Engineering Advances Implemented in ACS SASSI Version 3.0 for Seismic SSI Analysis of Nuclear Structures

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PART 2: SSI and SSSI Analysis Case Studies

Tokyo Station Convention Center
April 14, 2015
Comparative Probabilistic-Deterministic Studies and RVT-based SASSI Analyses of Nuclear Structures for Soil and Rock Sites

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2014 U.S. Department of Energy Natural Phenomena Hazards Meeting Germantown, MD
October 21-22, 2014
Purpose of This Presentation:

To answer to the following key questions:

- Is probabilistic SSI more accurate than deterministic SSI? Yes, but….
- Is deterministic SSI analysis providing the same non-exceedance probability level for soil and rock sites?
- Are the RVT SSI approaches based on RS-PSD transformation sufficiently accurate for application to complex nuclear structures?

Discuss the methodology effects the ISRS…

The ACS SASSI Version 3.0 with new Options PRO and RVT was used.
ASCE 04-2015 Standard Probabilistic SSI Analysis

The new ASCE 04-2014 draft standard states that the purpose of the analytical methods included in the standard is to provide reasonable levels of conservatism to account for uncertainties.

More specifically, in the same section is written that given the seismic design response spectra input, the goal of the standard is based on a set of recommendations to develop seismic *deterministic SSI responses* that correspond approximately to a 80% non-exceedance probability level.

For probabilistic seismic analyses, *probabilistic SSI responses* defined with the 80% non-exceedance probability level are considered adequate.

*Section 5.5 of the standard provides guidelines* for the acceptable probabilistic SSI approaches. The GRS spectral shape could be considered with variable shape or not (Methods 1 and 2). Soil profiles, Vs and D, should include spatial correlation with depth. Structural stiffness and damping should be also modeled by dependent or negatively correlated random variables.
Probabilistic SSI Analysis Chart

Stiffness

Damping

Effective Stiffness K and Damping D

GRS Shape

Spatial correlation

Negative Correlation

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Probabilistic Seismic Input Ground RS

**Method 1**

- Same Spectral Shape (Scaling)
- Full Correlation in Frequency….
- Simpler…
- Less information required….

**Method 2**

- Random Spectral Shape
- Correlation in Frequency….
- More physics-based…
- More information required….

Include Local Soil Conditions
Probabilistic Soil Profiles (at Low Shear Strains)

Soil Layering

Real Soil Profiles

Ideal Soil Profiles

Potential Situations that are not covered by Deterministic SSI…

- Perfect Correlation with depth looses physics…
- No Correlation with depth looses physics…

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Probabilistic Structural Modeling (Stiffness & Damping)
- *Effective or iterated* stiffness ratio $K_{eff}/K_{elastic}$ and damping ratio, $D_{eff}$, are modeled as statistically dependent pair of random variables for each element group (with different stress levels).
- $K_{eff}/K_{elastic}$ and $D_{eff}$ can be considered negatively correlated, or having a complementary probability relationship, or $D_{eff}$ be a *response function* of $K_{eff}/K_{elastic}$ based on experiments
- $D_{eff} = f(K_{eff}/Elastic)$

- $K_{eff}$ and $D_{eff}$ are defined separately for each element group.
EPRI AP1000 Stick Probabilistic SSI Study

EPRI AP1000 NI Stick Model

Experimental RS

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<td>1.00 0.05</td>
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</table>

Mean Values not Allowable Values

Case 1: Soil Site, Vs = 1,000 fps
Case 2: Rock Site, Vs = 6,000 fps
Seismic GRS (Method 2) and Soil Profiles for Soil Site
100 LHS Simulations

Horizontal, Y (c.o.v.=20%)
Vertical, Z (c.o.v.=25%)
Vs Profile (c.o.v.=20%)
D Profile (c.o.v.=30%, correl. = -60%)

Deterministic Input

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Seismic GRS (Method 2) and Soil Profiles for Rock Site
100 LHS Simulations

