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

10/19/16

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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

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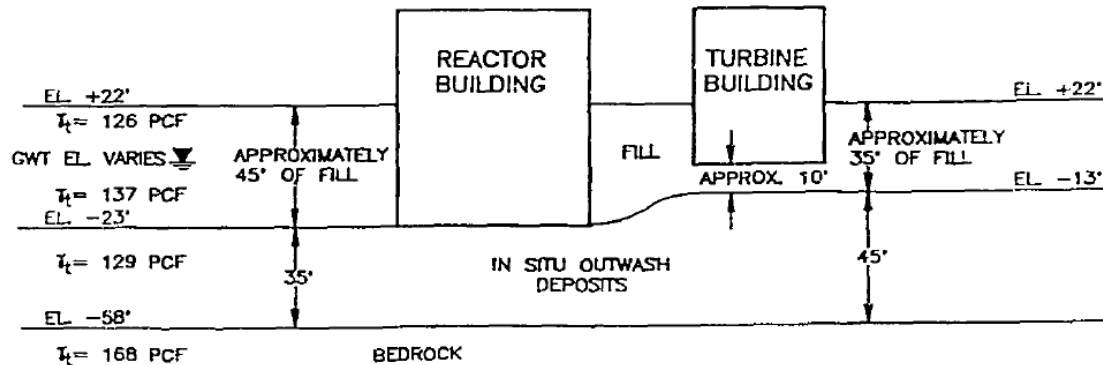THE POWER OF PEOPLE®

Outline

- Plant Overview and Seismic Hazard

- SSI Challenges for SPRA

- Probabilistic SSI Approach

- SSI Analysis Studies and Statistics

- Final Probabilistic SSI Analysis - Sample Results
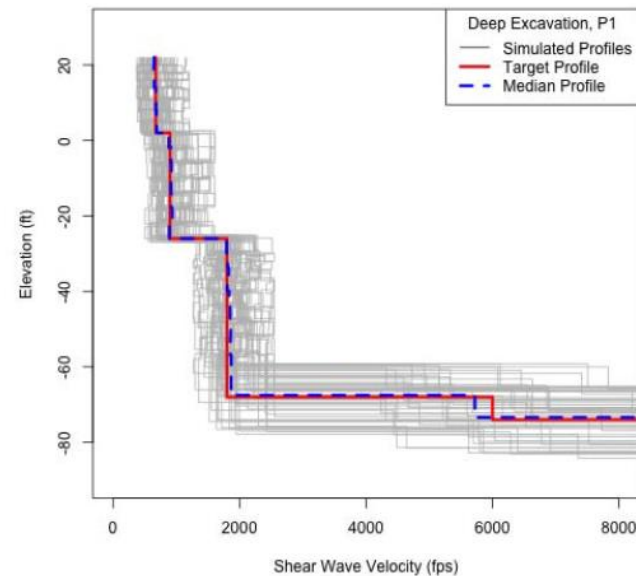
- Conclusions / Lessons Learned

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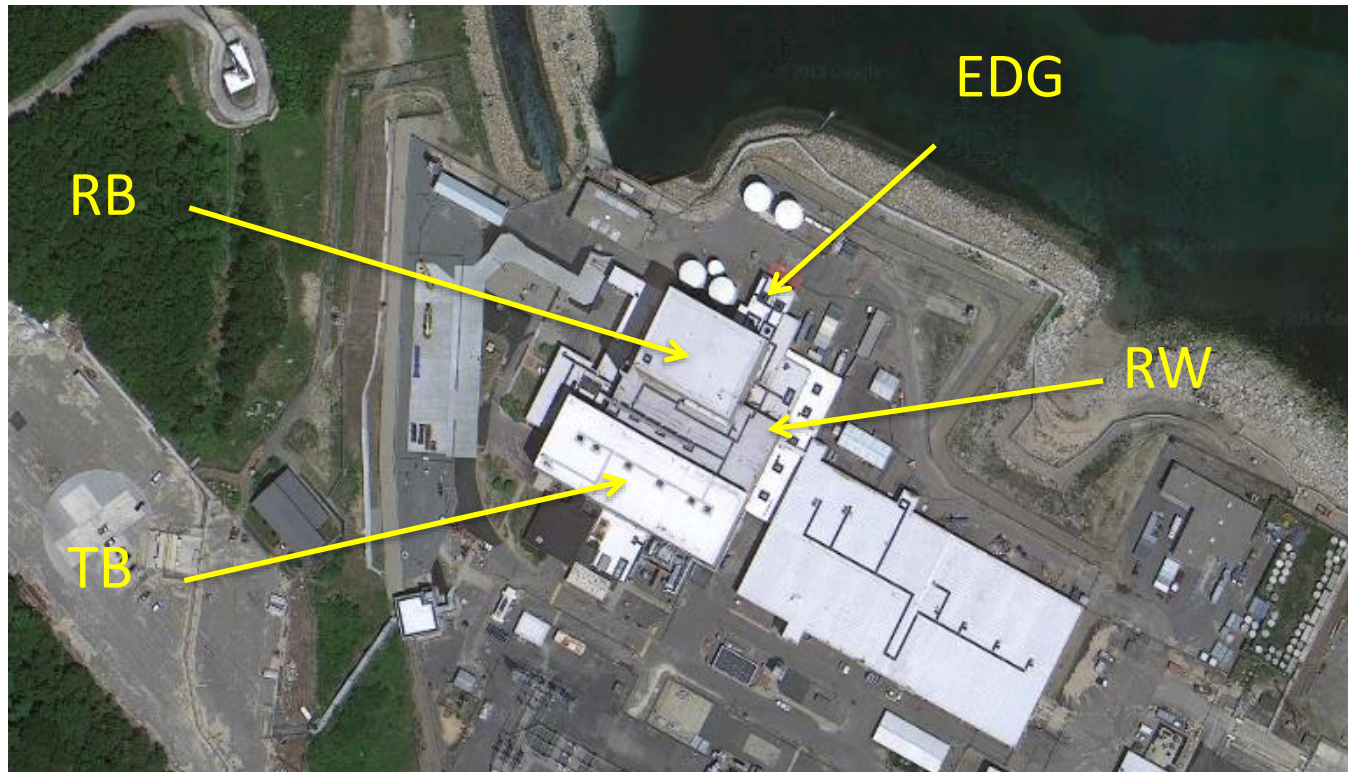
- Single-unit GE BWR
- Primary structures RB, TB, RW, EDG

