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NRC Meeting:
Update on Seismic Methodology Results

HOLTEC INTERNATIONAL

Date: 9 August 2023

Presented By: Chuck Bullard and John Zhai

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One Holtec Boulevard
Camden, NJ 08104, USA

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Meeting Agenda

- Introductions
- Purpose & Outcome
- Background and Previous Discussions
- Overview of SMR-160 Seismic Methodology
- Results
- Questions
- Open Forum

Introductions

- NRC Staff
- Holtec Staff
- Industry Consultant (SC Solutions)

Purpose and Outcome

- Purpose

  To provide a high-level overview of the soil-structure interaction (SSI) methodology for SMR-160 and discuss preliminary results and future plans.

- Outcome

  To obtain feedback from the NRC staff on presentation material and identify any potential risk areas or gaps in the SSI methodology for SMR-160.

Background and Previous Discussions

- NRC Public meeting 9-27-22 (*Time-Domain Nonlinear SSI Analysis Using A Hysteretic Soil Model*)
  - Discussed proposed method of analysis for seismic design including the use of a non-linear soil model
  - Following the meeting, and in consideration of the presentation and discussion, the NRC staff has a high-level understanding of the proposed non-linear soil analysis method. The NRC staff did not identify any immediate concerns with the approach.
  - NRC noted that it has not previously approved a non-linear soil-structure analysis. Since this will be a 'first-of-a-kind' review, the NRC staff may ask additional questions to fully understand the approach and its implementation.

Overview - Design Basis Seismic Ground Motion

- Seismic Design Response Spectra – Free field soil outcrop motion at the containment basemat elevation (EL. -86')

Horizontal directions

Frequency (Hz)	Acceleration (g)
0.1	0.0192
0.25	0.12
1.0	0.48
3.5	0.92
12	0.92
50	0.4
100	0.4

Vertical Direction

Frequency (Hz)	Acceleration (g)
0.1	0.0133
0.25	0.08
1.0	0.36
3.5	0.88
12	0.92
50	0.4
100	0.4

Overview - Design Basis Soil Properties

Shear Wave Velocities

Layer No.	Thickness (ft)	Depth (ft)	Shear Wave Velocity (ft/s)			Density (pcf)
			LB	BE	UB	
1	2	-2	635	900	1240	120
2	3	-5	705	1000	1415	120
3	15	-20	810	1150	1630	120
4	20	-40	985	1400	1980	120
5	20	-60	1130	1600	2265	120
6	20	-80	1200	1700	2405	120
7	20	-100	1255	1780	2520	120
8	20	-120	1305	1850	2620	120
9	20	-140	1360	1930	2730	130
10	30	-170	1410	2000	2830	130
11	Half Space		2825	4000	5660	150

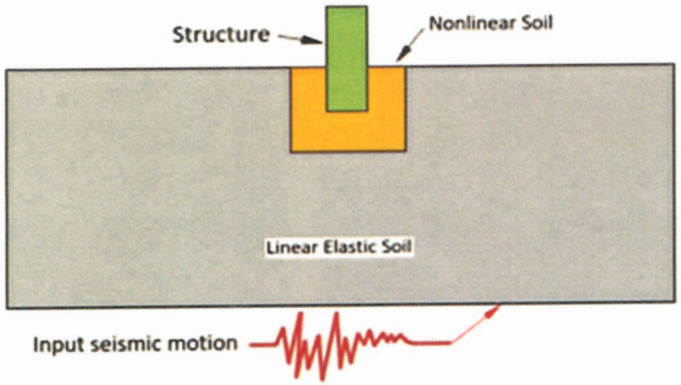
Note:
1. All the layers of the three soil profiles have a Poisson's ratio of 0.35.

Modulus Degradation & Damping

Depth (ft)	0-20		20-50	
Strain	G/G_{max}	Damping (%)	G/G_{max}	Damping (%)
0.0001	1	1.5	1	1.2
0.0003	1	1.6	1	1.2
0.001	0.985	1.9	0.995	1.3
0.003	0.915	2.8	0.95	2
0.01	0.75	5.1	0.825	3.6
0.03	0.52	9	0.62	6.8
0.1	0.275	15.4	0.36	12.6
0.3	0.125	21.5	0.175	18.7
1	0.045	28	0.067	25
Depth (ft)	50-120		120-170	
Strain	G/G_{max}	Damping (%)	G/G_{max}	Damping (%)
0.0001	1	1	1	0.8
0.0003	1	11	1	0.8
0.001	1	1.1	1	0.9
0.003	0.97	1.7	0.975	1.3
0.01	0.875	2.8	0.905	2.2
0.03	0.695	5.3	0.755	4.3
0.1	0.43	10.3	0.495	8.8
0.3	0.23	16.3	0.28	14.3
1	0.09	22.8	0.115	21

Overview: Proposed Seismic Analysis Methodology

- Proposed SMR-160 SSI Analysis – Time Domain & Nonlinear



- Global soil behavior is equivalent linear elastic, which is modeled based on strain compatible soil properties obtained from SHAKE analysis
- Nonlinear soil model maybe be used locally in the region where SSI effect is strong with relatively large strain
- Structures are modeled as linear elastic materials
- Contact interfaces are defined to account for geometric nonlinearity, i.e., potential gapping and sliding at soil-structure interface

Overview: Validation of Soil Material Models

- Two hysteretic soil material models will be used in the LS-DYNA SSI analysis:
  - *MAT_232 – Equivalent linear elastic material model used to predict the global behavior of the soil site
  - *MAT_079 – Nonlinear inelastic material model to capture relatively large energy dissipation in soil adjacent to structures
- Demonstrate that MAT_232 can reasonably match SHAKE 1D seismic response analysis results
- Demonstrate that MAT_079 can absorb the same amount of energy as predicted by the theoretical solution at the element level or lab-measured damping of soil sample

Overview - Validation of Time Domain SSI Analysis

- Validation will be performed using a representative SSI model which consists of a deeply embedded simple structure.
- Perform a time domain LS-DYNA analysis (using *MAT_232 to model soil) and a frequency domain SASSI analysis to demonstrate that seismic responses of the structure (when bonded with the soil) predicted by the two methods are similar
- Define the contact interface between the embedded structure and the soil and reperform the LS-DYNA SSI analysis. Show the difference between the results obtained from the two methods due to the geometric nonlinearity in the LS-DYNA model as the seismic intensity increases

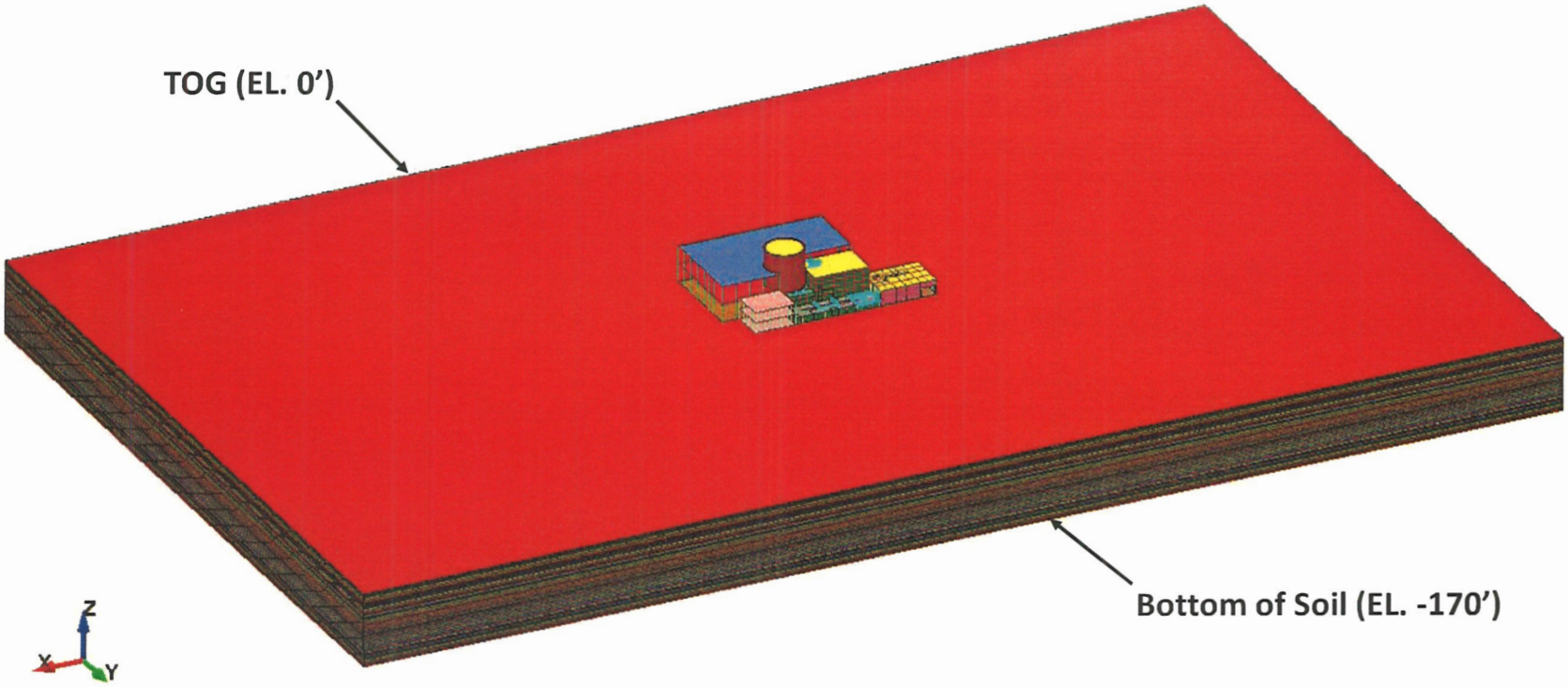
Progress – 1D Soil Seismic Response Analysis

- Seven sets of input acceleration time histories have been developed according to the SMR-160 seismic design response spectra and used for the SHAKE 1D ground response analysis
- SHAKE 1D analyses have been completed to obtain strain compatible soil properties (modulus and damping ratio) for the LB, BE and UB soil profiles
- Bedrock elevation (-170') acceleration time histories in three directions obtained from SHAKE analysis will be used as the seismic input of the time domain LS-DYNA SSI analysis

