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SSI-Analysis of Nuclear Structures in the Time-Domain using Real-ESSI

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ABSTRACT

The operators of the Swiss nuclear power plants (NPPs) are legally obliged to update their seismic safety assessments for the recently updated seismic hazard. The new seismic demand is a significant increase compared to the original design basis of all four sites. One important aspect of the seismic safety update is the adequate consideration of Soil-Structure-Interaction (SSI). In the present study, analyses are carried out for a reference NPP at a representative central-European site with relatively stiff soil. The Real-ESSI software package is used, which can account for the full nonlinear response of the entire SSI system, i.e. soil, structure and their interface, directly in the time-domain based on the Domain Reduction Method (DRM). The study encompasses the assessment of SSI using a comprehensive gradual approach with stepwise increasing complexity, i.e. basic linear wave propagation, impedance functions of ideal surface foundations as well as determining In-Structure Response Spectra (ISRS) for key locations in a simplified model of the reference reactor building structure. Additionally, the effect of nonlinearity at the soil-structure-interface, i.e. slippage and foundation uplift, is investigated. Obtained results are compared with analytical solutions as well as with results from established engineering software in order to verify the applicability of Real-ESSI in the regulator's review practice of complex linear and nonlinear seismic analysis.

INTRODUCTION

With the official acceptance of the "ENSI-2015" seismic hazard study (Proseis AG, 2015) by the Swiss Federal Nuclear Safety Inspectorate (ENSI) the seismic demand at all four Swiss NPP sites increased significantly compared to the original design basis. Accordingly, the operators are legally obliged to update their seismic safety assessments and to verify that all safety requirements are met.

An important aspect of the seismic safety verifications is the re-calculation of the ISRS, which in turn will be used for the safety assessment of structures, systems and components. A central and probably the most demanding step in the ISRS calculation is the SSI analysis. The current state-of-the-practice SSI analysis approach is based on the sub-structuring method in the frequency domain, employing equivalent-linear methods to consider the material nonlinearity of the soil. Recently, however, there has been a strong shift towards the direct method in the time domain accounting for the full nonlinear response of the entire SSI system, i.e. soil, structure and their interface.

The ENSI considers it essential for ongoing and future regulatory activities to have a verified and reliable software tool available to deal with complex linear and nonlinear SSI problems. In the present study, time-domain analyses are carried out for a reference NPP at a representative central-European site with relatively stiff soil, using Real-ESSI. The software, which implements the Domain Reduction Method, has been developed by the research team of Professor Boris Jeremić at UC Davis (Jeremić et al., 2020) in collaboration and with support from, among others, the US Department of Energy (DoE), the US Nuclear Regulatory Commission (NRC) and the Canadian Nuclear Safety Commission (CNSC).

The present study encompasses the assessment of SSI using a comprehensive gradual approach with stepwise increasing complexity. As a first step, the results for basic wave propagation are compared with existing analytical solutions as well as with results from the established frequency-domain analysis software SHAKE2000 (Ordonez, 2012), assuming linear soil properties. Additionally, impedance functions of ideal surface foundations are determined and compared against well-known theoretical solutions (Sieffert and Cevaer, 1992). Furthermore, the ISRS for key locations in a simplified multi-degree-of-freedom model of the reference reactor building structure are calculated assuming linear material properties and compared with ISRS obtained based on a frequency-domain approach with SASSI2010 (Ostadan and Deng, 2012). Further studies are carried out in order to investigate the effect of nonlinearity at the soil-structure-interface, which is expected to cause slippage and/or uplift of the foundation. Finally, another important aspect to be examined in the near future is the influence of soil material nonlinearity in the foundation near-field on the SSI response, especially in the case of design extension events.

LINEAR WAVE PROPAGATION

The foundation soil conditions have been selected with a view to representing a realistic central-European NPP site. The soil profile (7 layers on bedrock) for low shear strains is shown in Figure 1. Alongside this profile, two simplified soil models are also used, comprising:

- a homogenous half-space with the average soil characteristics of the first 30 m ($v_{s,30} \approx 500$ m/s),
- a single homogenous soil layer with the same characteristics resting on rock at depth of -42 m.

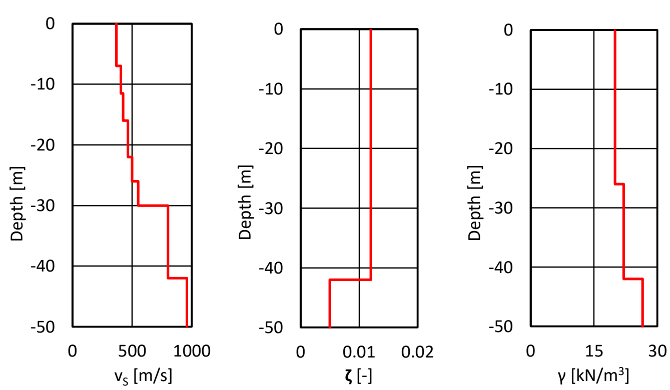

Figure 1. Soil properties (shear wave velocity, damping and specific weight) at modelled site.

