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SITE-SPECIFIC SSSI ANALYSIS FOR DEEPLY EMBEDDED SMR USING FLEXIBLE VOLUME REDUCED-ORDER MODELING WITH IMPEDANCE INTERPOLATION (FVROM-INT)

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ABSTRACT

Site-specific Soil-Structure Interaction (SSI) analyses are performed on a model of a deeply embedded Small Modular Reactor (SMR) including its surrounding surface-founded structures to capture effects of Structure-Soil-Structure Interaction (SSSI). An effective and efficient approach for solving the SSI solution for the structure is implemented to effectively address the complexities of the model and the need for consideration of several sensitivity studies, where different bounding variation of the structural model parameters are included. The Flexible Volume Reduced-Order Modelling approach with Impedance Interpolation option (FVROM-INT) of ACS SASSI was employed that significantly reduces the analysis time, especially when different variations of the structural model are considered without loss of accuracy of the solution. The selection of an adequate set of condensation frequencies is critical in obtaining the accurate solution and depends on the geometry and boundary conditions of the excavated volume and subgrade material properties. The use of this approach is recommended when repetitions of the SSI analysis are required for design development, sensitivity analysis cases, or probabilistic studies, and results in significant savings in the required computational effort.

INTRODUCTION

One-step approach SSI analyses following the guidance in Section 5 of NEDO 33914-A (2021), on a detailed finite element model (FEM) with a refined mesh for the deeply embedded SMR structure is carried out. The purpose of analysis is to estimate forces and stresses for structural design, in addition to in-structure-response spectra (ISRS), for the design and qualification of systems, structures, and components (SSCs). In addition to design basis SSI analysis that account for uncertainty in the site-specific soil properties, several sensitivity studies are carried out to assess the sensitivity of the solution to various aspects of structural modelling such as structural stiffness variations, potential separation of structure from surrounding soil at their interface, and stiffness of the excavation support and surrounding concrete backfill. The results and insights from these sensitivity studies are discussed in Todorovski, et. al. (2024). In addition, several design alternatives are considered that necessitate changes to the SMR structural model including alternative excavation support designs, as well as alternative designs for the slabs and connections.

Because of the complexities of the model and considerations of large number of sensitivity studies and design alternatives, where different bounding variation of the structural model parameters are included, implementation of an effective and efficient approach for solving the SSI solution for the structure was necessary. To achieve this goal, the Flexible Volume Reduced-Order Modelling approach with Impedance Interpolation option (FVROM-INT) of ACS SASSI (GP Technologies, 2022) was employed.

The FVROM-INT approach uses static condensation to obtain the soil impedance matrix at the subgrade-structure interface and in a 2nd step performs that structural analysis using the calculated soil impedance matrix. Thus, the FVROM-INT approach significantly reduces the analysis time when different variations of the structural model are considered without loss of accuracy of the solution. In addition, the FVROM-INT is implemented using fewer frequencies (less than half) for soil-impedance calculations than those required for evaluation of the structure. For the deeply embedded SMR used in this study, the ratio between solution time for one analysis frequency between soil impedance matrix calculation and structural calculation is about 28 to 1.

The selection of an adequate set of "Condensation" frequencies is critical in obtaining an accurate solution and depends on the geometry and boundary conditions of the excavated volume and subgrade material properties. In this paper, the accuracy of the solution obtained from the FVROM-INT analysis is demonstrated by comparing the calculated seismic response to that obtained using the conventional SASSI implementation of the Enhanced Subtraction Method (ESM) approach. The seismic response is represented by the acceleration transfer functions (ATFs) at key nodal locations obtained from the two sets of analyses of the best estimate (BE) subgrade profile.

