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Division V

SIMPLIFIED APPROACH TO ESTABLISH THE DYNAMIC IMPEDENCE OF DEEPLY EMBEDDED SMALL MODULAR REACTORS

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ABSTRACT

Small Modular Reactor (SMR) designs include deeply embedded structures with important safety related systems and components located below the grade. Complex Soil Structure Interaction (SSI) analyses are frequently performed to estimate the dynamic response of the structure and establish In-Structure Response Spectra (ISRS). However, SSI software is typically not suited for the design of structural components. Such designs are performed in other specialized software tools. There exist numerical approaches to link SSI and structural design tools by means of numerical determination of foundation impedance at the grid level of the Finite Element Models (FEM). Such approaches involve exhaustive numerical simulations that require iteration and passing of information between applications and even between engineering organizations.

This publication presents an approach to establish the lateral and vertical dynamic impedance of a deeply embedded shaft. It utilizes common closed solutions of dynamic impedance as shown in Wolf (1994), Gazetas (1991), or Luco (1987), modified to address site-specific soil conditions characterized by the shear wave velocity distribution at the base and throughout the walls of the embedded foundation. A particular example with a specific structural configuration and soil profile is used throughout the analysis. The methodology is theoretically applicable to general structure-soil configurations though it is concluded that additional research is required to verify the practical applicability.

INTRODUCTION

Deeply embedded configurations are currently considered for deployment of "small" modular reactor technologies. Two examples are the X-Energy Xe-100 and the GE-Hitachi BWRX-300. Both technologies considered deep embedment within an outer cylinder containment of 20 m to 30 m diameter and approximately 30 m deep. Embedment requires Soil Structure Interaction (SSI) analysis which is traditionally and successfully conducted using the computer code SASSI (Ghiocel 2014), for three-dimensional frequency domain linear SSI analysis for shallow, embedded, deeply embedded and buried structures under earthquake ground motion. The SSI analysis provides maximum response accelerations or Zero Period Accelerations (ZPA), time history acceleration response, and In-Structure Response Spectra (ISRS). It can also be used to estimate foundation impedance (stiffness and damping). The estimation of such dynamic or static impedance for complex designs with a fully embedded cylindrical foundation like those of the Xe-100 or BWRX-300, can be a challenging and time-consuming effort. Engineering designers frequently go through exhaustive and timely numerical simulations that require multiple iterations and transfer of information between software applications and engineering organizations.

The following content presents an approach to establish the lateral and vertical dynamic impedance of deeply embedded shafts like those of the Xe-100 and BWRX-300. It utilizes common closed solutions of dynamic impedance (Wolf, 1994, Gazetas, 1991, Luco,1987), modified to address site-specific soil conditions characterized by the shear wave velocity distribution at the base and throughout the walls of the embedded foundation. It is not the intent of this publication's analyses and results to provide detailed modelling of either of the Xe-100 or BWRX-300 technologies. These are only used as examples of deeply embedded shafts. A generic geometry with a Lumped Mass Stick Model (LMSM) with dynamic properties to resemble these technologies is used to demonstrate the effectiveness of the proposed methodologies.

The cylindrical containers are deeply embedded with a particular embedment aspect ratio and must be analysed with site-specific subsurface conditions. Impedance will depend on these factors plus the stiffness and damping of the structure itself. It therefore follows that an accurate estimation of the impedance involves an iterative process between seismic SSI analysis and structural design. Either of the following paths is commonly implemented:

- Develop a SASSI consistent Stiffness-Damping impedance function throughout the interface of the shaft. The impedance would be used as part of a two-step design approach performing a full structural dynamic simulation with spring and dashpot supports at each point of the foundation interface. Such simulations are performed in powerful structural analyses FEM tools such as ANSYS or GT-STRUCLE. This approach is rigorous though maybe not recommended for initial design stages, given the complexity and associated cost and schedule challenges.

- Generate a SASSI counterpart model using dynamic or static forced vibrations and measure displacements to get the spring and damping constants. This is a significant effort still, but not as rigorous. It would result in an impedance function that can be used for pseudo-static and dynamic analyses with other structural tools. The impedance would be obtained independent of the dynamic structural response.

