# THE SASSI FLEXIBLE VOLUME SUBSTRUCTURING METHODOLOGIES

## TECHNICAL NOTE

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BACKGROUND HISTORY:

The SASSI flexible volume substructuring uses an extremely ingenious substructuring approach (Lysmer, 1981) that makes the soil impedance calculation trivial. As I know directly from John Lysmer (Lysmer, 1990), it should be noted that the original idea of the flexible volume substructuring for seismic SSI analysis came from Joseph Penzien. Clough and Penzien published in 1975 (Clough and Penzien, 1975) a new substructuring method for seismic SSI analysis that defines a new way of defining the equations of motion of the SSI system in which the forcing function is expressed in terms of the free-field soil motion of the excavated soil rather than the baserock input motion. In a short period of few years, Lysmer took over the concept and had the vision to transform and to make it applicable in the complex frequency domain (Lysmer, 1978), and further to refine and implement it into a novel frequency domain SSI substructuring approach called the Flexible Volume substructuring. The Flexible Volume substructuring took a great advantage of Kausel's accurate frequency domain transmitting boundary algorithms (Kausel, 1974). The result of Lysmer's research efforts between 1976 and 1981 was the magnificent university SASSI code (Lysmer, 1981). It should be noted that the original SASSI code was developed using a highly numerically efficient framework at that time based on the skyline per block algorithm that was the state-of-the-art SSI solution algorithm in 1980s.

METHODOLOGY DESCRIPTION:

In the SASSI flexible volume method only the free-field soil impedances and the free-field motions are needed for computing the seismic forces on the foundation. The soil impedance evaluation problem applied to free-field site conditions is solved extremely efficiently using fast numerical solutions that take full advantage of axisymmetric consistent boundaries (Kausel, 1974). Thus, instead of performing the SSI analysis for the structure coupled with the surrounding, unbounded soil deposit, the SSI analysis using the FV substructuring is performed for the structure dynamically coupled with the excavated soil (the soil removed by the embedment).

In flexible volume substructuring theory, the structure-excavated soil dynamic coupling is essential to capture correctly the wave scattering effects due to the embedment cavity within the soil deposit. The original wave propagation or *external source or wave propagation SSI* problem with the force excitation defined at the far distant external boundaries of the SSI system, at the bottom baserock, is reduced to a much smaller *internal source SSI* problem with the force excitation defined inside the excavated soil system. The flexible volume method as implemented in SASSI is an unique SSI substructuring approach in the complex frequency domain that provides fast and accurate solutions for linearized SSI systems. It also handles correctly the material damping in hysteresis systems, as frequency independent.

The flexible volume substructuring as implemented in SASSI in the so-called Flexible Volume or Direct method (DM) is described in Figure 1. The DM method assumes that all translational degrees of freedoms of the excavated soil are considered in the SSI solution. The Subtraction Method (SM) and the more recent Modified Subtraction Methods 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 SSI interaction nodes of the excavated soil without losing significant accuracy for the SSI solution for a range of practical problems.

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. Thus, 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 equations that correspond to the non-interaction nodes of the excavated soil, the seismic load vector components are zero and the system stiffness terms do not include the local free-field soil impedance terms. Thus, these non-interaction node equations are not correctly defined. The inaccurate SSI solutions obtained for the excavated soil non-interaction nodes could affect the entire SSI solution, including structural response that is of main interest to the analyst. Depending on the level of inaccuracies propagating from the non-interaction node solutions to the structural motion solution, the SM could provide either “reasonable” approximation or “unreasonable” approximation of the SSI solution. It is expected that short-wavelength excitaions will always amplify the SM modeling inaccuracies.