**Horizontal, Y (c.o.v.=20%)**

**Vertical, Z (c.o.v.=25%)**

**Vs Profile (c.o.v.=20%)**

**D Profile (c.o.v.=30%, correl. = -60)**

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Deterministic vs. Probabilistic SSI Analysis for Rock Site

UNCERTAIN STRUCTURE – Means: $K_{eff}/K_{el}=0.8$ and $D_{eff}=7\%$

Direction Y

BASEMAT
Prob 60\%-70\%

OK

Top of CIS

DECK LEVEL
Prob 60\%-95\%
Deterministic vs. Probabilistic SSI Analysis for Rock Site

UNCERTAIN STRUCTURE – Means: $K_{eff}/K_{el}=0.8$ and $D_{eff}=7\%$

Direction Y

Direction Z

Basemat

Det ranges Prob 75%-85%

Conservative

Top of CIS

Det ranges Prob 80%-95%
Structure Uncertainty Effects on ISRS

SAME PROBABILISTIC STRUCTURE – Means: $K_{\text{eff}}/K_{\text{el}} = 1 \& 0.8$ and $D_{\text{eff}} = 4\% \& 7\%$

Direction Y
- Top of ASB
- SOIL SITE
  - Small Effects
  - Large Effects
- ROCK SITE
  - Moderate Effects
  - Large Effects

Direction Z
- Top of ASB
- SOIL SITE
  - Small Effects
  - Large Effects
- ROCK SITE
  - Large Effects

Smoothing due to frequency shifting effects

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SMR Probabilistic-Deterministic SSI Analysis Study

Generic SMR Structure

- 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)
Probabilistic SSI Input Simulations
Using N LHS Samples

GSITE.IN → ProSite → N .sit → ProEquake → N .acc

GSOIL.IN → ProSoil → N .soi → Soil → Loop j=1,N → N .th → ProMotion → N .mot

GMOT.IN → ProMotion

GSTR.IN → ProStress → N .str

Loop j=1,N → Equake

GHOU.IN → ProHouse → N .hou

Probabilistic SSI Analysis Simulations (see separate figure) → ProResponse
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 04-2015. 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.
UHSRS Seismic Input Defined at the Baserock (with $V_s = 9,200$ fps) Situated at 500 ft Depth

**Deterministic (Mean) Spectra**

**Probabilistic (Simulated) Spectra**

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**UHSRS Inputs defined at 500 ft Depth**

- **Horizontal**
- **Vertical**

**Simulated GRS Shapes - CSDRS (HARD)**
Comparative Non-exceedance Probabilistic Curves for 16%, 50% and 84% -- HORIZONTAL
Probabilistic and Deterministic Soil Profiles

Probabilistic Soil Layers Simulation
Including for 16%, 50% and 84%
Non-exceedence Probability Excites

Vs (fps)

Vs=9,200 fps

Prob. Input

Det. FIRS Input

Depth (ft)
In-Column Probabilistic Mean RS Computed for Deterministic and Probabilistic UHSRS Inputs

40 ft Depth

140 ft Depth (FIRS)
Probabilistic Outcrop and In-Column FIRS vs. Deterministic In-column FIRS for LB, BE and UB Soils

Outcrop FIRS

In-Column FIRS

![Graphs showing comparison between Outcrop and In-Column FIRS](image)

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Deterministic (for LB, BE, UB) vs. Probabilistic ISRS (for Mean and 80% NEP) at Elevation 40 ft (-100 ft Depth)
Deterministic (for LB, BE, UB) vs. Probabilistic ISRS (for Mean and 80% NEP) at Elevation 140 ft (Surface)
Deterministic (for LB, BE, UB) vs. Probabilistic ISRS (for Mean and 80% NEP) at Elevation 200 ft (Roof Level)
Random Frequency Shift Effects on Spectral Response