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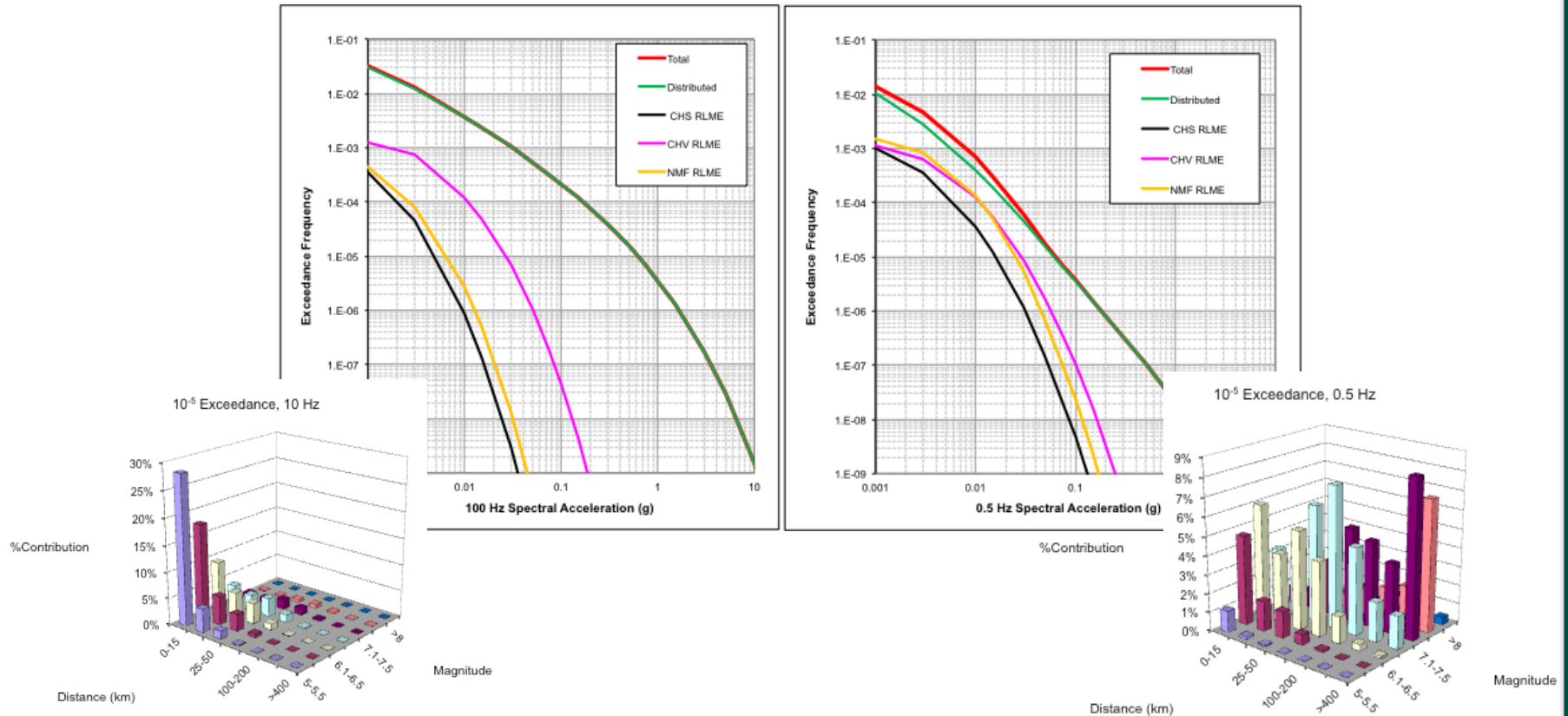
Site Soil Profile

Soil Profile (from PSHA)

- Soil Layers
    - ~35-45 ft. compacted fill   ($V_s \approx$ 700-900 fps)
    - ~35-55 ft. glacial outwash ($V_s \approx$ 1800 fps)
    - ~5-10 ft. weathered rock   ($V_s \approx$ 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)

