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EXTENDING SASSI METHODOLOGY TO SEISMIC SSI ANALYSIS FOR NPP BUILDINGS ON SOIL DEPOSITS WITH INCLINED LAYERING

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ABSTRACT

The paper introduces an extended SASSI methodology capable of dealing efficiently with the effects of 2D soil layering variations on the seismic SSI responses. This capability extension of the SASSI methodology for the 2D soil layering has been implemented in the ACS SASSI V4 Option 2DSOIL (Ghiocel, 2019). The Option 2DSOIL replaces the standard SASSI modelling with 3D structure FE model and 1D layered soil model (3D1D) by a new SASSI modelling with 3D structure FE model and 2D layered soil model (3D2D). As shown in the paper, the 3D2D SASSI modelling captures more accurately the specific site conditions related to the soil nonuniform variations in the vicinity of nuclear buildings, including topography effects, than the standard 3D1D SASSI modelling. Few case studies of the application of the 3D2D SASSI methodology for surface and deeply embedded nuclear complexes are presented.

INTRODUCTION TO NEW 3D2D SASSI MODELING CONCEPT

The standard SASSI flexible volume subtructuring concept (Lysmer et al., 1980) for seismic SSI analysis assumes that the soil deposit is described by infinite horizontal soil layers, as illustrated in Figure 1. The beauty of the standard SASSI methodology is that the free-field soil motion and the free-field soil impedance can be directly used to build the SSI system frequency-dependent complex stiffness matrix and the seismic load vector.

In the standard SASSI methodology, the structure model can be a 3D FE model, but the soil layering must be a 1D soil layer FE model. Therefore, for the standard SASSI methodology we use the notation "3D1D SASSI". However, this 1D soil layer variation model is apparent and only applicable to the free-field analysis under vertically propagating seismic waves, not to SSI analysis. For the SSI analysis that involves a full 3D wave propagation within the horizontally layered soil media, the soil model is idealized by a 3D axisymmetric layered soil model. The SASSI assumption of the horizontal soil layering implies the use of a 3D axisymmetric soil model in complex frequency. It should be noted that the soil model "axisymmetry" provides a large numerical efficiency to SASSI methodology, especially due to the implementation in the complex frequency of an extremely accurate 3D axisymmetric consistent boundary in horizontal directions for simulating the infinite soil media.

To include the effect of the inclined soil layering, the free-field soil motion and the free-field soil impedance should be computed based on a 2D soil variation model instead of a 1D soil variation model. For SSI analysis, instead of using a 3D axisymmetric soil model (3DASM), a 3D cylindrical soil model (3DCSM) is required. This 3DCSM model includes in a 2D soil variation in a horizontal direction and a 1D soil variation in the orthogonal horizontal direction, for example, a 2D soil variation in the X-Z coordinate plane, and a 1D soil variation in the Y-Z coordinate plane.

The 3DCSM has its axis parallel with the direction of the 1D soil variation. The brief notation for the 3D2D SASSI model can be made more explicit by using the notation 3D2D-1D SASSI model, indicating a 2D soil variation in one horizontal direction and a 1D soil variation in the orthogonal horizontal direction.

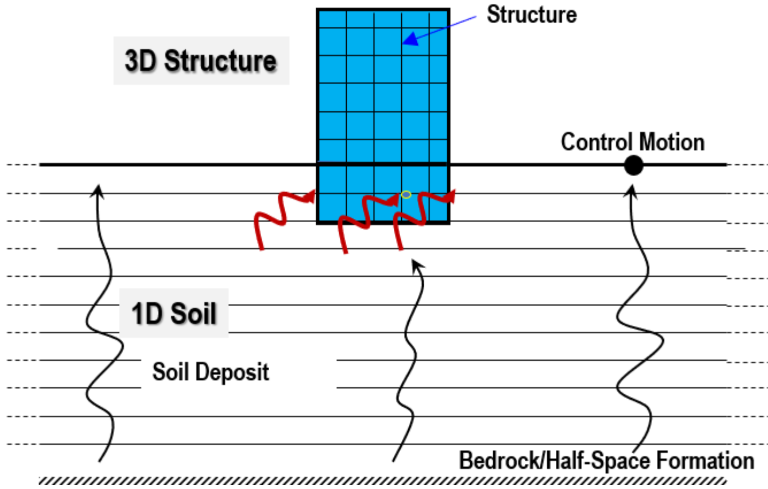


Figure 1 Traditional 3D1D SASSI Modelling (3D Structure and 1D Soil Layer Variation)

The new SASSI methodology based on the 3DCSM for the soil layering variation can be further extended to more complex 3D soil variations that can be described by two uncoupled 2D soil variations in two orthogonal planes. For such 3D2D-2D SASSI model vs. the 3D2D-1D SASSI model, the free-field motion and free-field soil impedances should be computed independently. This is achieved by performing two 2D site response analyses separately for the two orthogonal planes and combine their directional results. This 2D soil variations directional separation within the 3D2D-2D SASSI model is quite reasonably for practical purposes being also consistent with the current engineering standard recommendations and regulatory requirements which define seismic inputs by incident seismic plane-waves.