Progress – Development of LS-DYNA SSI Model for Single Unit SMR-160

- The LS-DYNA SSI model consists of soil, seismic structures, and adjacent non-seismic structures. These structures are CES (including CS, CS Internal structures), RAB, CB, RWB, TB and AB.
- Solid elements are used to model soil and thick civil structure components (e.g., basemats), as well as water in the annular reservoir and in the spent fuel pool through a simple fluid material model
- Shell or thick shell elements are used to model walls and slabs of civil structures or thin steel equipment/structures.
- Beam elements are used to model beams and columns of civil or steel structures and certain equipment
- Mass elements are used to account for equipments of significant mass

Progress – Development of LS-DYNA SSI Model for Single Unit SMR-160



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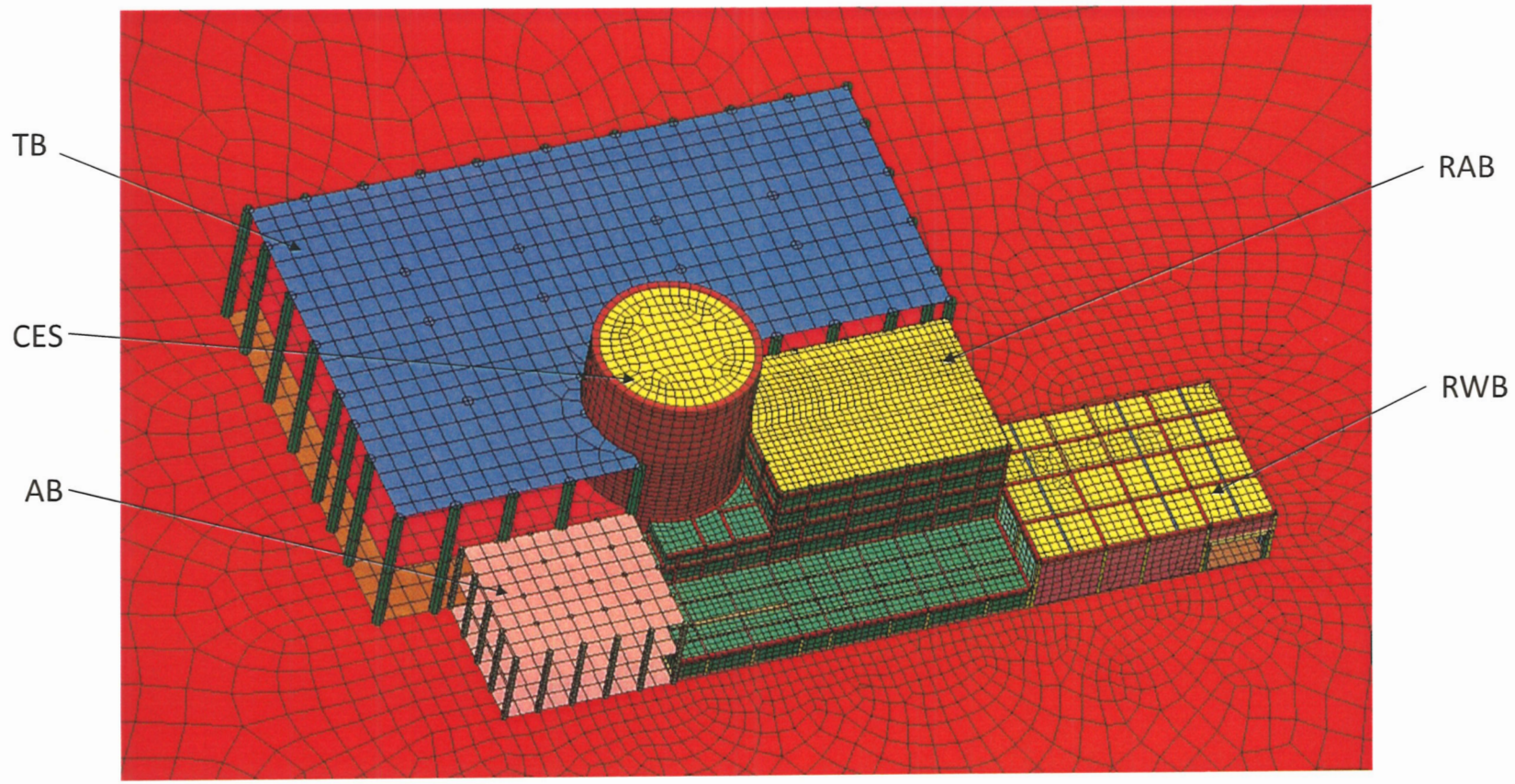

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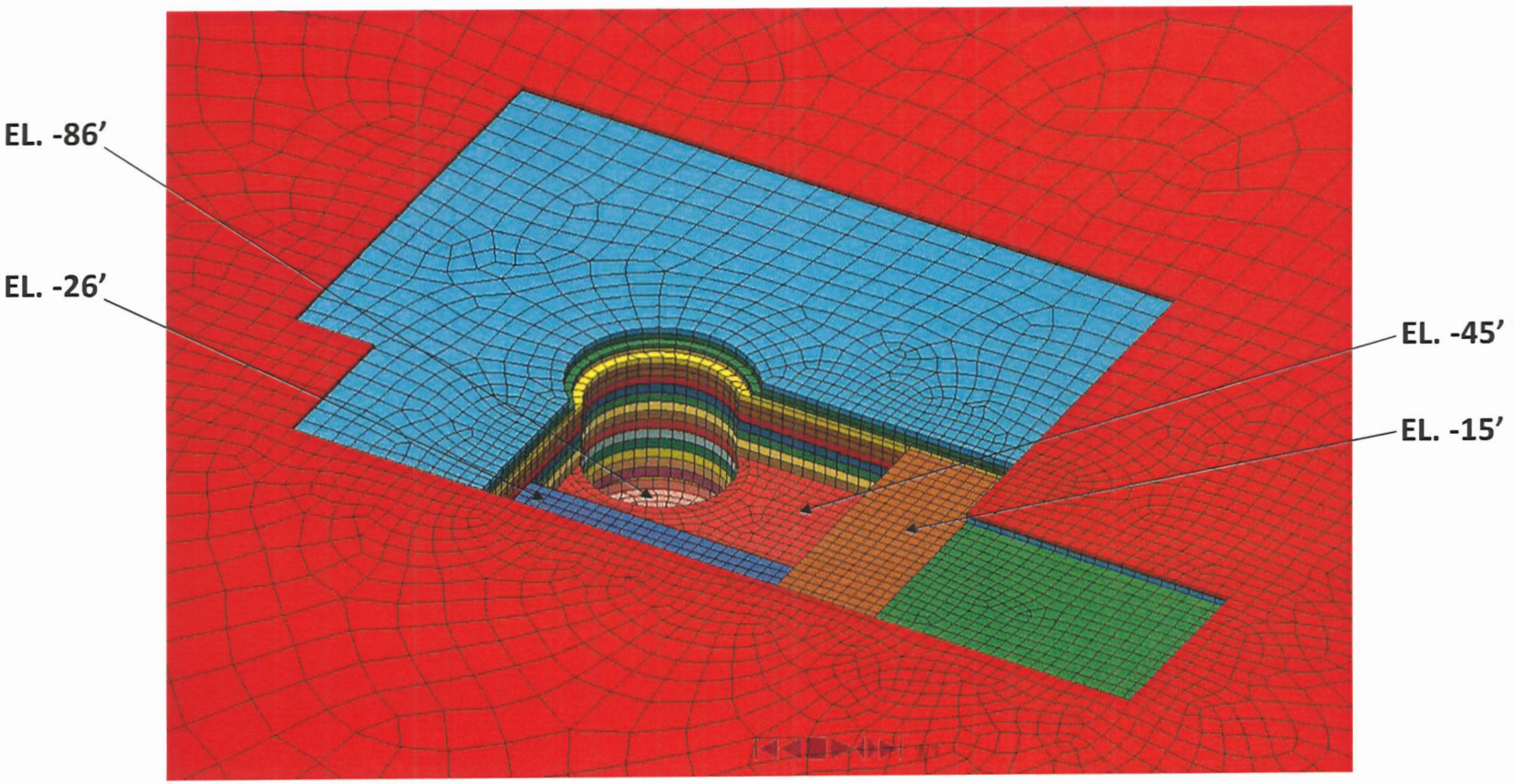

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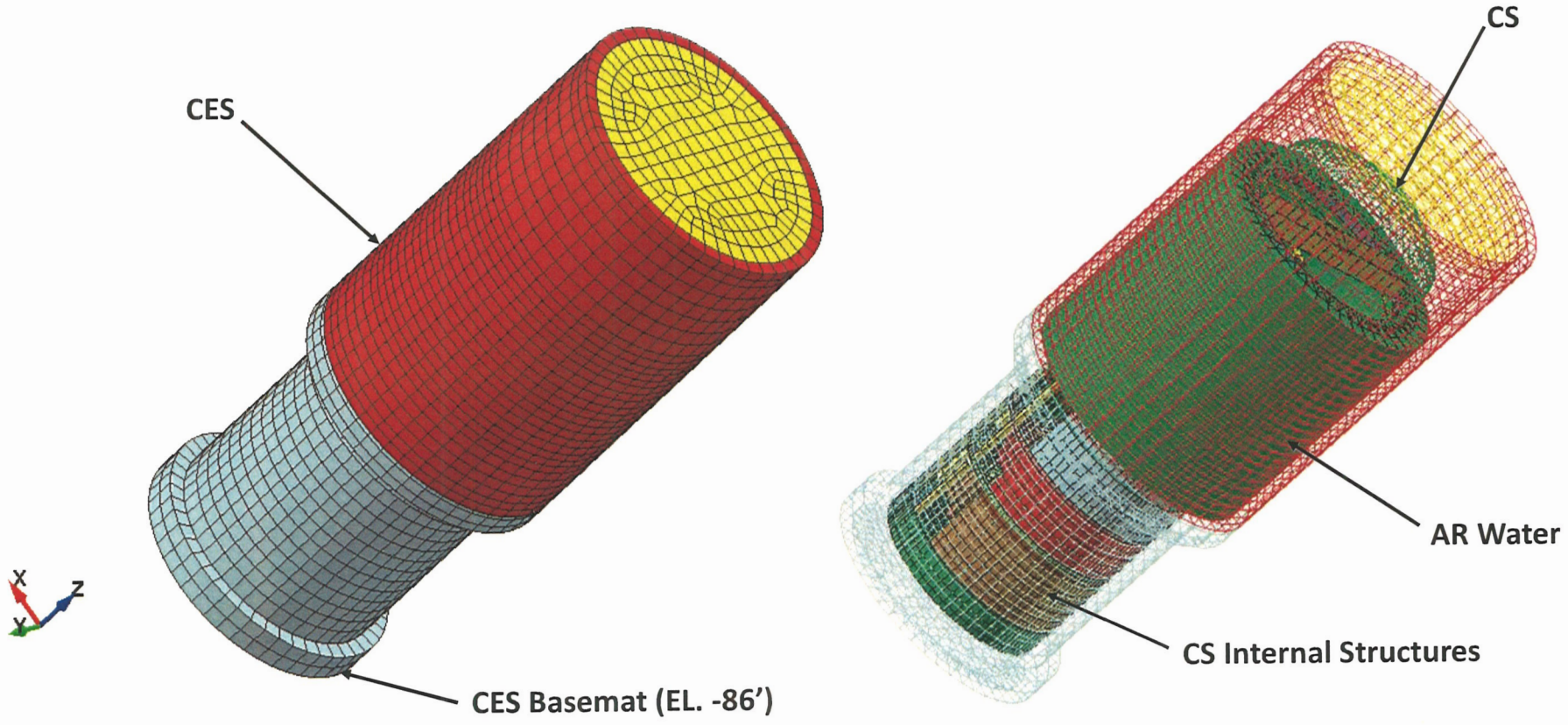