- Perform a one-step calculation analysis at which design forces are directly obtained from the SSI simulation. Even though rigorous, SSI analysis for deeply embedded structures is still time consuming and not yet efficient to generate results that are used for structural design. The structural design is typically burdened by configuration changes and multiple SSI iterations involve significant expense.

For early stages of analysis and design, a simplified approach to develop a foundation stiffness is proposed to avoid the repetition of lengthy SSI simulations. The approach relies on closed solutions that are published in literature for embedded foundations. These solutions have been around for some time. Some are endorsed by ASCE 4-16 (Seismic analysis of Nuclear Structures) but just for surface models. These solutions will provide frequency dependent spring constants for general lateral, vertical, rocking, and torsional vibrations. The solutions assume that the embedded foundation is rigid and placed within a homogenous soil media. The proposed methodology adapts these solutions to the specific configurations of the recent proposed shafts and the horizontally layered media assumption followed by the SASSI formulation.

THE EMBEDDED SHAFT

SSI models that resemble the configurations proposed by actual technologies can be represented by a lumped mass stick model (LMSM) connected to a perimeter cylindrical shaft and a round foundation basemat. Figure 1 provides a representation of the FEM model used throughout this publication. For visibility purposes, only half cylinder is depicted. The main features of the LMSM are:

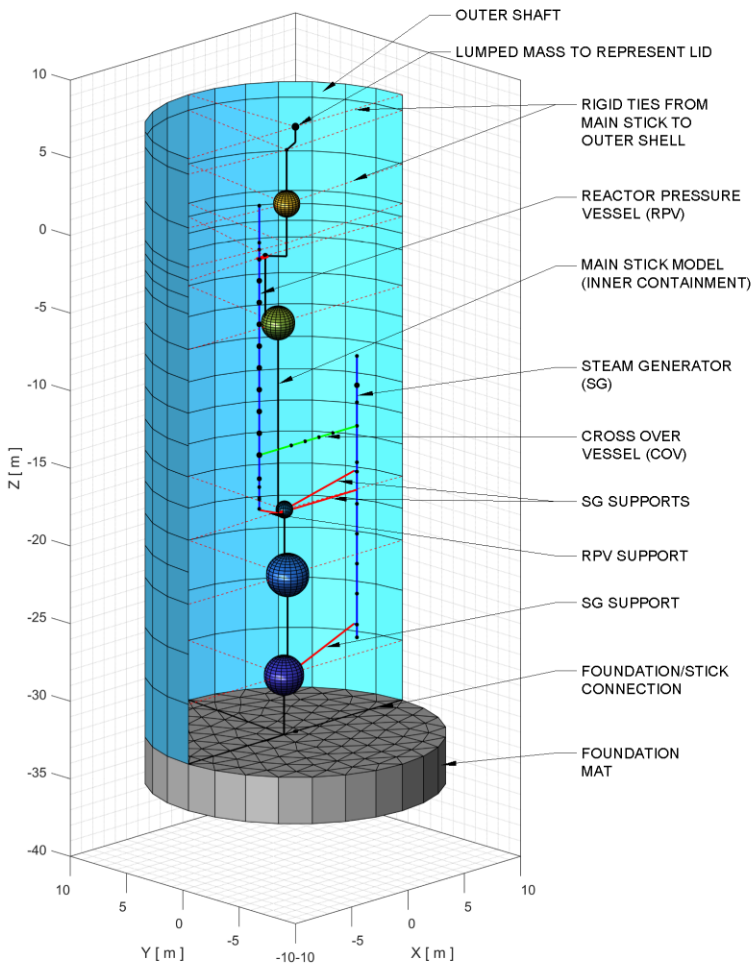


Figure 1. FEM model of the embedded shaft.

- Internal containment is represented by the inner concrete structures stick model.
- The outer shaft is realistically modelled with plate elements. The thickness of the plates is 1.0 m.
- The foundation mat is 3.0 m thick and is represented by solid prism elements.
- The main stick is rigidly connected to the foundation mat.
- The main stick is connected to the outer cylinder by a series of rigid elements or ties that represent floor slabs.
- The reactor components are:
    - Reactor Pressure Vessel (RPV),
    - Cross Over Vessel (COV),
    - Steam Generator (SG).
- The reactor components are attached to the main stick by means of rigid beam element supports with certain release specifications.
- The outside diameter of the outer shaft is 19.0 m.
- The length of the shaft is 42.0 m, including the 3.0 m thick basemat; embedment is 35 m.