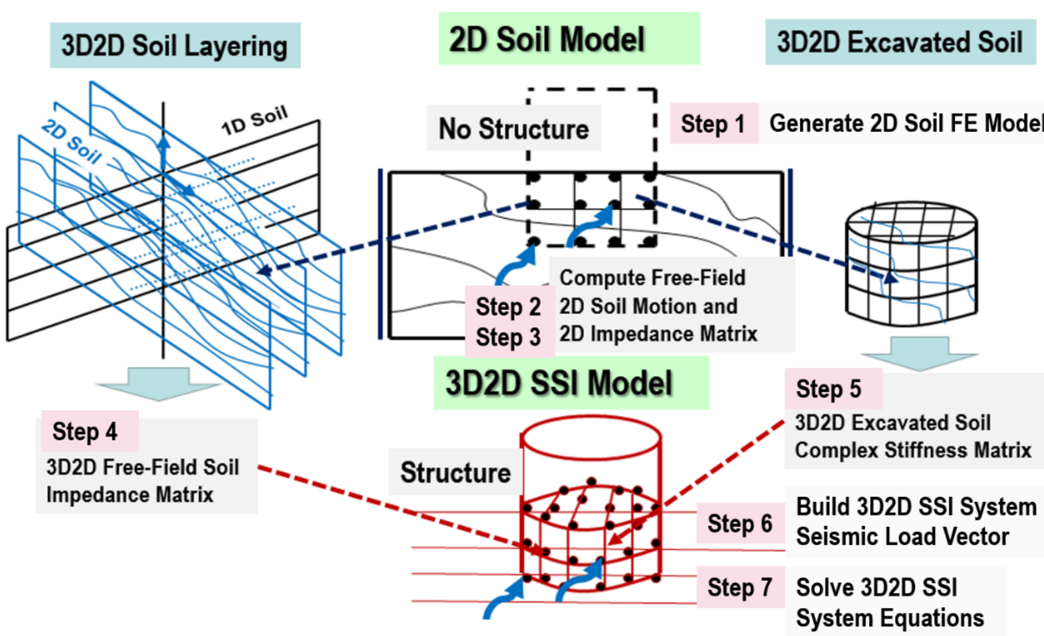


Figure 2 New 3D2D SASSI Modelling (3D Structure and 2D Soil Layer Variation)

Figure 2 shows a brief description of the 3D2D SASSI modelling (or 3D2D-1D) implementation including seven key computational steps as follows:

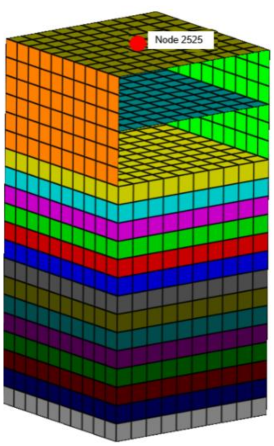
1) Build the 2D layered soil FE model based on site-specific soil data (2D plane-strain model)
2) Compute free-field soil motion based on 2D layered soil model (2D plane-wave assumption)
3) Compute free-field soil impedance based on 2D layered soil model (2D plane-strain model)
4) Compute free-field soil impedance based on 3DCSM (3D soil including 2D and 1D variations)
5) Build excavated soil model for the 3DCSM (3D soil including 2D and 1D variations)
6) Assemble the 3D SSI system, including the 3D structure FE model and the 3DCSM-based soil impedances and the 3D excavated soil FE model, and the 3D seismic plane-wave load vectors
7) Solve the 3D SSI motion equation system in the complex frequency

It should be noted that selected 2D soil variation plane is not required to be parallel with one of the global coordinate axes of the building foundation. It is suggested to select the 2D soil variation plane based on the principal variation direction of the steepest gradients of soil layer inclination, and not related to the building axes. In the ACS SASSI software, the building can be automatically rotated with respect to the soil variation principal axes.

VALIDATING NEW SASSI APPROACH AGAINST TRADITIONAL SASSI APPROACH

In this section the 3D2D SASSI approach implementation is validated against the standard 3D1D SASSI approach. To be able to achieve this, the 2D soil model was assumed to have horizontal soil layers as in 3D1D SASSI modelling, basically identical to the 1D soil model. The validation case study is a deeply embedded generic SMR model as described in Figure 3 The SMR structure has a total height of 200 ft with only 60 ft above ground. The SMR foundation area is a square area of 100 ft x 100 ft. Table 1 shows the soil layer material dynamic properties.

Figure 4 describes the 2D soil layering model with horizontal layers (truncated in the horizontal direction), including the SMR location and embedment in the soil layering.



Layer	Thickness	Specific Weight	SV Wave Velocity	P Wave Velocity	Damping Ratio
1	20	0.15	1500	3000	0.04
2	30	0.15	1750	3500	0.04
3	30	0.15	2000	4000	0.035
4	30	0.15	2500	5000	0.03
5	30	0.15	2750	5500	0.025
6	30	0.15	3000	6000	0.02
7	30	0.15	4000	8000	0.02
Base	200 ft Halfspace	0.15	4000	8000	0.02

Figure 3 3D SMR Model

Table 1. Soil Layer Iterated Properties

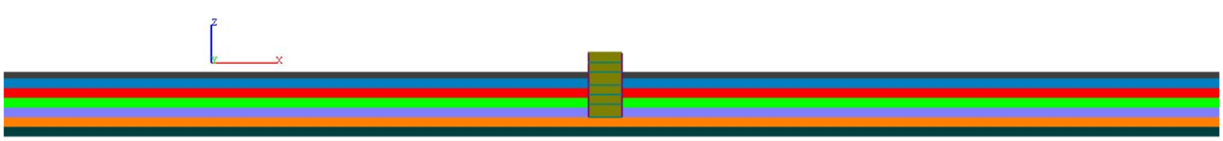


Figure 4 2D Soil Variation Model with Horizontal Layers (truncated in horizontal direction)

Figure 5 shows the complex acceleration transfer function (ATF) amplitudes in the horizontal direction at the top and the basemat of the SMR structure computed using the 3D1D SASSI approach with the 1D soil layer variation model, and the 3D2D SASSI approach with the 2D soil layer variation model.