One of the main advantages of the Domain Reduction Method (DRM) implemented in Real-ESSI is that only a small part of the soil in the foundation near-field needs to be modeled to obtain an adequate approximation of the expected wave propagation response. To achieve this, displacement wave-field demands and corresponding effective seismic forces acting on the near-field DRM boundary (single layer of solid elements) are computed based on the free-field motion and soil properties. These forces are then applied at the boundary to derive results within the modeled near-field soil region. Outgoing waves radiated from a vibrating structure in the SSI model are absorbed by damping-layers outside the DRM boundary consisting of solid elements with relatively high viscous damping.

In order to study the influence of model size, two near-field soil bodies (also called "soil box") are modeled (see Figure 2) having dimensions of either 84×84×50 m or 126×126×50 m. These dimensions were chosen in correspondence with the size of the structure considered later. The mesh size in the case of the multi-layer model is approx. 2×2×2 m at the top, with gradually increasing layer thickness towards the bottom (Figure 2), i.e. following the shear wave velocity increase with depth. In the case of the half-space and single-layer model, the element size is kept constant at around 2.5×2.5×2.5 m. This leads to a cut-off frequency of roughly 15-22 Hz, assuming eight elements per wavelength to capture a wave of interest. Two damping layers are defined in all models at the bottom and sides of the soil box with a Rayleigh target damping of 20% at 0.5 Hz and 5 Hz. No damping is assigned to the rest of the modelled soil

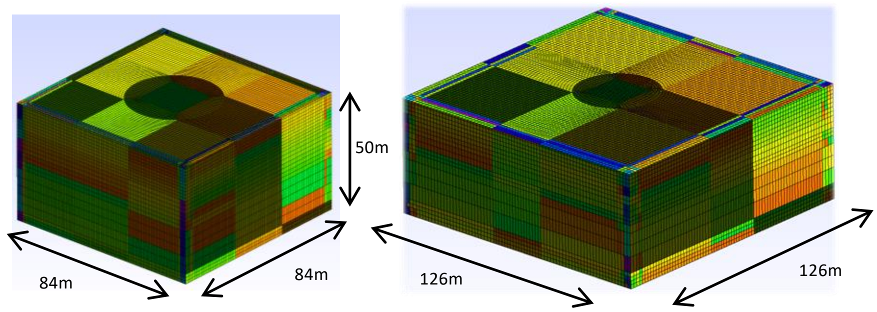

Figure 2. Soil box models in Real-ESSI (colors irrelevant).

The ground motion is defined at the free-field surface as a 1D time-history in the horizontal direction (Figure 3, left). This artificial accelerogram represents an "ENSI-2015" mean uniform hazard spectrum for annual frequency of exceedance of 10^{-4}/a. The time-history has a maximum acceleration of 0.33g, velocity of 0.233 m/s and displacement of 4.46 cm. The significant duration (5%-75% of Arias intensity) is 2.37 sec (red area in Figure 3, left) and the standardized CAV is 0.51 g×sec; according to EPRI (2005) a standardized free-field CAV value of 0.16 g×sec is a conservative threshold of damaging earthquakes for well-engineered structures. A time-step of 0.005 s is used, leading to a Nyquist frequency of 100 Hz. The corresponding ground response spectrum for 5% damping can be seen in Figure 3, right.

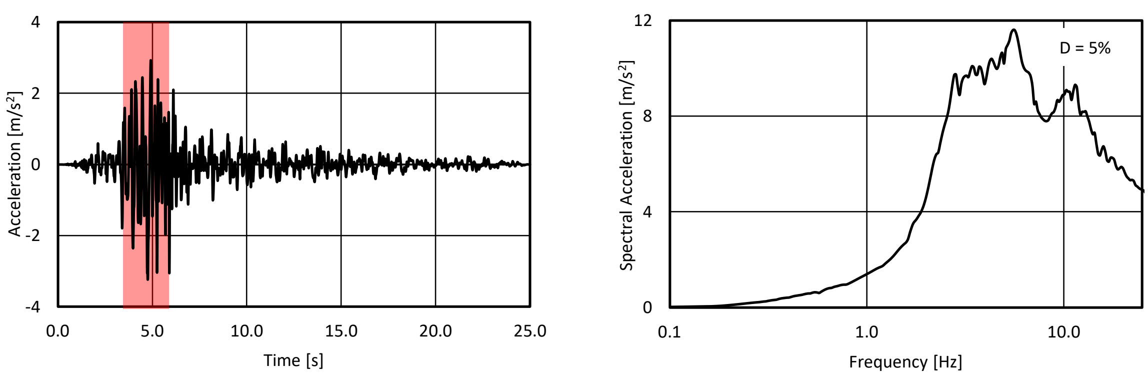

Figure 3. Input motion time-history (left) and spectral acceleration for 5% of critical damping (right).