- The mass of the system is incorporated either by (1) density in members (such as the foundation mat, shaft walls, and some RPV and SG portions) or (2) by lumped masses that represent equipment mass.

PROPOSED APPROACH

Suppose that a subset of the impedance, the stiffness portion, is required to perform pseudo-static seismic analysis with the use of an FEM structural model implemented in a structural analysis tool without SSI simulation capabilities. It is desirable to develop foundation stiffness for an embedded shaft in the horizontal and vertical directions. Torsion and rocking stiffnesses are not calculated since a single stiffness spring will be assigned at each mesh grid point of the FEM outer shell model.

The approach to develop the foundation springs consists of the following steps:

1. Equations are available for simple closed form solutions for a rigid cylindrical embedded foundation of radius r_o and embedment e, embedded in a homogeneous three-dimensional halfspace. These equations are those of Aspel and Luco (1987) (or Pais and Kausel, 1988) as published in Wolf 1994. The total static (low frequency & low strain) stiffness in the horizontal and vertical directions are:

$$K_h = \frac{8 \cdot G \cdot r_o}{2 - \nu} \cdot \left(1 + \frac{e}{r_o}\right) \tag{1}$$

$$K_v = \frac{4 \cdot G \cdot r_o}{1 - \nu} \cdot \left(1 + 0.54\frac{e}{r_o}\right) \tag{2}$$

$$G = \rho \cdot V_s^2 \tag{3}$$

Where:

K_h	→	Total horizontal stiffness
K_v	→	Total vertical stiffness
G	→	Shear modulus of halfspace
r_o	→	Radius of cylinder
ν	→	Poisson's ratio
e	→	Embedment
ρ	→	Density
V_s	→	Shear wave velocity

Limitations of the use of the previous equations for models such as that depicted in Figure 1 are: (a) the cylinder is not fully embedded, (b) the system is not completely rigid, (c) the embedment ratio (e/r_o) of the model under consideration is 35/9.5 = 3.7, which is beyond the range of analysis reported in the referenced publications, and (d) the solutions are developed for a homogeneous halfspace rather than a layered soil profile. The first limitation should not be prohibitive given that the cylinder embedment is significant. The second assumption (rigid foundation) is reasonable for soil sites and analysis under linear elastic response. The third and fourth assumptions are counteracted by the approaches explained in the following steps.

2. Calculate the average shear modulus of the soil media in which the cylinder is embedded. To calculate the average shear modulus, weighted averages of the density, Poisson's Ratio, and shear wave velocity are calculated for the 35 m embedment length.

3. Calculate the total horizontal and vertical stiffnesses using equations (1) and (2).

4. The dynamic horizontal ($K_{H\text{-}DYN}$) and vertical ($K_{V\text{-}DYN}$) stiffnesses are modified using the frequency dependent dynamic stiffness coefficients (DSC) published in Wolf (1996).

$$K_{H-DYN} = K_h \cdot DSC_{Hor} \tag{4}$$

$$K_{V-DYN} = K_v \cdot DSC_{Ver} \tag{5}$$

   The DSC, for the frequencies of interest are very close to 1.0. Therefore, for the specific case study, a value of 1.0 may be selected.

5. A portion of the total stiffness is assigned to the base and the rest to the walls in the cylinder. For the horizontal direction in a soil case analysis, it is assumed that the base will carry about 10% of the total stiffness and the walls will take 90%. This distribution is similar to the proportional contact areas of the base and walls respectively. For the vertical direction, 20% of the stiffness is assigned to the base and 80% to the walls. It is a fact that these assumed distributions have been arbitrarily set using good judgement. Even though additional research is required to provide further recommendations, the results later discussed indicate that the assumption is reasonable.