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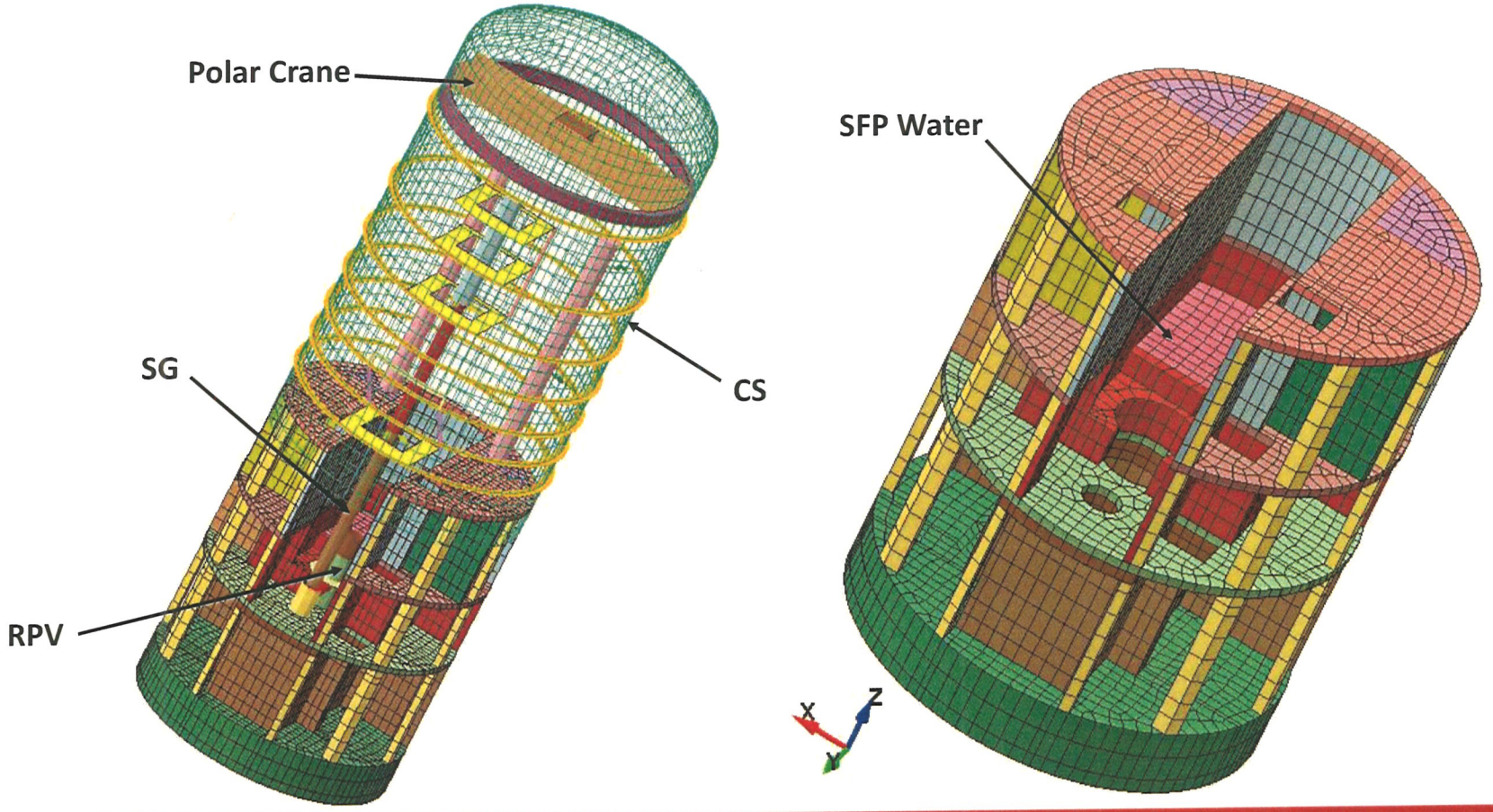

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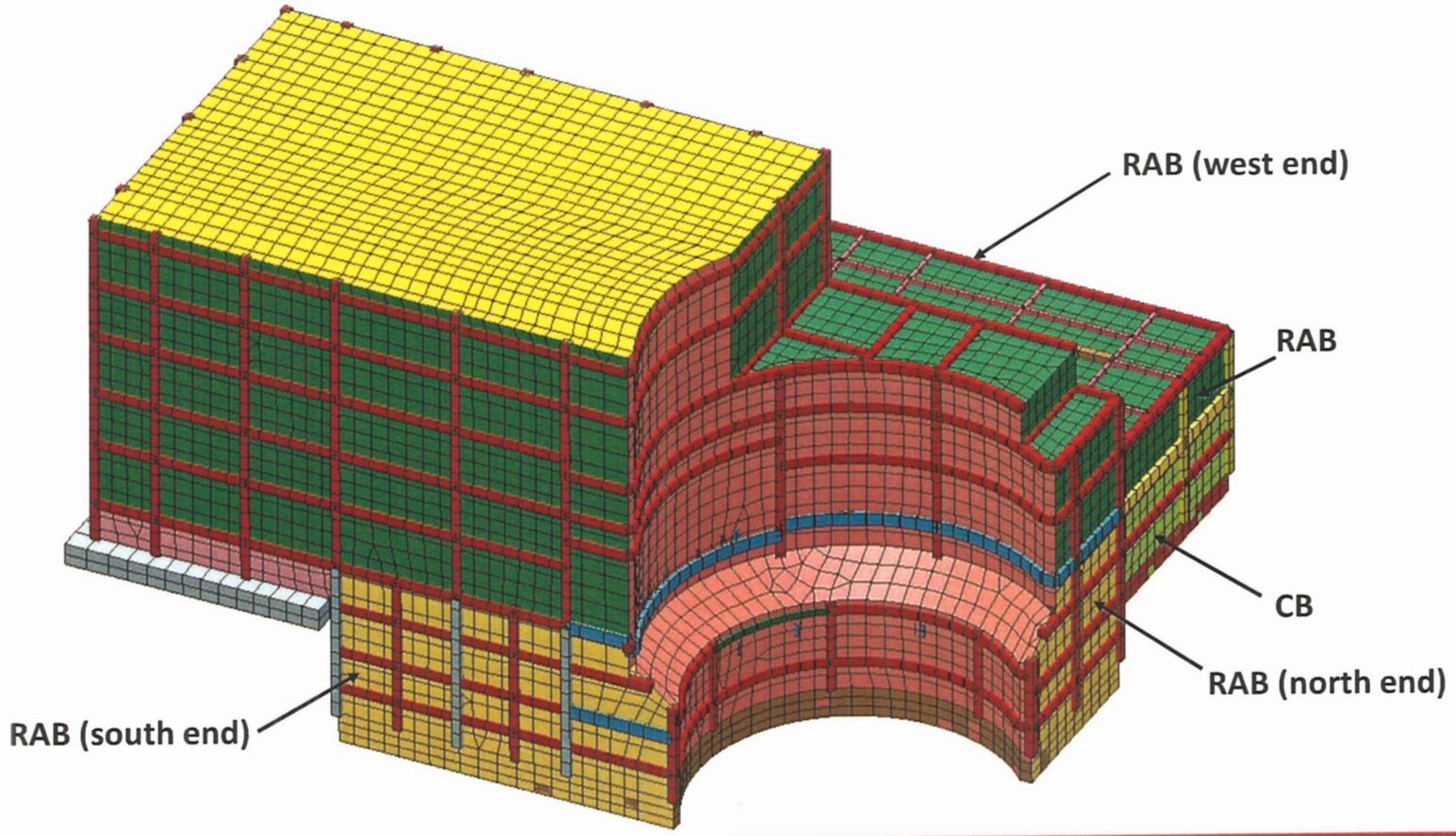