Initially, the simple case of linear 1-D SV-wave propagation (i.e. without building) is analyzed in order to verify the Real-ESSI against SHAKE results. The results from successive deconvolution and convolution analysis are examined, comparing the acceleration spectra of input and output motions at rock (-50 m) and at the surface (±0 m), see Figure 4. The calculated spectra at rock from deconvolution are found to be identical. The agreement is similar between input and output motions at the surface, having only minor deviations. This result confirms that convolution is also carried out correctly in the case of 7 layers on bedrock. The same results were obtained in the case of the homogenous half-space and the single layer on bedrock, but are not shown here for the sake of brevity.

The influence of model size is found to be minor for the case of 1-D wave propagation, practically obtaining the same output for all model cases, both at the surface and at rock, as would be expected for a wave propagation analysis. The adequacy of the DRM and absorbing boundaries is additionally verified through comparison of the output motions generated with Real-ESSI at spatially varying positions at the soil box surface (Figure 5). As expected for 1D- wave propagation, the output is practically identical at every position.

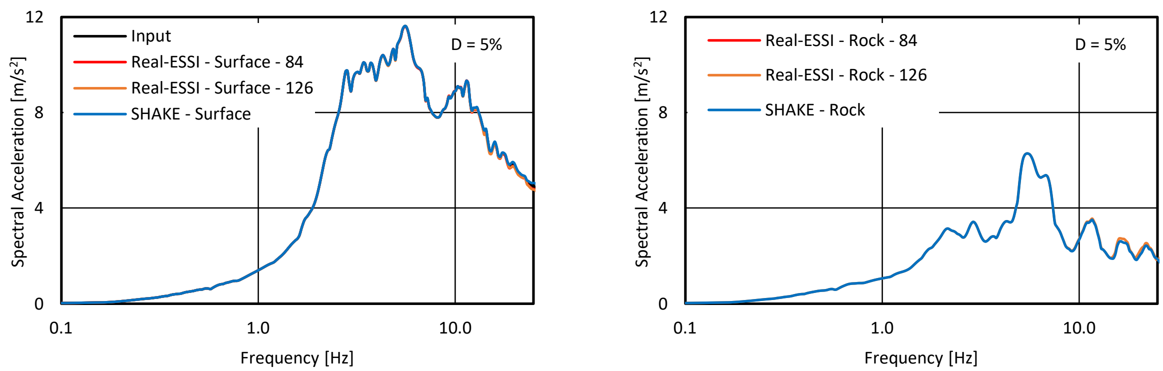

Figure 4. Spectral acceleration against frequency for 5% of critical damping: Comparison of input with output motions at the soil surface (left) and at rock (within) (right) for the case of 7 layers on bedrock based on linear analyses with SHAKE and Real-ESSI.

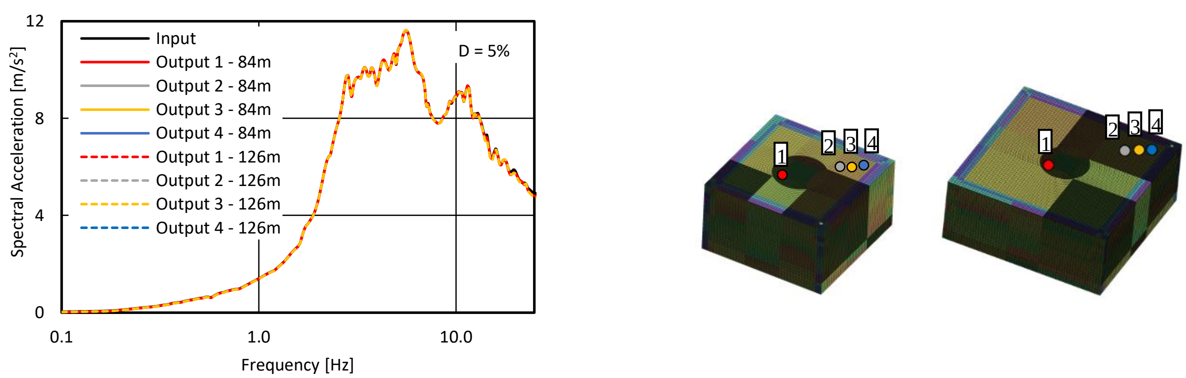

Figure 5. Spectral acceleration against frequency for 5% of critical damping for the small and big models of 7 layers on bedrock: Comparison of input with output motions at various points at the soil surface, based on linear analyses with Real-ESSI.

