SASSI Methodology-Based Sensitivity Studies for Deeply Embedded Structures, Such As Small Modular Reactors (SMRs)

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Purpose of This Presentation:

To disseminate results of some internal multiyear research projects done in GP Technologies for a better understanding of the behavior of deeply embedded nuclear structures such as SMRs in nonuniform soil layering.

To answer to the following key questions:
- How the SSI uncertainties affect the ISRS in SMRs?
- Is deterministic SSI analysis more or less conservative for SMR?
- How important is inertial SSI vs. kinematic SSI for SMRs?
- How accurate are the SASSI MSM or ESM methods for SMRs?
- How sensitive are SSI responses to the excavated soil mesh size variation and mesh nonuniformity?
- Are HO Rayleigh wave mode effects significant for nonuniform soils?
- How important are SSSI effects due to Annex Bldgs.?
- How important is the influence of ground water level on SMR response?

The ACS SASSI Version 3.0 including new Option PRO was used.
SMR Probabilistic-Deterministic SSI Case Studies

SEISMIC INPUT:
We considered a typical UHSRS shape input corresponding to the baserock (Vs=9200 fps) at the 500ft depth. Assume deterministic and probabilistic UHSRS shape at the 500 ft depth.

SOIL LAYERING:
Probabilistic SSI: We considered the 60 randomized soil profiles. The Vs and Damping for each soil profile were considered as dependent random variables with lognormal distribution. Damping variable is considered statistically dependent (varying inversely than Vs) as recommended by ASCE 04-2013. Vs c.o.v. was 0.20 and Damping c.o.v. was 0.35. The Vs profiles were assumed to have a spatial correlation corresponding to a 20 ft correlation length.

Deterministic SSI: The deterministic LB, BE and UB soil profiles were computed as the 16%, 50% and 84% NEP for the Vs and Damping profiles.

SSI ANALYSIS:
Probabilistic SSI: We considered the 60 simulated in-column soil motions at the foundation level for the embedded models, and simulated surface motions for the surface model.

Deterministic SSI: We considered the outcrop probabilistic mean response spectra of the 60 simulations as the outcrop FIRS. Then, we performed 3 SHAKE type deterministic analyses for LB, BE and UB soil profiles to compute the in-column FIRS motions to be used for the deterministic SSI analysis.
SMR Seismic Deeply Embedded SSI Model

SMR size: 100 ft x 100 ft x 200 ft
Embedment: 140 ft
Mesh size: 10 ft x 10 ft x 10 ft
Number of Nodes: 2,580
Interaction Nodes: 1,815

140 ft Embedment
SMR SSI Model
(use FV method)
UHSRS Seismic Input Defined at the Baserock (with Vs= 9,200 fps) Situated at 500 ft Depth

Deterministic (Mean) Spectra

Probabilistic (Simulated) Spectra

UHSRS Inputs defined at 500 ft Depth

Simulated GRS Shapes - CSDRS (HARD) Comparative Non-exceedance Probabilistic Curves for 16%, 50% and 84% – HORIZONTAL
In-Column Probabilistic Mean RS Computed for Deterministic and Probabilistic UHSRS Inputs

40 ft Depth

140 ft Depth
Deterministic ISRS (for LB, BE, UB) vs. Probabilistic ISRS (for Mean and 84% NEP)

Horizontal Basemat

Deterministic SSI results are conservative.

Vertical Roof
Probabilistic ISRS – Simulated vs. Mean and 84% NEP

Very skewed PDF! Statistical estimates are quite low.....due to shifted peaks...
Effects of Kinematic SSI for Embedded SMRs

Relative Displacement wrt Basemat Center

140 ft Embedment

For 140 ft embedment the kinematic SSI effects are dominant, 80-90%, up to the ground surface elevation at 140 ft.

40 ft Embedment

For 40 ft embedment the kinematic SSI much less significant, 20-30%, below the ground surface elevation at 40 ft.
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<th>Runtime/freq.</th>
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SMR Case Studies on FV Substructuring Methods

NONUNIFORM SOIL PROFILE
SMR Massless Foundation (Fully Embedded) Model
Volume Size: 120 ft x 80 ft x 80 ft

Model View

Vertical Section

Corner Nodes from top to bottom layers:
7681, 6913, 6145, 5377, 4609, 3841, 3073, 2305, 1537, 769, 1

Z-coordinates (ft): 0, -12, -24, -36, -48, -60, -72, -84, -96, -108, -120

FFV-Skip 2 Levels

Mesh 4 ft x 8 ft x 8ft
7,938 Interaction Nodes
Comparative ATF at -120 ft Depth (Foundation Level)

Direction X

Excavated Volume Plus Shells Model Test - TFU
Nonuniform Soil -- at Elevation (-120 ft., Node 1) -- Direction X

Direction Z

Excavated Volume Plus Shells Model Test - TFU
Nonuniform Soil -- at Elevation (-120 ft., Node 1) -- Direction Z

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Comparative ATF at -32 ft Depth (1/4 of Embedment)

Direction X

Direction Z

FFV-Skip2 is highly accurate; 5 less int. nodes, and 5 faster than FV method

Excavated Volume Plus Shells Model Test - TFU
Nonuniform Soil -- at Elevation (-32 ft., Node 5633) -- Direction X