6. To obtain the spring constants for nodes at the base, the total dynamic stiffness is divided over the number of mesh points at the base. The resulting stiffnesses at the node level are:

$$k_{n-h} = 0.1 \cdot \frac{K_{H-DYN}}{n_{base}} \tag{6}$$

$$k_{n-v} = 0.2 \cdot \frac{K_{V-DYN}}{n_{base}} \tag{7}$$

   Where:

   k_{n-h} → Horizontal spring constant per node for nodes at base
   k_{n-v} → Vertical spring constant per node for nodes at base
   n_{base} → Number of nodes at base

7. To obtain the spring constants at the nodes in the cylinder wall outer face:

   a) A percentage of the total wall stiffness is assigned to each soil layer proportional to the specific shear modulus of the soil layer:

$$LF_i = \frac{G_i}{\bar{G} \cdot n_{layers}} \tag{8}$$

   Where:

LF_i → Percentage of stiffness assigned to layer i
G_i → Shear modulus of layer i
$\bar{G}$ → Average shear modulus
n_{layers} → Number of layers in contact with wall

b) The grid spring constants are then established:

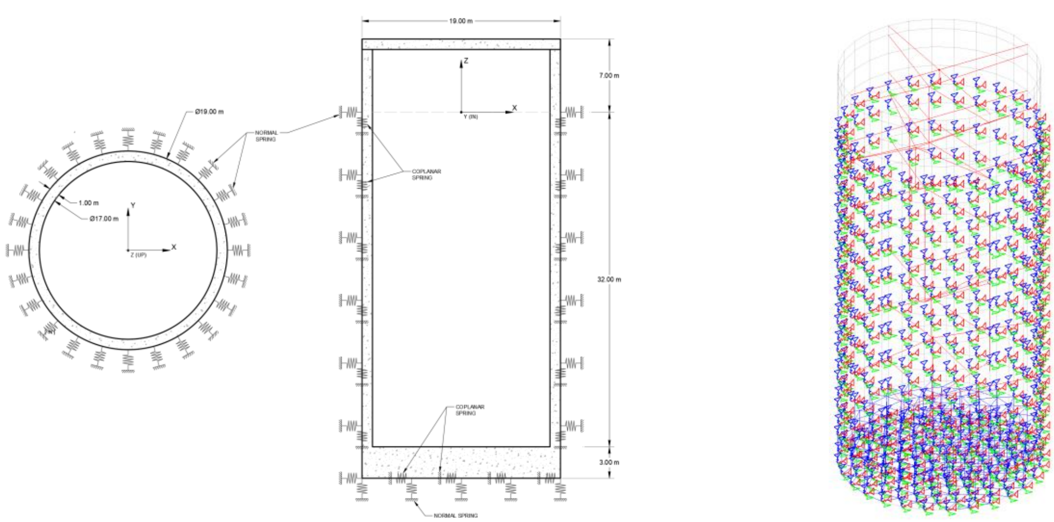
$$k_h = 0.9 \cdot LF_i \cdot \frac{K_{H-DYN}}{n_{perimeter}} \tag{9}$$

$$k_v = 0.8 \cdot LF_i \cdot \frac{K_{V-DYN}}{n_{perimeter}} \tag{10}$$

Where:

LF_i → Percentage of stiffness assigned to layer i
k_h → Horizontal spring constant for nodes at wall
k_v → Vertical spring constant for nodes at wall
$n_{perimeter}$ → Number of nodes at perimeter contact

8. Adjust spring constants by π/2 to transform into cylindrical coordinates. The approach assumes a radial orientation of the spring (Figure 2). The wall springs are radially oriented, and the base springs are provided in cartesian coordinates that match the global coordinate system. It is then assumed that horizontal stiffness is all developed by normal spring reaction. The vertical springs are oriented also in the cartesian vertical direction as shown in Figure 2 (a).



(a) (b)

Figure 2. Orientation of nodal foundation springs

ANALYTICAL MODELS

Three FEM models of the LMSM of Figure 1 are developed to evaluate the effectiveness of the proposed methodologies: (1) the SSI SASSI model, (2) a STAAD model with the spring supports calculated as per the proposed methodology (K Model), and (3) a fixed based STAAD model, rigidly supported at the base of the foundation mat only. The fixed-base model is not supported laterally in the cylinder wall and is developed only to compare frequencies of the main vibration modes between fixed-base and flexible foundation cases. Figure 2(b) provides a representation of the spring supported STAAD model.

The SASSI soil media was obtained from an actual site in the Western United states. The shear wave velocity distribution is provided in Figure 3.

