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VALIDATION OF MODIFIED SUBSTRACTION METHOD FOR SEISMIC SSI ANALYSIS OF LARGE-SIZE EMBEDDED NUCLEAR ISLANDS

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ABSTRACT

The paper presents the selected results of the validation study for the application of the Modified Subtraction Method (MSM) to the seismic soil-structure interaction (SSI) analysis of the MHI US-APWR Reactor Building complex. The MSM method is based on the SASSI Flexible Volume substructuring approach in the complex frequency domain. The MSM is much faster than the reference Flexible Volume (FV) method that could be impractical due the large computational resources needed for large-size SSI models. However, the recent drafts of the ASCE 04-2013 Standard and USNRC SRP 3.7.2-2013 recommend that MSM is checked against the reference FV method before is applied to SSI production runs for seismic design-basis analyses of nuclear structures. The focus of this paper is on the MSM validation when applied to SSI analyses of large-size embedded NI complex SSI models. The comparisons of the SSI results of the MSM and FV methods obtained for the investigated case studies indicated that MSM is a highly accurate and efficient SSI analysis method. In addition, the paper introduces new methods, called Fast Flexible Volume (FFV) methods, that for particular excavation configurations could be more accurate than MSM, and still maintain a high numerical efficiency when compared with the reference FV method.

BASIC THEORETICAL ASPECTS

The SASSI Flexible Volume substructuring as implemented the reference Flexible Volume (FV) method or Direct Method (DM) is described in Figure 1 (Lysmer et. al, 1981). The FV substructuring is based on splitting the overall SSI system in three subsystems. In the SASSI Flexible Volume (FV) substructuring only the free-field soil impedances and the free-field motions are needed for computing the seismic excitation forces on the foundation. Both free-field soil motions and impedance functions for embedment soil layers are computed fast using frequency-dependent consistent boundaries for the reflected wave propagation in the infinite soil 3D space. An unique feature of the FV substructuring approach, is that the SSI analysis is performed for the structure dynamically coupled with the excavated soil (the soil removed by the embedment) . The embedment complex dynamic stiffness is the difference of the structure and the excavated soil complex dynamic stiffnesses. It should be understood that in the context of the FV substructuring, the wave scattering effects are included by the excavated soil motion that act as a cavity within the free-field soil. If the excavated soil motion is predicted inaccurately, then this could directly affect the wave scattering effects, and further the SSI responses.

Based on the FV substructuring, there are different methods that are implemented. These methods differ on how accurate the handle the exacavated soil dynamic modeling. The FV method assumes that all translational degrees of freedom of the excavated soil are considered to be SSI interaction nodes. This modeling assumption corresponds to the theoretical exact SSI modeling for the excavated soil dynamics. For this reason FV is considered to be the reference method. The Subtraction Method (SM) and the more robust Modified Subtraction Methods (MSM) are “short cuts” of the FV substructuring implementation as shown in Figures 2 and 3. The basic idea of SM and MSM is to reduce the number of the excavated soil SSI interaction nodes for which the soil impedances must be calculated and by doing this to save computational time and memory storage. This makes SM and MSM much faster, but also more approximate than the reference FV method. For the excavated soil non-interaction nodes, the seismic load components and the free-field soil impedances are neglected. Thus, the non-interaction node equations are not correctly defined with all terms, which could affect the accuracy of SSI results in some situations.

