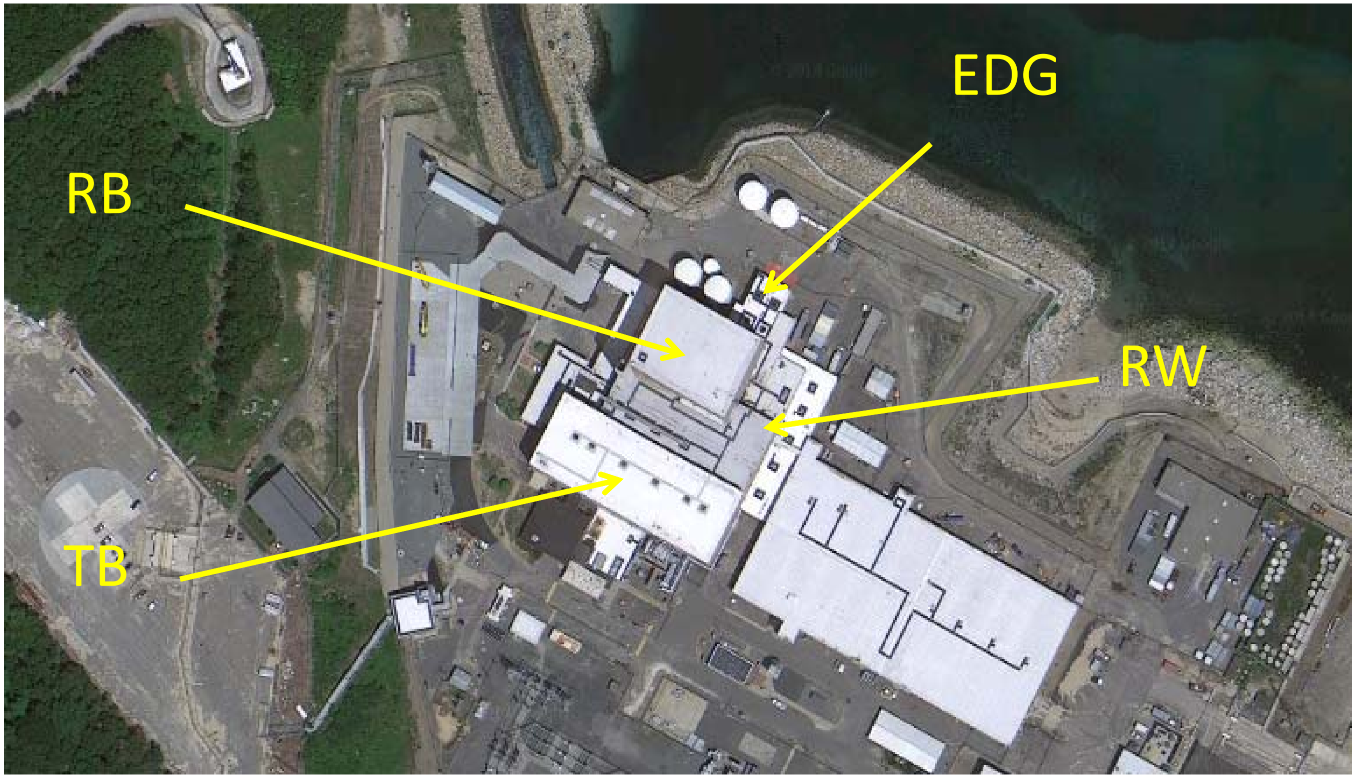
Introduction

- Initiated by NTTF 2.1 / post-Fukushima
- GMRS vs SSE screening → SPRA
- Considerations for re-evaluation of risk
  - Avoid unnecessary conservatisms in SPRA
  - More refined seismic demand with soil-structure interaction (SSI) to achieve more realistic risk
  - Particularly at challenging plants/sites
- High performance computing (HPC) for FEM detail within probabilistic SSI framework

Outline

- Plant Overview and Seismic Hazard
- SSI Challenges for SPRA
- Probabilistic SSI Approach
- SSI Analysis Studies and Statistics
- Final Probabilistic SSI Analysis - Sample Results
- Conclusions / Lessons Learned

Site Structure Layout



- Single-unit GE BWR
- Primary structures RB, TB, RW, EDG

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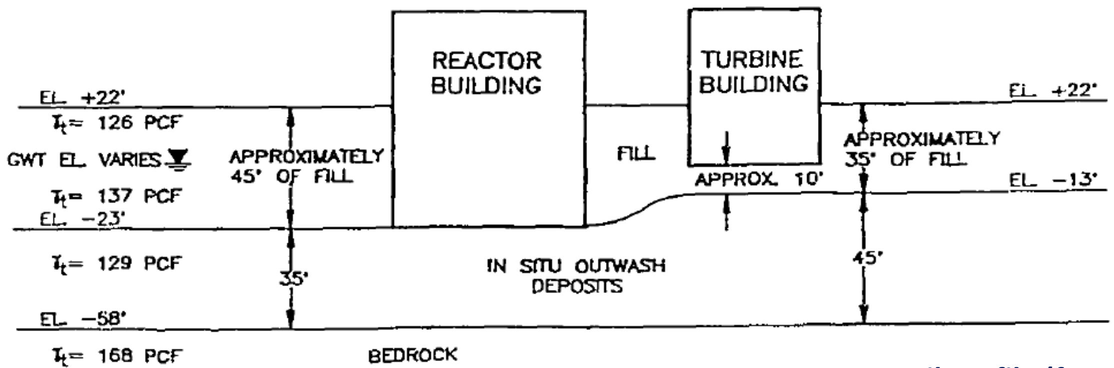
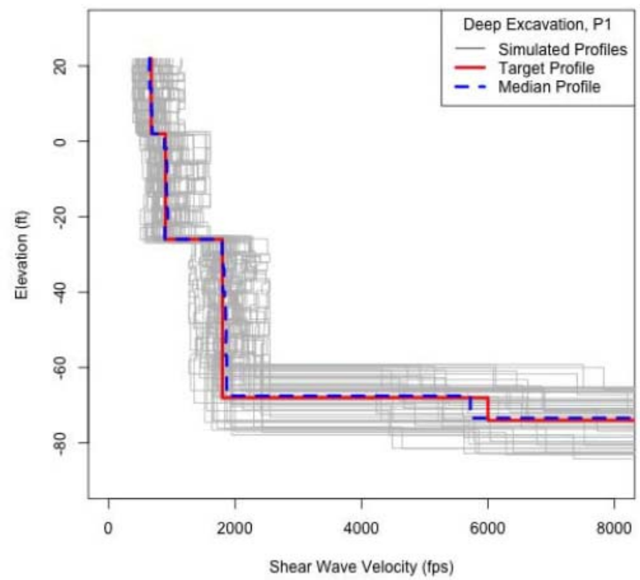
Site Soil Profile



Soil Profile (from PSHA)



- Soil Layers
  - ~35-45 ft. compacted fill (V_s ≈ 700-900 fps)
  - ~35-55 ft. glacial outwash (V_s ≈ 1800 fps)
  - ~5-10 ft. weathered rock (V_s ≈ 6000 fps)
- Structure Foundations (variable embedment)
  - RB founded on glacial outwash
  - TB and RW founded within fill
  - EDG founded at ground surface (on fill)