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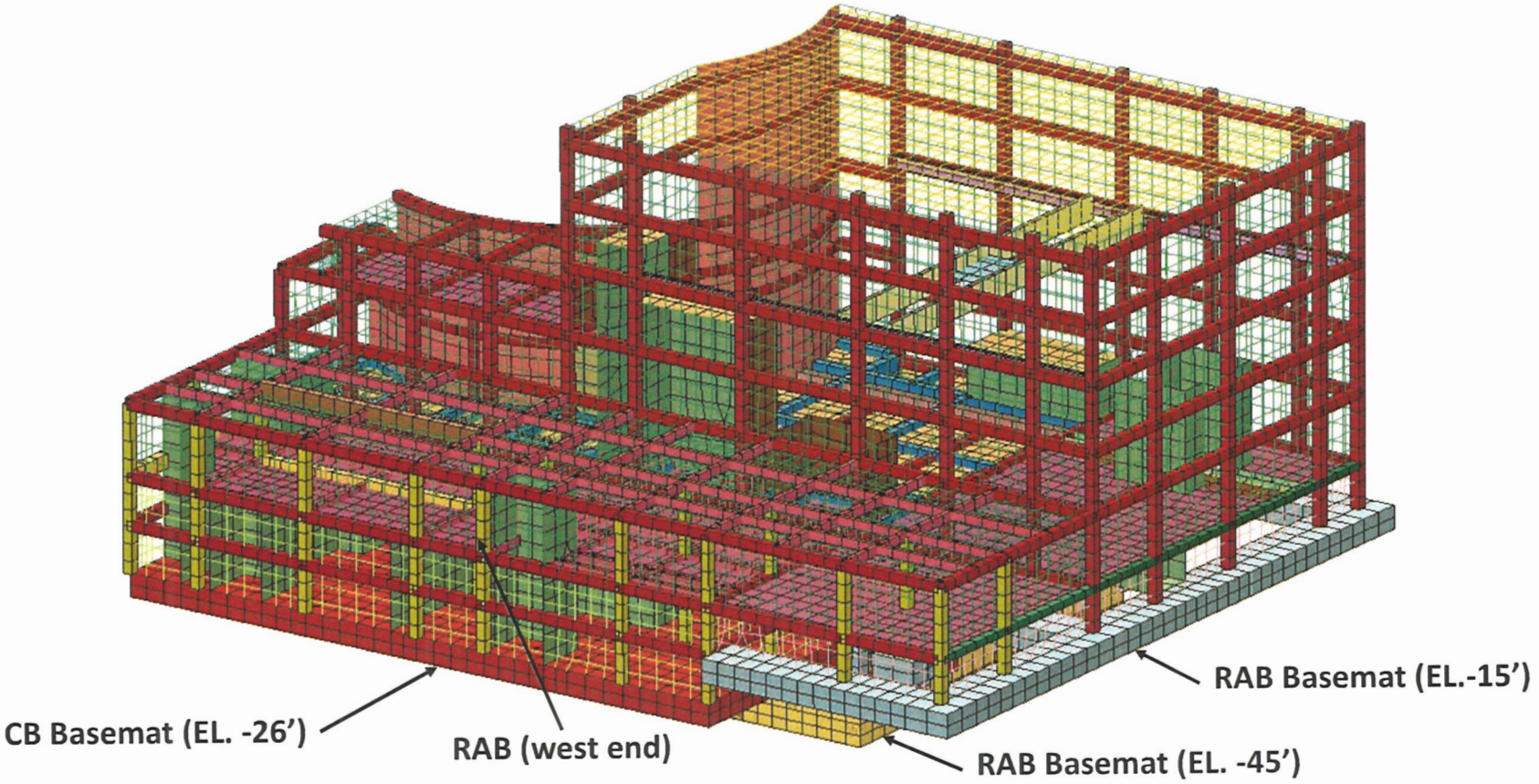
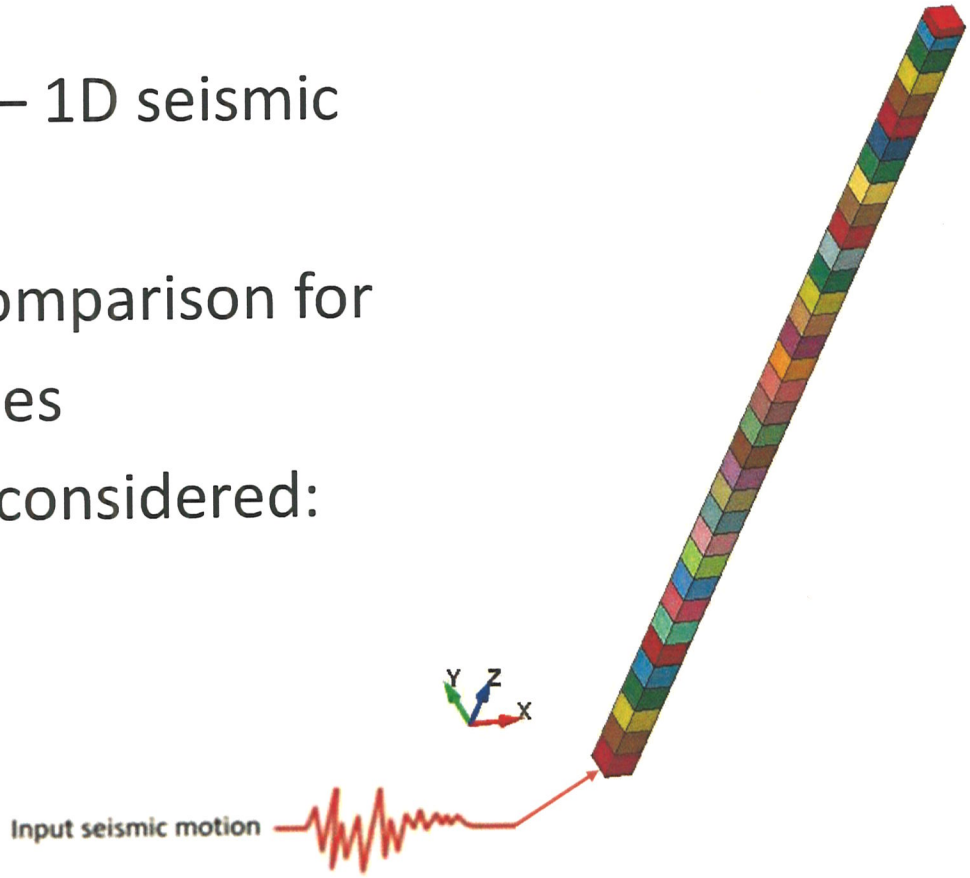


Progress – Benchmarking of Soil Models

- Soil seismic response significantly affects the accuracy of the predicted structural response of the SSI model
- Benchmarking ensures that the soil behaves as expected
- Benchmark studies have been performed for the LS-DYNA hysteretic soil models used for the SMR-160 SSI analysis
- *MAT_232 is benchmarked against SHAKE 2000 1D ground response solution
- *MAT_079 is benchmarked against theoretical solution at the element level

Progress – Benchmarking of Soil Models

- *MAT_232 benchmarking – 1D seismic response analysis model
  - TOG response spectrum comparison for BE, LB and UB soil properties
  - Other soil material model considered: *MAT_01 (*MAT_ELASTIC)



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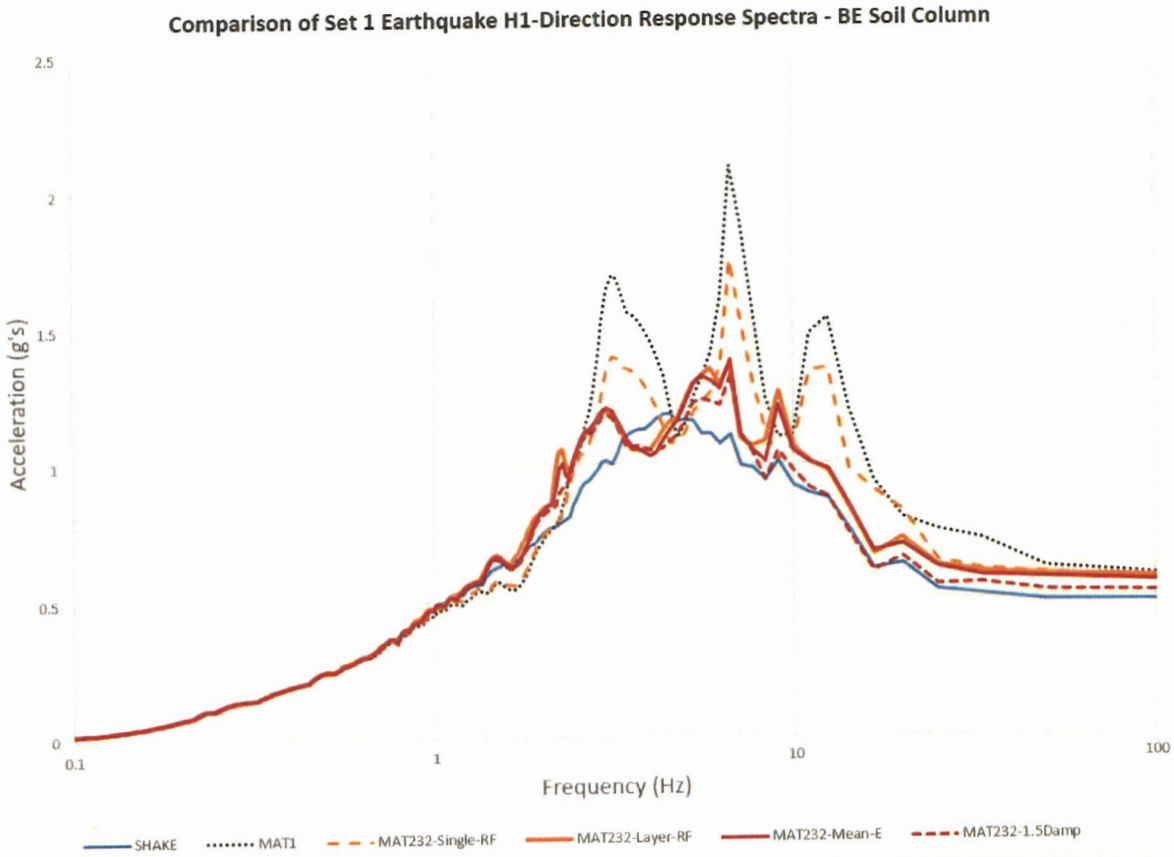