For probabilistic SSI, the 80% NEP spectral response is determined using a statistical estimate of sample CDF at each frequency. More realistic than deterministic SSI that uses the spectral envelope.
Deterministic (LB, BE, UB) vs. Probabilistic ISRS (Mean and 80% NEP) for 1 and 5 Deterministic Seismic Inputs at Elevation 140 ft (Surface Level)
Deterministic (LB, BE, UB) ISRS Results for 5 Input Sets at Elevation 140 ft (Ground Surface Level)

Horizontal

Vertical
Effects of Seismic Motion Incoherency on SSI and SSSI Responses of Nuclear Structures for Different Soil Site Conditions

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Revised in April 2015

2014 U.S. Department of Energy Natural Phenomena Hazards Meeting, Germantown, MD
October 21-22, 2014
Purpose of This Presentation:

To answer to the following important questions:

- What is the meaning of “incoherent motion”?
- How the foundation flexibility impact on the incoherent SSI methodology and in-structure responses?
- How much can the foundation size influence incoherent responses?
- How much can the seismic input directionality affect incoherent results?
- How much can incoherency influence SSSI effects for rock and soil sites?

Discuss effects on ISRS, soil pressures, structural shear forces, and foundation wall bending moments, SSI relative displacement between neighboring buildings....

The ACS SASSI Version 3.0 code was used for all these studies.
Coherent vs. Incoherent Wave Propagation Models

3D Rigid Body Soil Motion (Idealized)

1 D Wave Propagation Analytical Model (Coherent)

Vertically Propagating S and P waves (1D)
- No other waves types included
- No heterogeneity random orientation and arrivals included
- Results in a rigid body soil motion, even for large-size foundations

3D Random Wave Field Soil Motion (Realistic)

3D Wave Propagation Data-Based Model (Incoherent – Database-Driven Adjusted Coherent)

Includes real field records information, including implicitly motion field heterogeneity, random arrivals of different wave types under random incident angles.

ANIMATIONS
How Many Modes Do we Need to Consider?

Low Frequency/Large Wavelengths/Only Few Low Order Incoherency Modes

High Frequency/Short Wavelengths/Low and High Order Incoherency Modes

Is the foundation sufficiently rigid to neglect high order modes at high frequency due to kinematic interaction effects?
Basemat Flexibility Effects on RB Complex ISRS

Elastic is 65% (!) up for vertical
Elastic is 20% up for horizontal
### Cumulative Modal Contribution for 10 Modes

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<th>Vertical</th>
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</tr>
<tr>
<td>39.062</td>
<td>16.31%</td>
<td>25.74%</td>
</tr>
</tbody>
</table>

2007 Abrahamson Rock Site Model
Effects of Number of Incoherent Modes on ISRS

Elastic Basemat Corner – X Direction

- Mean (All modes)
- Mean (Modes = 10)
- Mean (Modes = 50)
- Mean (Modes = 25)

10 Modes
25 Modes
50 Modes
All Modes (186 Modes)

Large Loss In Accuracy Due to Limited Number of Incoherency Modes
Effects of Number of Incoherent Modes on ISRS.

Vertical ISRS Using SRSS with 20 and 40 Modes
SRSS ISRS Sometimes Lower than Mean ISRS

Rock Site

Soil Site

5% Damping SRSS - ContainerCornerTop (Node 3346) at Coordinates(1008.5, 957.34, 327.41) - Direction Y

5% Damping SRSS - ContainerCornerTop (Node 3346) at Coordinates(1008.5, 957.34, 327.41) - Direction X
Motion Incoherency Differential Phasing Effects

Differential phasing produces time and space lags and through these, amplitude variations.

Greg Mertz’s example with phasing effect on Symmetric beam.