10⁻⁵ Exceedance, 10 Hz

10⁻⁵ Exceedance, 0.5 Hz

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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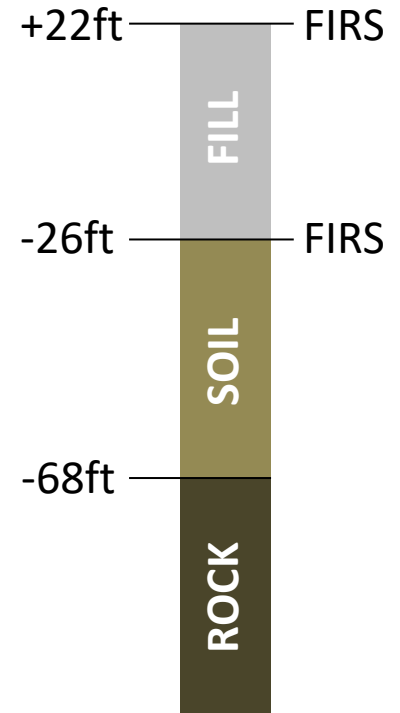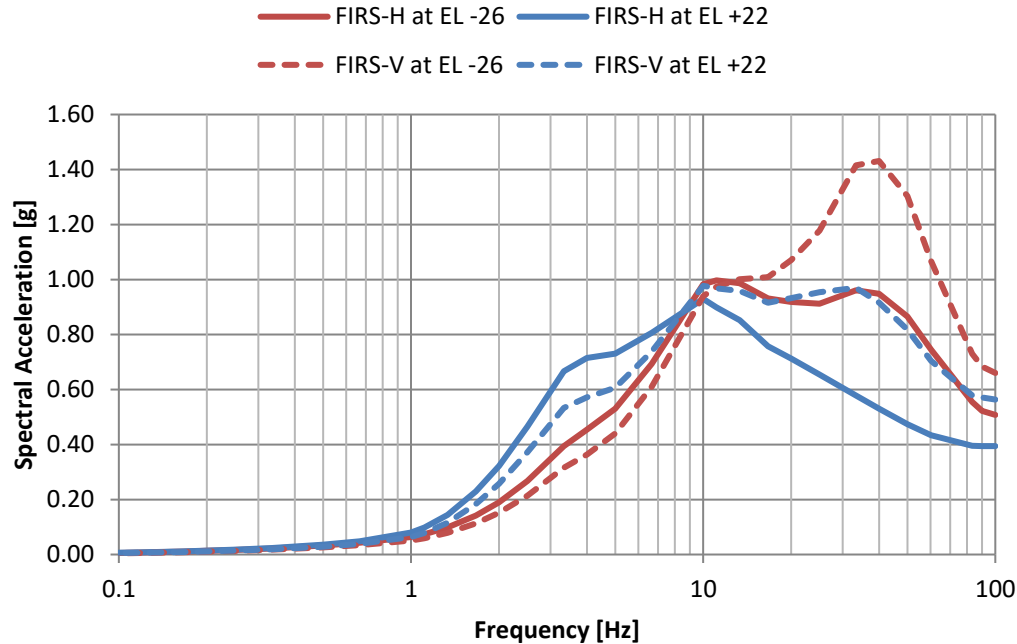
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Site Seismic Hazard (2)
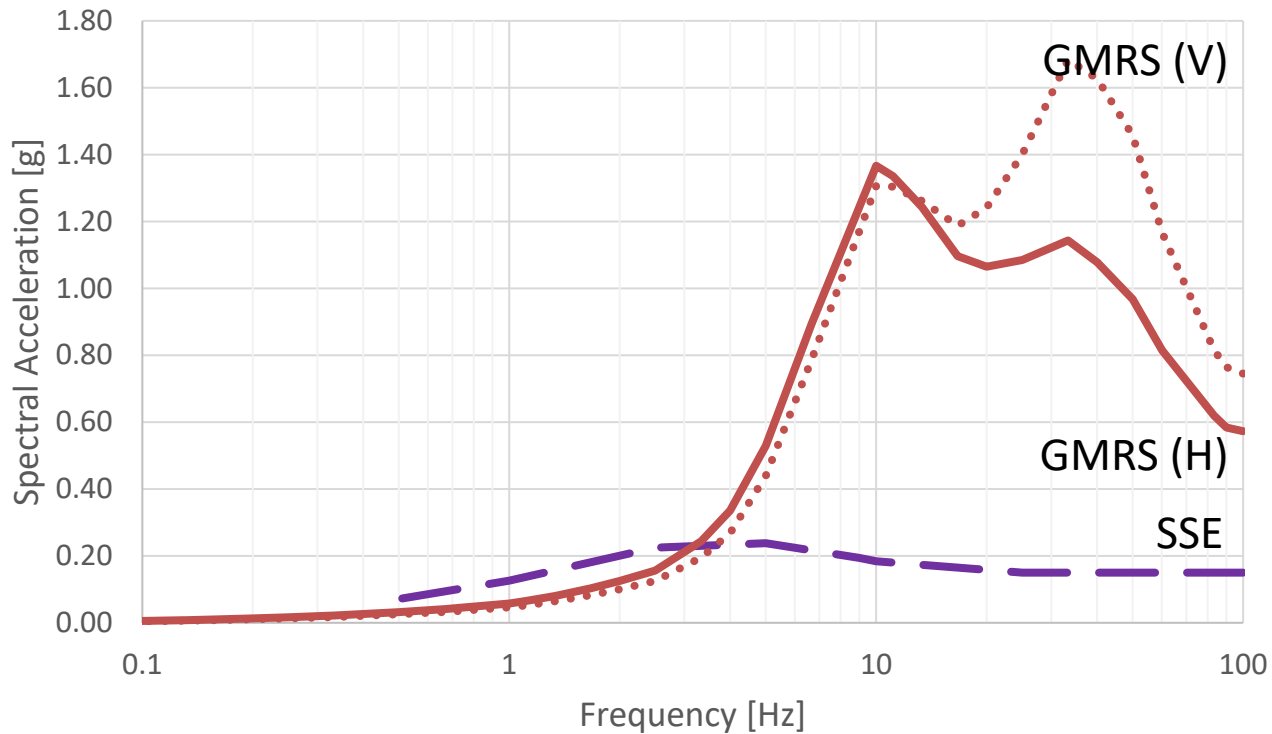
Site GMRS from modern PSHA has higher spectral accelerations than plant design basis SSE at frequencies above ~3 Hz (i.e. motivation for SPRA)

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Site Seismic Hazard (3)

Foundation Input Response Spectra (FIRS)

Legend:
— FIRS-H at EL -26 — FIRS-H at EL +22
-- FIRS-V at EL -26 -- FIRS-V at EL +22

Chart: Spectral Acceleration [g] vs Frequency [Hz]

Soil profile column:
- +22ft — FIRS (FILL)
- -26ft — FIRS (SOIL)
- -68ft (ROCK)