SMR STRUCTURE

The analyses presented in this paper are performed on the FE model of the cylindrical SMR, shown in Figure 1, with a diameter of 34 m and a total height of approximately 60 m, of which more than half (35 m) is embedded. The structural FEM consists of shell elements representing the walls, slabs and basemat. The dynamic properties of the Reactor Pressure Vessel (RPV) and its internals are included in the model and represented by beams, springs, and lumped mass elements. The SMR is surrounded by other surface-founded buildings as shown in Figure 2. Results of the SSI analysis of the site-specific shear-wave velocity and damping ratio profiles in Figure 3, are presented in this paper. The site is characterized as a shallow rock site with 24 m of soil on top of underlying rock. The V_{S30} for the site is estimated as 470 m/s considering ground surface as the reference elevation and 2636 m/s considering top of rock as the reference elevation.

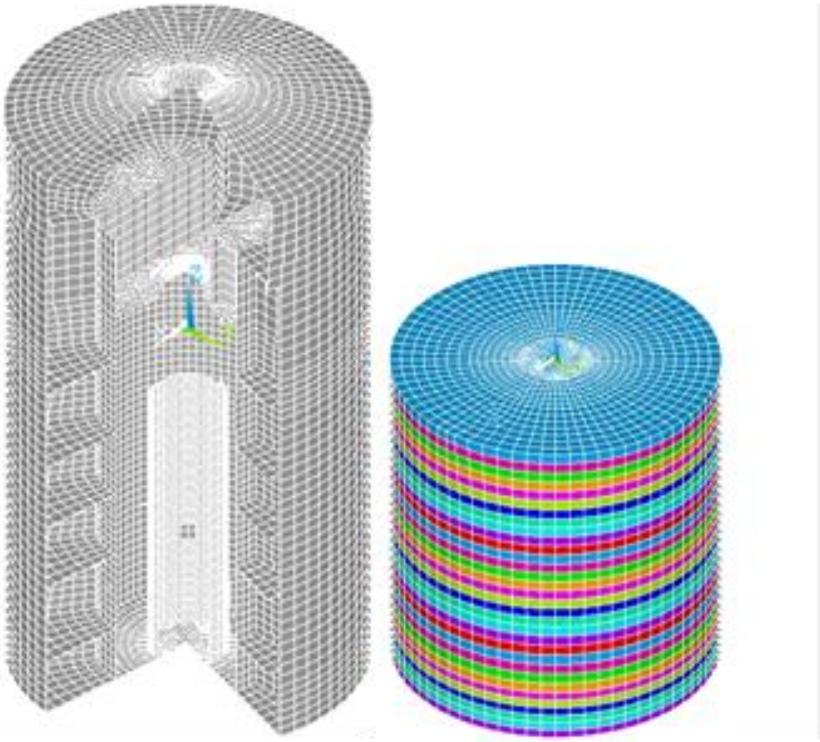

Figure 1. SMR Structure and Excavated Volume FE Model

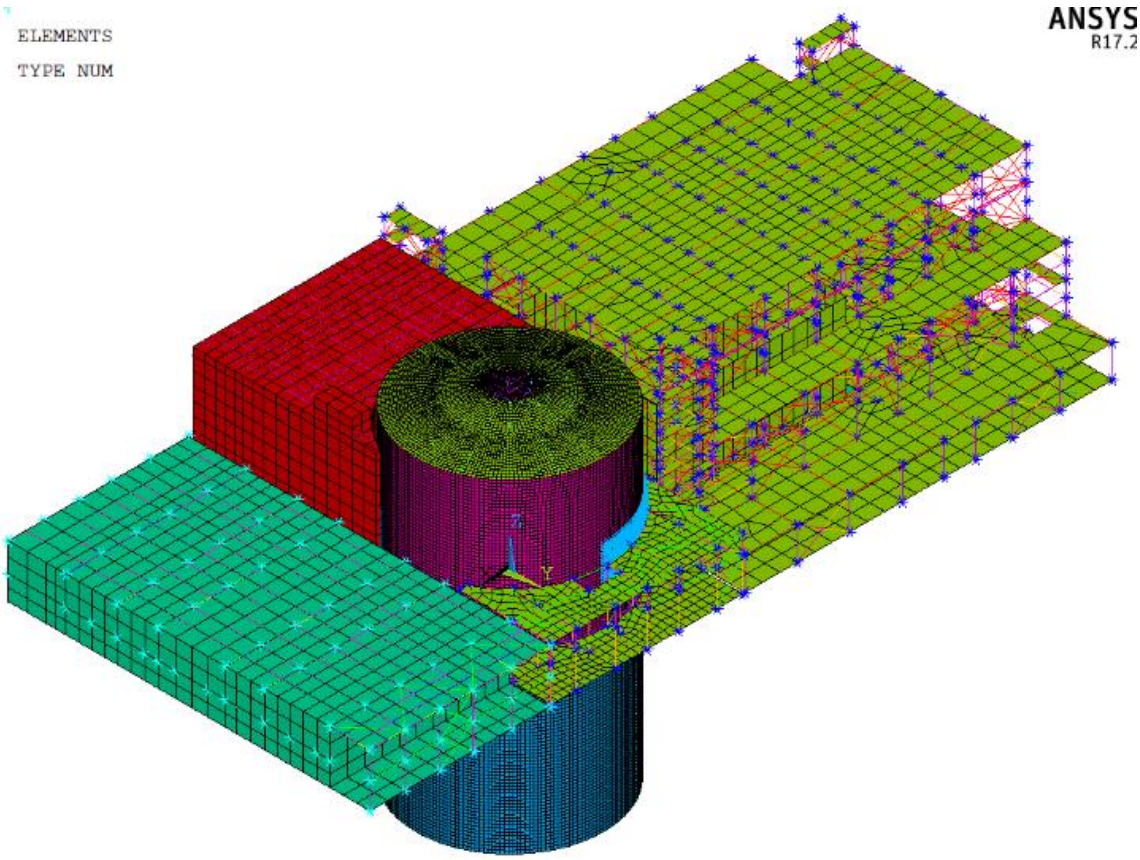

Figure 2. Site specific power block buildings included in the site-specific studies