Kinematic SSI is important.
Simple Supported Beam Under Harmonic Inputs

Zero Differential Phase (Coherent)

180 Degree Differential Phase (Incoherent)

Time Lag

Mode 1

Mode 2
Effects of Zeroing Phases of Complex Responses in Frequency on Time Domain Responses

Fourier Transform Example

Acceleration Time History Compare Without using the Phasing

Original random wave motion

Zero-phase random wave motion
Effect of Zeroing Differential Phases at Lower-Mid Frequencies

For dominant single mode situations (in lower frequency range), the *neglect of the (differential) phases* that produce random amplitude variations in space, *basically changes the problem and departs from reality.*

Zero-Phases means No Differential Phasing

Single Mode “Zero-Phase” Motion produces a “deterministic rigid body” motion

Non-Zero-Phases Means Differential Phasing

Single Mode “Non-Zero-Phase” Motion produces a “random field” motion

Differential Amplitude Variations due to Differential Random Phasing

### Mode 1 Contribution

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<th>Part V</th>
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<td>8 Hz</td>
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<td>67%</td>
</tr>
<tr>
<td>25 Hz</td>
<td>7%</td>
<td>21%</td>
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</tbody>
</table>

At the lower frequencies, below 10 Hz, where a single mode (Mode 1) is governing, the zero-phase assumption practically neglects the differential phase variations between motion components due to incoherency.

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Incoherency Simulation With Zero-Phasing (Loss of Physics)

Incoherency Simulation With Random Phasing (No Loss of Physics)
2007 Abrahamson Coherence for Hard-Rock and Soil Sites

120m x 100m
Reductions for 75m:
At 10 Hz 40%?
At 20 Hz 70%?

Larger differential displacements for soils.
May affect SSSI..?

Figure 6-1
Plane-Wave Coherency for the Horizontal Component

Figure 7-1
Plane-Wave Coherency for the Vertical Component

Figure 6-2
Plane-Wave Coherency for the Vertical Component

Figure 7-2
Plane-Wave Coherency for the Vertical Component for soil sites

(EPRI TR # 1015110, December 2007)
Incoherency Effects on Multiple Mode SSI Responses

Seismic Motion Amplitude Shape

ATF Amplitude Spectral Shape

Remark: For the above GMRS, the ISRS at the selected location will be dominated by the 10 Hz, 12 Hz and 17 Hz mode responses. The 5 Hz component will be much lower. Incoherent ISRS reductions will correspond to a mix of components in the 10-17 Hz range.
Effects of Random Phasing on ISRS for Large-Size 420ft x 330ft RB Complex with Stiff Mat

“EXACT” Including Correct Phasing for All Fourier frequencies (5,700 up 60 Hz)

EPRI validated approaches overestimate incoherent ISRS for large-size foundations

SRP 3.7.2

ASCE 04-1998 for 300ft size
Effects of Incoherency on Basemat Bending

Coherent

Incoherent

Remark: Incoherent bending moments are 130%-240% of coherent bending moments.

Table 1: Basemat Bending Moments for A Soil Deposit with $V_s = 3,300$ ft/s

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<thead>
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<th>Zone #</th>
<th>Coherent MXX</th>
<th>Incoherent MXX</th>
<th>Ratio Incoh/Coh</th>
<th>Coherent MYY</th>
<th>Incoherent MYY</th>
<th>Ratio Incoh/Coh</th>
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<td>8.386</td>
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<td>5</td>
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</table>

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Effects of Incoherency on Basemat Bending

It should be noted that incoherent bending moments increase by 30% to 130% in comparison with coherent bending moments. It should be noted that the computed baseslab bending moments from SSI analysis include the contributions of both the primary stresses due to structural loads, and the secondary stresses due to SSI induced displacements.

The current ASCE standards do not consider in the structural design procedures for concrete footers below columns or wall lines or basemats, the effects of the secondary stresses produced by the SSI induced displacements. The neglect of the secondary stresses could produce a large under evaluation of the elastic bending moments. However, it should be noted that for the ultimate strength design approach used in the ASCE code for concrete design, the effects of the secondary stresses could be neglected if the baseslab has sufficient ductility to accommodate the SSI induced displacements.
Incoherent vs. Coherent Seismic SSSI Effects

Generic NPP SSSI Model 1

(55,000 nodes with 5,000 int. nodes, 27,000 shells, 13000 solids, 11000 beams)

Soil Profiles

“Rock”

“Soil”

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Seismic GMRS Surface Input for Soil and Rock Sites