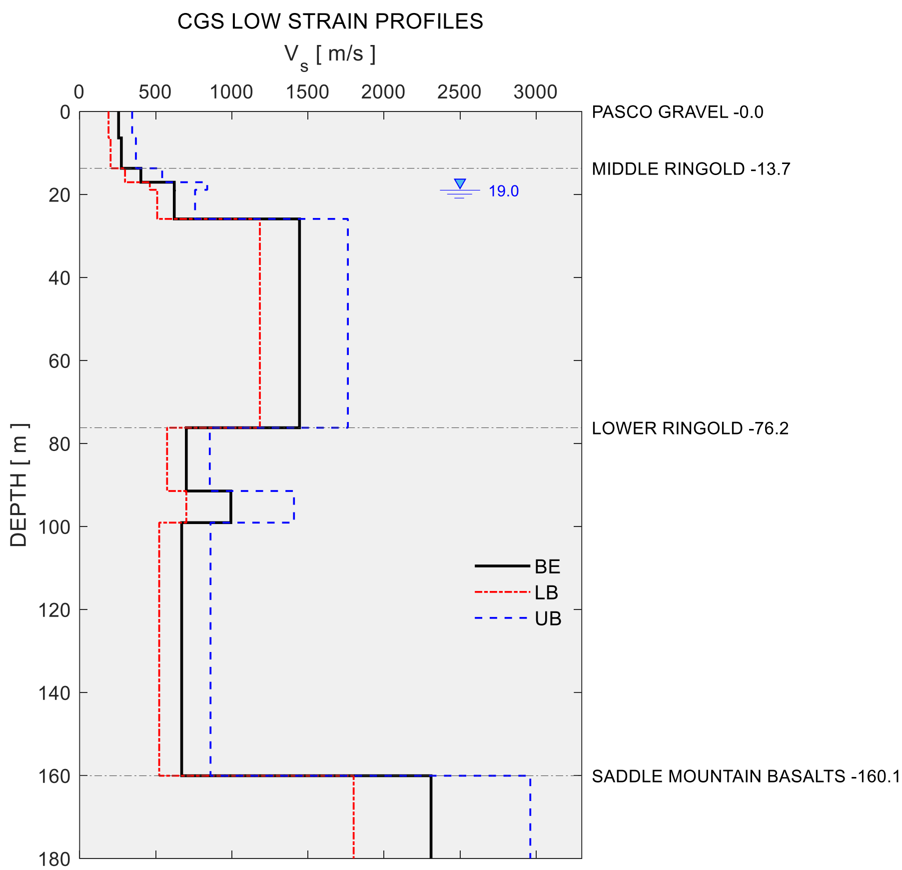


Figure 3. Shear wave velocity used in SASSI model

ANALYSIS AND RESULTS

Figure 4 presents the results from a time history analysis performed with the K-Model compared to the frequency domain SASSI results. The maximum floor acceleration or Zero Period Acceleration (ZPA) was obtained throughout the height of the LMSM core. A damping constant (5%) is assigned. The comparison of the reported ZPA's is remarkably satisfactory. These results indicate that the K-Model can potentially be used for seismic analysis that accounts for SSI effects. Evidently, additional research is needed to add more sophistication to the methodology and perform additional testing with other geometries, other soil configurations and other more realistic FEM representations of the inner structural components.

