Effects of Nonlinearities on Seismic Soil-Structure-Interaction Behavior of a Nuclear Plant Reactor Building: A Case Study

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A comparative seismic soil-structure-interaction (SSI) study was performed for the reactor building of a nuclear power plant in Switzerland in order to gain insights into the relative significance of nonlinear response effects which may be triggered during beyond-design-basis seismic events. The case study reactor building is founded on 20m of gravel underlain by bedrock and with an embedment depth of 9m.The analysis program was designed as a sequential study to investigate both the independent and combined effects of nonlinear response of soil, soil-structure interface, and structure on the characteristics of in-structure response spectra (ISRS) throughout the reactor building at a hazard level greater than the design basis earthquake.

An integrated finite element (FE) model of the soil-structure system, including soil continuum and detailed structure, was built to perform nonlinear time domain analysis (NLTD). For comparison to the commonly employed equivalent linear approach in frequency domain (ELFD), the modeling assumptions in time domain were made consistent with the ELFD approach in an equivalent linear time domain analysis (ELTD). Subsequently, the nonlinear effects were added to the ELTD model, one at a time, to create various NLTD models. Finally, different combinations of nonlinear effects were considered. The interface nonlinearity was introduced through contact surfaces. Soil nonlinearity was incorporated through a hysteretic plasticity model whose shear response is dependent on soil effective pressure. To calibrate the plasticity model, gravel's shear stiffness degradation curve was modified to produce shear strength values consistent with the laboratory-measured friction angle. Composite layered shell finite elements with nonlinear material properties were used to model key structural shear walls.

The reasonable match between ELFD and ELTD results confirmed the general viability of time domain approaches for seismic SSI analysis in nuclear industry. The comparison of ISRS obtained from NLTD models (with single and combined nonlinearity) with those obtained from ELTD indicated a significant effect on response due to energy dissipation through interface sliding and soil nonlinearity, neither of which are captured in typical practice using ELFD approaches. In general, the relative importance of site and interface nonlinearities is a function of contact friction coefficient, soil stiffness, and excitation intensity. Details of this case study further demonstrate that the relative importance of nonlinear effects is site- and case-specific.

KEYWORDS: Seismic, Soil-Structure Interaction, Nonlinear, Linear, Nuclear

Introduction

Soil-structure-interaction (SSI) analysis has been an important component of the seismic safety assessment of nuclear facilities. Equivalent linear approach in frequency domain (ELFD) has been the state of practice for performing such SSI analyses in the nuclear industry. Even though ELFD approach can produce reliable response predictions at low to moderate seismic intensity, its application at large return periods has been shown to be problematic ([10] and [21]) mainly because the linear assumptions for the response of SSI system components, i.e. soil, structure, and soil-structure interface, would break down under large-intensity ground motions. However, reliable evaluation of seismic response under rare events with extremely low probability of exceedance is necessary for the seismic risk assessment of nuclear power plants. Nonlinear SSI analysis in time domain (NLTD) would allow the application of a single simulation model to all hazard levels.

The explicit modeling of nonlinear effects and integrating them into a single simulation is gaining momentum within the nuclear civil engineering research community (see [4], [7], and [10]), and is starting to be recognized by nuclear industry practice such as by the recent addition of a related non-mandatory appendix to ASCE 4-16 [1]. Through a novel treatment of damping in time domain, the authors in [10] were able to demonstrate a good match between the results of the SSI analyses performed in time domain and frequency domain when their modeling assumptions were made equivalent. They then incorporated nonlinear effects into the analysis and showed that in-structure response spectra (ISRS) can be significantly affected without studying the relative significance of nonlinear effects. Researchers in [5] and [8] have been working on the development of tools for performing nonlinear SSI analyses of nuclear facilities. A recent study focused on the effects of soil, structure, and interface nonlinearities on the structural response and concluded that they can significantly affect the response especially for structures with shallow foundations [2]. In addition to soil, structure, and interface nonlinearities, the NLTD approach would also allow the explicit modeling of surface topography and slope stability [3], non-horizontal site stratigraphy ([3] and [12]), soil pore pressure [21], seismic base isolation ([9], [13], and [22]), and fluid-structure interaction ([11],[14], and [23]) which are commonly present at nuclear plants and other facilities.