Figure 6 shows the comparative ISRS computed at the same to locations, at the top and respectively at the basemat center of the deeply embedded SMR structure.

The computed ATF and ISRS curves are practically identical for the two SASSI modelling approaches. To achieve the "exact" matching between the 3D2D and 3D1D SASSI approaches, the 2D soil variation FE mesh and the 3D excavated soil FE model should have same mesh sizes.

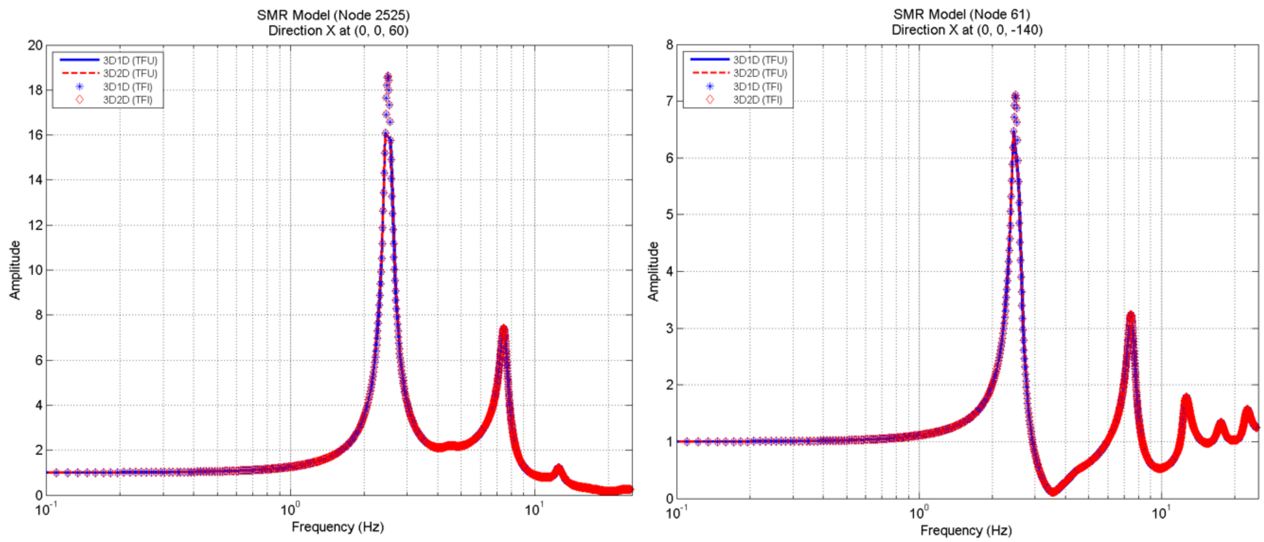


Figure 5 Comparative ATF Computed at Top (left) and Basemat of SMR Structure

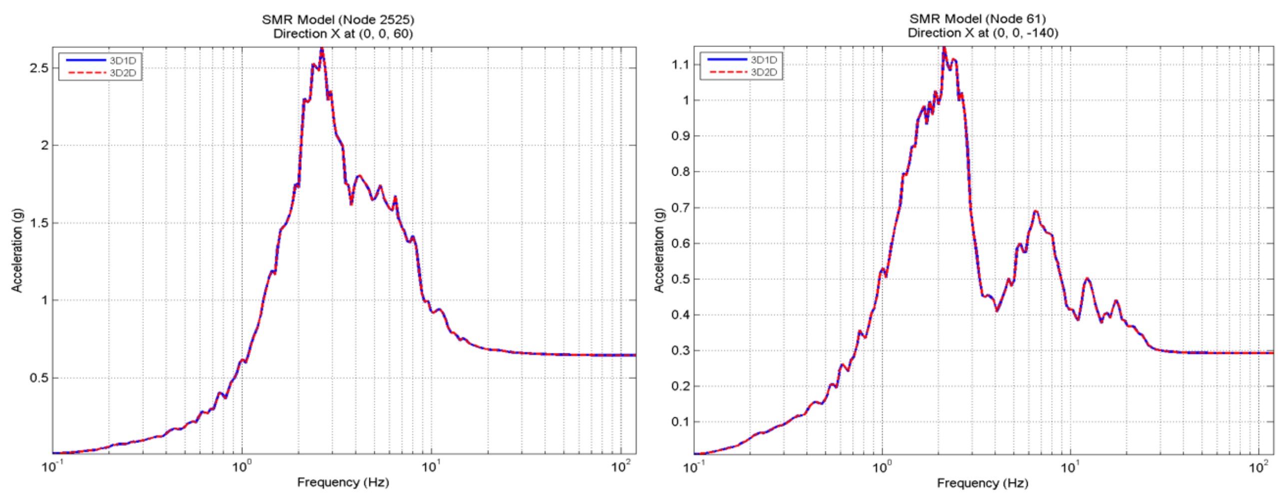


Figure 6 Comparative ISRS Computed at Top (left) and Basemat of SMR Structure

2D SOIL VARIATION FE MODEL MESH SENSITIVITY STUDY

An important SSI modelling aspect is related to the mesh sizes of the 2D soil variation FE model and the 3D excavated soil FE model. To get "exact" results the two meshes of the 2D and 3D FE models should be coincident. This can be only achieved if the 3D excavated soil model has a regular mesh, which in fact is highly desirable for the SASSI modelling of deeply embedded foundations. This is an important SSI modelling aspect for capturing accurately the wave scattering effects for the deeply embedded structures, but at the same time it provides a significant numerical efficiency. The use of regular meshes for the excavated soil models is also recommended by USNRC BNL consultants (Nie, Braveman and Costantino, 2013).