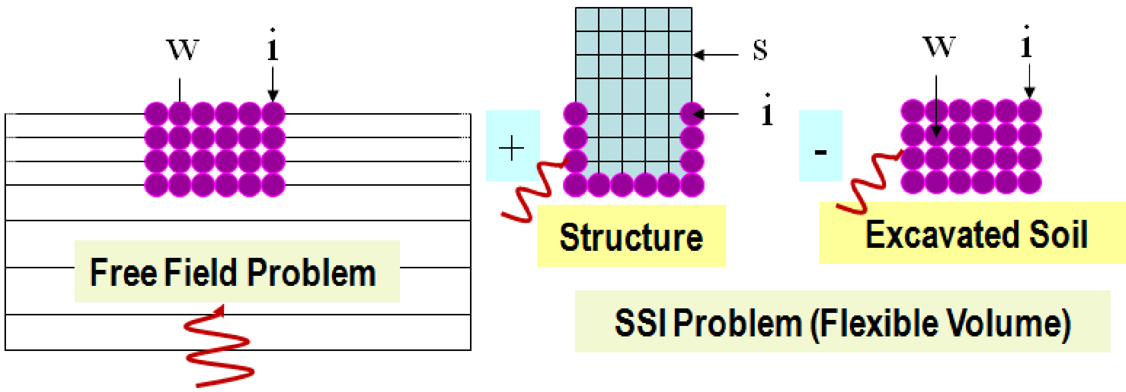


Figure 1. Flexible Volume (FV) Implementation

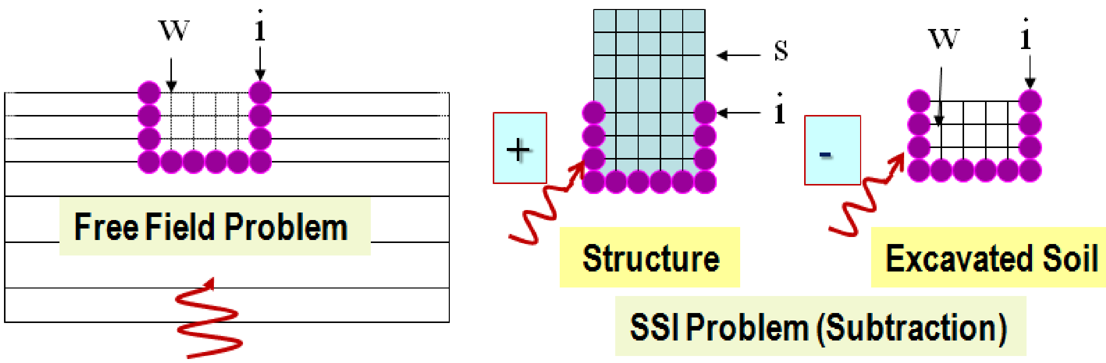


Figure 2. Subtraction Method (SM) Implementation

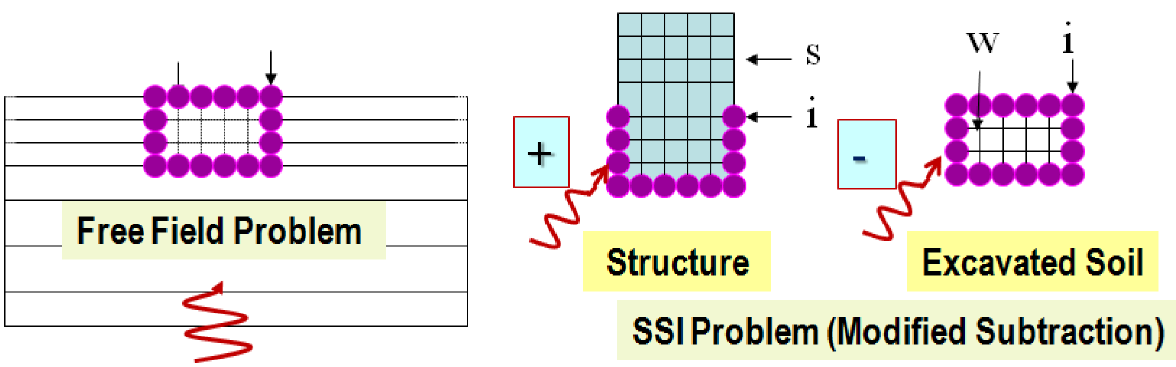


Figure 3. Modified Subtraction Method (MSM) Implementation

The SM assumes that the interaction nodes are defined only by the nodes at the interface of the excavated soil with the surrounding soil deposit. This implies that SM uses correct equations of motion only for part of the excavated soil nodes that are the interaction nodes at the interface of the FE model with the surrounding soil deposit. For the rest of the excavated soil equations that correspond to the non-interaction nodes, the seismic load and free-field impedance terms are neglected.

As a result of the approximate SSI modeling for a number of equations of motion in the excavated soil at the non-interaction nodes, the excavated soil motion will include a number of spurious vibration modes. These spurious modes are more excited by the short wavelength components in the mid and high frequency ranges. For softer excavated soils there is a larger number of spurious modes in the mid-high frequency range of engineering interest than in stiffer soils. Thus, the SM solution depreciates faster for the softer excavated soils and higher frequency seismic excitations. For low frequency inputs, since the wave scattering effects are reduced, the effects of the approximate modeling and prediction of the excavation soil dynamics is much less important, and, therefore, SM is reasonably accurate for such situations. These SM behavioral trends are consistent with the SSI results obtained by the DOE SSI studies done using SM (Gutierez, 2011).

In addition to the interaction nodes defined by SM at the FE model-free-field soil interface, MSM includes the nodes at the ground surface of the excavated soil as interaction nodes. By adding interaction nodes at the ground surface, the scattered surface waves that manifest at the ground surface are captured much more accurately in the mid-high frequency range. In addition, the inclusion of the ground surface nodes as interaction nodes provides significantly improved boundary conditions for simulating the excavated soil dynamic behavior. It should be noted that SSI scattered waves manifest primarily by Rayleigh and Love surface waves. Thus, it is very important to have a correct SSI modeling for the equations of motion of the excavated soil nodes situated at ground surface that are heavily driven by surface wave components. Thus, including surface nodes as interaction nodes greatly improves the excavation soil response accuracy since the surface wave motions are captured much more accurately. These SM behavioral trends are consistent with the SSI results obtained by the DOE SSI studies done using SM (Gutierez, 2011).