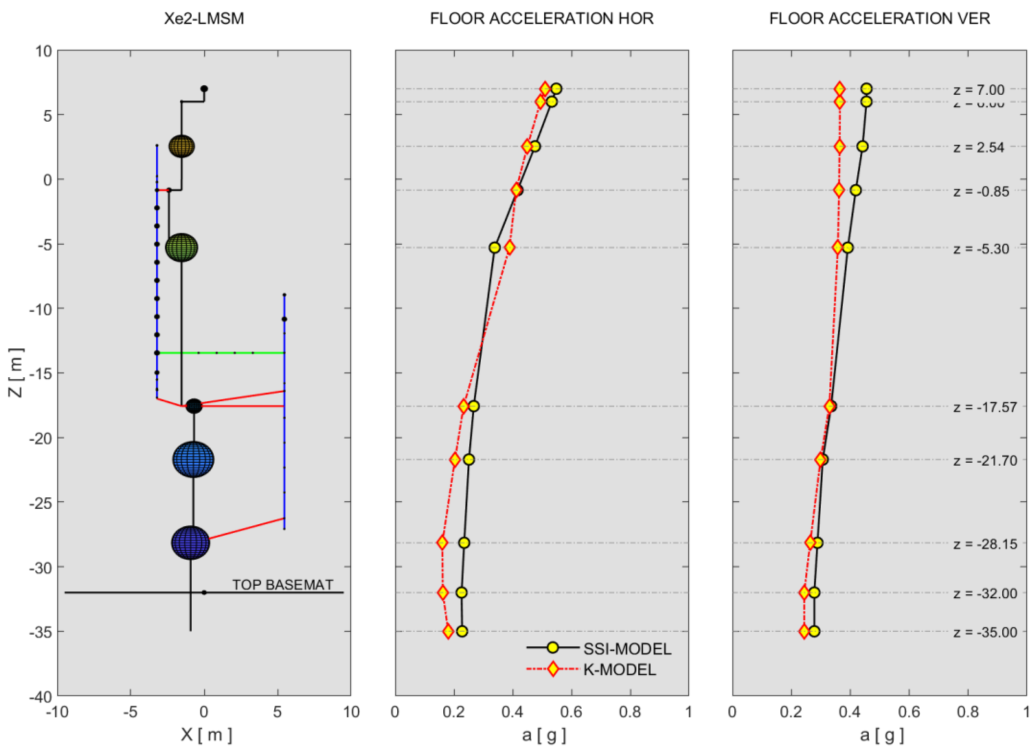


Figure 4. Zero Period Acceleration

Comparison of In-Structure-Response-Spectra (5%) is provided in Figure 5. The comparison is not quite satisfactory though it is important to recall that no attempt was made to calibrate the K-Model springs. The K-model does not capture the lower frequency mode observed in the SASSI response which was confirmed in the transfer function (Figure 6).

CONCLUSIONS

The settings for time history analysis between SASSI and STAAD-PRO are different. The purpose of this methodology is not to imply that these two analyses could be equivalent. The purpose is to develop a foundation interface for deeply embedded structures that can reasonably perform in conventional structural analysis applications. SSI analysis is time-consuming, and iterations are not desirable for initial design stages. The most significant advantage of the proposed approach is its simplicity. A simple spreadsheet can be used to calculate the spring constants, and these can easily be transferred into the structural analysis applications. Another, maybe equally important advantage, is the running time of the conventional time history analysis vs. the SASSI SSI analysis. For this particular model and with the particular hardware resources used by the authors, the K Model running time is less than 20 seconds, as opposed to the 8-hour span when using the flexible volume formulation in SASSI.

The results obtained are acceptable, especially when no effort was devoted in calibrating the distribution of the spring energy. The same results were not recorded when using uniform distributions of the spring constants. Also, the radial orientation approach worked remarkably well for the cylindrical shaft, avoiding the need of developing three-directional springs.

There is a very sizeable amount of research that can and should be devoted to check the effectiveness of the proposed approach. Other models and case histories for which results from detailed SSI simulations are available can be used to develop similar K models and perform comparisons. A larger sample of models, involving different embedment, and aspect ratios can be analysed to develop adjustment rules to the distribution of the nodal impedance. An important objective is to always keep the simplicity of the approach so that it remains as very valuable tool for initial design phases.