This paper presents the first comprehensive application of the NLTD approach to the seismic SSI response analysis of a commercial nuclear reactor building to date outside of a research environment. First, the reactor building, site, and ground motions are briefly introduced. The equivalent linear SSI analyses are then used to demonstrate the viability of the time domain approach (ELTD) for performing SSI analyses of the reactor building via comparison to ELFD. The modeling approach for the incorporation of nonlinear effects, i.e. soil, structure, and soil-structure interface nonlinearities, into the developed ELTD model to create NLTD models is subsequently presented. Finally, the effect of each nonlinearity on ISRS as well as their various combinations is presented and conclusions are made on the relative importance of nonlinear effects as it relates to their influence on the response within the reactor building under study.

Gösgen Nuclear Power Plant

The Gösgen Nuclear Power Plant, commissioned in November 1979 is located in the Däniken municipality, Switzerland. As shown in Figure 1, the plant has several buildings including the reactor building (ZA00/ZB00) which is surrounded by the reactor auxiliary building (ZC00) on the west side and the emergency feed building (ZV00) and switchgear building (ZE00) on the south side. This study focuses on the seismic behavior of the reactor building. The building is about 60m tall and is founded on a 62m diameter mat foundation which is 2.7m thick. The bottom 9m of the reactor building is embedded, though embedment is effective only along approximately half of the building perimeter since there is no effective embedment along the boundary with the neighbor buildings.

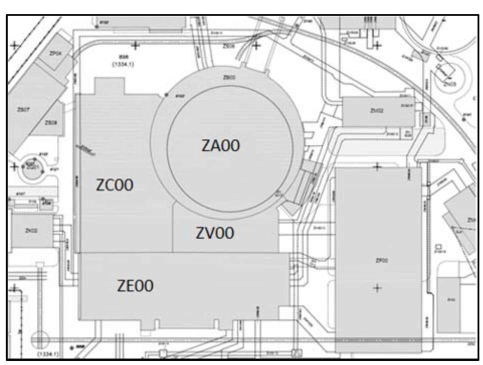

Figure 1: Gösgen Reactor Building and Surrounding Structures - Plan View

Site Soil Profile

The site at the plant consists of about 27.5m of gravel laid on a solid limestone formation, which provides a stable base for the plant. The shear wave (V_s) and compression wave (V_p) velocities versus depth are shown in Figure 2. The ground water table is at a depth of about 6.0m below surface.

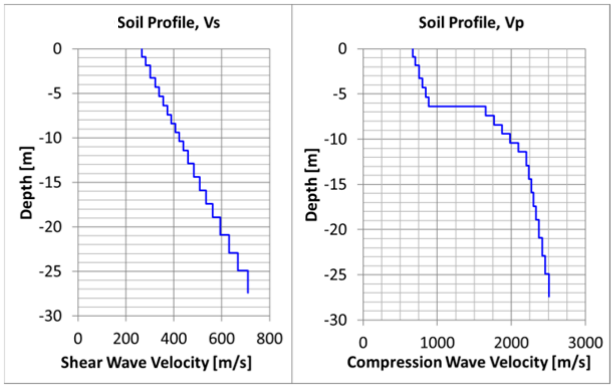

Figure 2: Soil Low-Strain Shear Wave Velocity (Left) and Compression Wave Velocity (Right) Profiles

Input Ground Motion

Total of six sets of input ground motions developed as spectrally matched to 1E-4 UHS (three sets) and 1E-5 UHS (three sets) - were used in this study. They were applied at the base of the soil domain (top of the bedrock) as outcrop motion. The rock outcrop spectra at 1E-4 UHS is shown in Figure 5.

Equivalent Linear SSI Analysis

Before studying the nonlinear effects, the equivalent linear SSI model of the reactor building and the site was developed and analyzed in both time domain (ELTD) and frequency domain (ELFD) at 1E-4 UHS hazard level. The ELTD results were compared to those of the commonly employed ELFD analyses to establish a base alignment between the two approaches. The verified ELTD "base" model was then modified to study the nonlinear effects.