Figure 7 shows the impact on ISRS of using different regular mesh sizes for the 2D soil FE model which are 33% smaller or, respectively, 33% larger than the 3D excavated soil model mesh size. The 2D horizontal element size is 5 ft and 10 ft, while the 3D excavated soil horizontal element size is 7.5 ft.

Figure 8 shows the computed ISRS at the top and the mid-height of the SMR structure for 10 ft element size for the 2D soil FE model and 7.5 ft element size for the 3D excavated soil FE model.

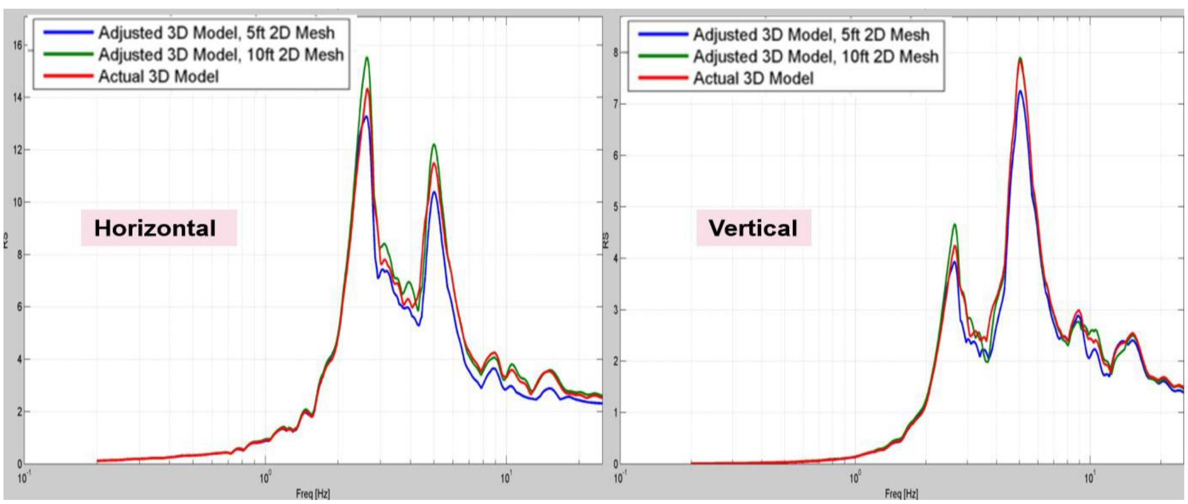


Figure 7 Comparative 3D2D vs. 3D1D ISRS Computed at Top of SMR Using Different Mesh Sizes (in the legend 3D2D model is "Adjusted 3D Model", while 3D1D model is "Actual 3D Model")

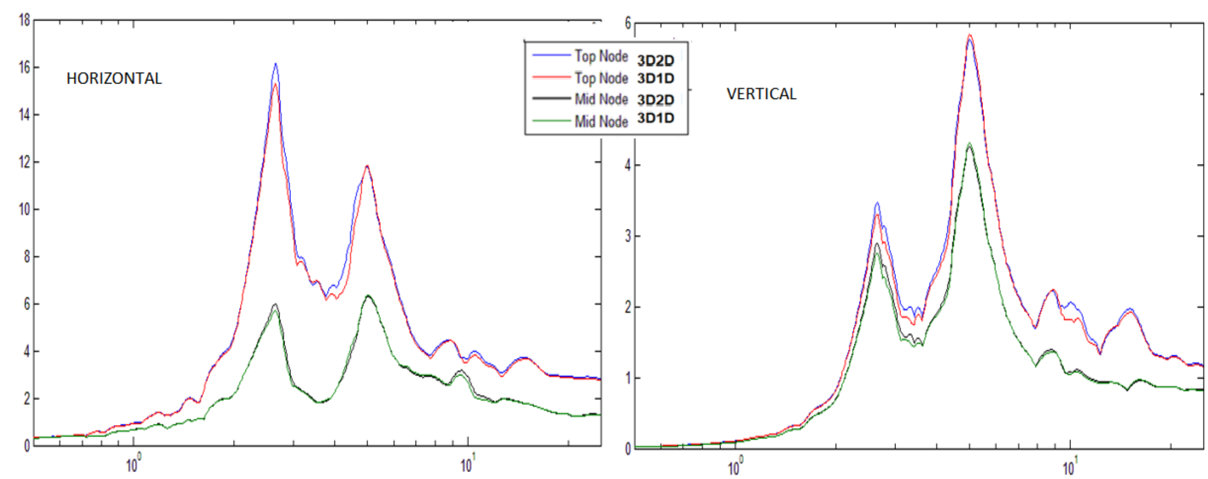


Figure 8 Comparative 3D2D vs. 3D1D ISRS at Top and Mid-height of SMR Using a 10 ft 2D Mesh Size

ILLUSTRATIVE CASE STUDIES

Three examples on the application of the 3D2D SASSI modelling against the 3D1D SASSI modelling are presented herein. The examples show a surface SMR, a deeply embedded SMR, and a surface large-size, heavy RB complex.