FREE-FIELD ANALYSIS VS. KINEMATIC SSI ANALYSIS VS. COMPLETE SSI ANALYSIS

Based on the FV substructuring theory, the complete SSI interaction system is split in two steps as shown in Figures 1 through 3. The two steps are 1) the free-field or site response analysis and 2) the complete SSI interaction analysis. It should be noted that the free-field response analysis includes no seismic wave scattering effects or kinematic SSI effects due to the foundation stiffness presence in the soil. The complete SSI analysis step requires to include both the effects of kinematic SSI interaction (or wave scattering) and the inertial SSI interaction. Based on the FV substructuring, this is obtained by using a coupled dynamic system that includes both the structure and the excavated soil subsystems. Per the FV substructuring formulation, the overall SSI system dynamic stiffness is defined by the structure dynamic stiffness minus the excavated soil dynamic stiffness. By including the structure-excavated soil dynamic coupling in the SSI analysis step, both the kinematic and inertial effects are incorporated. It is obvious that the role of the excavated soil system is to capture the kinematic SSI or wave scattering effects.

The FV substructuring methods, such as FV, SM and MSM are different by how the excavated soil is modeled. Therefore, these methods differ in the level of approximation introduced for capturing the excavated soil dynamic behavior under the free-field soil excitation. The difference in the excavated soil modeling introduced by the different selection of the SSI interaction nodes in the FV, SM and MSM methods, impacts directly on the kinematic SSI (or wave scattering) solution accuracy. Therefore, if the SSI results of FV, SM and MSM differ for a particular case study, the differences between the SSI responses come basically from the differences between the computed kinematic SSI effects, as a result of different excavated soil modeling introduced by the selection of interaction nodes.

CASE STUDIES

Reactor Building Nuclear Island (RBNI) has a foundation footprint area of about 300 ft x 400 ft and an embedment of about 40 ft depth. In this section, the MSM results are compared with the FV method results for selected case studies. The MSM validation included three types of confirmatory investigations for the investigated RBNI embedded model on 1) the excavation soil cavity effects, 2) the wave scattering or kinematic SSI analysis effects, and 3) the complete SSI analysis effects (including both kinematic and inertial effects). All SSI analyses were performed using ACS SASSI (Ghiocel, 2012a).

The RBNI excavation cavity model, the masless NI foundation model and the NI SSI model are shown in Figure 2. For excavation and foundation model (bonded) the output node locations is indicated in the figure. The foundation and SSI models were considered to be either bonded or unbonded to the surrounding free-field soil. The unbonded models corresponded to the embedded models that assume separation between the foundation walls and the side backfill soil.

As shown in Figure 2, the excavation cavity effects are computed using a simple RBNI excavation model (upper plot) that includes no foundation or structure parts. The wave scattering or kinematic SSI model (middle plot) includes both the NI excavation model and the massless embedded foundation model. Different soil profiles were considered. The complete SSI model (lower plot) includes the NI excavation model and the NI foundation model and structures.

All SSI analyses were performed for soil sites with shear wave velocity of the embedment soil layers of about 800 fps, denoted 270-200 soil, and about 1650 fps, denoted 560-500 soil, respectively. For the 270-200 soil profile there is a stiff soil formation at 200 ft depth, while for the 560-500 soil profile there is a stiff soil formation at 500 ft depth. The seismic input was described by a typical flat CSDRS spectra defined at ground surface obtained by modifying the RG 1.60 spectra in the high-frequency range up to 25 Hz. The in-column input motions at the foundation level were computed for ech soil profiles. The cut-off frequency was 40 Hz for 270-200 soil and 50 Hz for 560-500 soil.

RESULTS

In this section the SSI results obtain for the RBNI cavity model, RBNI masless foundation model and RBNI complete SSI model. Because of the paper space limitations only few selected results are included. To help the interpretation of the computed results, the results for the cavity model are presented at the end of this section instead of the beginning of this section.

Figure 3 shows the wave scattering or kinematic SSI analysis results obtained using the massless the RBNI foundation model. Figure 3 includes comparisons of the ATF and 5% damping ARS curves computed for the MSM and FVM methods at the foundation model top corner. The MSM and FV results are matching almost perfect. The foundation walls were considered to be bonded with the surrounding free-field soil.

Figures 4 shows the complete SSI analysis results obtained using the complete RBNI complex FEA model. Figure 4 includes comparisons of the ATF and 5% damping ARS curves computed for the MSM and FV methods at the support of the reactor vessel. The MSM and FV results are matching again almost perfectly. The foundation walls were considered to be unbonded with the surrounding free-field soil. Results in other locations show very good matching everywhere.

Finally, the excavation cavity analysis results are shown in Figure 5. The 270-200 soft soil profile was considered. Comparative ATF computed at the bottom and the top corners of the soil excavation are plotted. It should be noted that MSM and FV are matching again very well. However, at a very close look for the top corner location ATF plots indicate that for this cross-shaped excavation, the ATF curve computed at the top corner using FV is a bit shaky due some minor numerical noise. It should be noted that more generally, the excavation cavity models are particularly exposed to some numerical noise existence in the computed ATF solution since the excavation cavity problem itself appears to be quite numerically ill-conditioned for soft soil excavations. It should be also noted that if the excavation cavity model is approximated by a double symmetric shape excavation, the top corner ATF becomes very smoothed with no slight line tremor.

Based on the shown results, it should be noted that the ATF results from the kinematic SSI analysis and the complete SSI analysis are much more numerically robust than the excavation cavity analysis results as indicated in Figure 4. For practical NI applications it appears that it could be more appropriate to use massless foundation models or full SSI FEA models for checking MSM against FV, than use potentially numerically sensitive excavation cavity models.