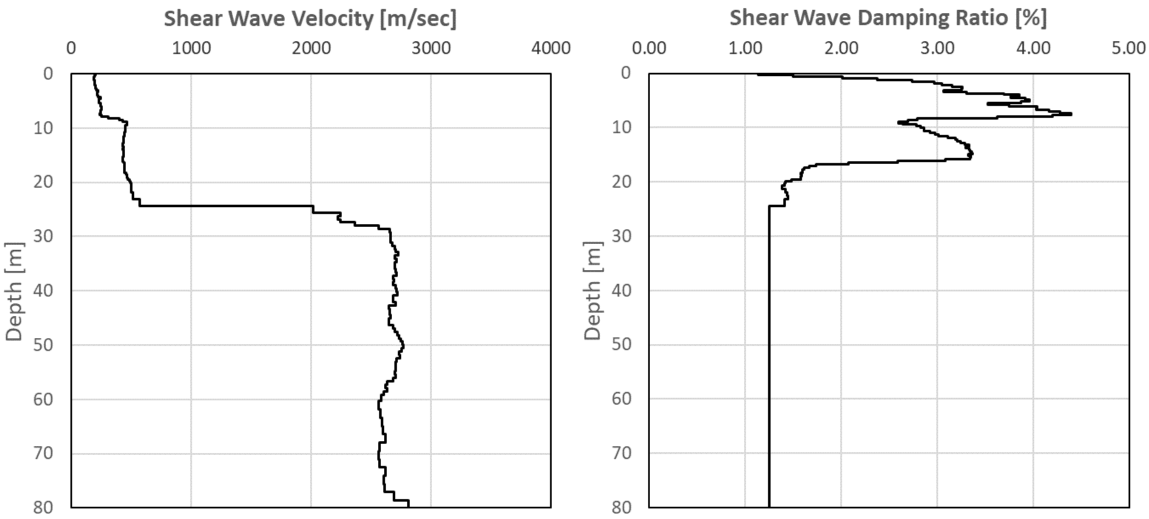

Figure 3. Site specific soil profile

METHODOLOGY

The common approach for solving the SSI problem in frequency domain (e.g. using SASSI) involves finding the solution to the free field site response within the embedded parts of the structure, solving the impedance problem which represents the dynamic stiffness of the foundation at the interaction nodes, and solving the structural problem to obtain final displacements, stresses and ISRS. These steps are typically carried out for each frequency of analysis and need to be repeated if changes are made to the structural configuration or additional analysis frequencies are required to refine the structural response. The FVROM-INT approach involves the same steps; however, it recognizes that the contribution of the excavation portion to the overall impedance can be obtained by performing the analysis at fewer frequencies. In addition, it performs the analysis in two stages by separating the calculation of the condensed impedance matrix at interaction nodes from the structural analysis which offers significant advantage in that changes to the structural configuration can be addressed without the need to recalculate the soil impedance matrix at interaction nodes.

At each frequency of analysis, the FVROM-INT approach computes the linearized SSI solution in complex frequency using a reduced-size soil impedance matrix obtained by the static condensation of the excavated soil impedance matrix at the subgrade-structure interface nodes. This matrix condensation is combined with the frequency-domain interpolation of the computed reduced-size impedance matrix. Accordingly, the analysis is sub-divided into the following steps:

- SASSI solution for the excavated soil only at a limited set of condensation frequencies (a subset of the SSI frequencies used for the full SSI solution),
- Static condensation of the excavated soil impedance matrix at the subgrade-structure interface nodes,
- Frequency-domain interpolation of the reduced-size condensed matrix to the full set of selected SSI frequencies,
- SASSI solution for the full SSI system at the expanded set of SSI frequencies.
- Computation of the acceleration transfer functions (ATFs) at the SSI frequencies and their further interpolation in between to provide smooth functions. The interpolated ATFs are then integrated with the Fourier Transform of the input ATHs to calculate seismic response quantities.

RESULTS

The accuracy of the solution obtained from the FVROM-INT analysis is demonstrated by comparing the calculated seismic response to that obtained using the conventional SASSI implementation of the Enhanced Subtraction Method (ESM) approach. The seismic response is represented by the acceleration transfer functions (ATFs) at four key nodal locations obtained from the two sets of analyses. The key points selected for this demonstration are listed in Table 1. The ATF comparisons for the key nodes in X and Z directions are shown in Figure 4 through Figure 5. The figures show the 38 condensation frequencies (with grey circles and the 87 SSI analysis frequencies with green squares. The Y direction results are similar to the results in X direction and are not shown for brevity. The results demonstrate that the FVROM-INT solution with limited condensation frequencies (in this case less than half of the SSI frequency set) adequately reproduces the full solution.

Table 1: List of key locations

Node	Elevation	Description
47693	-34.153 m	Center of basement
89097	-8.273 m	Top of RPV pedestal
100792	0 m	Slab at grade level
129688	30.48 m	Center of roof