Equivalent Linear Structure for ELTD Analysis

The finite element model of the reactor building structure is shown in Figure 3. The mat foundation, exterior concrete dome, and interior steel sphere are represented with shell elements. The floor beams and columns are modeled with beam elements. A viscoelastic constitutive model is used for all beam and shell elements. Damping ratios of 4% and 2% are assumed for the reinforced concrete and steel respectively.

Equivalent Linear Site for ELTD Analysis

The underlying soil medium shown in Figure 3 was modeled using solid finite elements. The model bottom boundary is -27.55m below the ground surface. The soil domain's side boundaries are 470m from the center of the structure in each direction. There are 20 soil layers in the FE model with passing frequency in excess of 40Hz at 1E-4 UHS hazard level.

As opposed to the common practice of employing simplified and frequency-dependent damping formulations, e.g. Rayleigh, in time domain, a viscoelastic hysteretic material model was used to simulate the soil response to seismic excitations [10]. This material model is capable of modeling the nearly-frequency-independent viscoelastic behavior of soil subjected to cyclic loading.

The in-situ total soil stresses were initialized in the beginning of the analysis to properly simulate the soil equilibrium under the gravity load. The material properties for the underlying elastic half-space modeled as a nonreflecting boundary via Lysmer's approach [16] were derived based on the V_s (2.500 m/s) and V_p (4,330 m/s) at a depth of 27.55m below the surface. The side boundaries are modeled far enough from the structure to prevent any boundary wave reflection by utilizing soil domain's radiation damping. The verification of free field response close to the side boundaries will be discussed later (see Figure 11).

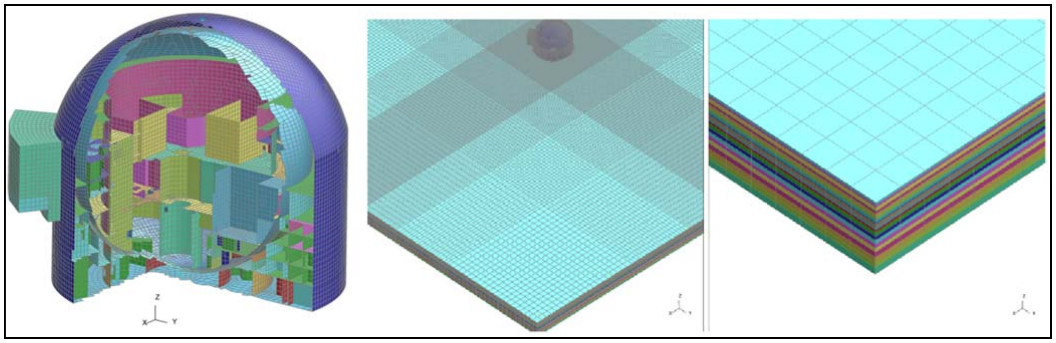

Figure 3: Isometric View of the Reactor Building FE Model (Left) and Soil FE Model (Middle and Right)

Soil-Structure Interface for ELTD Analysis

Consistent with structural drawings and to account for the expansion joints between reactor building and neighbor buildings, structural nodes are detached from the soil nodes at the interface with the neighbor buildings. This configuration is referred to as partial embedment. Another embedment configuration, referred to as full embedment, was also considered in which all structural nodes on the perimeter of the structure are fully connected to the soil nodes. For both configurations, the bottom of the mat foundation is fully connected to the underlying soil layer.

ELTD and ELFD SSI Results Comparison

SSI results in the form of In-Structure-Response-Spectra (ISRS) obtained via ELTD and ELFD approaches are compared to verify the general alignment between the two approaches. ELFD analyses, which represent the state of practice within the nuclear industry, were performed in SC-SASSI [19]. The ELTD analyses were performed by simultaneously applying the three components of ground motions (1E-4 UHS) at the base of the soil domain as rock outcrop.