Surface SMR Structure

Figure 9 describes the 2D soil variation FE model including the surface SMR structure location. The lateral size of the 2D soil model is about 8,000 ft. The 2D soil model was considered to be a large-size embedded model with frequency-dependent consistent boundaries around the FE model domain. The seven soil material properties included in the 2D soil model are shown in Table 2. The seismic input was defined in the X horizontal direction at the bedrock at the 200 ft depth.

Comparative ISRS computed using the 3D2D and 3D1D models at the basemat center and top of the structure in X and Z directions are plotted in Figure 10. It should be noted that the 1D soil variation is based on the average of the 2D soil variation across a horizontal window of 500 ft around the structure location.

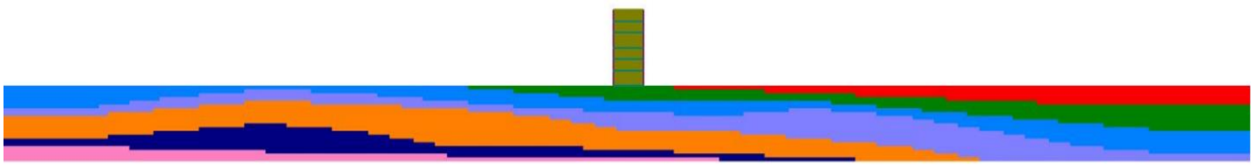


Figure 9 2D Soil Layer Variation Model (Truncated) Including the Surface SMR Structure Location

Layer	Thickness	Specific Weight	SV Wave Velocity	P Wave Velocity	Damping Ratio
1	20	0.15	1500	3000	0.04
2	30	0.15	1750	3500	0.04
3	30	0.15	2000	4000	0.035
4	30	0.15	2500	5000	0.03
5	30	0.15	2750	5500	0.025
6	30	0.15	3000	6000	0.02
7	30	0.15	4000	8000	0.02
Base	200 ft Depth Bedrock	0.15	10000	20000	0.001

Table 2. Soil Layer Properties

Figure 10 shows that the 3D2D SSI model provides lower ISRS with exception of the spectral peak at 1.60 Hz for which the 3D2D SSI model provides a higher amplitude than the 3D1D SSI model in both X and Z directions. This 1.60 Hz spectral peak corresponds to the SSI rocking motion of the structure that is amplified by the surface and the non-vertically propagating SV and P incoming waves.

The SSI rocking motion amplification for the 3D2D model due to the non-vertically propagating waves is visible in Figure 11 which shows a comparison of the SMR instant accelerations and the relative displacements with respect to the free-field reference motion which are computed at the same time step.

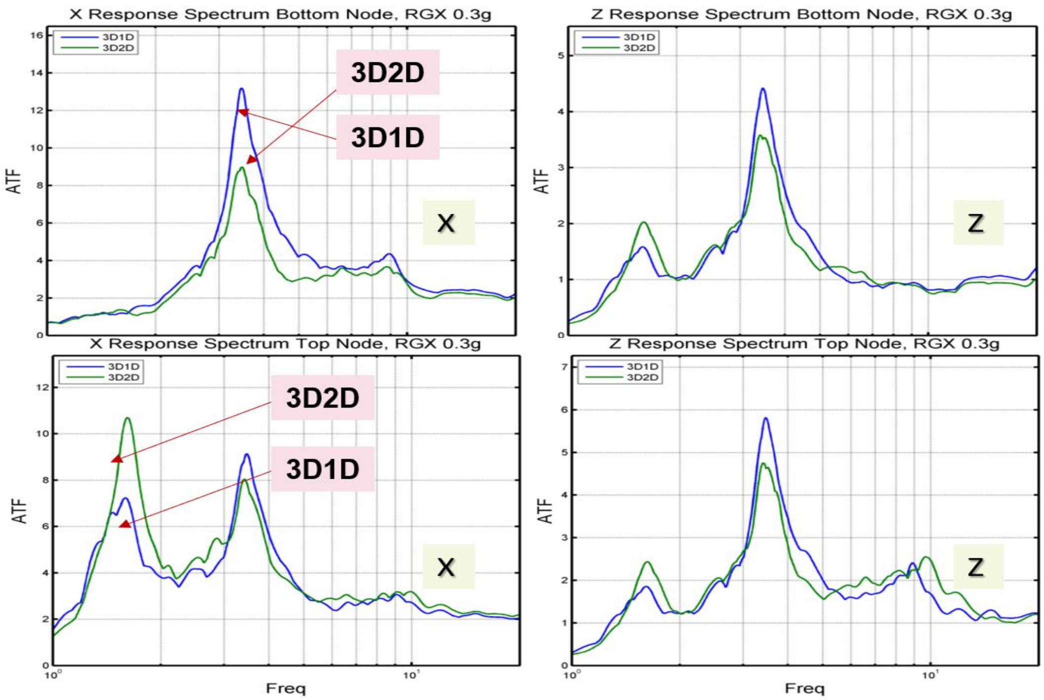


Figure 10 Comparative 3D2D vs. 3D1D ISRS Computed at Bottom and Top of SMR Structure