IMPEDANCE FUNCTIONS

Impedance functions have been traditionally used in linear and equivalent linear SSI analyses with the sub-structuring approach in the frequency domain to account for SSI in terms of frequency-dependent effective stiffness and damping at the base of the structure. Analyzing a soil-structure system in the time domain naturally makes the use of impedance functions obsolete. However, for verification purposes impedance functions for circular surface foundations are derived in Real-ESSI, with a focus on model size, radiation damping and boundary effects. The calculated impedances are compared with tabulated values commonly used in practice (Sieffert and Cevaer, 1992; Gazetas, 1983) and results from CLASSI (Wong and Luco, 1980).

Two basic cases are investigated: a half-space and a single soil layer atop a fixed rock base, see Figure 6 . The vertical direction is investigated for both cases, while the horizontal is looked at only in the case of the single soil layer on fixed rock base. The foundation basemat is modeled as a 2.4 m thick, rigid and massless shell. The excitation is represented by a harmonic area load acting on the basemat with different frequencies and amplitude of ±450 MN. Zero-padding of about 0.25 s is built into the time-history and a free oscillation stage of about 3 s after the excitation is allowed.

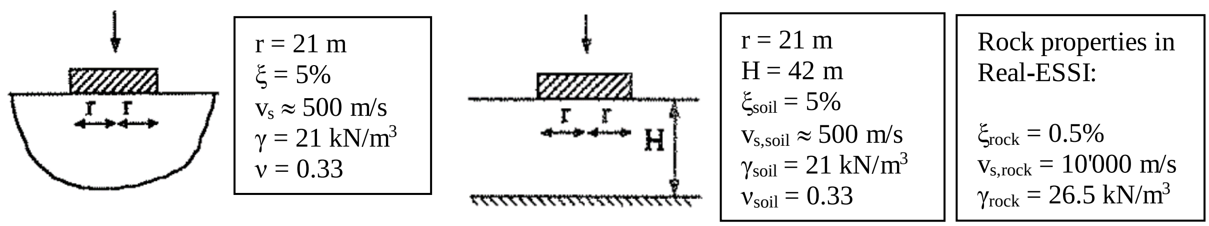

Figure 6. Investigated cases of soil box models.

The mesh size of the soil box in the case of the single-layer-on-bedrock model is approximately 2.5×2.5×2.5 m, except for the rock layer, where shear wave velocity increases and the element size is correspondingly increased to 4×4×4 m (Figure 2). In the case of half-space, element size is kept constant at around 2.5×2.5×2.5 m throughout the whole model. This leads to a cut-off frequency of roughly 25 Hz, assuming 8 elements along the wave length to reliably transmit the wave. The modeled soil box with dimensions of 126×126×50 m and 126×126×200 m for the single-layer-on-bedrock and the half-space model, respectively. Modelling the half-space using shallower models results in a similar response to a corresponding single-layer-on-bedrock model with the layer depth equal to the height of the model rather than an actual half-space, as the bottom model boundary is pinned and behaves effectively as rigid rock. The same models are also constructed with a 252 m width, in order to study the influence of the model size.

The connection between soil (solid elements) and foundation basemat (shell elements) is achieved through a kinematic constraint, whereby the displacement at each point on the soil surface below the shell is constrained either in vertical or horizontal direction by the shell above; i.e. soil displacement is exactly equal to the corresponding displacement of the basemat above.

Soil and rock damping (Figure 6) is modeled through Rayleigh damping, i.e. damping ratio is not constant across the entire frequency range, thus influencing the results differently at each excitation frequency. The desired damping ratio is defined at the natural frequencies of the soil model. In all models, the two absorbing (damping) layers defined at the bottom and sides of the modelled soil box are assigned a Rayleigh damping ratio of 50% at the same frequencies as the soil material damping. The results are herein presented in terms of:

- vertical displacement and phase difference,
- impedance factors *K* and *C*, and
- total system damping ratio derived from the response (based on logarithmic decrement at the free oscillation stage of the response) and radiation damping ratio, which is derived by subtracting the material damping corresponding to the natural frequency of the system from the total damping.