Comparison of ISRS extracted at multiple component locations within the reactor building shows a good agreement in the resonance frequency predictions as well as some response amplitude differences between the ELTD and ELFD results. The ISRS comparisons for two example locations, one at low elevation and close to the center of the structure (designated with FE node 30681) and one at higher elevation and close to the perimeter of the structure (designated with FE node 52596) are shown in Figure 4. The observed amplitude differences are small in comparison to the structural response variability observed due to ground motion variation as shown in Figure 5. Also included in Figure 5 are the input motions spectra showing significantly less variation compared to the ISRS results for different input motions. This comparison establishes a reasonable alignment between the equivalent approaches in time domain and frequency domain.

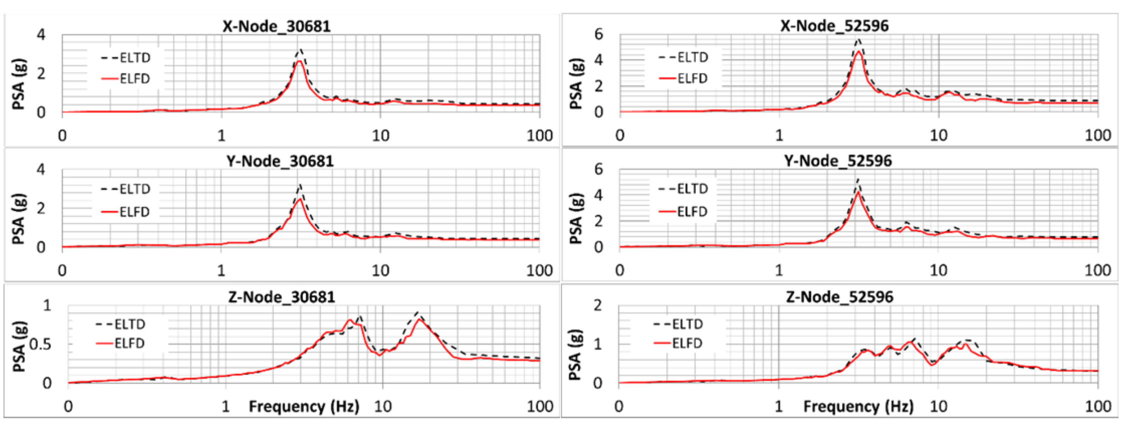

Figure 4: ELFD and ELTD ISRS Comparison for Motion-02 (1E-4UHS)

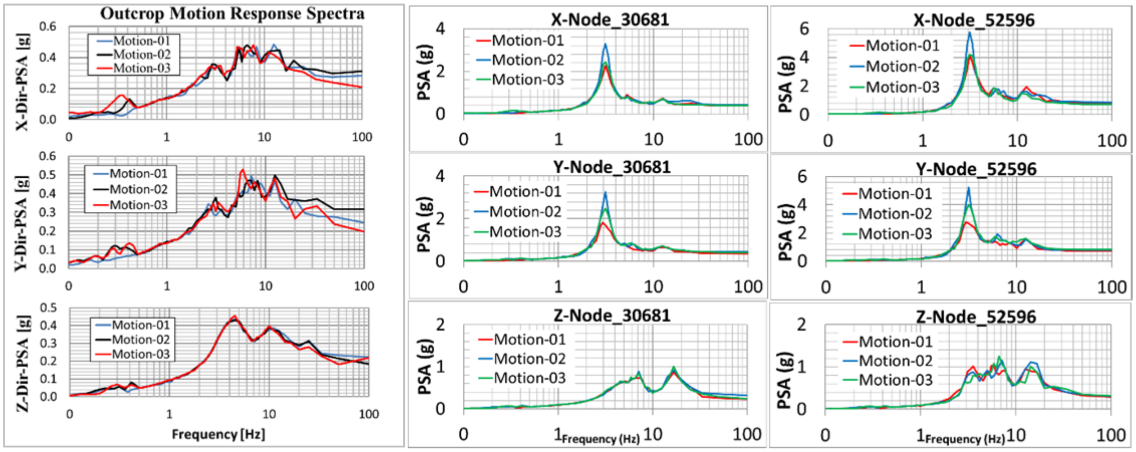

Figure 5: Rock Outcrop Motion Spectra (Left) and ISRS due to Different Motions (Middle and Right)

Nonlinear Time Domain (NLTD) Analysis

The nonlinear effects including structure, site, and interface nonlinearities are added to the ELTD model to create various nonlinear FE models for analysis in time domain. NLTD models are used to study the effects of nonlinearities on the seismic response, one at a time and in combination. This comparative study is carried out at higher 1E-5 UHS hazard level where the nonlinear effects are more pronounced in comparison to at 1E-4 UHS hazard level.