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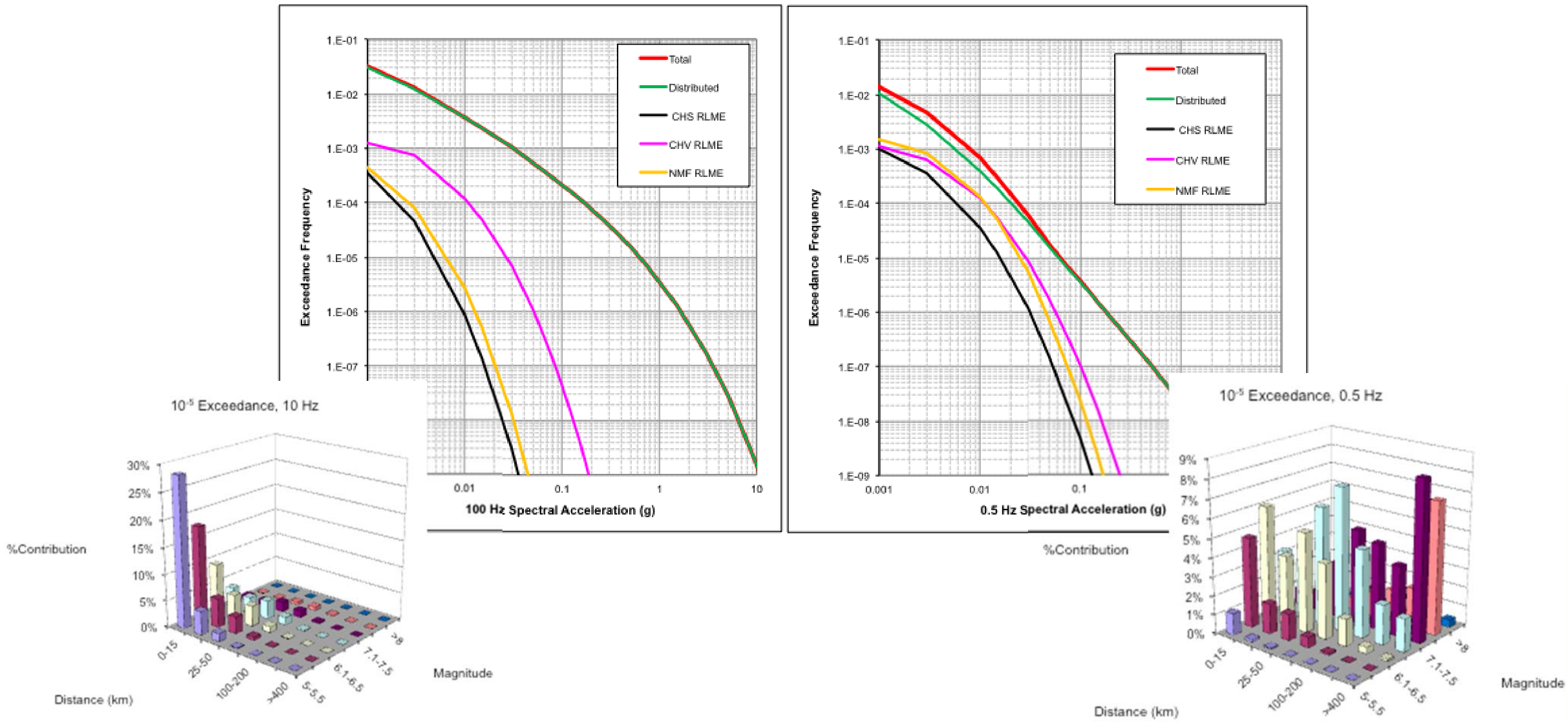
Site Seismic Hazard (1)



Seismic hazard is typical of CEUS:

(1) controlled by distributed seismicity sources

(2) HF is small/close event; LF is larger/further

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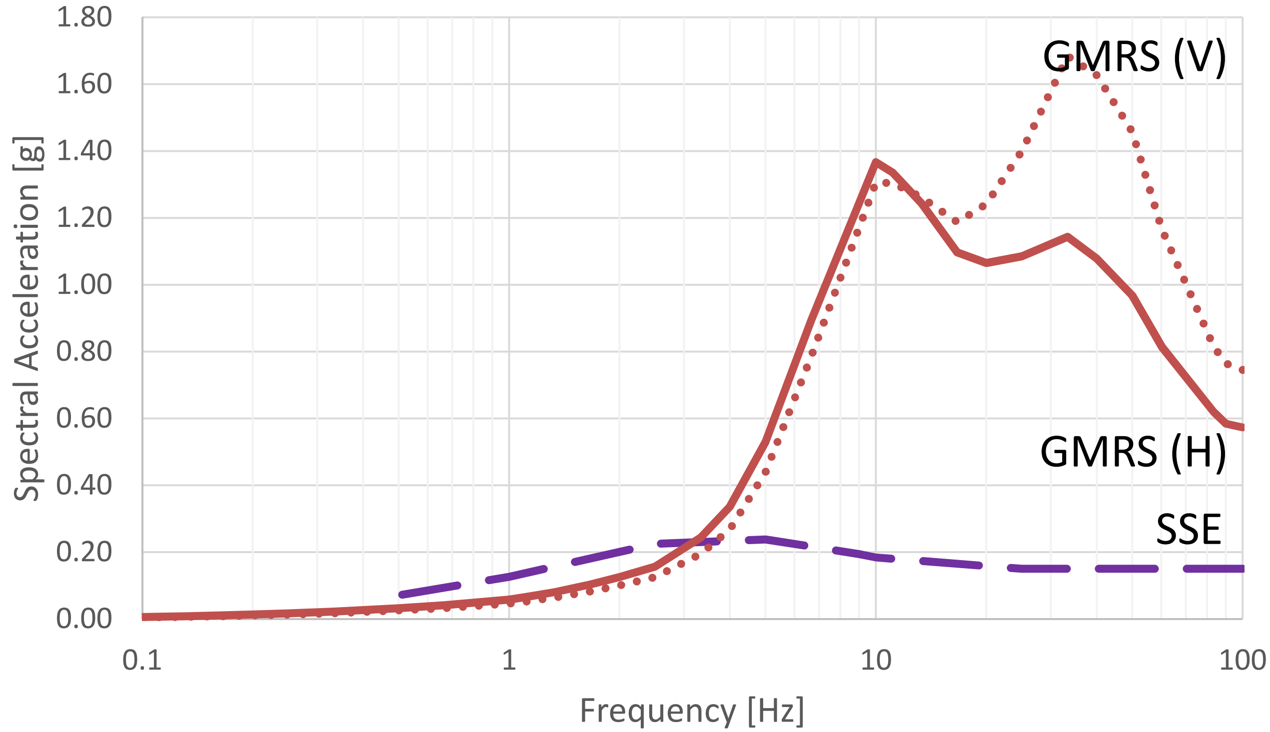
Site Seismic Hazard (2)