It should be noted that for long-wavelength, low-frequency free-field seismic waves, the effect of using a reduced number of interaction nodes for the excavated soil including only the nodes at the interface of the FE model with the surrounding soil deposit as in SM has less impact on the overall SSI solution. On the other hand, for short-wavelength, high frequency free-field seismic waves that produce larger scattering effects, the use of a reduced number of interaction nodes without including the ground surface nodes as in SM could affect significantly the excavated soil dynamics and as a result of this affect also the overall SSI solution. As a result of the incorrect 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 will be more excited by the short-wavelength components in the mid and high frequency ranges. The softer the excavated soil is, the larger the number of spurious modes in the mid-high frequency range of engineering interest is.

Further, it should be understood that in the context of the FV substructuring, the wave scattering effects are included by the excavation soil motion and its dynamic coupling with the structure and surrounding soil deposit. If the excavated soil motion is predicted inaccurately, then, this affects directly the wave scattering effects that will be predicted inaccurately. It should be noted that 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 improves greatly the excavation soil response accuracy since the surface wave motions are captured much more accurately.

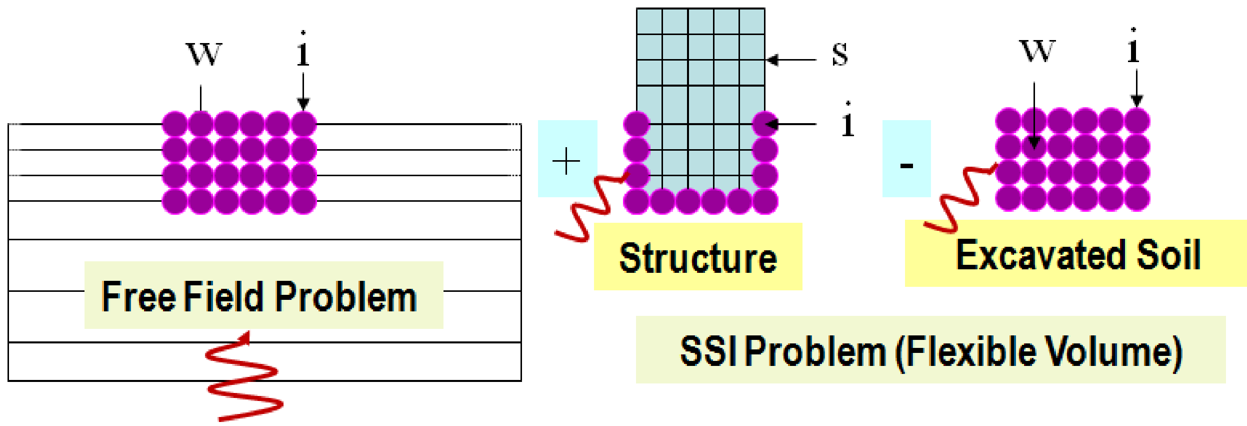


Figure 1. Flexible Volume or Direct Method (DM) Implementation (FV in ACS SASSI)