The results for the vertical direction of the single-layer-on-bedrock model can be seen in Figure 7 up to 8 Hz. The vertical displacement predicted by Real-ESSI agrees well with the theoretical curve. Two deviations can be observed: The natural frequency of the modelled soil box (5.8 Hz) is slightly higher than the theoretical one (5.4 Hz) and the deformation peak at the natural frequency is higher. The predicted natural frequency still lies in the purple area defined by the expected natural frequency based on Lysmer's analogy (4.97 Hz) and 6.10 Hz estimated by the simple formula v_P / 4×H. This minor shift of the natural vibration frequency could be explained by the fact that the side and bottom boundaries of the model might stiffen it up to a certain extent. The 40% higher displacement amplitude (16.5 mm) at the natural frequency instead of 12 mm predicted by the theory, can be explained by the model size and damping. When the Rayleigh material damping is set at 5% at this frequency, the amplitude is reduced by about 2 mm (blue point in Figure 5). Furthermore, a model with a width of 252 m, i.e. about 6 times the diameter of the foundation, yields a 4 mm lower amplitude (green point in Figure 5). Consequently, the combination of these two effects reduces the amplitude roughly to the theoretical value. Hence, damping ratio and model width are shown to play an important role in the obtained response.

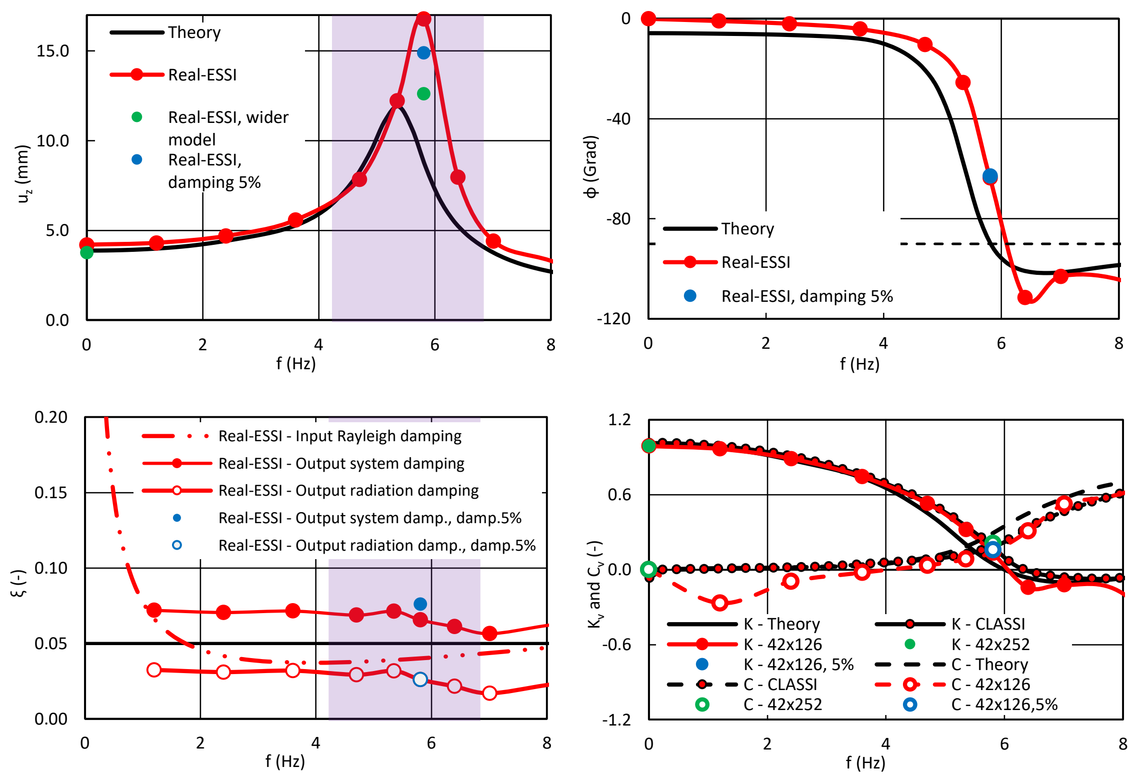

Figure 7. Results in the vertical direction as a function of frequency f for the single-layer-on-bedrock model, in terms of vertical displacement u_z (upper left), phase difference φ of the response (upper right), obtained total and radiation damping ξ (lower left) and impedance factors K_v and C_v (lower right).