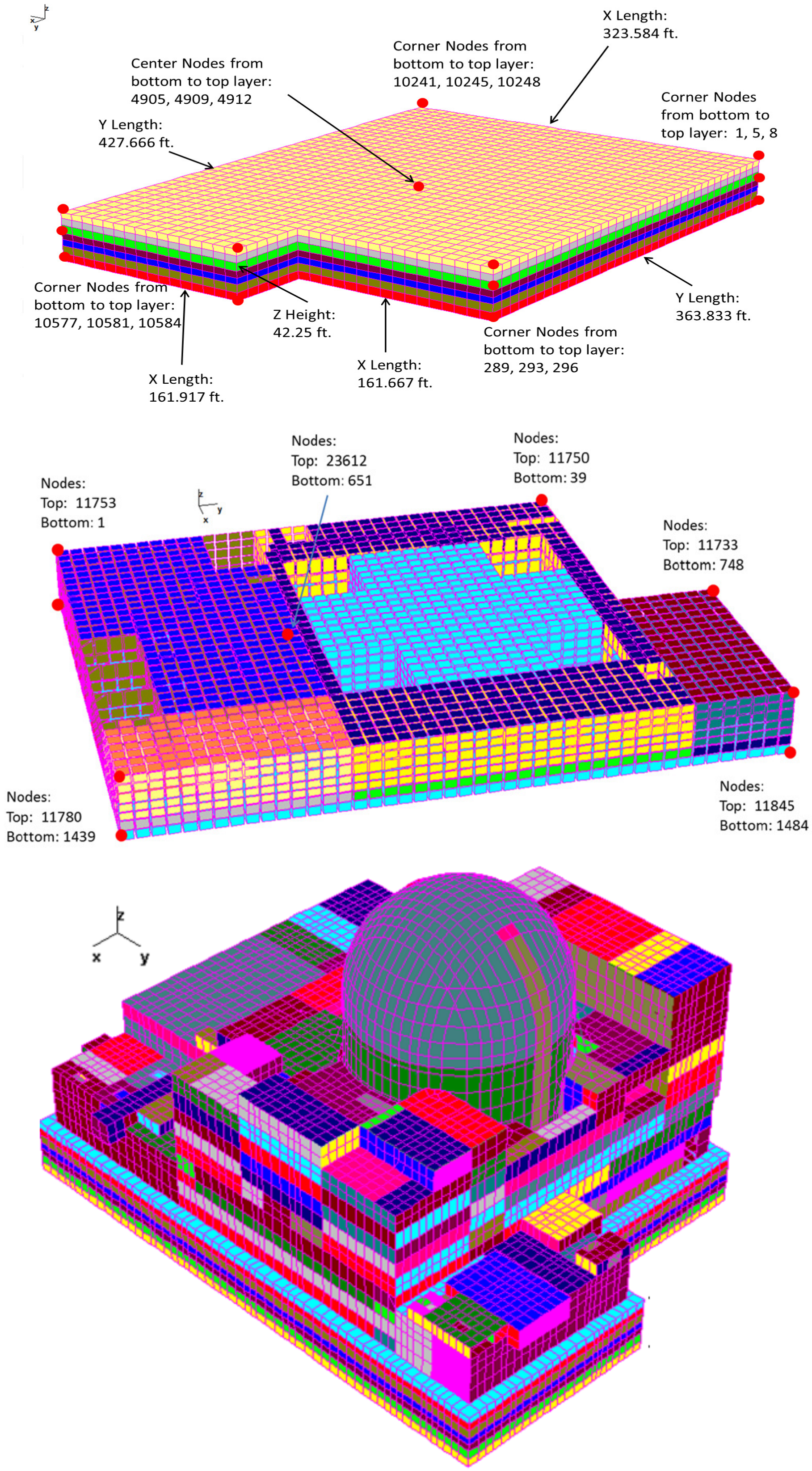
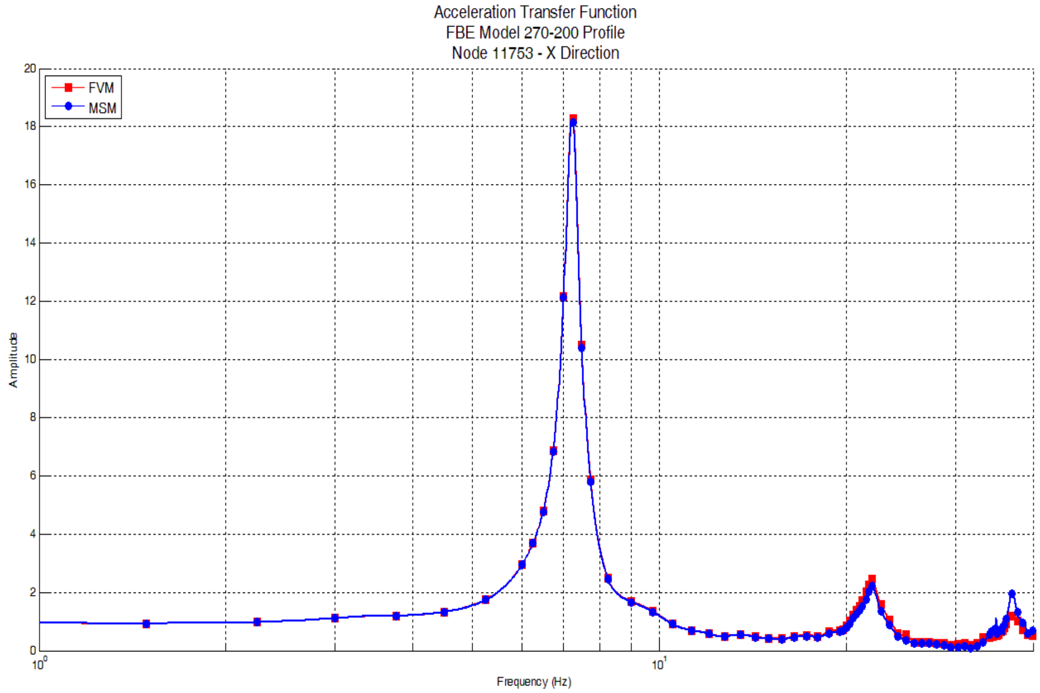