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)
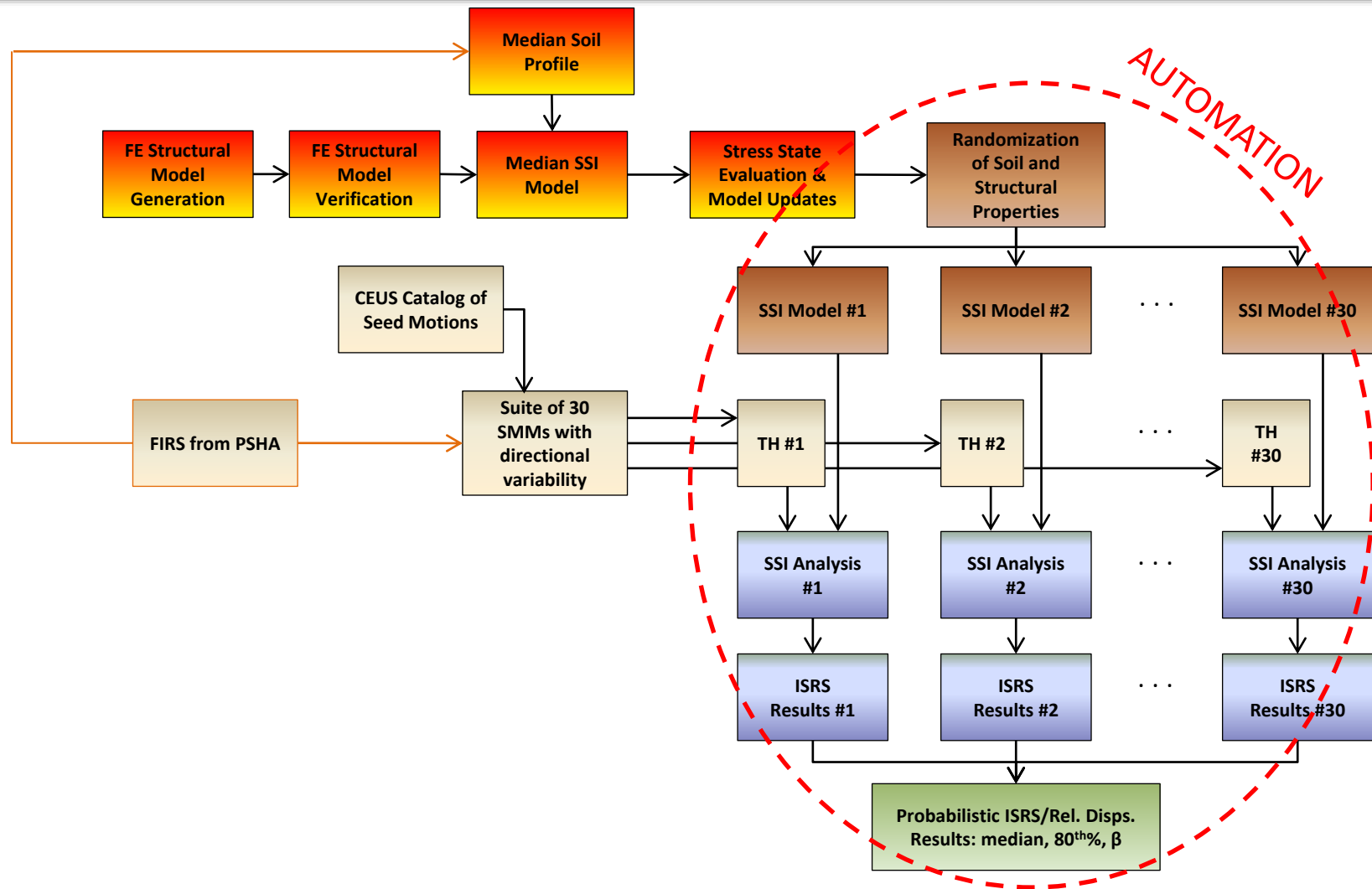- Desired Model Refinement/Fidelity

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

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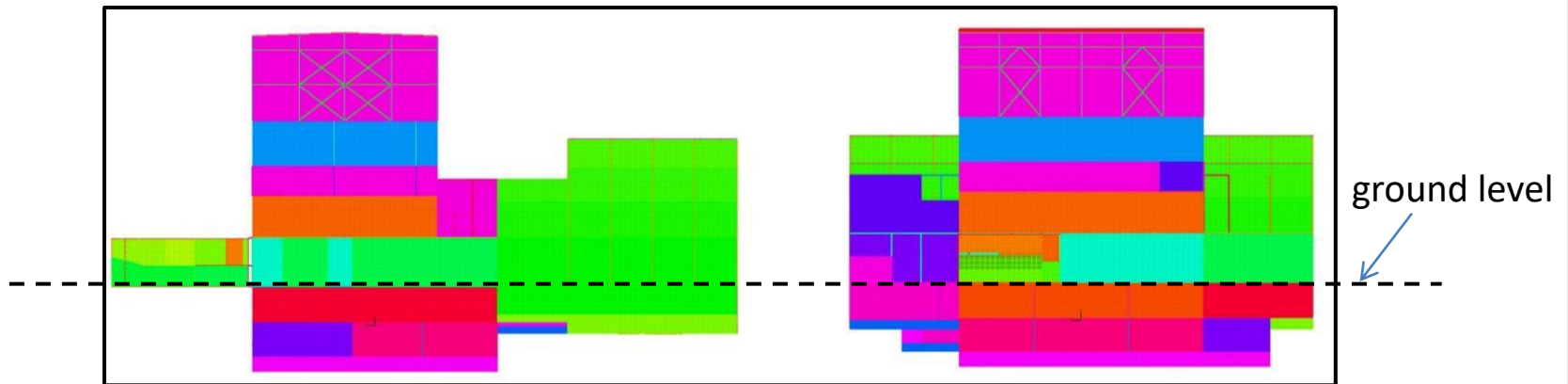THE POWER OF PEOPLE®
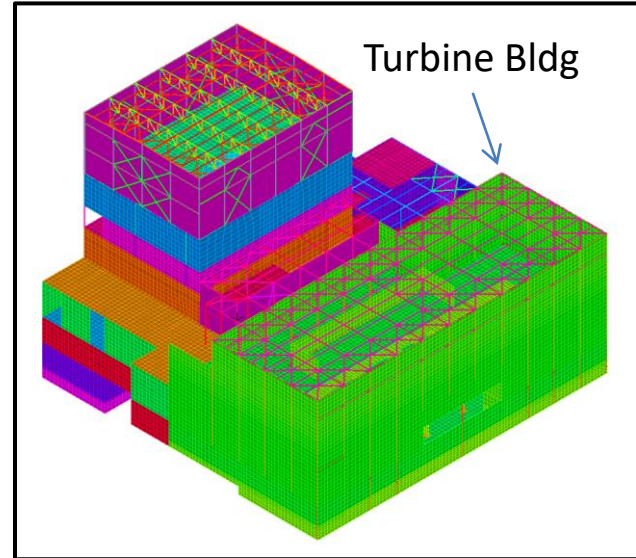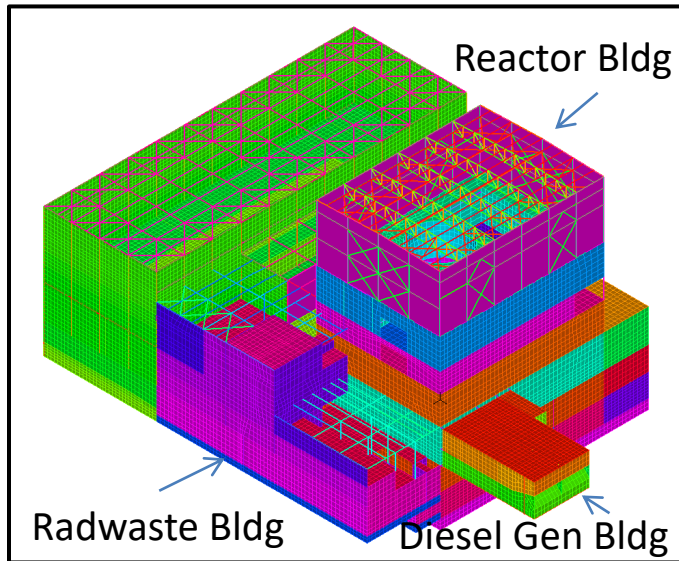
SSI Project Plan