GMRS for Soil Site

GMRS Input for Rock Site

Frequency (Hz)

Acceleration (g)

X    Y    Z

0.00  0.20  0.40  0.60  0.80  1.00  1.20  1.40  1.60  1.80

0.00  0.20  0.40  0.60  0.80  1.00  1.20  1.40  1.60  1.80

0.10  1.00  10.00  100.00

0.10  1.00  10.00  100.00
ABW Bldg. Coherent vs. Incoherent SSI and SSSI Effects for Roof Corner ISRS for Rock Site
ABW Bldg. Coherent vs. Incoherent SSI and SSSI Effects for Roof Corner ISRS for Soil Site
ABW Bldg. Coherent vs. Incoherent SSSI Simulated Responses for Roof Corner ISRS for Soil Site
ABW Bldg. Coherent vs. Incoherent SSSI Effects on Bending Moments in Corner Walls Near RB Complex

Rock Site

Soil Site

SSSI Model (AB-WEST: Side) Moments for Shells (Rock Site) – MXX

SSSI Model (AB-WEST: Side) Moments for Shells (Soil Site) – MXX

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RB Complex Coherent vs. Incoherent SSSI Effects on ISRS on Top of Internal Structure – Y and Z Directions

Rock Site

Horizontal

Vertical

Soil Site
RB Complex Coherent vs. Incoherent SSSI Effects on ISRS at Top Corner Near AB Bldg. for Soil Site
RB Complex Coherent vs. Incoherent SSSI Effects on Bending Moments in Corner Wall Near ABW Bldg.

Rock Site

Soil Site
Incoherent vs. Coherent Seismic SSSI Effects

Generic NPP SSSI Model 2

(75,000 nodes with 11,000 int. nodes, 45,000 solids, 11,000 shells)

Compute relative displacements between NB and RB buildings:

Differential motion amplitude is twice larger for incoherent input

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<th>Displacements</th>
<th>Absolute Difference of Displacements</th>
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<td>Coherent</td>
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<td>-73.941</td>
<td>33.611</td>
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Seismic SSSI Effects on the Adjacent NB ISRS

Roof Elevation

SSSI reduction effects due to presence of deeply embedded RB
Seismic SSSI Effects on NB Basemat Pressures

SSSI Effects may increase severely seismic pressures on foundation walls and basemat. Suggestion to include local nonlinear soil behavior (only 2-3 iterations).

SSSI Effects due to RB

SSSI Effects due to AB
Seismic SSSI Effects on Shear Forces in RB

Shear Force Diagram

Incoherent SSSI analysis provides the largest shear forces in RB structure
Abrahamson Radial vs. Directional Coherency Models

RADIAL

\[ \alpha = 0.5 \]

DIRECTIONAL

\[ \alpha = 0.9 \]

Incoherency distance is

Global Axes

Rotated Axes

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EPRI AP1000 NI Stick Model Study

- Soil Site, Vs = 1,000 fps, CSDRS, AB2007Soil
- Rock Site, Vs = 6,000 fps, EPRIRockRS, AB2007Rock

Motion directionality has limited influence on SSI
Conclusions for Investigated Cases

- Incoherent motion describes a realistic, 3D random wave field motion.

- For realistic, elastic foundations, truncating the number of incoherent modes produces unconservative results in the high-frequency range.

- Zeroing the incoherent motion phasings produces overly conservative results in mid-frequency range at the price of the loss of physics – spatial correlation between support motions is neglected. Not applicable to the multiple time history analysis of RCL system.

- SSSI effects are significant for soil sites and possibly non-negligible for rock sites. Affect ISRS, soil pressures, foundation wall bending. Affect less the shear forces in the structure.

- Incoherent SSI effects are larger or different than the coherent SSSI effects.