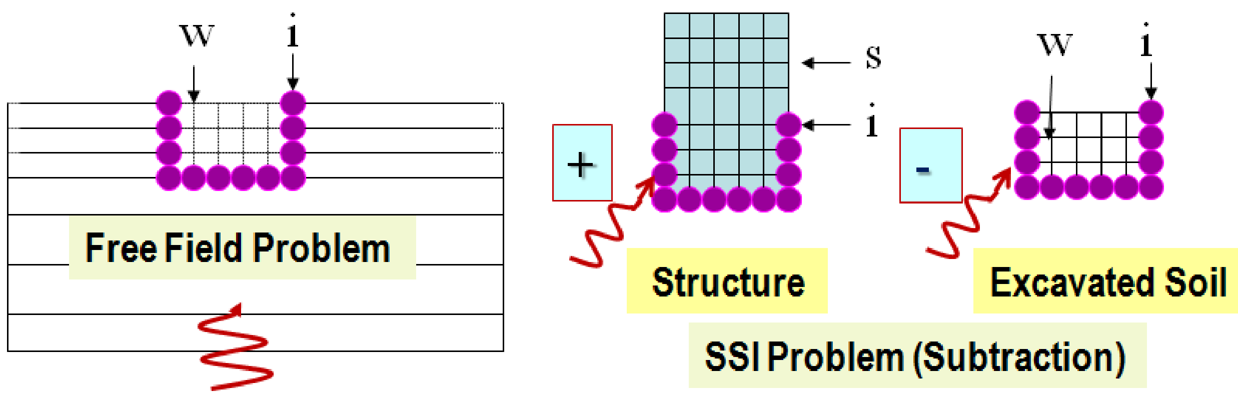


Figure 2. Subtraction Method (SM) Implementation (FI-FSIN in ACS SASSI)

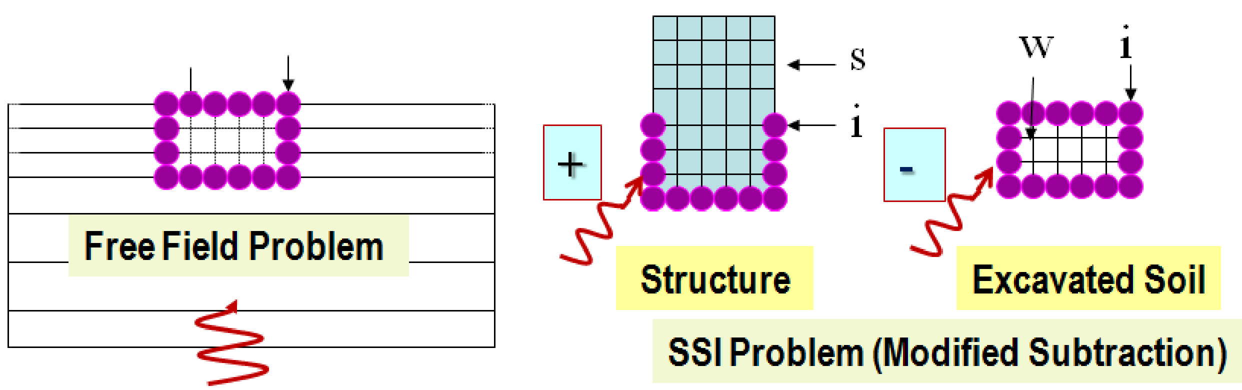


Figure 3. Modified Subtraction Method (MSM) Implementation (FI-EVBN in ACS SASSI)

Now, let's look again at SM and MSM described in Figures 2 and 3 to understand their SSI modeling limitations.

SM that includes no interaction nodes at the ground surface of the excavated soil offers a relatively poor modeling of the scattered surface waves, especially in the higher frequency range and for large-size embedded foundations. The larger and stiffer the foundation is, the larger the wave scattering effects are. If the excavated soil is soft, then, the number of spurious modes excited in the mid-high frequency range could be significantly larger, and the first spurious vibration mode frequency of the excavated soil is produced at a much lower frequency. Since the soil impedance terms are neglected in the non-interaction node equations, this creates an artificial dynamic behaviour of excavated soil. 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 inaccurate modeling and prediction of the excavation soil dynamics is much less important, and, therefore, SM is resonably accurate for such situations. These SM behavioral trends are consistent with the SSI results obtained by the DOE SSI studies done so far on SM.

MSM includes as interaction nodes, in addition to the interaction nodes defined by the SM at the FE model-soil layering interface, the nodes at the ground surface of the excavated soil. By adding interaction nodes at the ground surface, the significant 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.

CONCLUDING REMARKS:

For typical nuclear island configurations that are significantly larger than deeper, MSM is expected to perform very well at a small fraction of the runtime of the DM method. This is reflected by the several studies done by DOE for MSM. 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. So far, MSM appears to be an accurate and robust method for large footprint embedded nuclear islands for the frequency ranges of interest for practical applications. However, sensitivity studies are always suggested to validate MSM against DM for highly nonuniform excavated soil meshes and/or large-size deeply embedded structures.

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