- 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 50th% and ~80th% 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

Reactor Bldg

Radwaste Bldg

Diesel Gen Bldg

Turbine Bldg

ground level

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SSI Model – Soil Profile

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

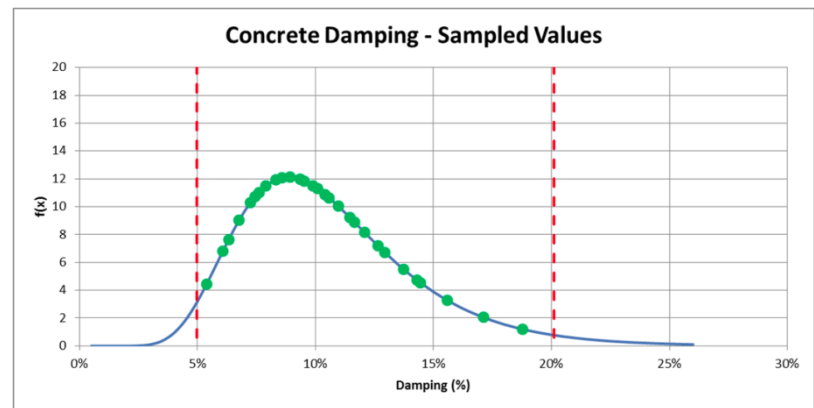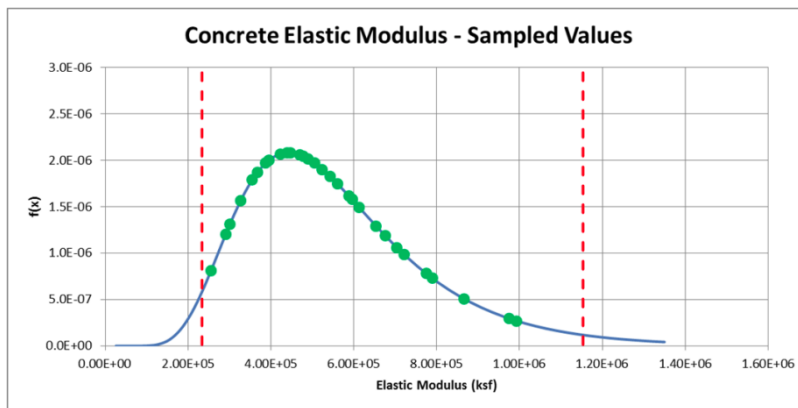| Layer	Thickness	Avg Vs
Unsaturated fill layers	10 ft	570 fps
Saturated fill layers	28 ft	790 fps
Glacial outwash	40 ft	1785 fps
Weathered rock	6 ft	5870 fps

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

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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

Concrete Elastic Modulus - Sampled Values

Concrete Damping - Sampled Values

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# Randomization of Properties (2)