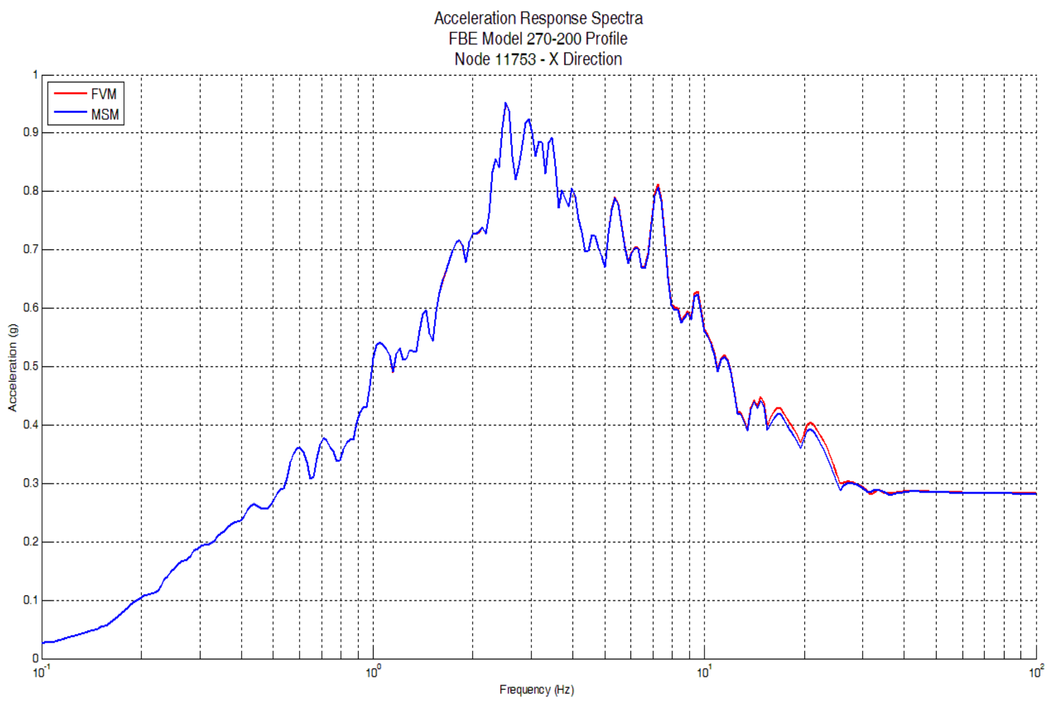