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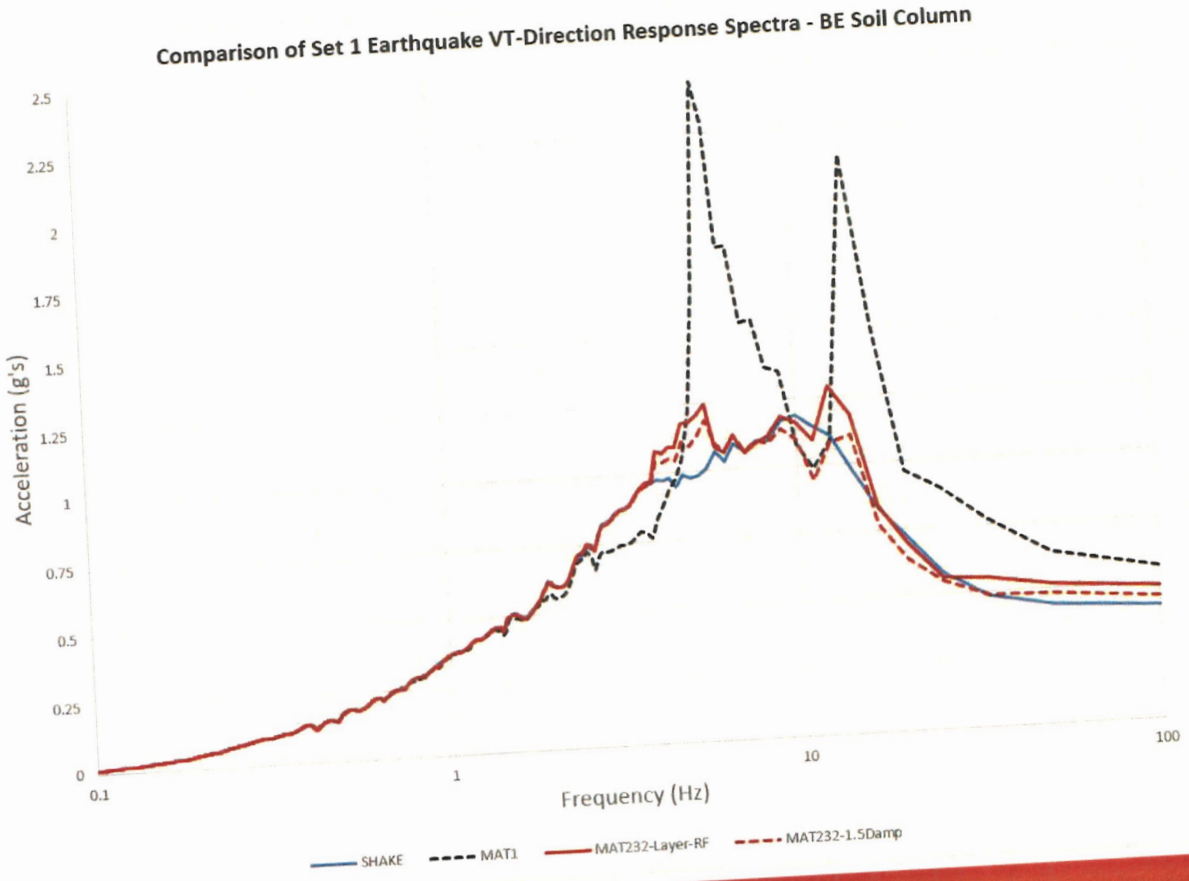

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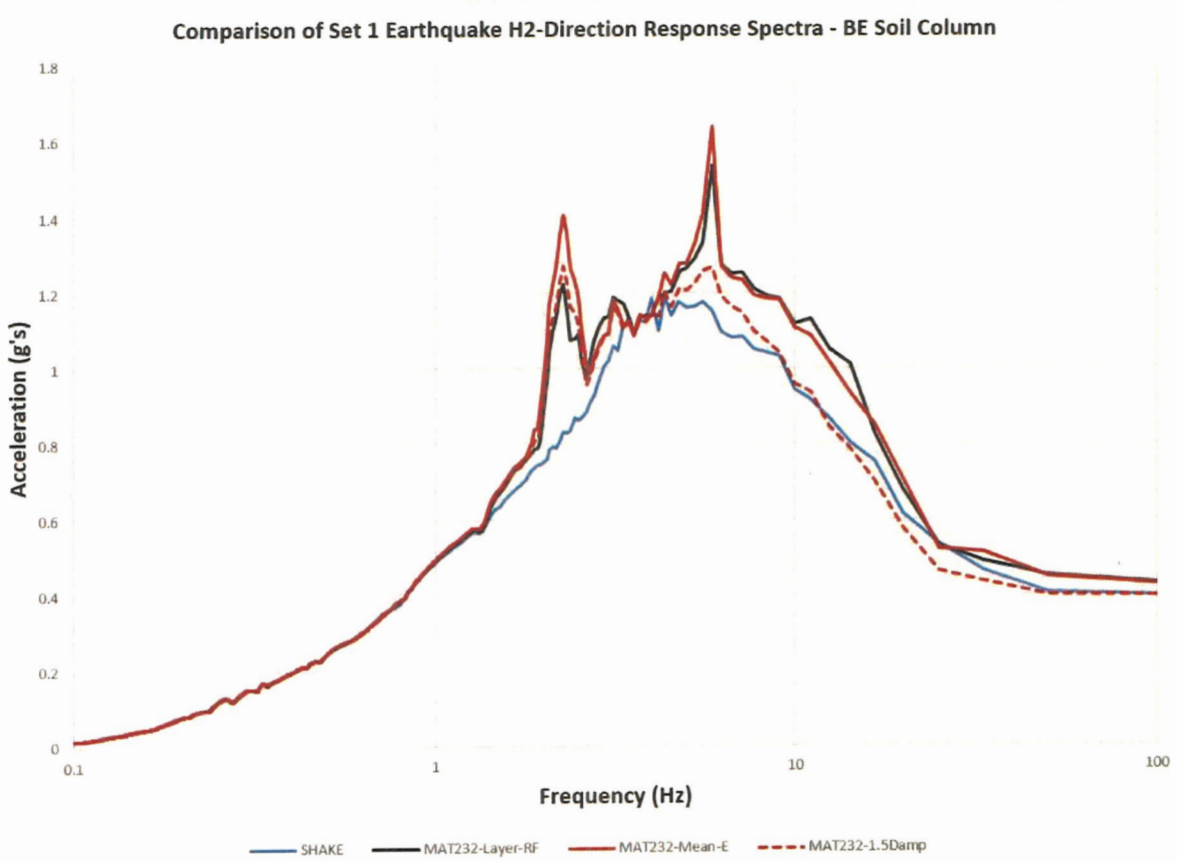
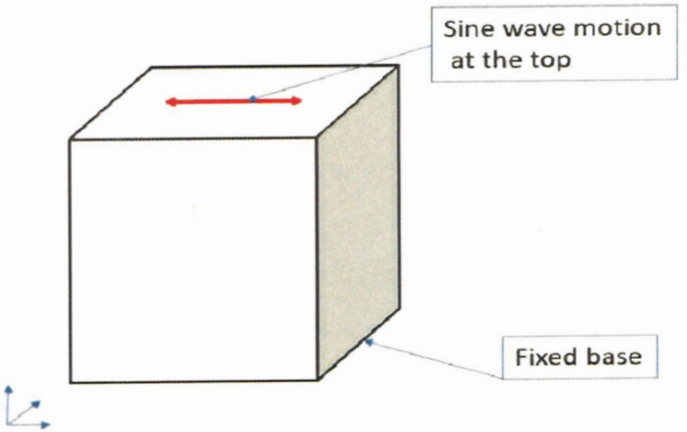


Progress – Benchmarking of Soil Models

- *MAT_079 benchmarking – LS-DYNA element level (1" cube element) response analysis
  - Demonstrate that the LS-DYNA predicted shear stress at the maximum strain matches the expected value
  - Demonstrate that the absorbed energy per loading/unloading cycle matches the frequency domain linear analysis (SHAKE) result
  - The element level SHAKE result of absorbed energy can be obtained through theoretical derivation
  - Benchmarking is done for several maximum strains (0.1, 0.0866, 0.05, 0.01)