Randomized soil profiles

- Vs and Ds – complementary correlation
- Vp and Dp – Vp related to Vs, v (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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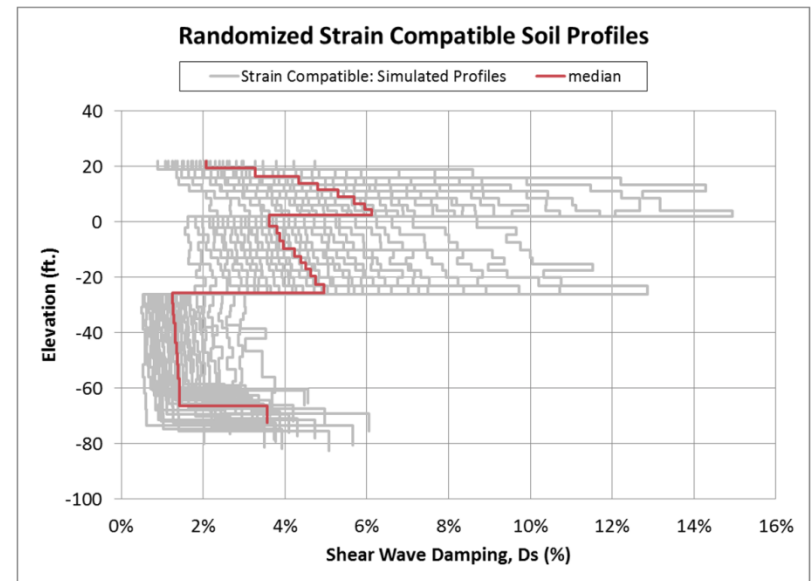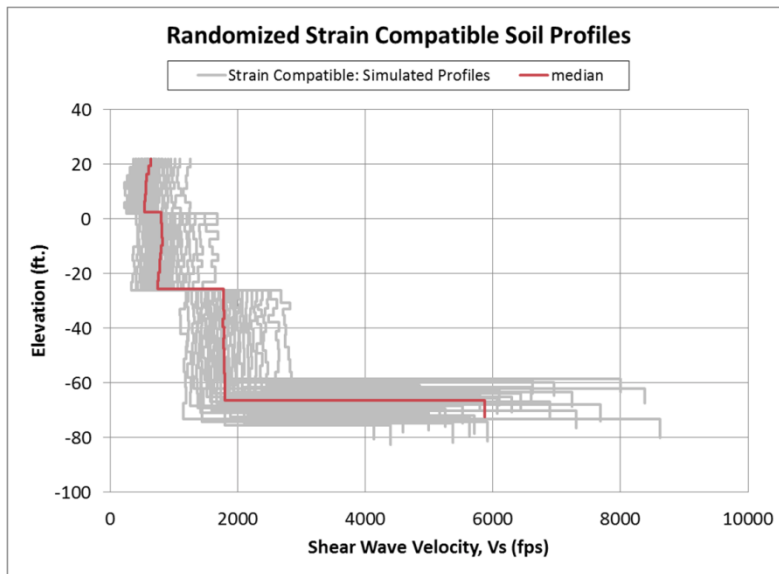
Suite of Time Histories
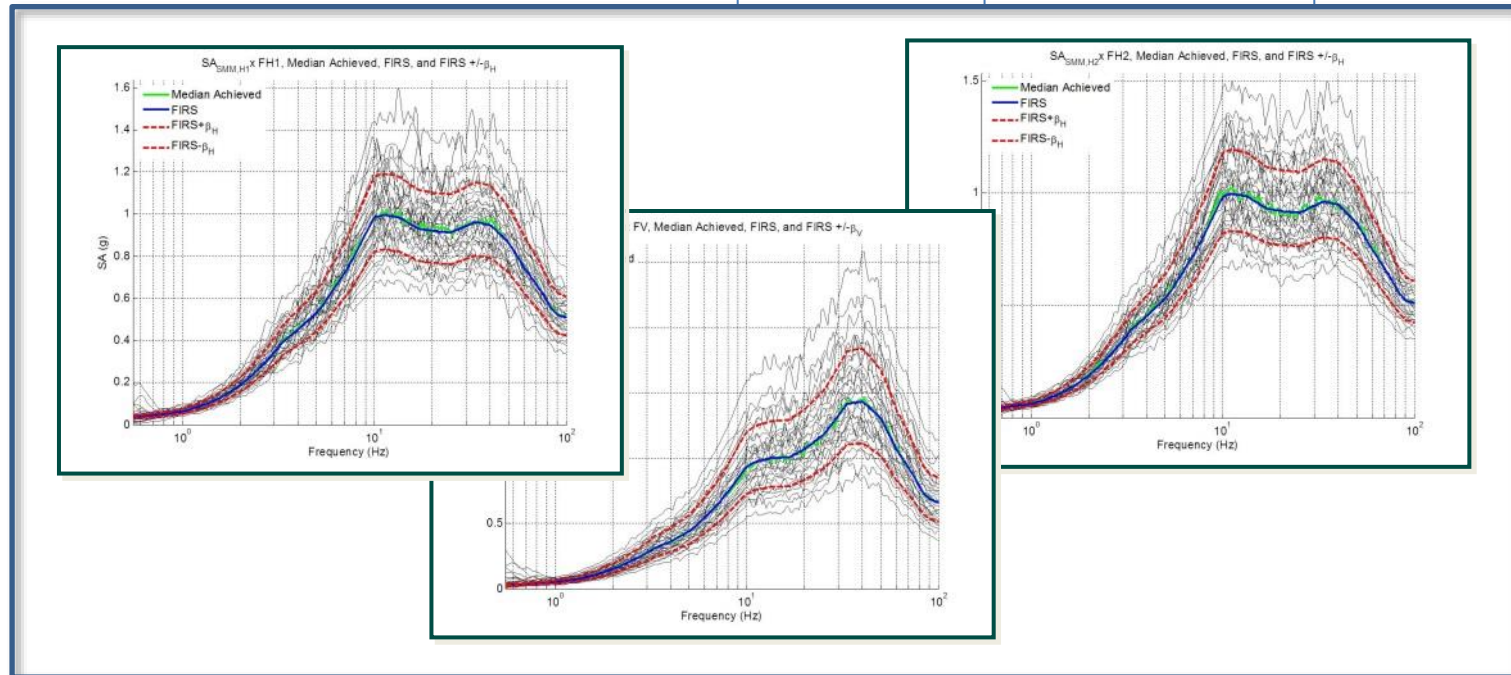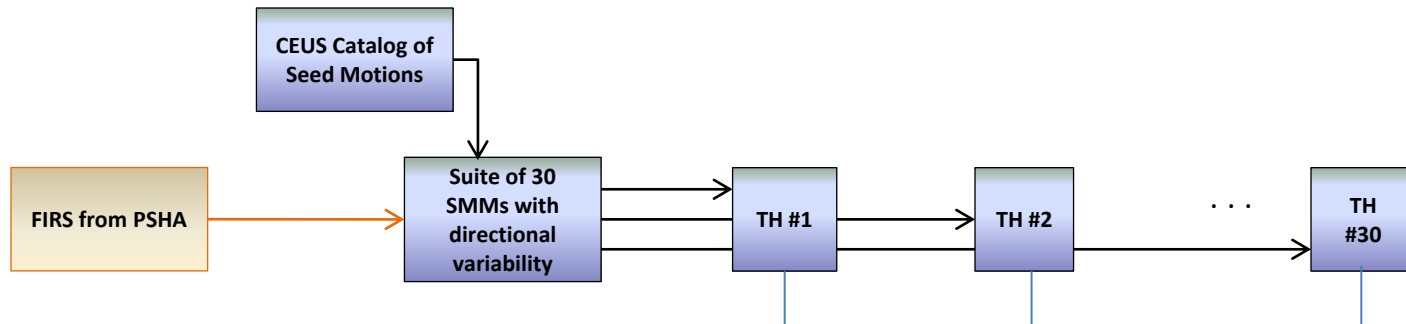
Generation of ISRS (1)