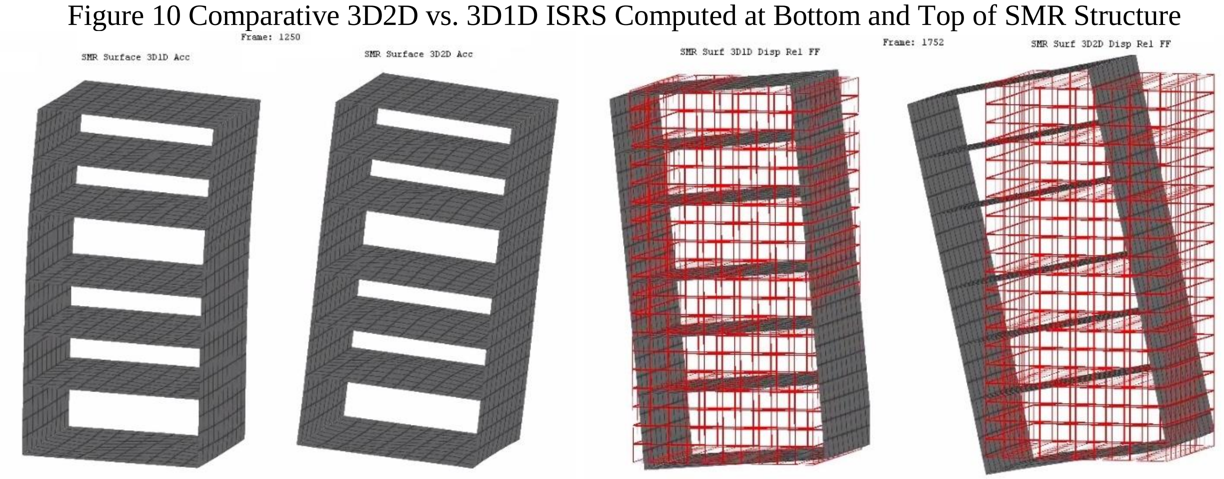


Figure 11 Comparative 3D1D vs. 3D2D Instant Accelerations (left) and Relative Displacements (right)

Deeply Embedded SMR Structure

Figure 12 illustrates the 2D soil variation model including the deeply embedded SMR structure location and embedment in the soil layering. The seven soil material properties included in the 2D soil model are the same as in Table 2. The seismic input was defined in the X horizontal direction at the bedrock and 200 ft depth.

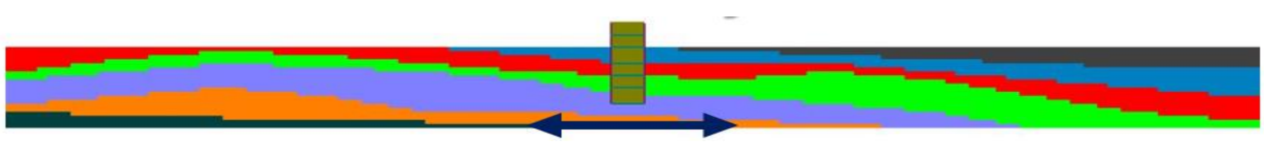


Figure 12 2D Soil Layering Variation Model (truncated) Including Embedded SMR Structure Location