The theoretically and numerically obtained impedance factors, K_v and C_v, can be seen in Figure 7 (bottom right) up to 8 Hz. Generally, the damping factor (C_v) seems to be in very good agreement, beside the first couple of unrealistically predicted negative values, which should asymptotically decrease to zero at $f = 0$ Hz. The stiffness factor (K_v), on the other hand, is very well predicted. CLASSI (Wong and Luco, 1980) seems to agree very well with the theoretical C_v and K_v factors. Generally, the predicted impedance factors are in line with the theoretical values.

The obtained system damping ratio is shown in Figure 7 (bottom left). The radiation damping is derived from it by subtracting the damping ratio at the fundamental vibration frequency of the system. System and radiation damping seem to be relatively constant throughout the frequency range, at about 7% and 3%, respectively. Setting the material damping ratio at the natural frequency of the soil to 5% (blue points in Figure 7, bottom left), results in correspondingly higher system damping ratio, while, as expected, the radiation damping does not change.

Similar results are achieved for the other two investigated cases (single-layer-on-bedrock model in horizontal and half-space model in vertical direction), which are not presented here for the sake of brevity.

SOIL-STRUCTURE INTERACTION

Similar near-field soil box models as described above are also used for the SSI analyses. The soil box of the half-space model has a depth of 200 m in order to obtain accurate results, since model depth was shown to play a crucial role in simulating a half-space-like behavior. The length and width of the box are again switched between 84×84 m and 126×126 m for every model, in order to study the influence of the model size. The diameter of the reactor building foundation is 42 m, i.e. a soil model width of twice and three times the foundation diameter is investigated.

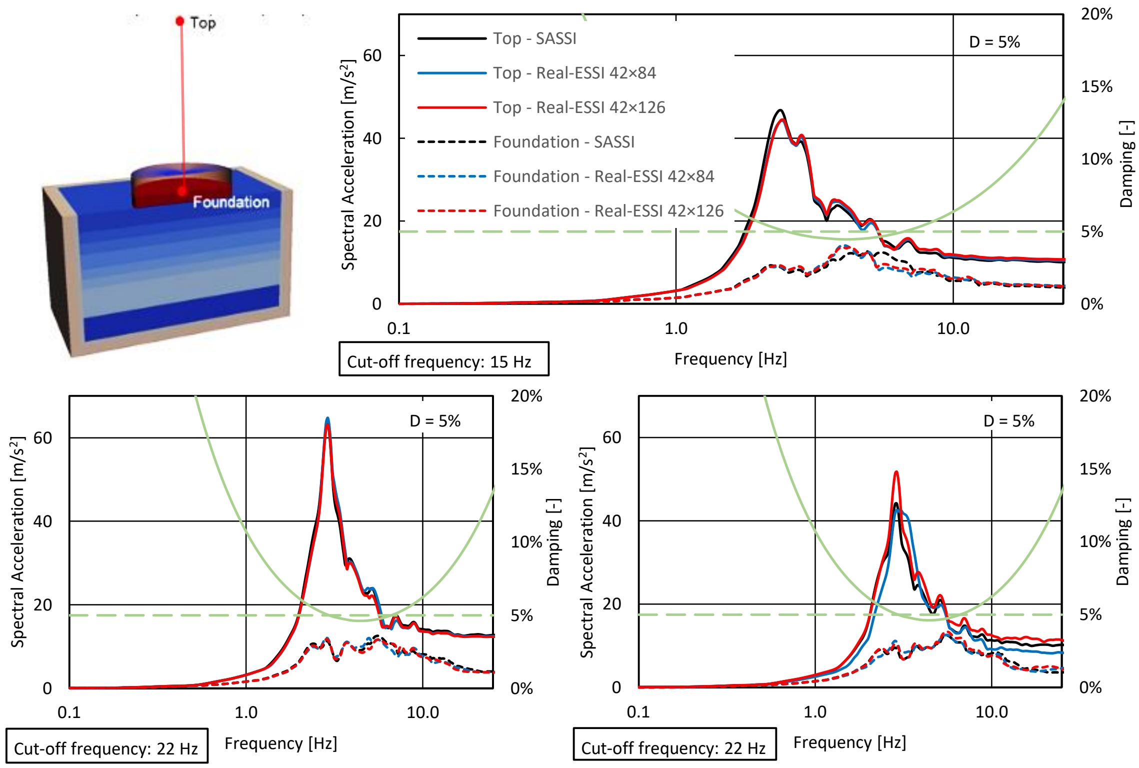

Figure 8. Spectral acceleration against frequency for 5% of critical damping: Comparison of output motions at top of concrete containment and foundation basemat for soil models: 7-layers-on-bedrock (top), single-layer-on-bedrock (bottom left) and half-space (bottom right), based on linear analyses of a small (84×84 m) and a big (126×126 m) model with SASSI and Real-ESSI. Frequency-dependent damping ratio is plotted with green for Real-ESSI (solid line) and SASSI (dashed line) on the right vertical axis.