Excavated Volume Plus Shells Model Test - TFU
Nonuniform Soil -- at Elevation (-32 ft., Node 5633) -- Direction Z
SMR Massless Foundation Excavation Mesh Size Study

Original

Volume Size: 120 ft x 80 ft x 80 ft

Mesh 4 ft x 4ft x 4ft
29,971 Interaction Nodes

Remeshed

Uniform soil
Vs=1000 fps;
Input at Surface

Mesh 4 ft x 8ft x 8ft
7,938 Interaction Nodes
Comparative ATF at Foundation and Surface Levels

120 ft Depth

Excavated Volume Plus Shells Model Test - ATF
Uniform Soil – Node 00001 Direction X

- Amplitude vs Frequency (Hz)
- Logarithmic scale
- Blue line: Original Model
- Red dots: Remeshed Model

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SMR Excavation Volume Mesh Nonuniformity Study

Volume Size: 200 ft x 100 ft x 100 ft

140 ft Embedded SMR Model

Vs Soil Profile (fps)

SMR size: 100 ft x 100 ft x 200 ft
Embedment: 140 ft
Mesh size: 10 ft x 10 ft x 10 ft
Number of Nodes: 2,580
Interaction Nodes: 1,815
For nonuniform meshes the average radius values are used.
Comparative ATF at -140 Depth (Foundation Level)

Horizontal

Vertical
Comparative ATF at Ground Surface Level

**Horizontal**

Acceleration Transfer Function X-Direction
Node Location: X=0, Y=0, Z=0

**Vertical**

Acceleration Transfer Function Z-Direction
Node Location: X=0, Y=0, Z=0

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SMR-AB Seismic SSSI Effects Study

140 ft Embedded SMR-AB SSSI Model

Vs Soil Profile (fps)

SMR size: 100 ft x 100 ft x 200 ft
Embedment: 140 ft
Mesh size: 10 ft x 10 ft x 10 ft
Number of Nodes: 2,580
Interaction Nodes: 1,815

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Seismic SSSI Effects on ISRS at Computed at Surface Level for Rock Site

Horizontal

Vertical

SMR-AB Combined Model (Rock Site) - SRSS (Node 1815)
SMR Corner at Coordinates(100, 100, 0) -- Direction X

SMR-AB Combined Model (Rock Site) - SRSS (Node 1815)
SMR Corner at Coordinates(100, 100, 0) -- Direction Z

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Seismic SSSI Effects on ISRS at Computed at 30 ft Above Surface for Soil Site

Horizontal

Vertical
SSSI Effects on Seismic Soil Pressure (Spring Forces) Along the SMR Vertical Corner Edge Near AB (140 ft)

Rock Site

Soil Site

Forces for Springs (SMR, Rock Site)
Elements 11 (Corner) -- PX

Forces for Springs (SMR, Soil Site)
Elements 11 (Corner) -- PX

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SSSI Effects on Wall O-P Bending Moments Along SMR Shell Element Vertical Line Near AB (60 ft)

Rock Site

Moments for Shells (SMR, Rock Site)
Elements 146 (Middle) – MYY

Soil Site

Moments for Shells (SMR, Soil Site)
Elements 146 (Middle) – MYY
HO Rayleigh Wave Modes Manifest at High Frequencies in Nonuniform Layered Soils (shown at 30 Hz)

Horizontal mesh size can be larger...

Layered Soil

Rock Formation
SSI and SSSI HO Rayleigh Wave Mode Effects on SMR ATF for Nonuniform Soil Layering – in X-Dir

-140 ft Depth

Surface Level

SSSI and SSI With Inclined Waves

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SSI and SSSI HO Rayleigh Wave Mode Effects on SMR ATF for Nonuniform Soil Layering – in Z-Dir

-140 ft Depth

Surface Level

SMR-AB Model (Coherent, Rock Site) - SRSS (Node 1331)
SMR Corner at Coordinates(100, 100, -40) – Direction Z

SMR-AB Model (Coherent, Rock Site) - SRSS (Node 2066)
SMR Corner at Coordinates(100, 0, 60) – Direction Z

SSI and SSSI With Inclined Waves

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Ground Water Level Effects on the Vertical SMR Vibration at 40 ft Depth Floor Level

140 ft Embedded SMR SSI Model

Floor Corner

Floor Center

SMR Model - SRSS (Node 1221)
Corner at Coordinates (100, 0, -40) -- Direction Z

SMR Model - SRSS (Node 2282)
Middle at Coordinates (50, 50, -40) -- Direction Z

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Conclusions for Investigated Case Studies

• Deterministic ISRS could be significantly higher than Probabilistic ISRS. However, it appears that the 84% NEP provided too low estimates, due to the smoothing effect produced by statistical averaging on the sharp ISRS peaks - frequency shifts due to soil stiffness variations are important.

• The use of the SASSI MSM and ESM with only one or two interaction node layers that are internal to the excavation volume provide crude results when compared with the FV method for the investigated SMR cases.

• Excavation horizontal mesh sensitivity studies indicate a good solution robustness for variations in the mesh size and its nonuniformity. This contradicts some published results. We will continue our investigations…

• The SMR-AB SSSI effects are important for deep soft soil deposits, especially on the seismic soil pressures and embedded walls o-p bending.

• The effects of HO Rayleigh wave modes in high-frequency appear to be significant for nonuniform layered soil deposits. We will continue…

• Ground water level can affect largely the SMR floor vertical vibration. This is not fully recognized by all.