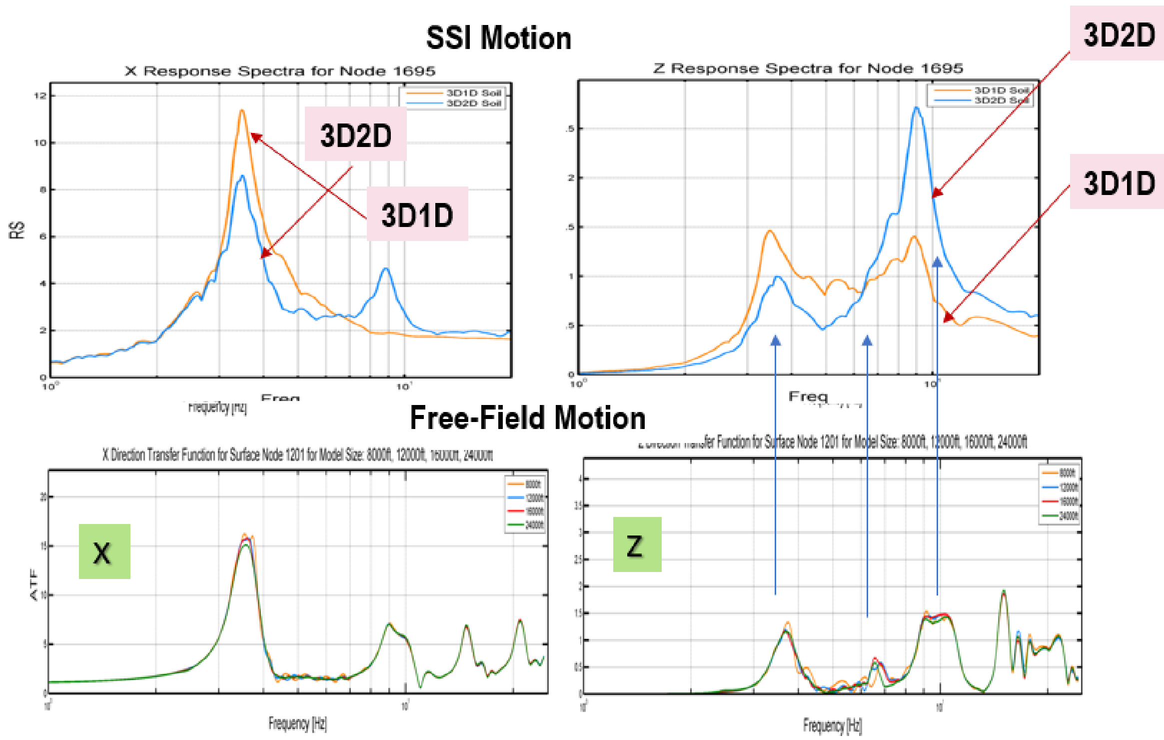


Figure 13 ISRS at Top of SMR (upper plots) and Free-Surface ATF (lower plots) for X and Z Directions

For the deeply embedded SMR structure the effects of kinematic SSI are more significant. Figure 13 shows two dominant ISRS spectral peaks at the 3.5 Hz frequency and 9.0 Hz frequency for the SMR structure (upper plots). The ISRS spectral peak @ 1.60 Hz that corresponded to the surface SMR structure rocking motion in Figure 10 is vanished.

The free-field surface ATF motion plots (lower plots) with respect to the bedrock input motion in the horizontal direction show the existence of some significant vertical motion components for the 2D soil model at the same two frequencies. The vertical motion components are due the motion coupling produced by the non-vertically propagating waves generated by the 2D soil property variation in horizontal direction. It should be noted that for the 1D soil model with infinite horizontal layers, there is no vertical motion components if the bedrock input motion is defined only in the horizontal direction.

As result of the free-field soil vertical motion components interacting with the SMR structure SSI motions, the ISRS spectral peak at 3.5 Hz frequency is reduced, while the ISRS peak at 9 Hz frequency is amplified. The motion phasing between the incoming free-field vertical motion components and the SMR vertical motions due the SSI rocking response plays a significant role in amplifying or reducing the ISRS of the SMR structure.

Figure 14 shows a comparison of the instant accelerations of the excavated soil FE model computed using the 3D2D model (right) vs. the 3D1D model (left). It is quite visible from the deformed shape plots that the kinematic SSI effects produced by the scattered surface waves are much larger for the 3D2D model in comparison with the 3D1D model.

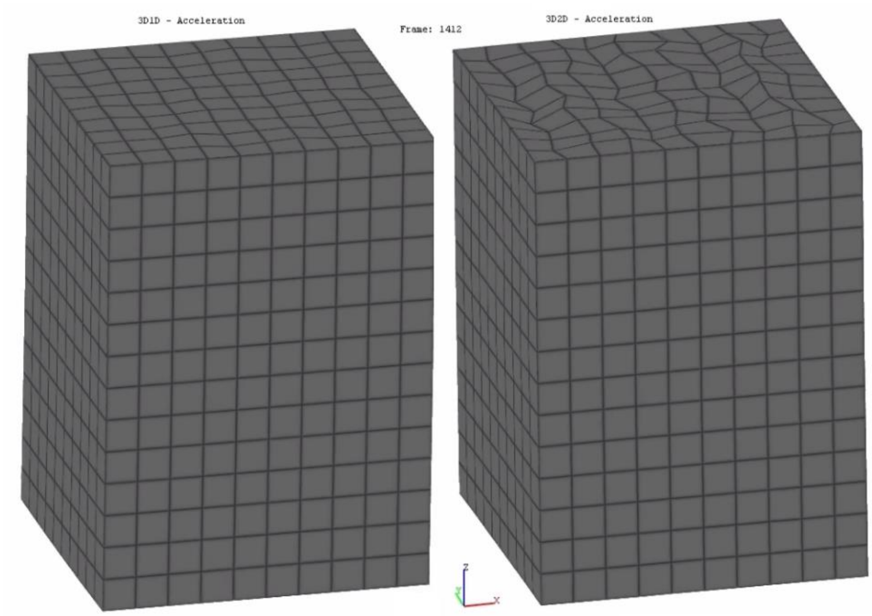


Figure 14 Instant Accelerations of SMR Excavated Soil for 3D1D (left) and 3D2D (right) Models

Large-Size Nuclear RB Complex

Figure 15 describes the 2D soil variation FE model including the large-size heavy nuclear RB complex model location. The seven soil material properties included in the 2D soil model are shown in Table 2. The seismic input was defined in the X horizontal direction at the bedrock at 200 tf depth.

Comparative ISRS computed using the 3D2D and 3D1D models at the top of the structure in X and Z directions (see red circle in Figure 15) are plotted in Figure 16. It should be noted that the 1D soil variation is based on the average of the 2D soil variation across a horizontal window of 500 ft placed around the structure location.