Nonlinear Structure

Prior to the development of the nonlinear structural model, stress contours obtained from the linear elastic model were used to identify the locations with high tensile stresses in excess of concrete tensile capacity. As a result, and as shown in Figure 6, walls transferring shear to the mat foundation (basement walls), mat foundation, and a structural slab were identified as zones showing the maximum tensile stresses larger than the concrete tensile capacity.

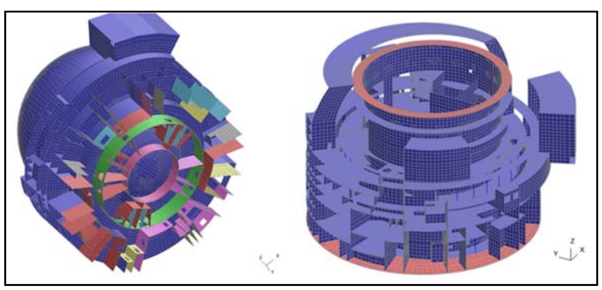

Figure 6: Nonlinear Walls (Left, Any Color Except Dark Blue) and Slabs (Right, Red)

Layered shell elements with multiple layers defined over their thickness each with potentially different material constitutive laws were used to model composite reinforced concrete sections. Perpendicular sets of rebars were modeled with orthotropic layers of smeared steel on each face of the section. Figure 7 shows a schematic of the composite shell section.

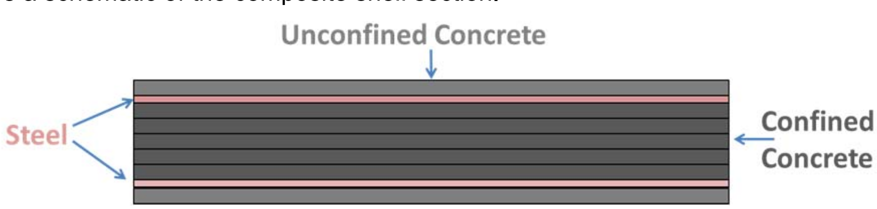

Figure 7: Layered Shell FE Model of Reinforced Concrete Composite Section

The nonlinear concrete material model, defined based on Mander equations [17], allows the simulation of concrete cracking in tension, crushing in compression, and post-peak strain softening. The nonlinear steel material model would capture yielding, hardening, and rupture. Both material models have appropriate unloading-reloading rules to model the response under cyclic loading, including the Bauschinger effect for rebars. Nonlinear material constitutive models were calibrated based on the aged concrete compressive strength of 62.5 MPa and steel rebar yield strength of 495 MPa.