Progress – Benchmarking of Soil Models

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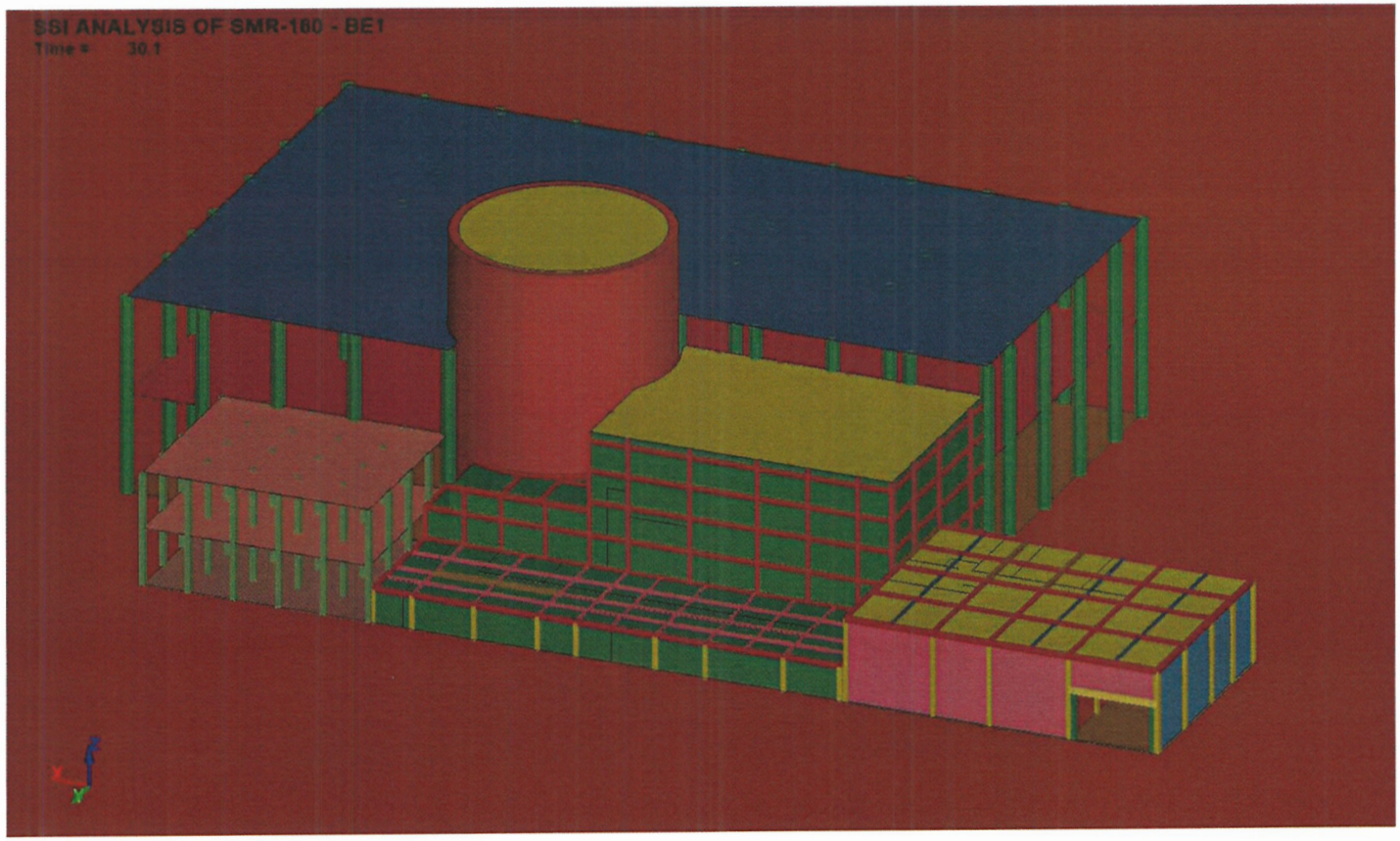
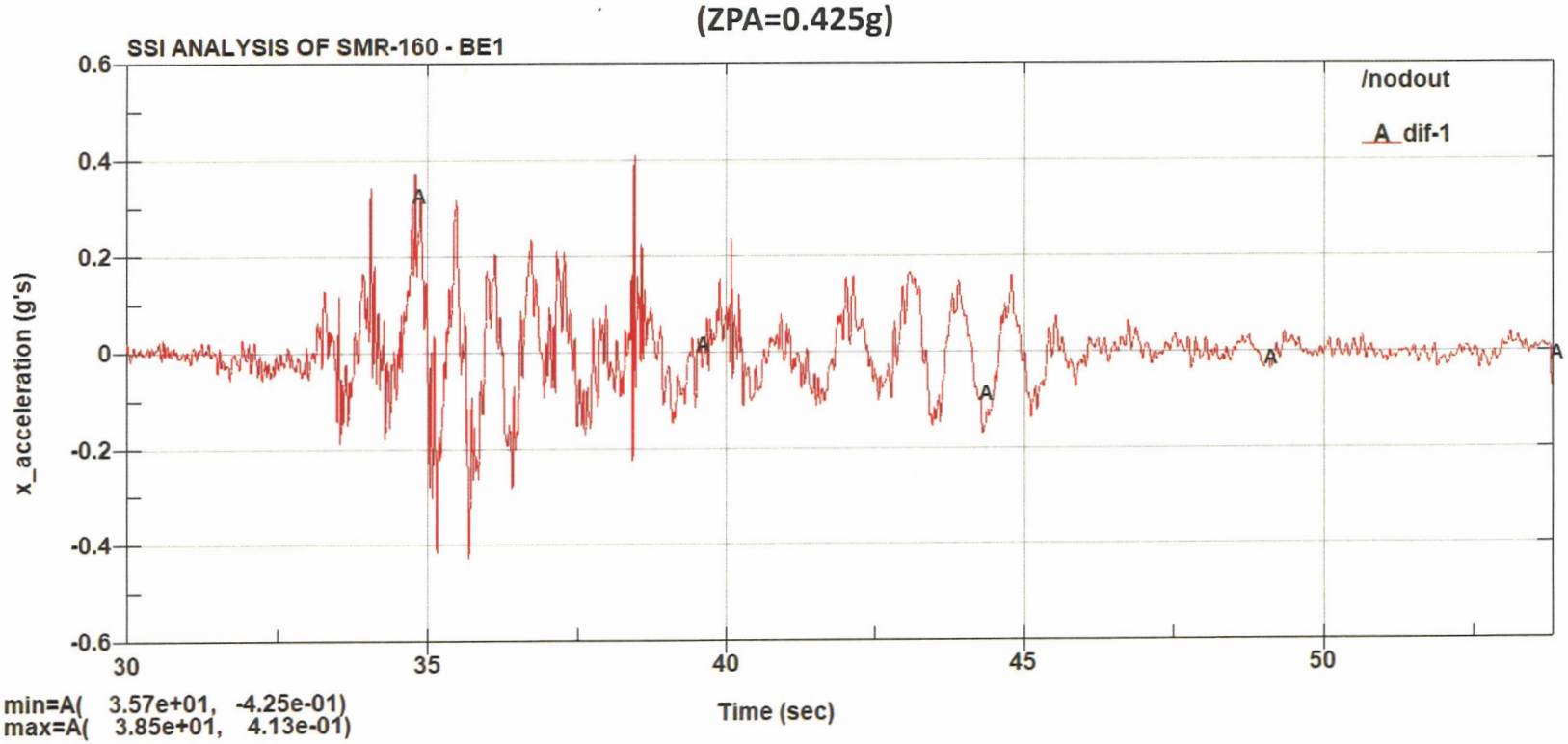
Progress – Preliminary Analysis Results



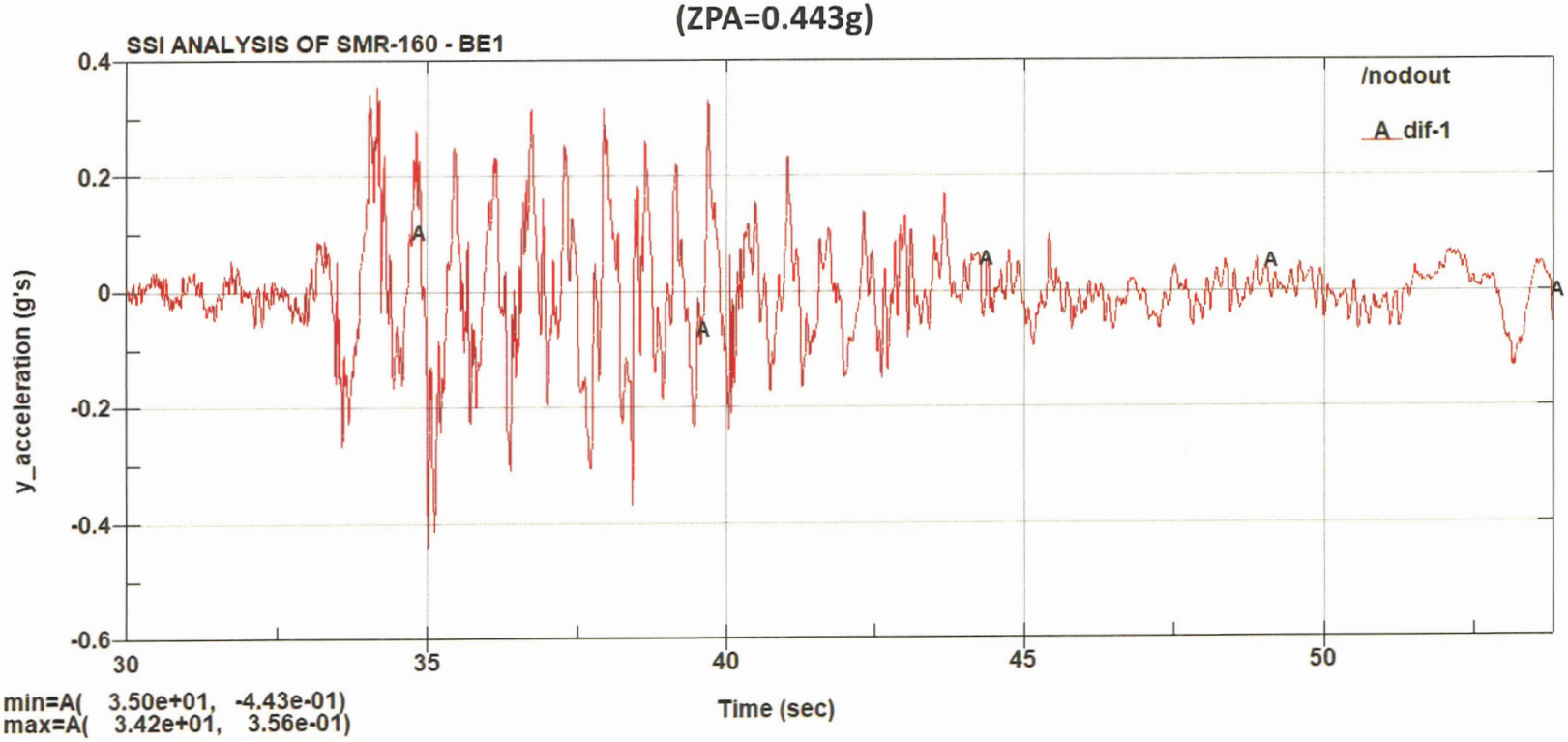
Progress – Preliminary Analysis Results

- Containment internal structure EL. 0’ floor RPV stand acceleration time history – x dir.