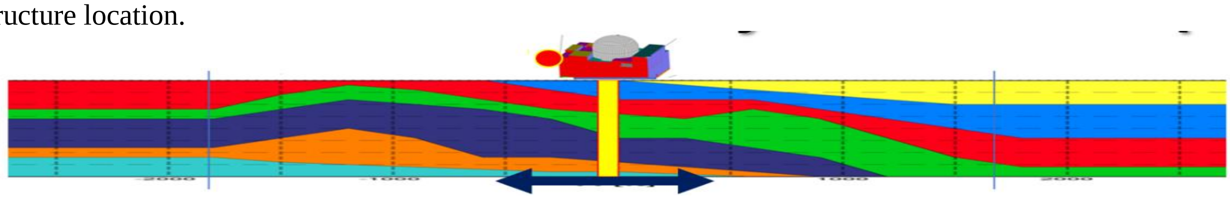


Figure 15 2D Soil Layering Variation Model (truncated) Including RB Complex Structure Location

Figure 16 also includes the free-field motion ATF amplitudes with respect to the bedrock input. The ISRS results show similar trends as in the previous case study. As result of the free-field 2D soil vertical motion components interacting with the structure motion, the ISRS spectral peak at 3.5 Hz frequency is reduced, while the ISRS peak at 9 Hz frequency is amplified, similar to the SMR case study.

However, Figure 16 also shows visibly a significant frequency shift of the dominant SSI mode for the 3D1D model to lower frequencies. This frequency shift is due to the use of the average soil properties based on the 500 ft horizontal window for the horizontal soil layers of the 3D1D model. The 3D1D model artificially creates infinite horizontal soil layers under the heavy nuclear complex with average soil properties. For the top 50m depth, the soil Vs average value is about 1650 fps. This Vs of 1650 fps value appears to be significantly less than the Vs values of the soil layers on the left-side of the RB complex.

The existence of the stiffer soil layers (red and green colours) with Vs of 2000 and 2500 fps on the left-side of the nuclear complex makes the soil impedance computed based on the 2D soil variation model to be stiffer in the horizontal direction for the 3D2D model than the soil impedance computed for the 3D1D model. This is an important remark for current practice based on the assumption of infinite horizontal layers for all site conditions. It shows the limits of the traditional 3D1D SASSI modelling for soil layers with significant inclination. The 2D soil variation model in Figure 15 includes interface layer slopes up to 1/10.

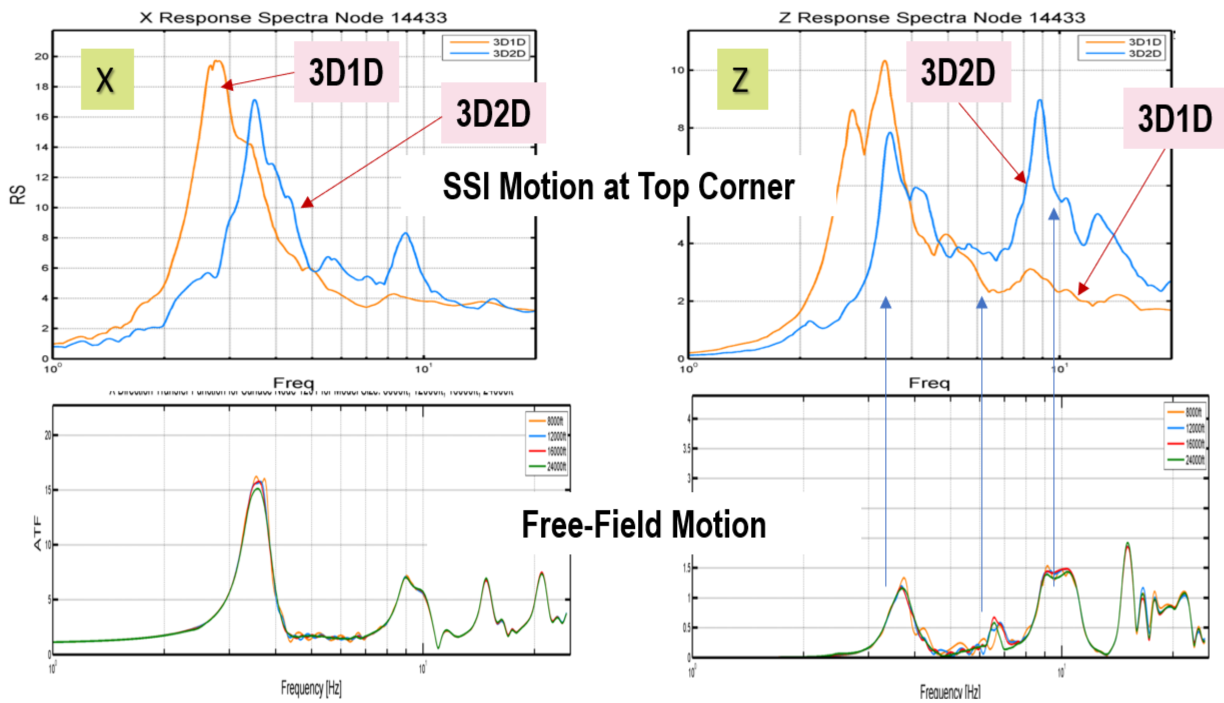


Figure 16 ISRS at Top of RB (upper plots) and Free-Field Surface ATF (lower plots) for X and Z Directions

CONCLUDING REMARKS

The paper introduces new 3D2D SASSI methodology applicable to the inclined soil layering SSI problems.

The 3D2D SASSI methodology has the capability of accurately capturing the 2D soil variation and the wave scattering effects due to the non-vertically propagating waves produced by the soil layer inclination, and eventual topography features. This aspect is of particularly significance for the deeply embedded structures such as SMR structures.

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