The mesh size of the half-space and the single-layer-on-bedrock models is kept constant at approximately 3×3×3 m, while the multi-layered model mesh size is around 2×2×2 m at the top with gradually increasing layer thickness towards the bottom in accordance with the increasing shear wave velocity with depth. This leads to cut-off frequencies of roughly 15-22 Hz, assuming eight elements per wavelength to reliably capture a wave of interest.

In all models, two absorbing layers are defined at the bottom and sides of the model with a Rayleigh target damping of 20% at around 2.5-3 Hz and 6.5 Hz, while the rest of the modelled soil is assigned a Rayleigh damping of 5% at the same target-frequencies. The structure stick-model consists of beam elements, representing the external concrete containment of a reactor building, connected through rigid elements to the basement walls modelled with shell elements, which are in turn connected to a 4.5 m thick basemat modeled with volume elements. A linear elastic reinforced concrete material is used for the structure with an elastic modulus of 35 GPa, a Poisson's ratio of 0.17, a specific weight of 25 kN/m^3 and 7% damping.

Comparisons between ISRS of output motions at the top of the concrete containment and the foundation basemat generated with Real-ESSI and SASSI are shown in Figure 8. For the single-layer-on-bedrock and seven-layers-on-bedrock models, Real-ESSI is found to agree very well with the response predicted by SASSI, having only minor discrepancies at the top and some deviation at the foundation basemat level. In the case of half-space, few discrepancies can be seen at the top of the foundation slab, while higher discrepancies are observed (locally up to ca. 30%) at the top of the concrete containment, however, still achieving a similar result on average with higher variance than in the other model cases. In terms of model width, the differences are minor in the cases of the multi-layered models, practically obtaining the same output in both cases at both building locations. In the case of the half-space model, the discrepancies are higher, but no more than 30%.

The results of the verification analysis confirm that Real-ESSI can be reliably used to perform linear SSI-analyses in the time-domain. Radiation damping is modelled adequately with the adopted DRM approach. Soil model widths reduced to twice the foundation diameter (i.e. half a diameter on each side of the building) produce accurate results without boundary effects.

SOIL-BASEMAT INTERFACE NONLINEARITIES

Interface nonlinearities are investigated using the previously described SSI multi-layer model and adding nonlinear zero-length interface elements at the contact area of foundation basemat and soil surface. These interface elements can model slippage in the horizontal directions, using a nonlinear hardening shear model and uplift, using a penalty function for compression and zero stiffness for tension in the vertical direction. Two alternative models are analyzed, one with soft and one with stiff interface elements. The initial stiffness of the stiff interface is six times higher, while its friction coefficient is $\mu = 0.80$ as opposed to $\mu = 0.35$ for the soft interface.

Equivalent-linear soil properties for the previously described level of excitation (Figure 3) are determined using SHAKE2000 (Ordonez, 2012). The internal structures of the reactor building are also modelled using equivalent beams (stick-model) in order to capture the entire mass, realistic center of gravity and stiffness of the reactor building. Most of the internal structures are made of the same concrete as previously described, while the steel containment is modeled with an elastic modulus of 210 GPa, a Poisson's ratio of 0.30, a specific weight of 80 kN/m^3 and 4% damping.

The ISRS obtained with Real-ESSI (Figure 9) show that the resulting spectral accelerations are significantly reduced by taking into account the interface nonlinearities. The average reduction for the stiff-interface model is about 25%, while a reduction of about 60% in the range of relevant vibration frequencies is observed in the case of soft-interface model. Only slippage of the reactor building is observed in the case of soft interface, while the stiffer interface leads to a reduction in slippage and causes foundation uplift. Figure 10 shows that the relative horizontal displacements reach about 22 mm in the case of the soft-interface model with a permanent displacement of about 10 mm. On the other hand, the relative horizontal displacements of the stiff-interface model do not exceed 6.5 mm and uplift occurs at 5.4 s with a slight time lag to the displacement peak of the applied input motion (5.2 s), as expected.

The impact of simultaneous horizontal and vertical excitation was examined for both the soft- and stiff-interface model. For these cases, the vertical component was found to have a minor influence on the response.