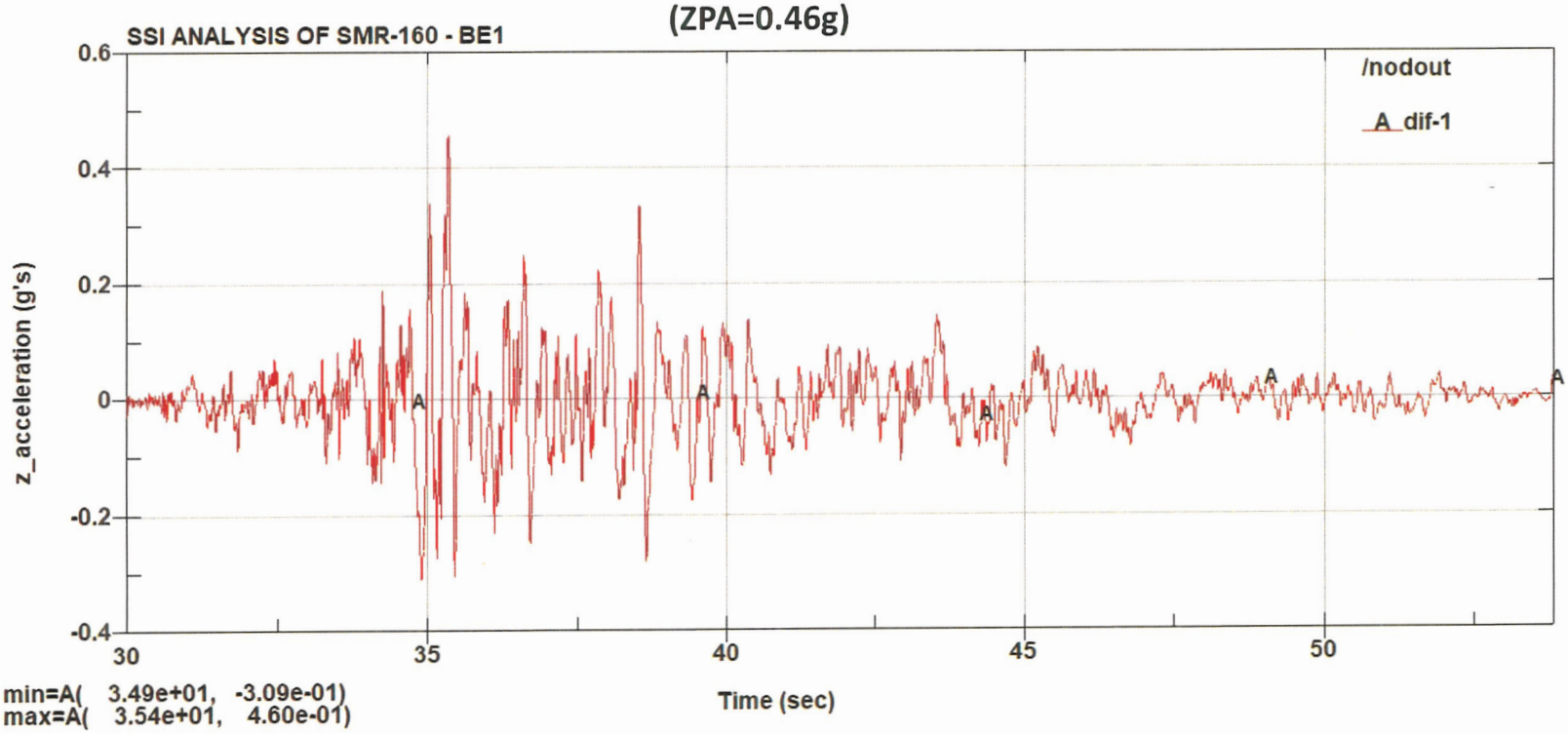
Progress – Preliminary Analysis Results

- Containment internal structure EL. 0’ floor RPV stand acceleration time history – y dir.



Progress – Preliminary Analysis Results

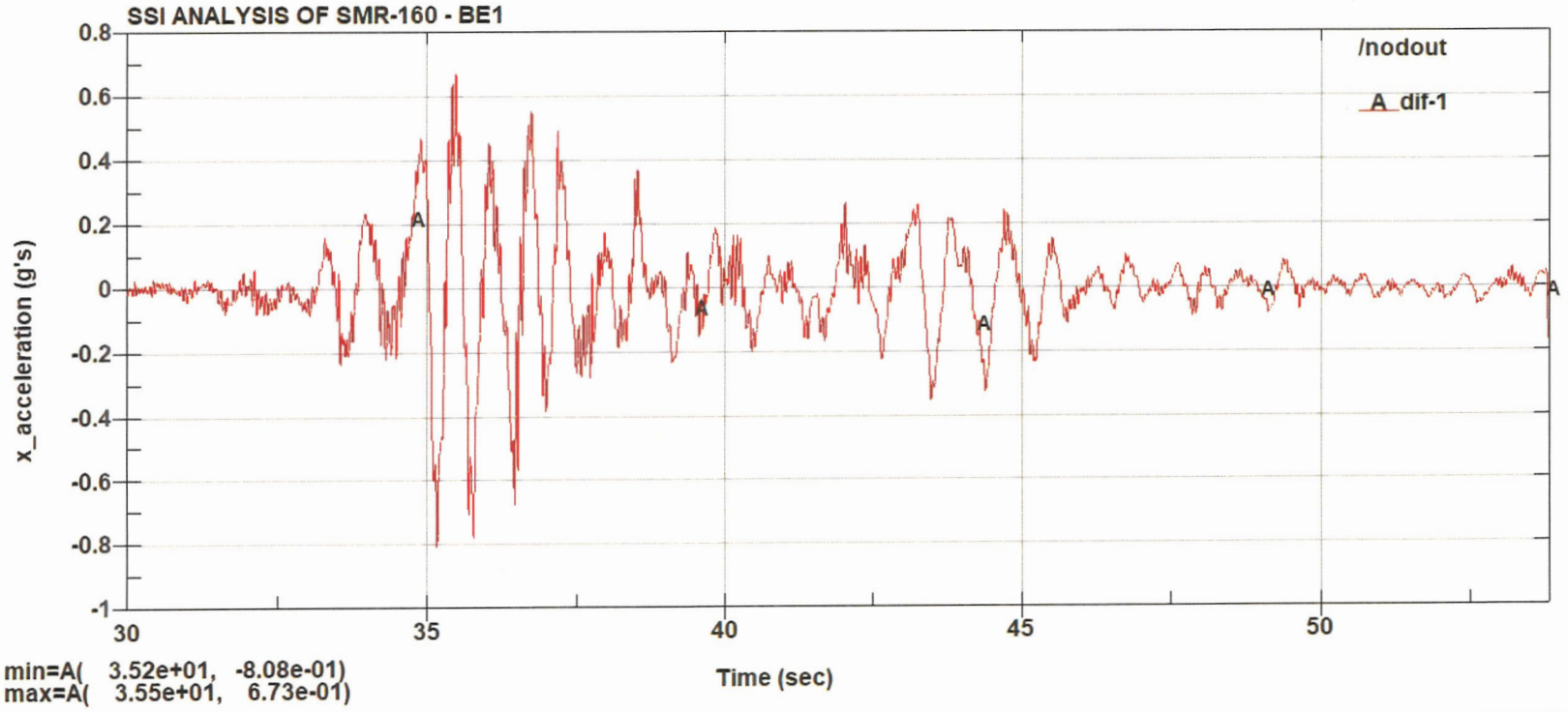
- Containment internal structure EL. 0’ floor RPV stand acceleration time history – z dir.



Progress – Preliminary Analysis Results

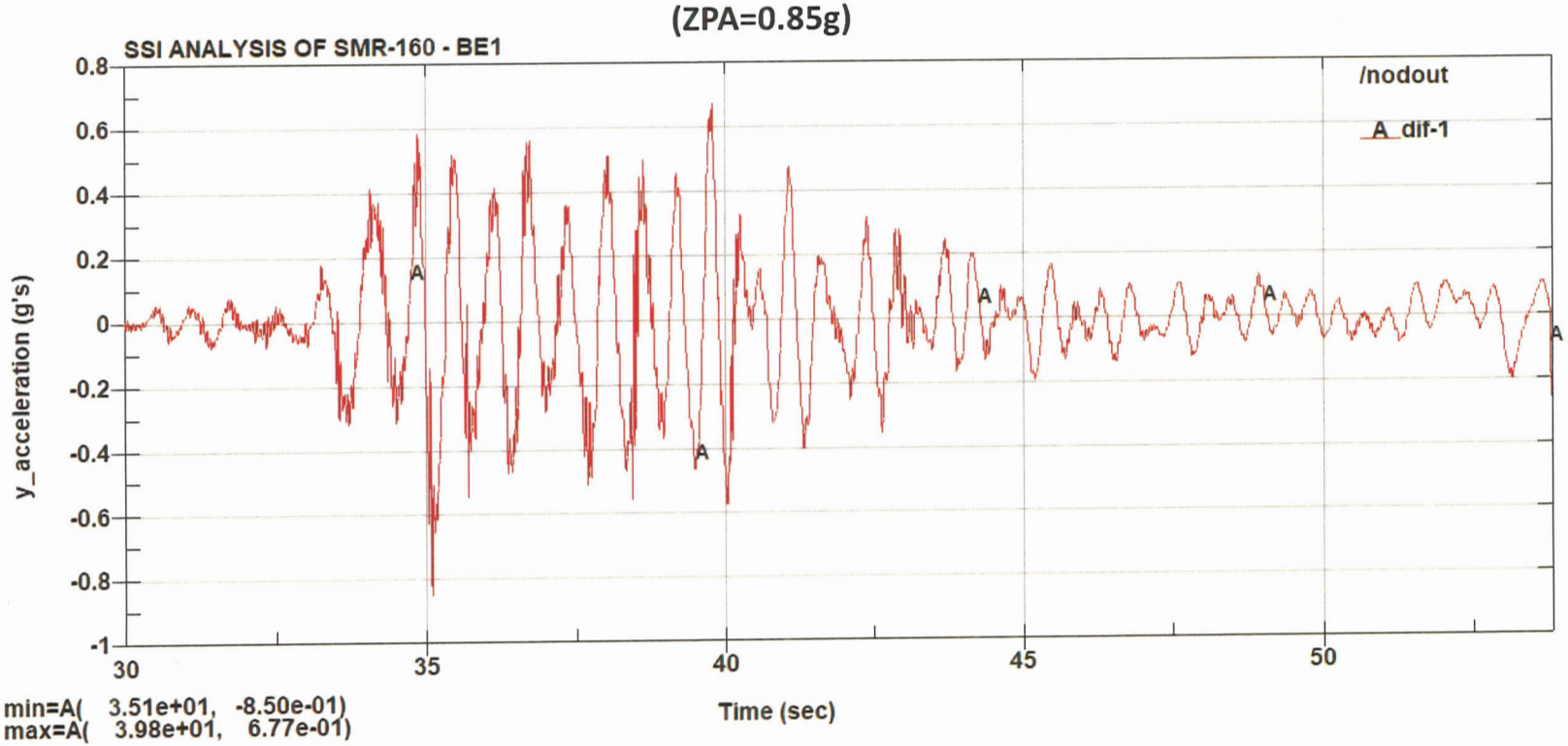
- Polar crane support (attached to the CS at EL. 81'-4") acceleration time history – x dir.