Site GMRS from modern PSHA has higher spectral accelerations than plant design basis SSE at frequencies above ~3 Hz (i.e. motivation for SPRA)

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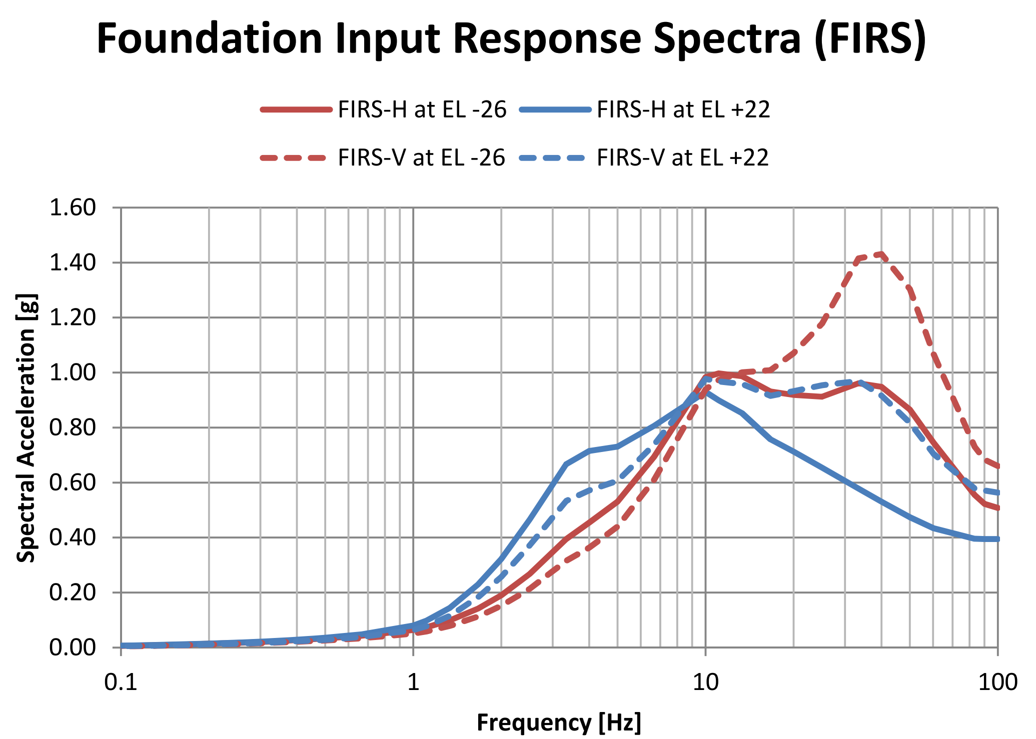
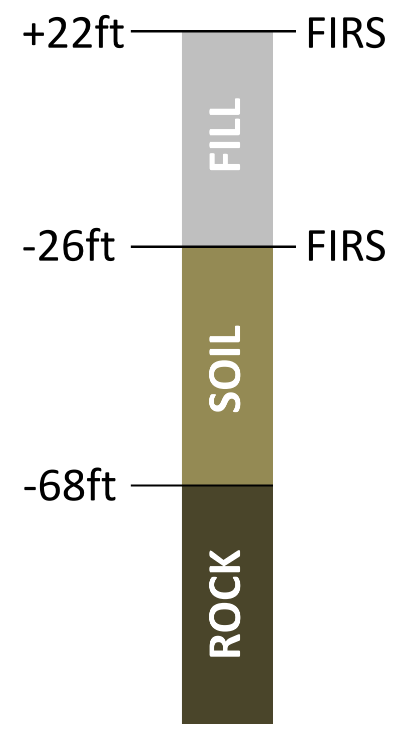
Site Seismic Hazard (3)





Ground surface: soft fill layer amplifies mid-range while de-amplifies HF

RB foundation elevation: 10 Hz soil freq. evident & minimal HF reduction

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SSI Challenges for SPRA

- Soft Soil
- High Frequency Hazard
- Moderate/Deep Embedment
- Coupled Building Response (with variable embedment)
- Desired Model Refinement/Fidelity

Advanced analysis needed to address technical SSI challenges without over-simplification and conservatism that compromises seismic demand for component fragility analysis.

SSI Project Plan

- Develop detailed FE models for each nuclear island structure (RB, TB, RW, EDG)
- Combine FE models into common SSSI model
- Perform probabilistic SSI using 30x time histories (TH) and randomized model properties
- Generate 50^{th}% and ~80^{th}% ISRS in each room with SPRA SEL equipment

Need advanced computational capability, modern and efficient software, and pre-/post-processing automation.

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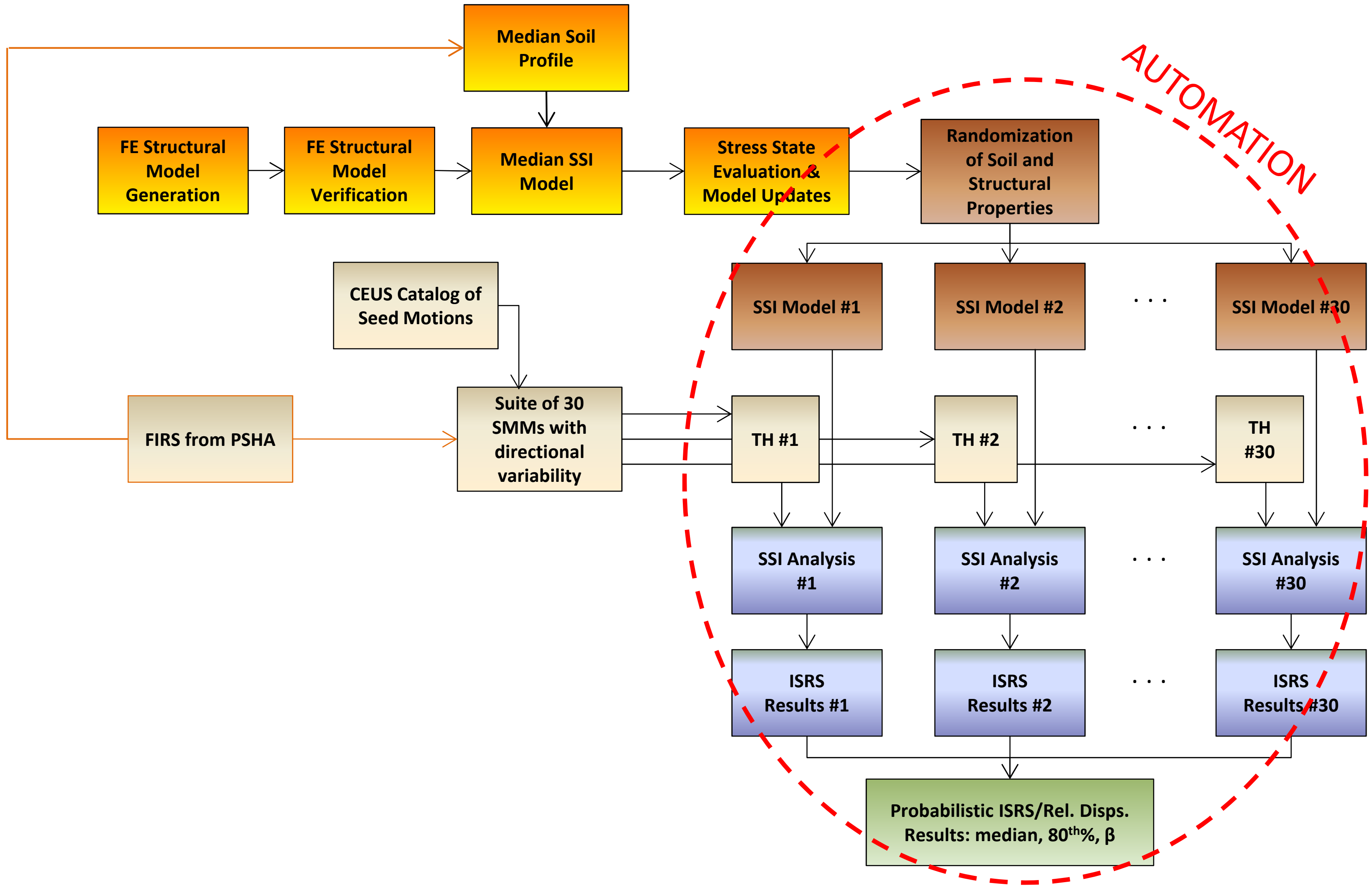
Probabilistic SSI Approach