Figure 2 NI Excavation Volume Model (upper), NI Masless Foundation Model (middle) and NI SSI Model including Surrounding Backfill Soil (lower)

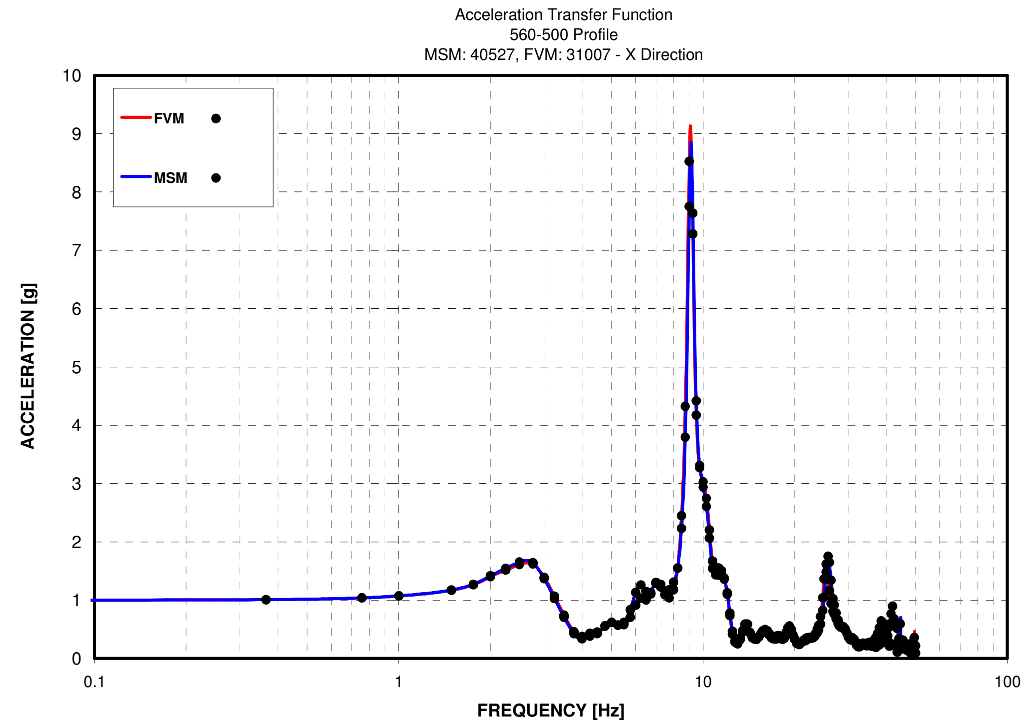


a) ATF Curve

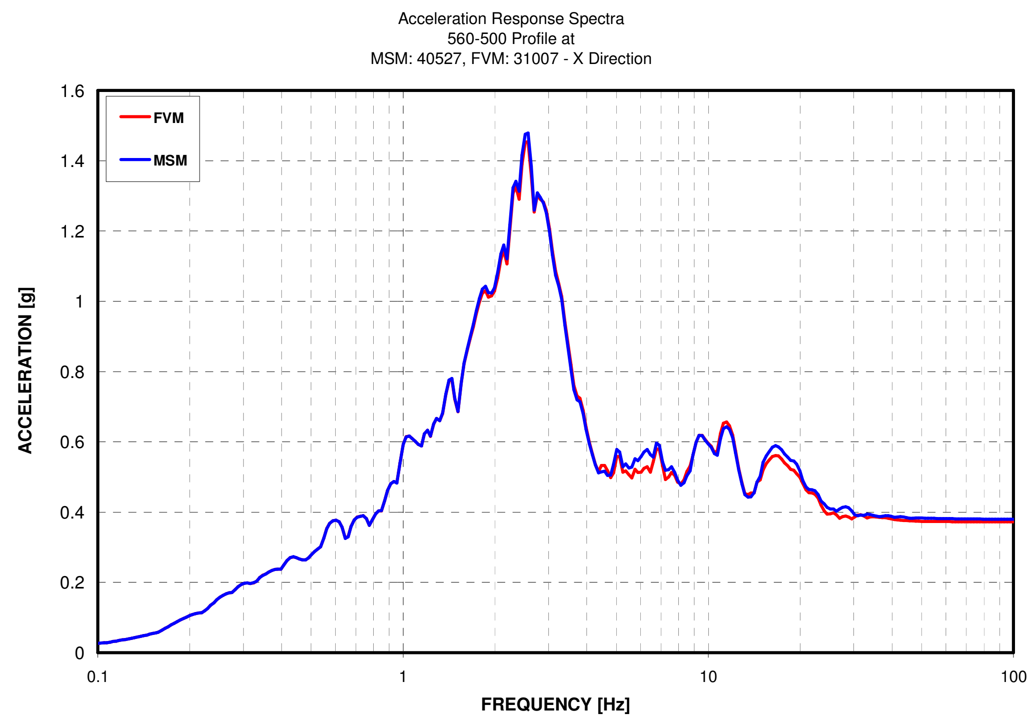


b) 5% Damping ARS

Figure 3 Comparative ATF and 5% Damping ARS Curves Computed at the Top Corner Location of the Massless Foundation Model (Node 17753 in Figure 2 middle plot)



c) ATF Curve



d) 5% Damping ARS

Figure 3 Comparative ATF and 5% Damping ARS Curves Computed at the Reactor Support for the NI Complex SSI Model (Figure 2 lower plot)