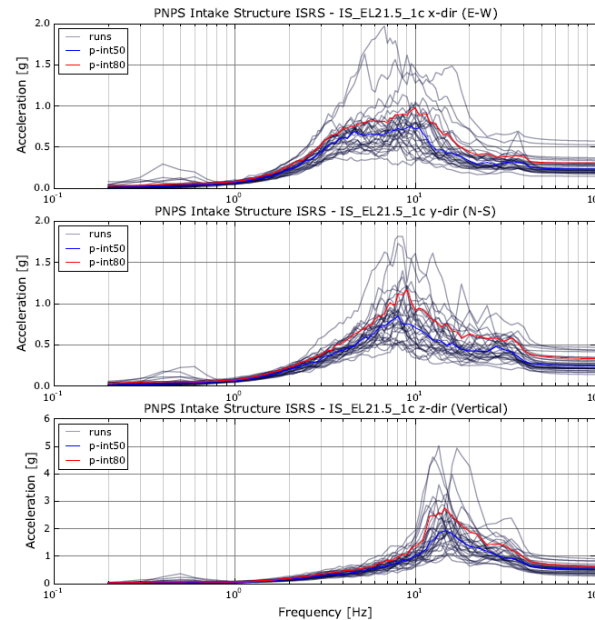## Generate ISRS for Each Node
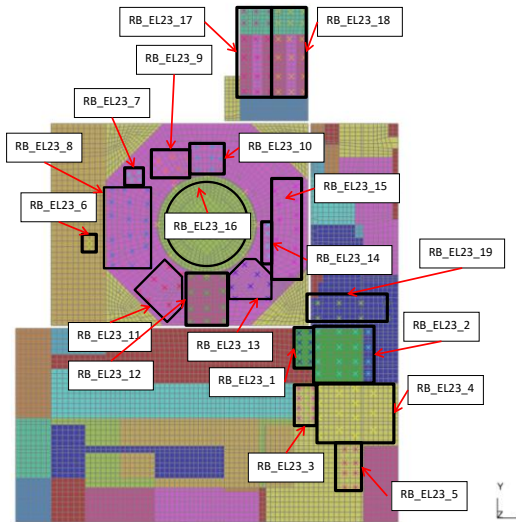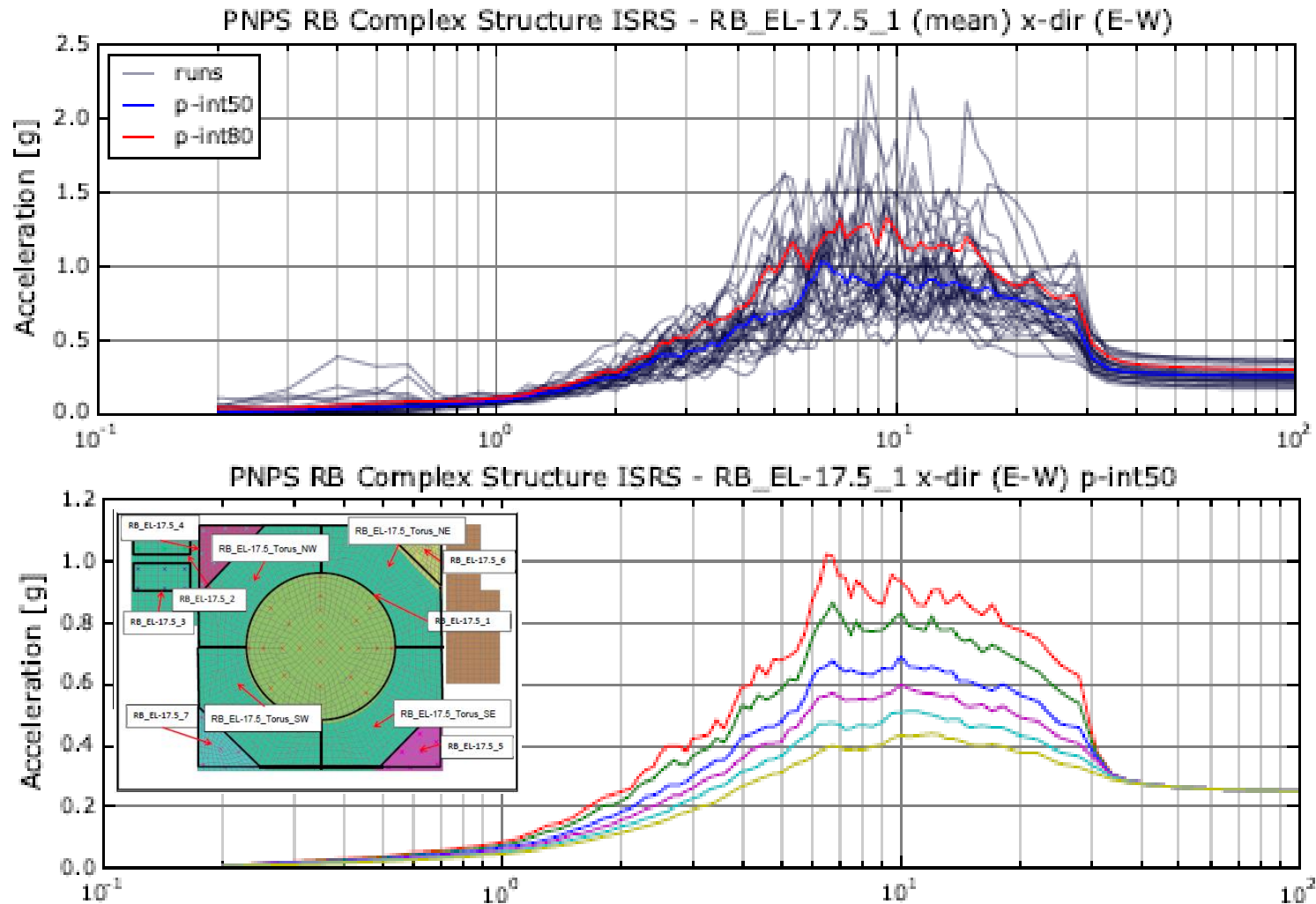

Combine ISRS from 30 Runs

- 50th% ISRS
- 80th% ISRS
- Var. (β_{RS})

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

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

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RB-Complex vs. RB-Standalone (1)
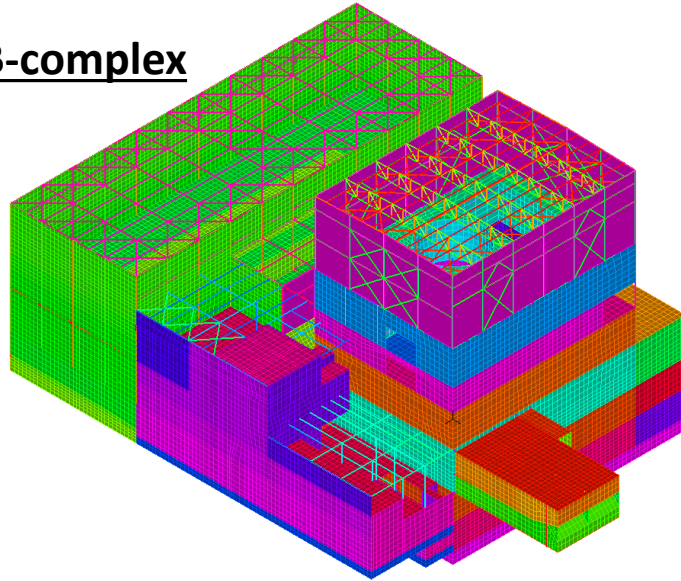
RB-complex　　　　　　　　　　　　　**RB-standalone**
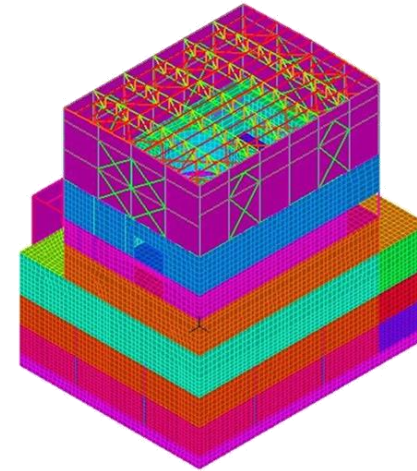
vs