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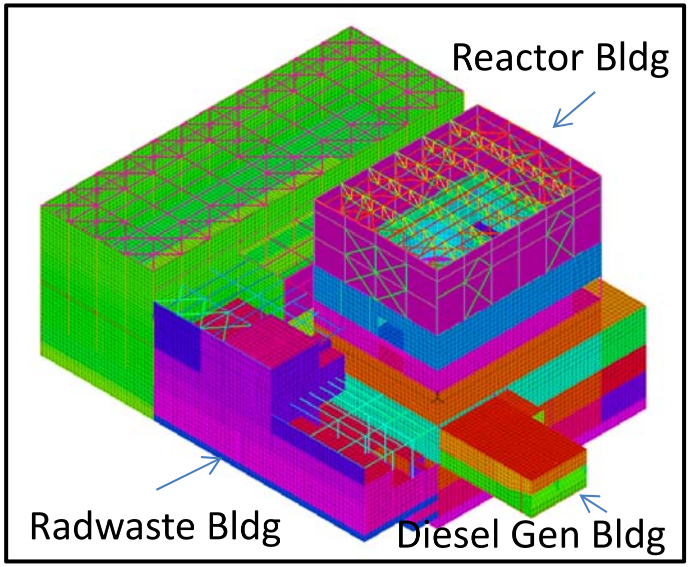
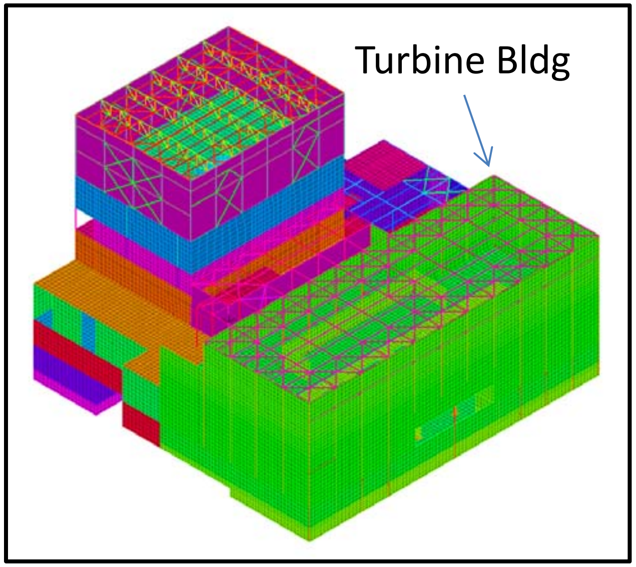
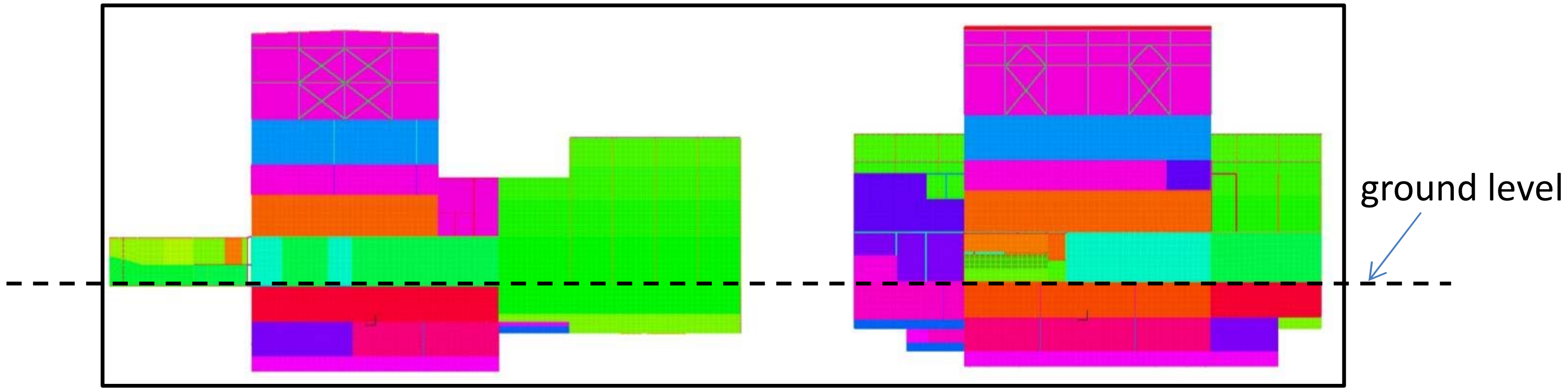
SSI Structural FE Model







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SSI Model – Soil Profile

- Stiffness and damping per PSHA SRA for FIRS
- Median shear wave velocity profile materials

Layer	Thickness	Avg Vs
Unsaturated fill layers	10 ft	570 fps
Saturated fill layers	28 ft	790 fps
Glacial outwash	40 ft	1785 fps
Weathered rock	6 ft	5870 fps

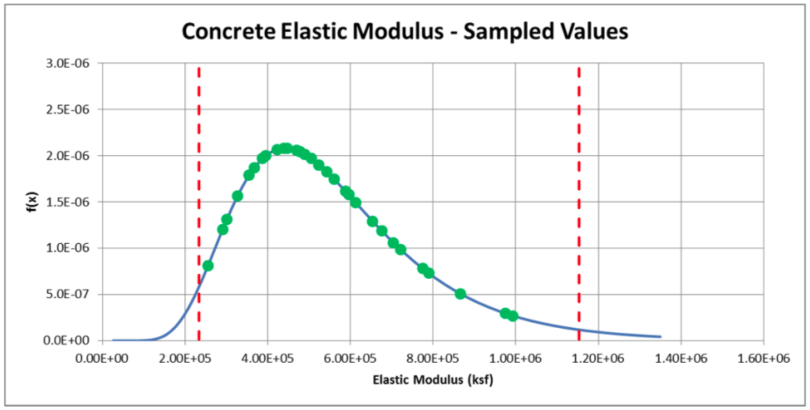
- Layering adjusted to optimize passing frequency and establish SSI model "horizons"
- Uniform halfspace at basement rock