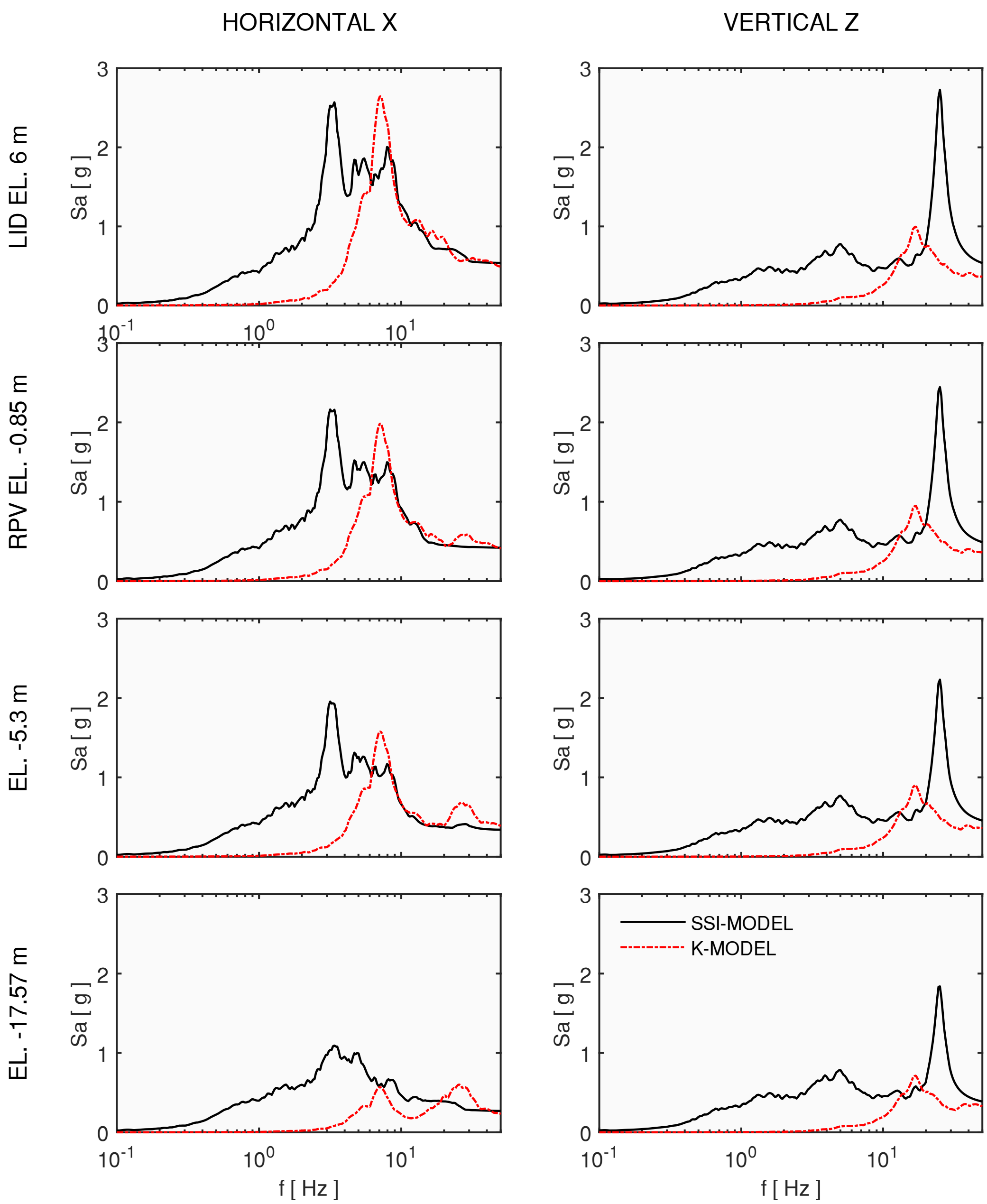


Figure 5. In-Structure Response Spectra

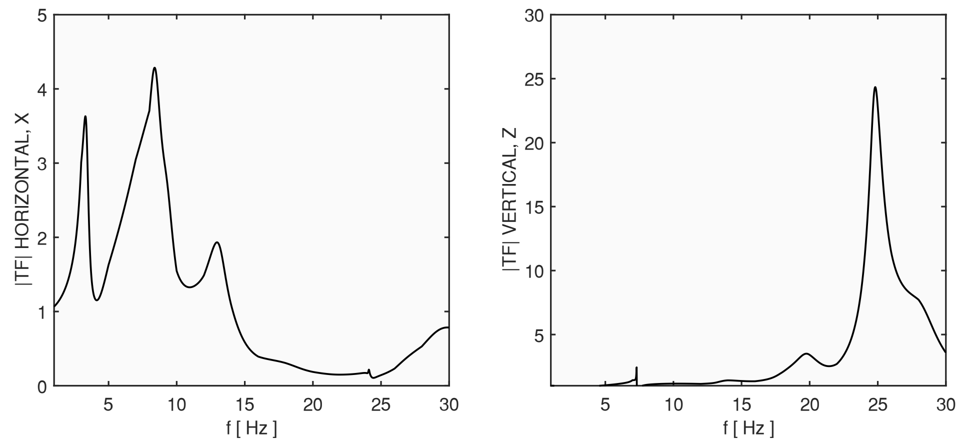


Figure 6. Transfer function at El. -0.85 (RPV Support)

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