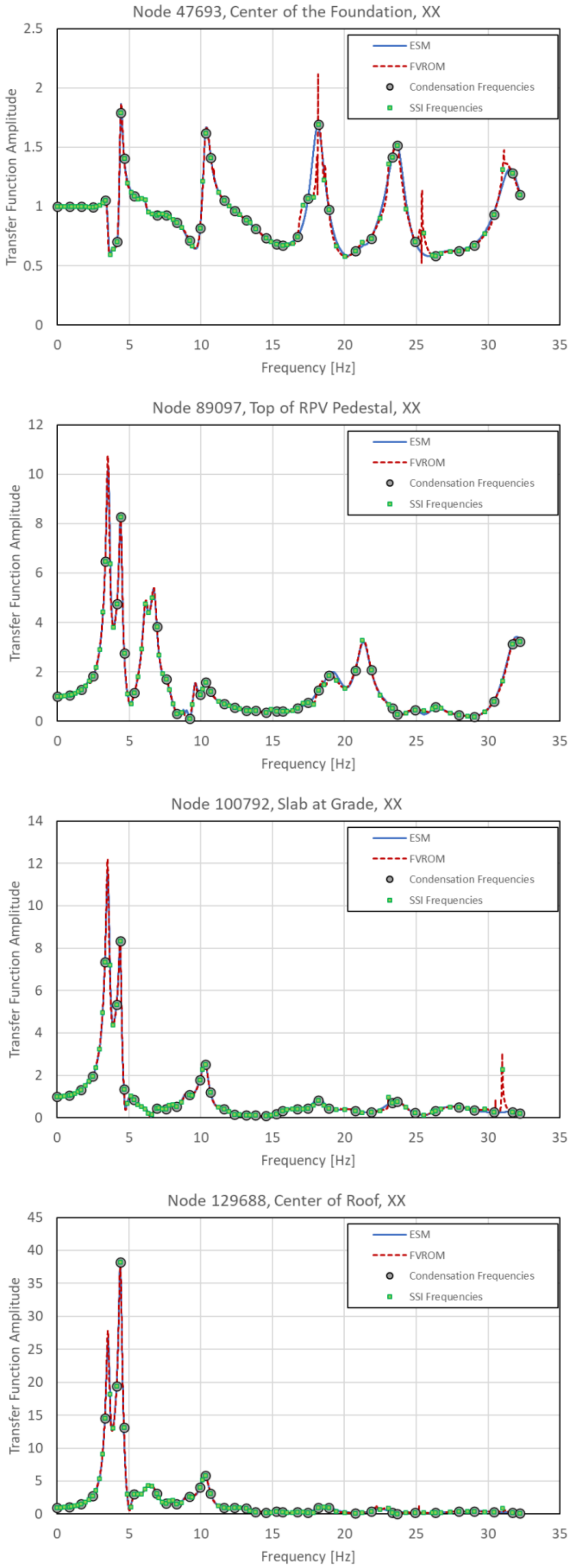

Figure 4. Acceleration Transfer Function Amplitudes at Key Locations – Horizontal (X) direction