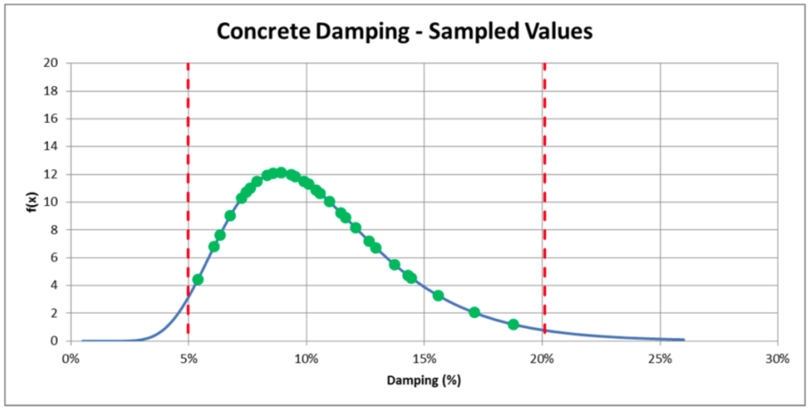
Randomization of Properties (1)

- 30 SSI models by sampling random variables via Latin Hypercube Sampling
- No correlation between soil and structure properties
- Lognormal characterization of properties
- Each SSI model randomly paired to 3-component TH

Randomized Structure Properties

- Frequency via stiffness proxy
- Damping (based on response level)
- Complementary correlation of stiffness/damping





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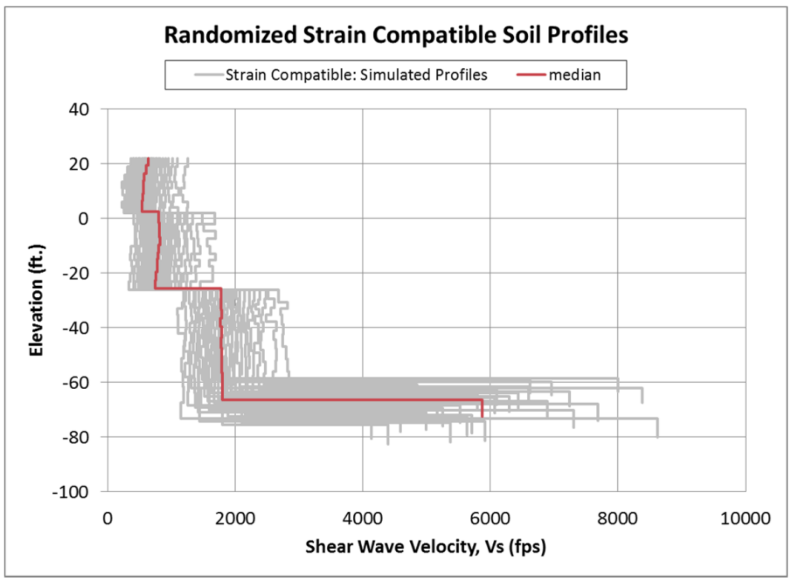
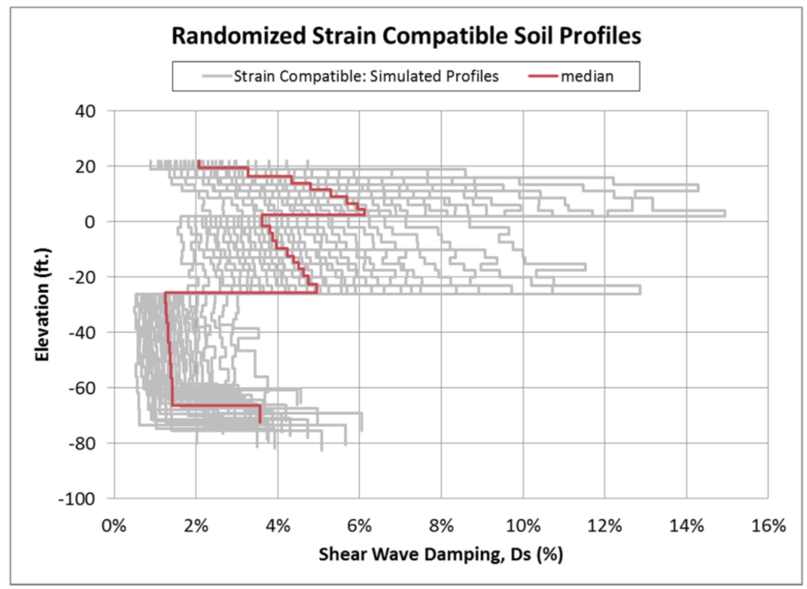
Randomization of Properties (2)

Randomized soil profiles

- Vs and Ds – complementary correlation
- Vp and Dp – Vp related to Vs, ν (Ds = Dp)
- Depth to competent rock – uniform ± 10ft
- Materials are uncorrelated, layers w/in material have interval correlation
- Screening for non-physical profiles