- Incoherency model directionality, radial vs. directional, produces less significant effects on SSI response.
SASSI Methodology-Based Sensitivity Studies for Deeply Embedded Structures, Such As Small Modular Reactors (SMRs)

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Revised in April 2015

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October 21-22, 2014
Purpose of This Presentation:

To answer to the following key questions:

- 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?
ACS SASSI V.3.0 Flexible Volume Methods for NI

FV
Free Field Problem

FI-FSIN SM
Free Field Problem

FI-EVBN MSM
Free Field Problem

Structure
Excavated Soil

SSI Problem (Flexible Volume)

SSI Problem (Subtraction)

SSI Problem (Modified Subtraction)
SASSI Flexible Volume Substructuring Methods

Flexible Volume or Direct

Flexible Interface FSIN or SM

Flexible Interface EVBN or MSM
SSI Analysis of APWR RB Complex Using MSM

RB Complex SSI Model

Acceleration Transfer Function
560-500 Profile
MSM: 40527, FVM: 31007 - X Direction

Acceleration Response Spectra
560-500 Profile at
MSM: 40527, FVM: 31007 - X Direction

5% Damping ARS

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SMR Seismic Deeply Embedded SSI Model Study

Generic SMR Structure

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
### SMR Case Studies on FV Substructuring Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Int. nodes</th>
<th>Runtime/freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FV</td>
<td>7936</td>
<td>7938 seconds</td>
</tr>
<tr>
<td>FFV-SKIP2</td>
<td>4016</td>
<td>1563 seconds</td>
</tr>
<tr>
<td>FFV-SKIP5</td>
<td>3036</td>
<td>880 seconds</td>
</tr>
<tr>
<td>ESM</td>
<td>2448</td>
<td>592 seconds</td>
</tr>
<tr>
<td>MSM</td>
<td>2252</td>
<td>483 seconds</td>
</tr>
</tbody>
</table>

- **NONUNIFORM SOIL PROFILE**
  - VS=1000
  - VS=5000

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SMR Massless Foundation (Fully Embedded) Model

Volume Size: 120 ft x 80 ft x 80 ft

Mesh 4 ft x 8 ft x 8 ft

7,938 Interaction Nodes

Corner Nodes from top to bottom layers:
7681, 6913, 6146, 5377, 4809, 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 8 ft

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

Direction X

Direction Z

Excavated Volume Plus Shells Model Test - TFU
Nonuniform Soil -- at Elevation (-32 ft., Node 5833) -- Direction X

Excavated Volume Plus Shells Model Test - TFU
Nonuniform Soil -- at Elevation (-32 ft., Node 5833) -- Direction Z

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

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SMR Massless Foundation Excavation Mesh Size Study

Volume Size: 120 ft x 80 ft x 80 ft

Uniform soil Vs=1000 fps; Input at Surface

Mesh 4 ft x 8ft x 8ft
7,938 Interaction Nodes

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

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Comparative ATF at Foundation and Surface Levels

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

Amplitude vs. Frequency (Hz)

120 ft Depth
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

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140 ft Embedment SMR Excavation Volume Meshes

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

Vertical

Academic Transfer Function X Direction
Node Location: X=0.0 Y=0.0 Z=0.0

Academic Transfer Function Z Direction
Node Location: X=0.0 Y=0.0 Z=0.0

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

Horizontal

Vertical

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SSSI Effects on Seismic Soil Pressure (Spring Forces) Along the SMR Vertical Corner Edge Near AB (140 ft)
SSSI Effects on Wall O-P Bending Moments Along SMR Shell Element Vertical Line Near AB (60 ft)

Comparison of bending moments for Shell Element 146 (Middle) at SMR Rock Site and Soil Site.

Rock Site}

- Combined (Coherent)
- Combined (Mean of Incoherent)
- Standalone (Coherent)
- Standalone (Mean of Incoherent)

Soil Site}

- Combined (Coherent)
- Combined (Mean of Incoherent)
- Standalone (Coherent)
- Standalone (Mean of Incoherent)
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

SSI and SSSI With Inclined Waves

Surface Level

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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 2088)
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

- 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 deposit case, especially on the seismic soil pressures and embedded walls o-p bending.

- The effects of HO Rayleigh wave modes in high-frequency appears 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.