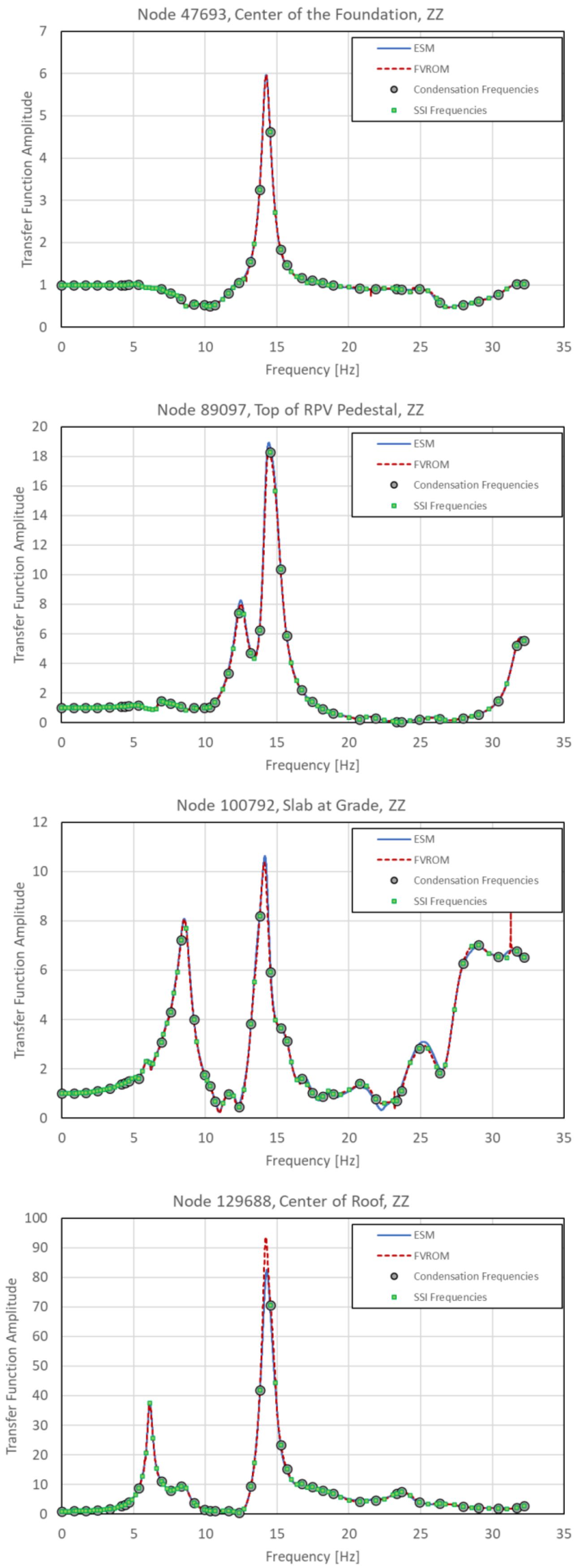

Figure 5. Acceleration Transfer Function Amplitudes at Key Locations – Vertical (Z) Direction

The main advantage of the FVROM-INT approach is the time saved for the main run and subsequent repeat runs of an SSI problem with alternative variations of the structural model. Table 2 summarizes the analysis time for the SSI solution presented here. The times presented for the full analysis are provided for the same computer (Dell Precision 7920 Rack with 16 Core CPU @3.30Ghz with 1TB Ram) for comparison purposes. The results show that the analysis time using FVROM-INT approach is reduced by more than half - mainly because the soil impedance problem is solved at fewer frequencies, and that the reduction in time for a repeat run with variations of the structural model is significantly less – by a factor of almost 28.

Table 2: Analysis time for different SSI analysis approaches

<table>
<tr><th colspan="2">Analysis Approach</th><th>Number of frequencies</th><th>Analysis time per frequency</th><th>Analysis time for full solution</th><th>Analysis time for a repeat analysis for a structural variation</th></tr>
<tr><td colspan="2">ESM</td><td>87</td><td>4.75 hrs</td><td>17.2 days</td><td>17.2 days</td></tr>
<tr><td rowspan="3">FVROM-INT</td><td>Excavated soil solution and static condensation</td><td>38</td><td>3.75 hrs</td><td rowspan="3">7.6 days</td><td rowspan="3">0.6 days</td></tr>
<tr><td>Frequency domain interpolation of the impedance matrix</td><td>49</td><td>0.5 hrs</td></tr>
<tr><td>SSI Analysis</td><td>87</td><td>0.17 hrs</td></tr>
</table>

It should be noted that for a more uniform soil profile, the number of condensation frequencies could be much lower, for example only 20, which makes the FVROM-INT for repeated SSI analyses with a modified structure to be more than 50 times faster than a standard SASSI analysis.

CONCLUSION

The FVROM-INT approach is considered which significantly reduces the SSI analysis runtime without loss of accuracy of the solution. These reductions can be tens of times when different variations of the structural model are considered. The selection of an adequate set of condensation frequencies is critical in obtaining the accurate solution and depends on the geometry and boundary conditions of the excavated volume and subgrade material properties. The use of this approach is recommended when repetitions of the SSI analysis are required for design development, sensitivity analysis cases, or probabilistic studies, and results in significant savings in the required computational effort.

REFERENCES

NEDO-33914 (2021), *BWRX 300 Advanced Civil Construction and Design Approach*, GE Hitachi Licensing Topical Report (https://www.nrc.gov/docs/ML2102/ML21020A137.pdf).

GP Technologies (2022), *ACS SASSI Version 4.3.4 User Manual, Including Advanced Options A-AA and NON*, Revision 7, Pittsford, New York, April 30, 2022.

Todorovski, L., Elkhoraibi, T., and Hashemi, A. (2024), *SSI Parameter Sensitivity Consideration for SMR Site-Specific Evaluation*, Transactions of the SMiRT 27, Yokohama, Japan, March 3-8, 2024 (in progress).