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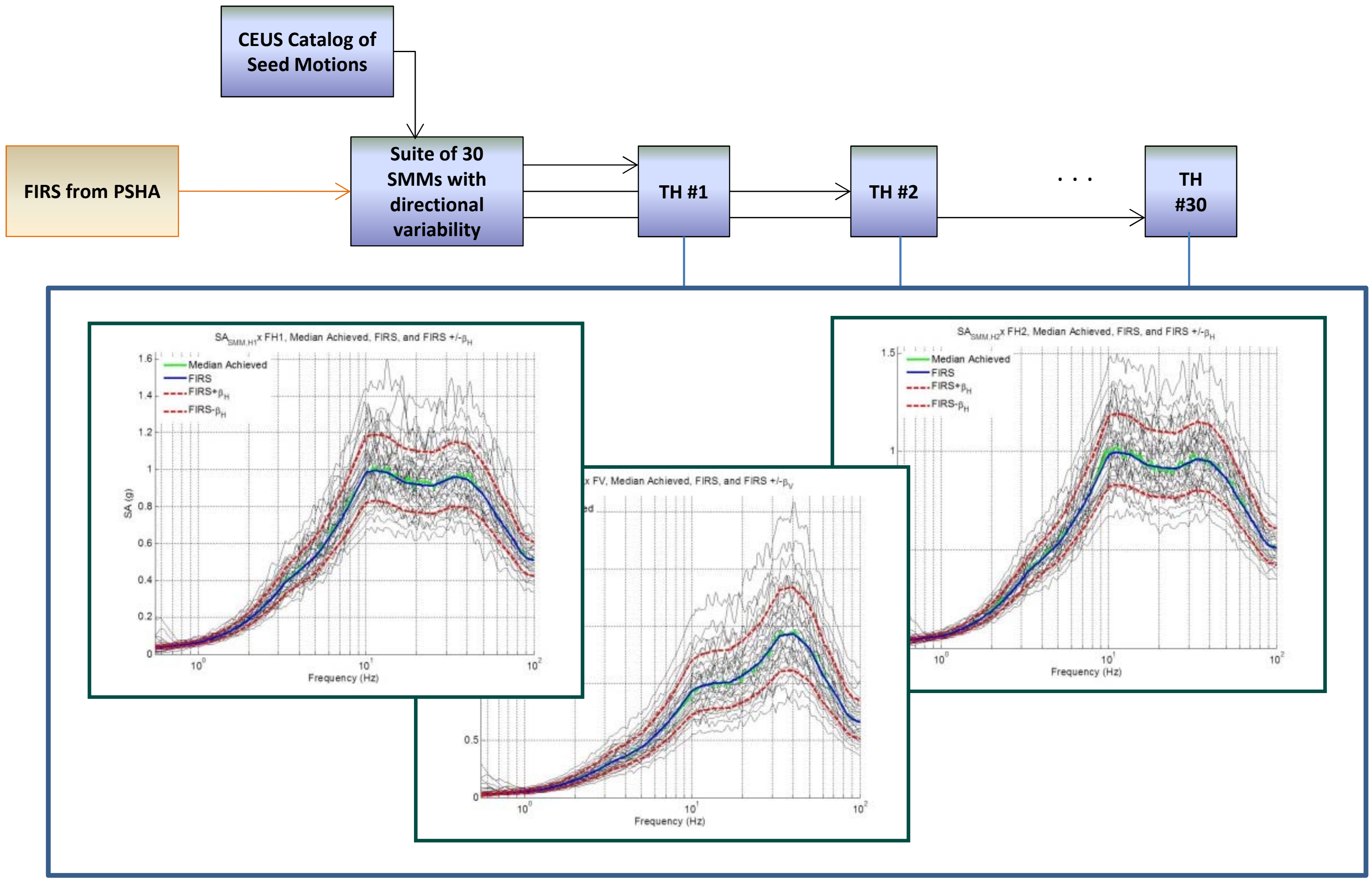
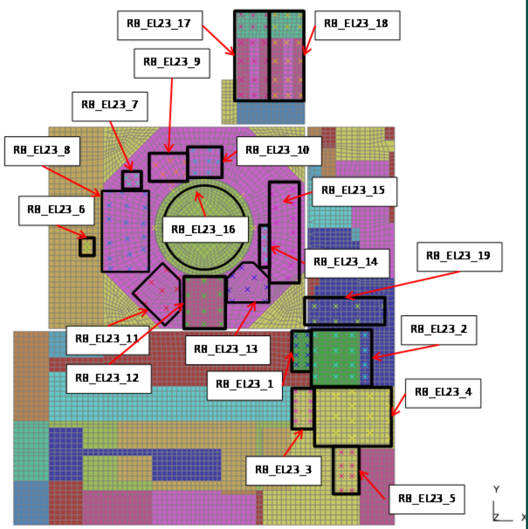
Suite of Time Histories



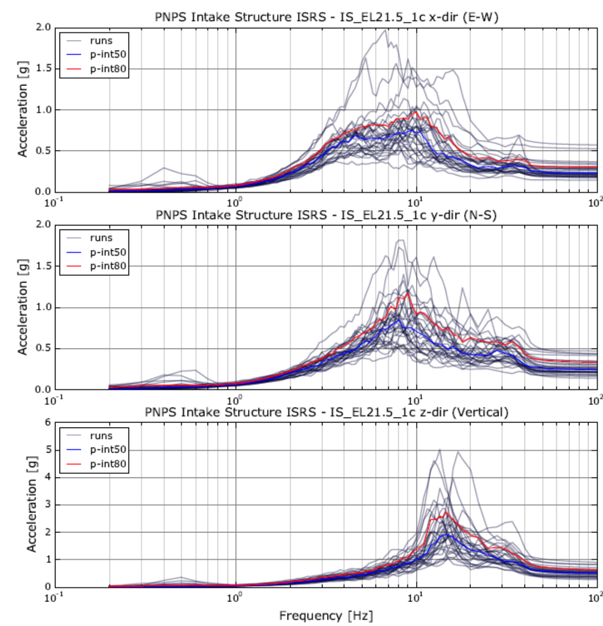
Generation of ISRS (1)

Generate ISRS for Each Node



- Each SEL Equipment Area
- Select Representative Nodes
- Broad Sampling of Nodes
- Average of Nodes in Area

Combine ISRS from 30 Runs



- Plot For Each Area
- ISRS for Each SSI Run
- 50th% and 80th% EP
- Variability (β_{RS})

50th% ISRS

80th% ISRS

Var. (β_{RS})