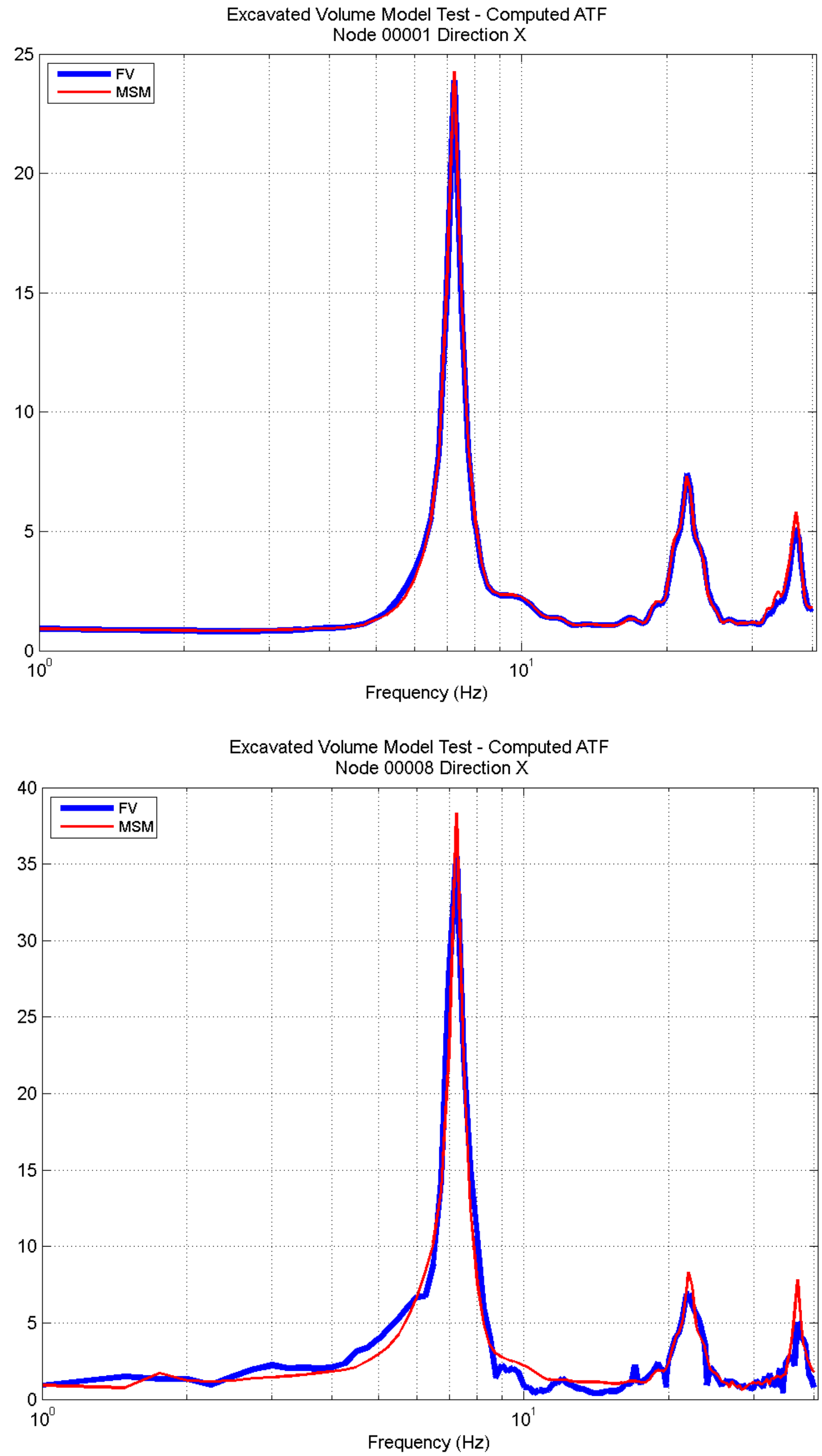


Figure 4 Comparative ATF Curves Computed at the Bottom Corner Location of Excavated Soil (Nodes 1 and 2 in Figure 2 upper plot)