- 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

Comparison of TFs for Node 14222/ X-input (E-W) /X-response (E-W)

Comparison of TFs for Node 14222/ X-input (E-W) /Y-response (N-S)

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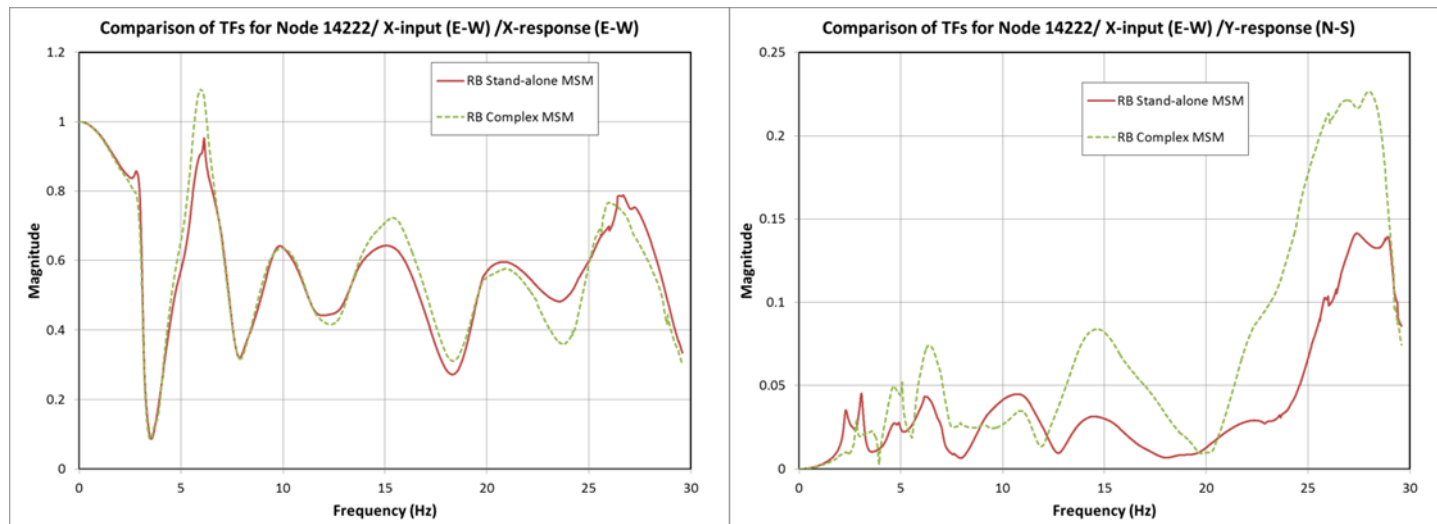
Sensitivity Studies (RB-Standalone Model)

Comparison of TFs for Node 6119/ X-input (E-W) /Z-response (Vertical)

Comparison of TFs for Wall Nodes vs FF Nodes / Z-input (Vertical) /Z-response (Vertical)

Comparison of TFs for Node 14222/ X-input (E-W) /X-response (E-W)
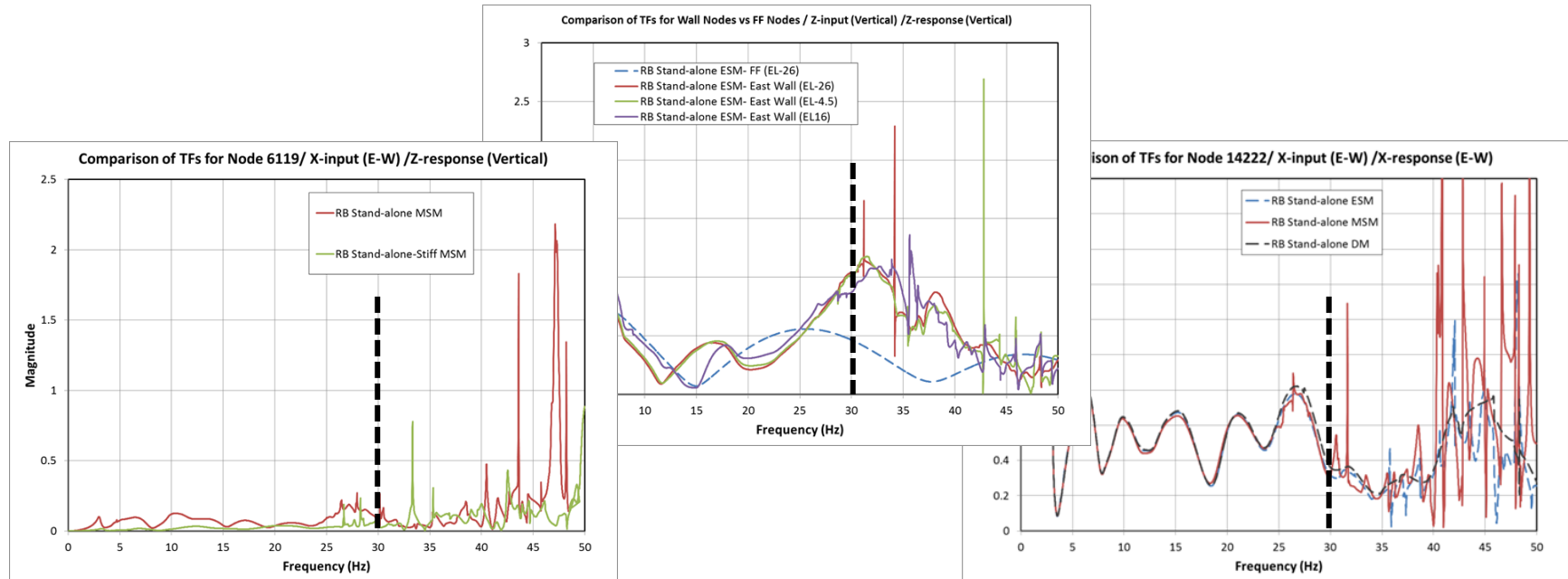
<u>Sensitivity studies – compared transfer functions at selected nodes</u> *(up to 30 Hz)*

- 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

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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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