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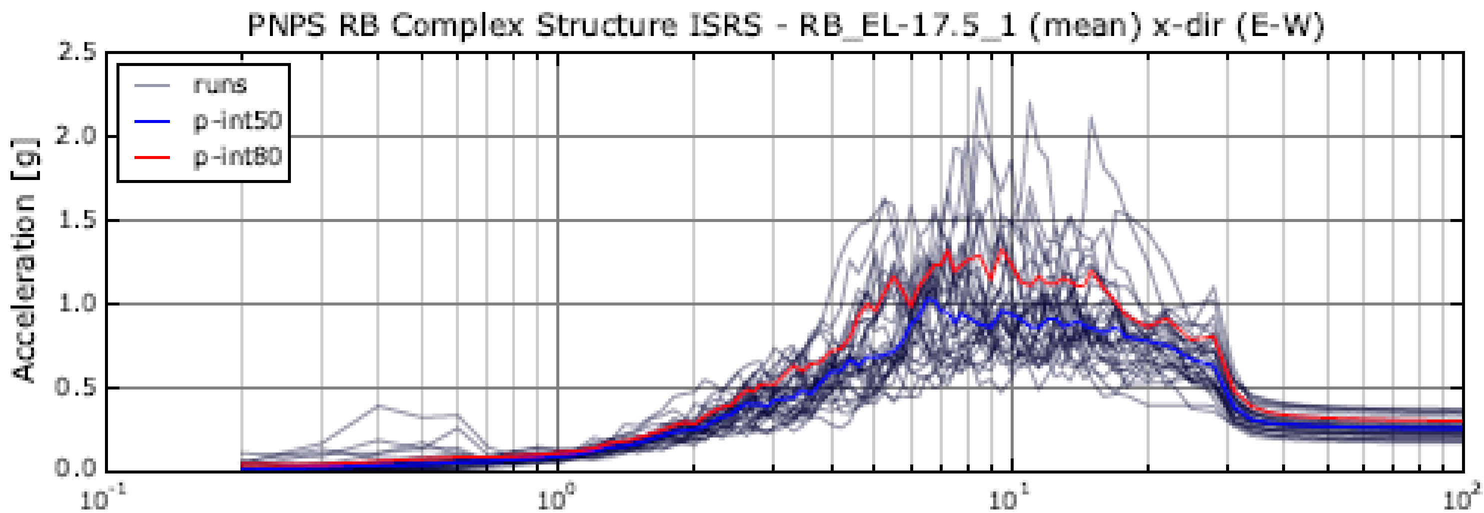
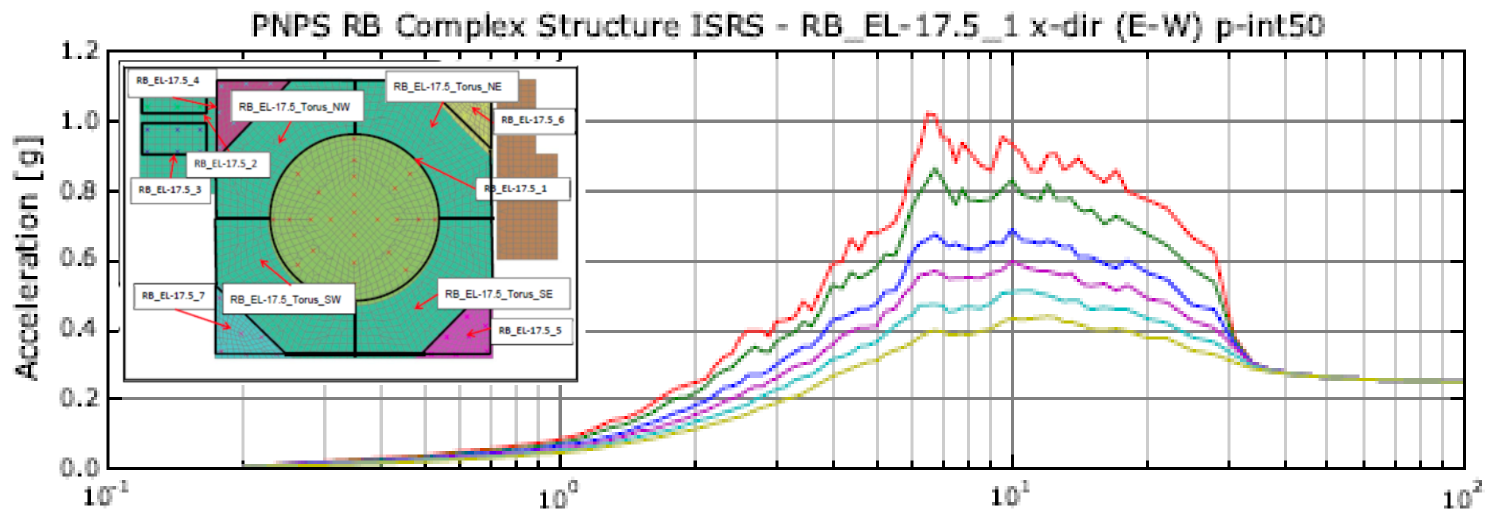
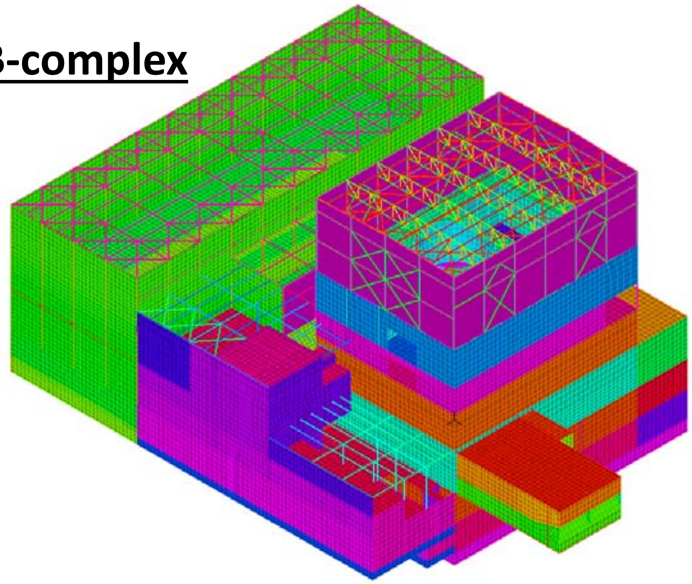
Generation of ISRS (2)





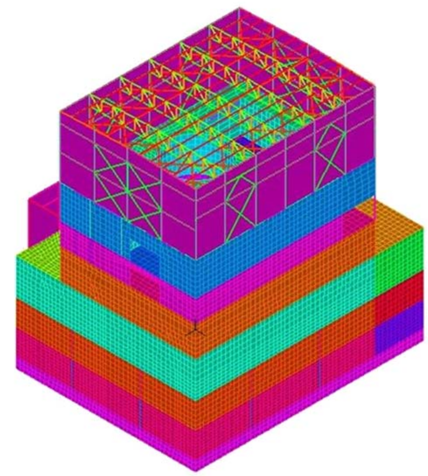
RB-Complex vs. RB-Standalone (1)

RB-complex



vs

RB-standalone



- Studies performed to understand and verify structural response of the RB in the RB-complex and RB-standalone models
- Good correlation in response confirms the use of the RB-standalone model in additional sensitivity and verification studies:
  - High frequency response
  - High vertical response
  - Substructuring methods for probabilistic SSI analysis

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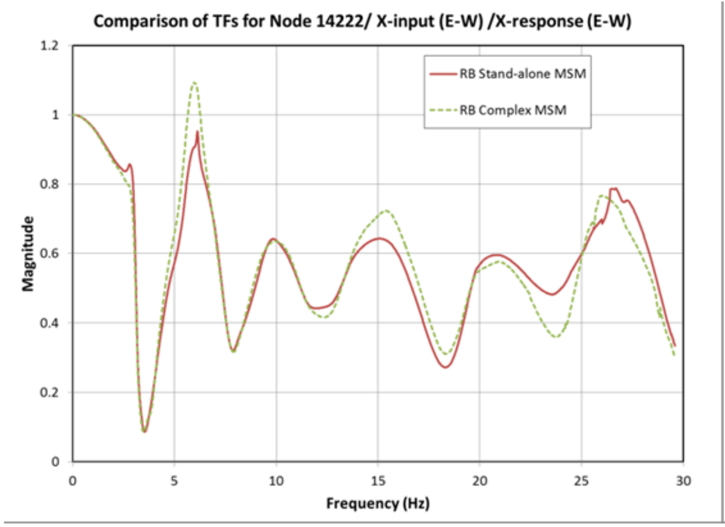
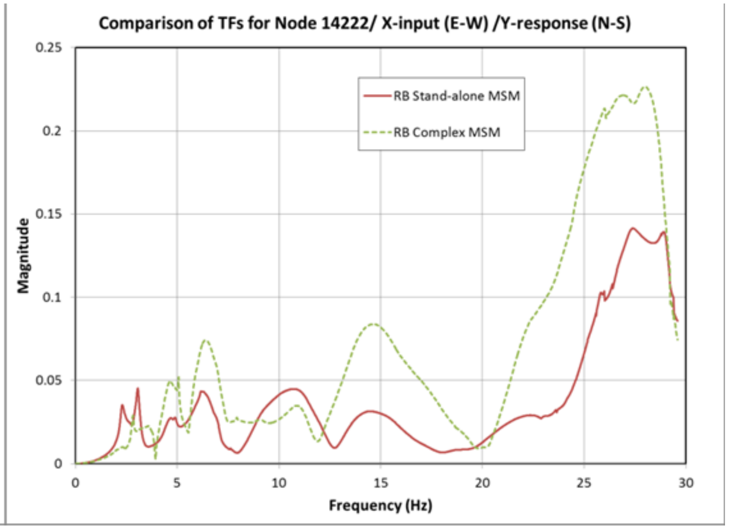
RB-Complex vs. RB-Standalone (2)