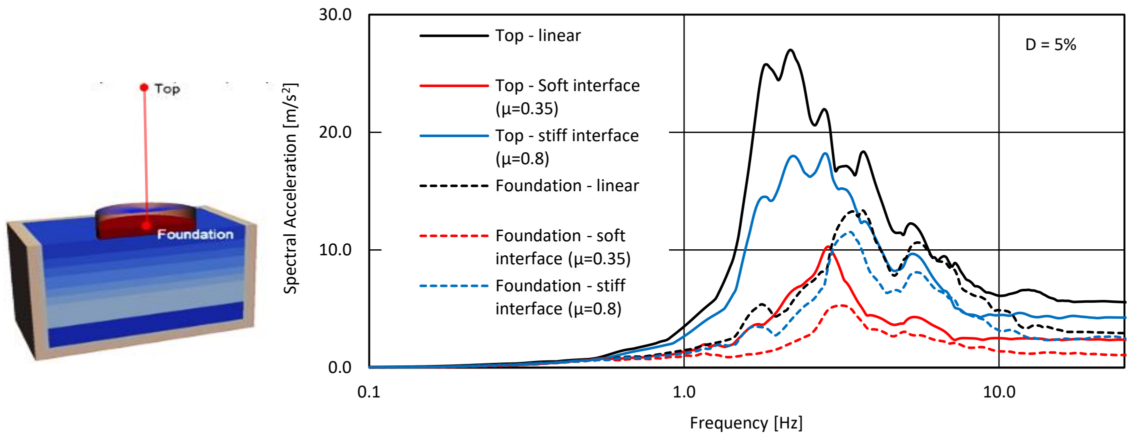

Figure 9. Spectral acceleration for 5% of critical damping at top nodes of concrete containment and foundation basemat.

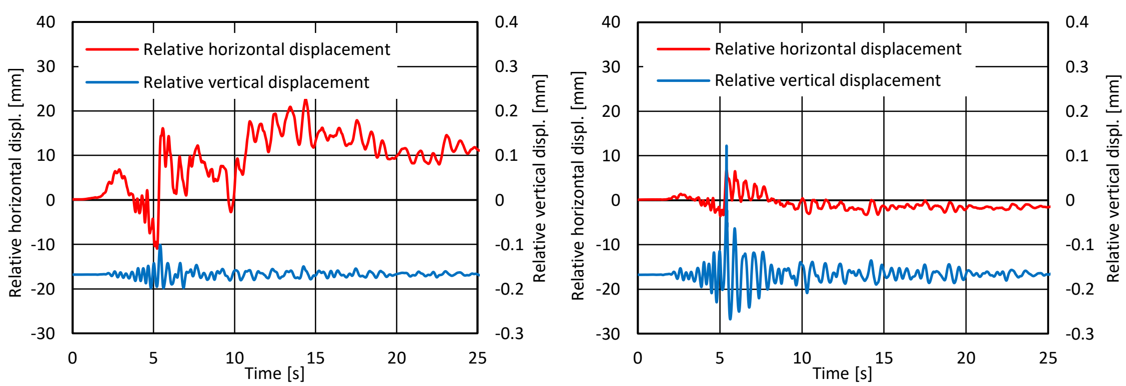

Figure 10. Relative horizontal and vertical displacements between foundation basemat and foundation soil for the soft-interface (left) and stiff-interface (right) models.

SUMMARY & CONCLUSIONS

A study of the features and performance of the software package Real-ESSI (Jeremić et al., 2020), based on the Domain Reduction Method, is conducted with the prospect of deploying it to the regulatory review practice of complex linear and nonlinear SSI problems. The results of the performed verification calculations of linear wave propagation, impedance functions, linear and nonlinear SSI analyses (considering interface nonlinearity) demonstrate a satisfactory degree of accuracy.

The present study shows that a near-field soil box model with lateral size twice the diameter of the reactor building and depth of about a diameter seems to be adequate to produce accurate results. This relatively small soil model with the defined absorbing (damping) layers is apparently unaffected by boundary effects.

Furthermore, nonlinearities in the foundation-soil-interface (horizontal slippage in both directions and foundation uplift) are investigated. The verification calculations demonstrate a significant reduction of the resulting ISRS with a simultaneous increase in relative displacements of the structure to the foundation soil, as compared to the assumed welded connection between building and foundation soil in a typical linear SSI analysis. Thus, interface nonlinearities play a crucial role in realistic SSI analysis of nuclear structures and determining the seismic demand on equipment. The selection of key modelling parameters of the interface is found to affect the SSI response to a high degree. Therefore, further studies on interface and material nonlinearity in the foundation near-field are underway and results will be presented in the near future. As a first step, the validity of the criterion for elastic design (i.e. design of basemat, ISRS, rel. displacements) in relation to foundation uplift, both in the case of design-basis and design extension events, will be the focus of investigation.

It should be noted that while the software package Real-ESSI allows for modelling and analysis of complex nonlinear SSI systems, the application of the program requires high expertise from the user.

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