(ZPA=0.808g)



Progress – Preliminary Analysis Results

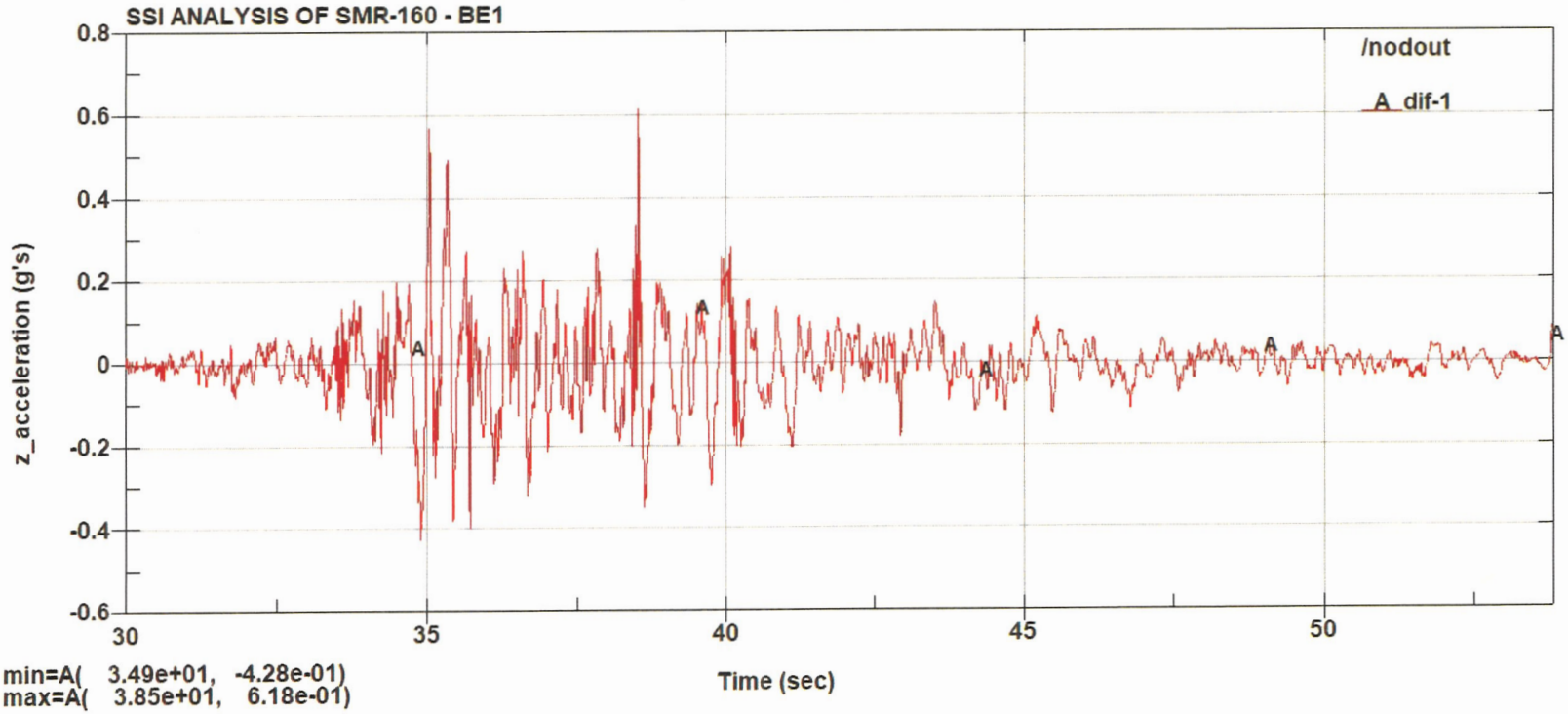
- Polar crane support (attached to the CS at EL. 81'-4") acceleration time history – y dir.



Progress – Preliminary Analysis Results

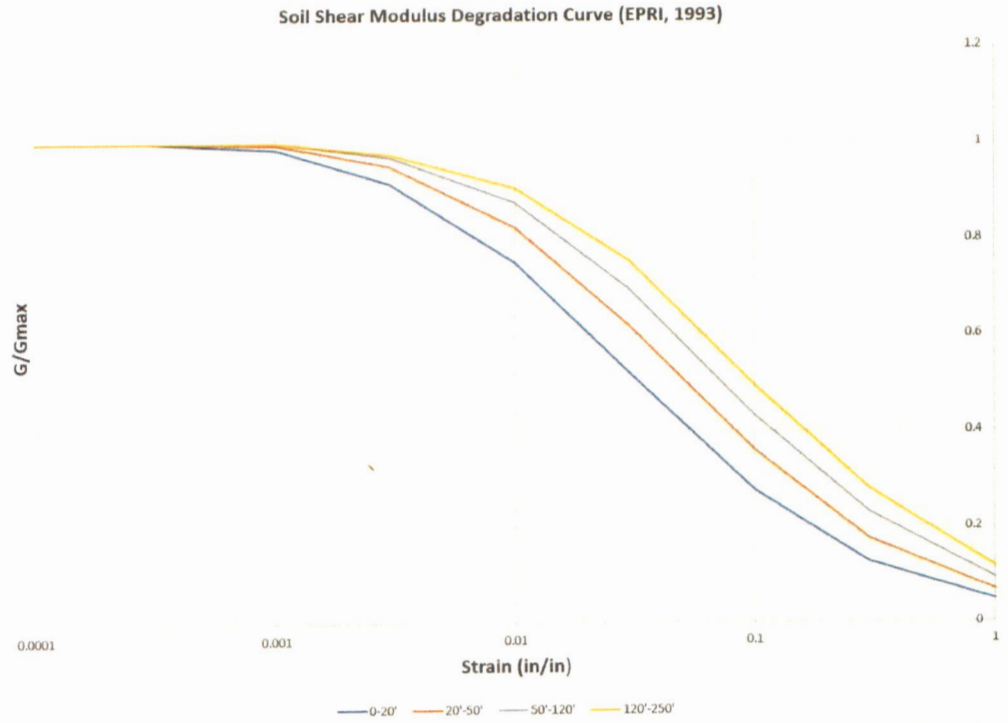
- Polar crane support (attached to the CS at EL. 81'-4") acceleration time history – z dir.

(ZPA=0.618g)



SSI Simulations

- Material model *MAT_079 will be used to simulate nonlinear soil behavior adjacent to embedded structures (strain>0.35%).

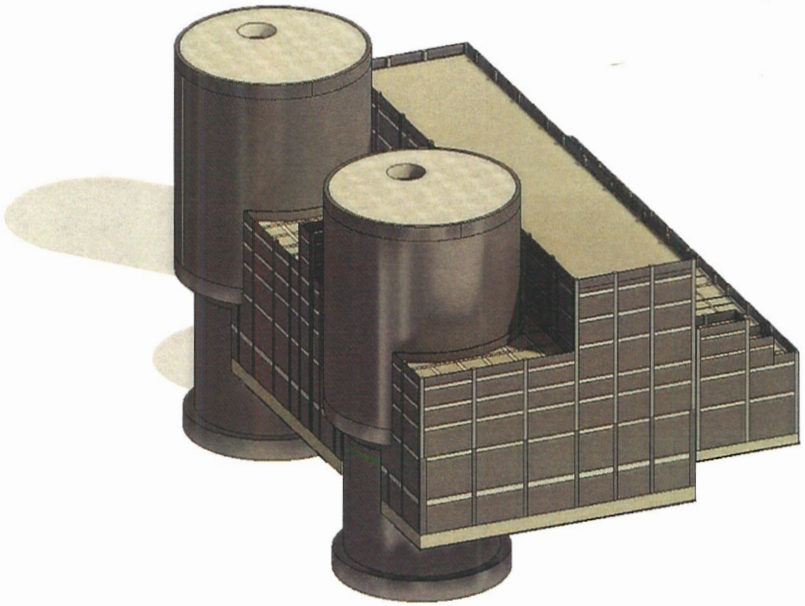


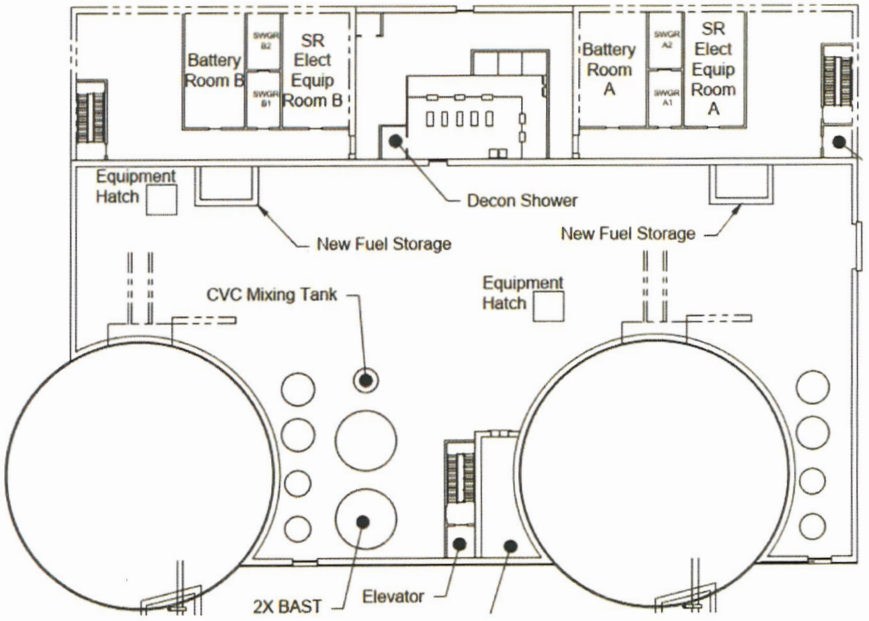
SSI Simulations

- LS-DYNA SSI analyses will be performed for 3 soil profiles (LB, BE, and UB) and 7 earthquake sets.
  - The effects of concrete cracking in building structures and water table in soil will also be considered.
- Each SSI analysis is performed in two steps: (1) Applying gravity load only to initialize the stress/deformation fields; (2) Restarting the run with transient seismic load
- SSI analysis results of the 7 earthquakes are averaged for each of the analyzed configurations.
- ISRS – Enveloping all averaged response results and then smoothing and broadening per RG 1.122 and SRP 3.7.2

Dual Unit Design

- Dual unit design will replace current single unit SMR-160 as the standard plant design. SSI model will be updated accordingly.





Licensing Approach

- Initial CPA will be to build a dual unit SMR at Palisades under Part 50
- After CPA approval, Holtec may consider seeking a design certification for potential future SMRs under Part 52 or submit a licensing topical report (LTR) requesting approval of the generic methodology
  - Potential future Part 52 application or LTR would likely include consideration for both soil and rock sites

Technical Questions

- Multi-Unit Sites
  - What is the minimum required separation distance between adjacent SMR sites for the individual site installations to be considered decoupled, e.g., greater than depth to bedrock?
  - Is there any NRC guidance or accepted industry standard regarding structure-soil-structure interaction?
- Water Table
  - What level of analysis is required with respect to water table elevation, e.g., best estimate only?
  - Is there any NRC guidance or accepted industry standard regarding effects of water table on SSI analysis?