- Compared transfer functions at selected nodes
- Generally good correlation in on-axis response (X-response to X-input), but some differences in off-axis response (Y-response to X-input)
  - Differences likely due to asymmetric boundary conditions/embedment and potential SSSI effects
- Similar trends for Y- and Z- on-axis response and for other nodes
- Confirms standalone model adequately captures on-axis response and can be used for additional sensitivity and verification studies





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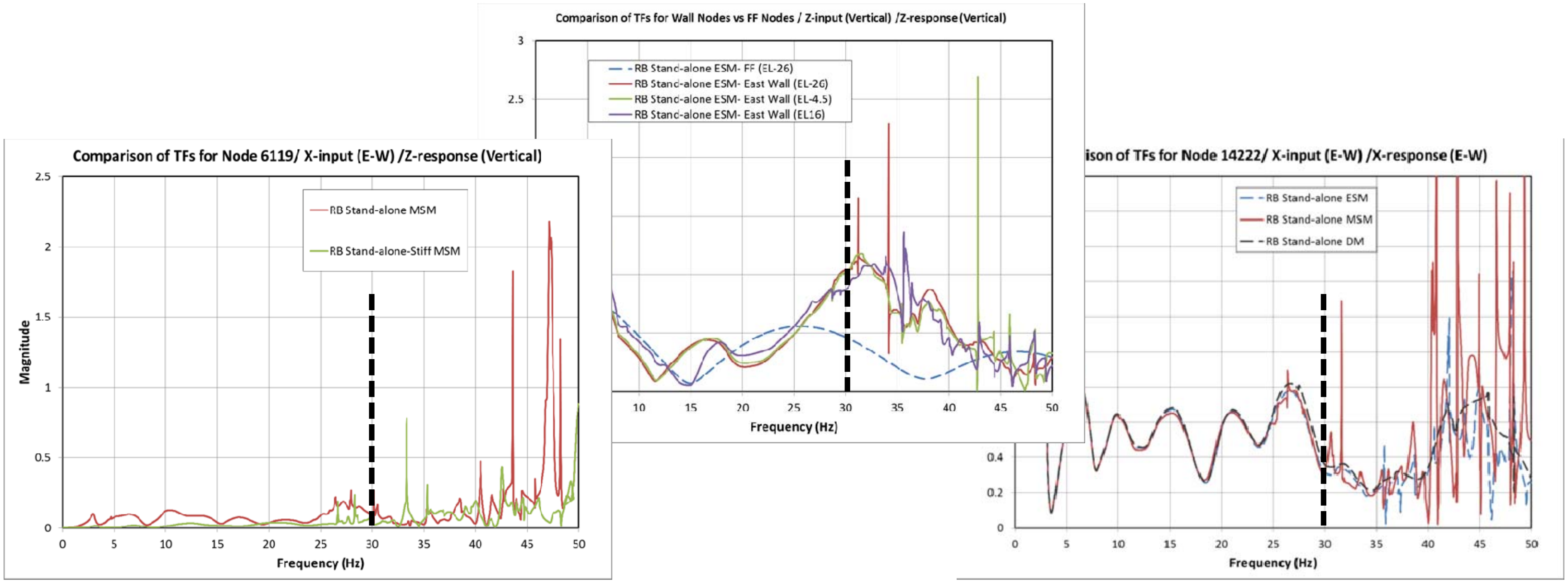
Sensitivity Studies (RB-Standalone Model)



<u>Sensitivity studies – compared transfer functions at selected nodes</u> *(up to 30 Hz)*

- High frequency response – results confirm rocking and torsional response in soft soil (fill layers)
- High vertical response – results confirm high response due to rocking and not vertical amplification through the structures
- Substructuring method – results show good correlation between MSM and ESM with the DM, but no significant improvement from the ESM cases considered

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Comparison of Substructuring Methods

Substructuring Method	Interaction Node Locations	# of Interaction Nodes (RB standalone)	# of Interaction Nodes (RB Complex)
Modified Subtraction Method (MSM)	Perimeter of excavated soil and surface	8125	18594
Enhanced Modified Subtraction Method (ESM)	MSM + 1 horizontal layer	10231	--
	MSM + 1 horiz. + 3 vertical layers	13575	--
	MSM + 3 horizontal layers	14673	--
	MSM + 5 horizontal layers	19115	--
Direct Method (DM)	All excavated soil nodes	45537	91294

- Final probabilistic SSI analysis
  - Use MSM RB-complex model, up to 30 Hz

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SSI Analysis Runtime Statistics

Comparison of In-House HPC System Run-Time

Model	Substructuring Method	# of Interaction Nodes	# of Processor Cores	RAM (GB)	Runtime / frequency (mins)
RB-standalone	MSM	8125	64	128	13
RB-standalone	ESM	14673	64	355	32
RB-complex	MSM	18594	64	650	48

Supplement with Offsite HPC System for "Heavy Lifting" Runs (examples)

- In-house HPC for model testing and moderate-scale sensitivity analyses

  5run x 100freq/run + 3x parallelization ≈ 3 calendar days computation
- Offsite HPC for large sensitivity analyses and confirmatory DM runs

  3run x 50freq/run + 4x parallelization ≈ 5 calendar days computation
- Offsite HPC for few optimization runs to calibrate system environment
- Offsite HPC for production probabilistic runs

  30TH x ~100freq/TH + 10x parallelization ≈ 8 calendar days computation

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Conclusions

- Refined SSI analysis may be warranted for re-evaluation of seismic risk for plants/sites with high hazards
- Probabilistic SSI analysis is feasible, even when faced with:
  - Large and detailed FE model with multiple buildings
  - Soft soil and embedment
  - High-frequency hazard (small layers/elements)
- ISRS can be economically generated for many SEL items
  - Area-specific and / or component-specific ISRS
  - Automation of post-processing across nodes and across runs
- Detailed SSI analysis believed to have contributed to refined fragilities and more realistic risk estimates

Lessons Learned

- Project schedule governed by FE model generation
- Relax horizontal mesh criteria versus inferred passing frequency requirement
- Verify single-structure behavior before combining multiple structures together
- HPC software/hardware handshake can remove computational runtime from critical path
  - Prudent to run different size models (MSM, ESM, DM) early to estimate resource and schedule requirements
- Consideration of multiple hazard levels (different degraded soil properties, different concrete cracking / damping) may be prudent

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