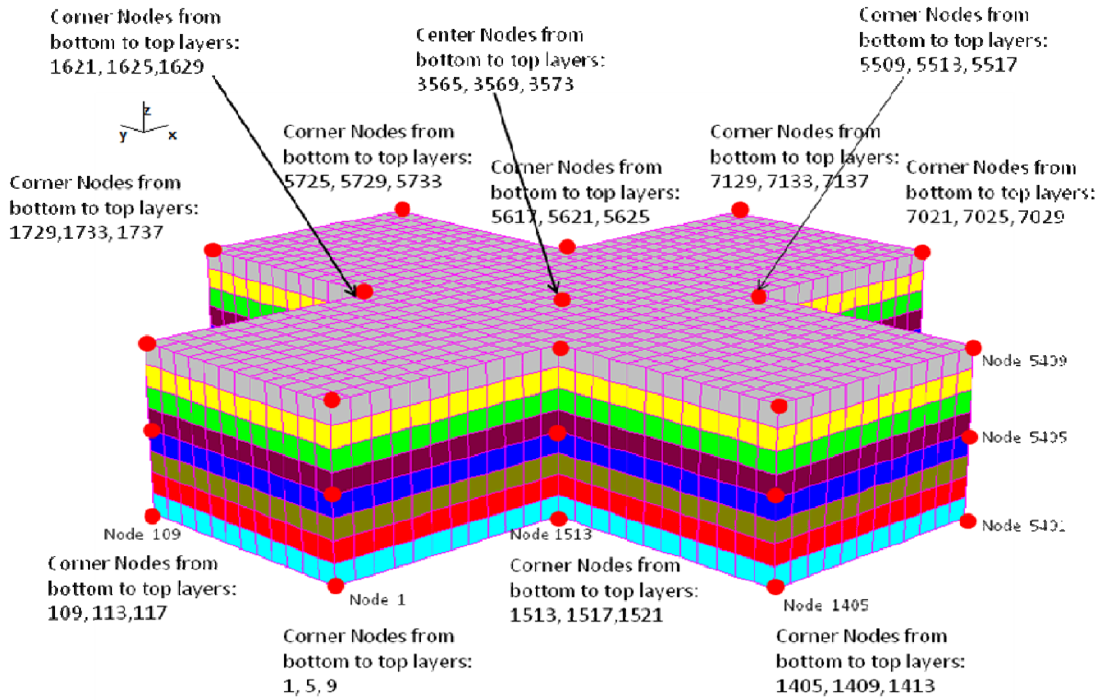


Figure 5 Soil Excavation Model With A Cross-Shape in Horizontal Plane

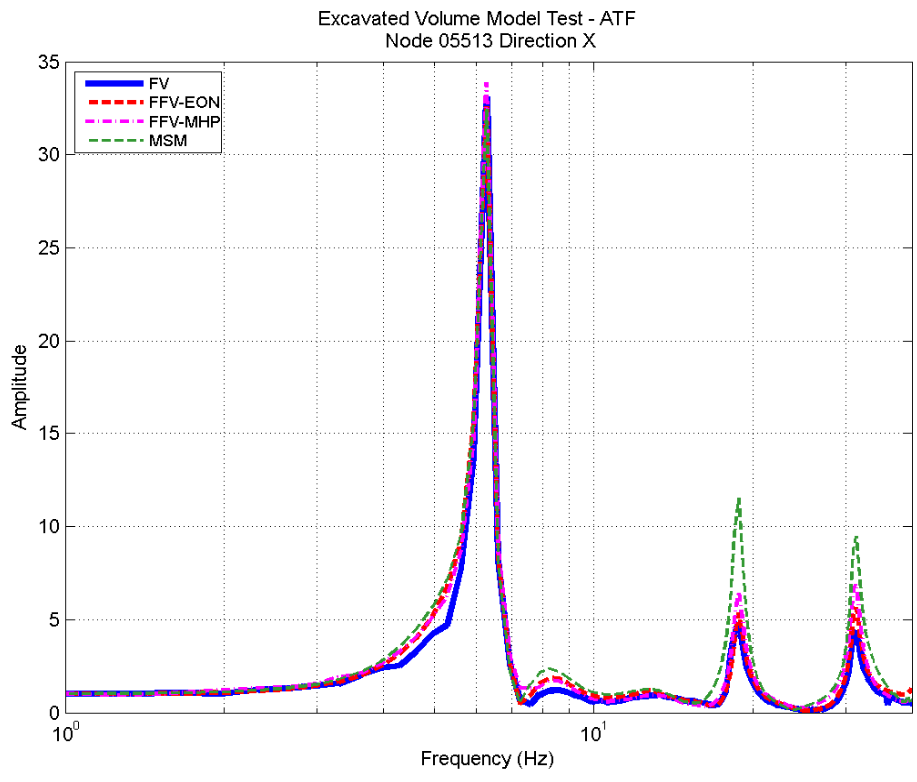


Figure 6 ATF Computed at Interior Corner Middle Level Location (Node 5513 in Figure 4)

There is also another remark of practical importance, that the non-double symmetric shape excavations are more numerically sensitive than the double symmetric shape excavations. This indicate that a greater attention should be given to the use of quarter excavation models to check SM or MSM accuracy when the real geometry of the foundation is not exactly a double symmetric shape in the horizontal plane.

The last case study is a cross-shaped excavation model as shown in Figure 5. It should noted that this excavation shape is very different than the US-APWR excavation shape. However, this foundation cross-shape looks closer to the EPR1500 NI complex excavation shape. As expected, the ATF computed results at the bottom and the top corners matched very well (not shown). However, at the interior corners at the the middle height level, not at the bottom and the top levels, the excavated soil responses for MSM and FVM differ slightly as shown in Figure 6.

To improve the accuracy of the MSM results at the middle level where no interaction nodes are present, then, in addition to the MSM interaction nodes that are defined at the outersurface of the soil excavation volume (Gutierez, 2012, Ghiocel, 2012b), suplementary interaction nodes could be added to represent the excavated soil interior dynamics by a "reduced-order" model with less interaction nodes. These excavated soil reduced-order models provide a different class of quite fast and accurate FV methods that we called "Fast FV" methods. Figure 6 shows the ATF results obtained by using the Fast FV (FFV) methods with two different selections of the interaction nodes from the excavated soil internal nodes in comparison with the MSM and FV method ATF results. The FFV method results are highly accurate, better than MSM. It should be noted that the FFV method runtimes were about 6-8 times shorter than the FV method runtime. The FFV-EON notation stands for including as interaction nodes all "each other nodes" of the excavation horizontal planes, while the FFV-MHP notation stands for including as interaction nodes the excavation "middle horizontal plane" nodes. The FFV methods are useful for highly nonuniform soil excavations or excavation with large dimensions in both all 3D space directions.

CONCLUSIONS

For typical NI configurations that are significantly larger in the horizontal directions than in the vertical direction, MSM is expected to perform very well at a small fraction of the SSI runtime of the FV method. It should be understood that the MSM provides a great increase in the accuracy for the predicted wave scattering effects for embedded foundations in comparison with SM.

MSM appears to be an accurate and robust method for large footprint embedded nuclear islands for typical frequency ranges of interest for practical applications. Particular attention should be given to situations when the excavated soil is highly nonuniform. The FFV methods are useful for more general soil excavation volume configurations.

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