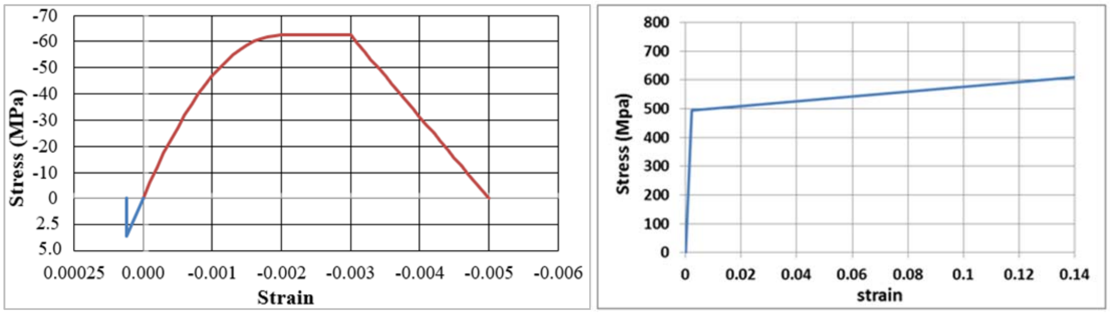

Figure 8: Concrete (Left) and Steel (Right) Stress-Strain Relationship

Nonlinear Site

A nested multi-surface hysteretic plasticity model with effective pressure-dependent stiffness and strength was used to simulate the nonlinear soil response. The main inputs are a constant value for the bulk modulus and a shear stress versus shear strain curve, i.e. yield surface, at a reference pressure (usually the at-rest in-situ effective pressure). The reference pressure is used to model the pressure dependency of gravel's shear strength as its confinement changes due to the building weight and shaking. The effect of structure's weight on gravel's shear response is more significant for surface/shallow founded structures because the weight of the structure can be significantly larger than the excavated soil weight. In the case of the reactor building, the structure's weight is about 3 times the weight of the soil it has replaced. Finally, The Masing rule [18] is used in the selected plasticity model to define the hysteretic response of the soil.

There are significant discrepancies between the soil shear strength implied based on G/Gmax curves and shear wave velocity, versus the soil shear strength determined based on the strength parameters measured in the laboratory, i.e. friction angle and cohesion. Thus, modifications to G/Gmax were made to limit the stress at high shear strains to cap it at correct shear strength of the soil. Figure 9 shows a representative soil property in terms of its modulus reduction and shear stress versus shear strain relationships. The in-situ effective soil stresses were initialized in the beginning of the analysis to properly simulate the soil equilibrium under the gravity load. Both vertical and horizontal effective stresses were initialized.

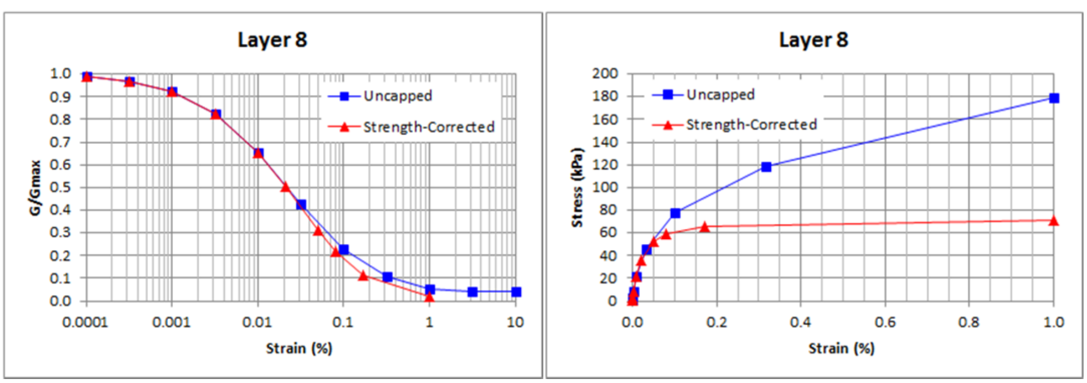

Figure 9: Representative Soil G/Gmax (Left) and Shear Stress-Shear Strain Curves (Right)

Prior to SSI analyses, 1D Site Response Analyses (SRA) were performed using a soil column shown in Figure 10 for each set of ground motions to verify that the seismic waves propagate properly through the soil medium. Similar analyses were performed using SHAKE91[20] and a widely used nonlinear SRA tool, DeepSoil [6]. The 5%-damped response spectra at the foundation elevation from 1D NLTD SRA are compared with those from SHAKE91and DeepSoil analyses in Figure 10. As can be seen from the comparison plots, the results from 1D NLTD SRA and DeepSoil are in good agreement over a wide range of frequencies. Minor differences between the two sets of results are primarily due to the internal curve-fitting that DeepSoil uses to develop G/Gmax curves from the input curves. It is also observed that SHAKE91 results deviate from nonlinear site response analyses over wide range of frequencies at 1E-5 UHS.

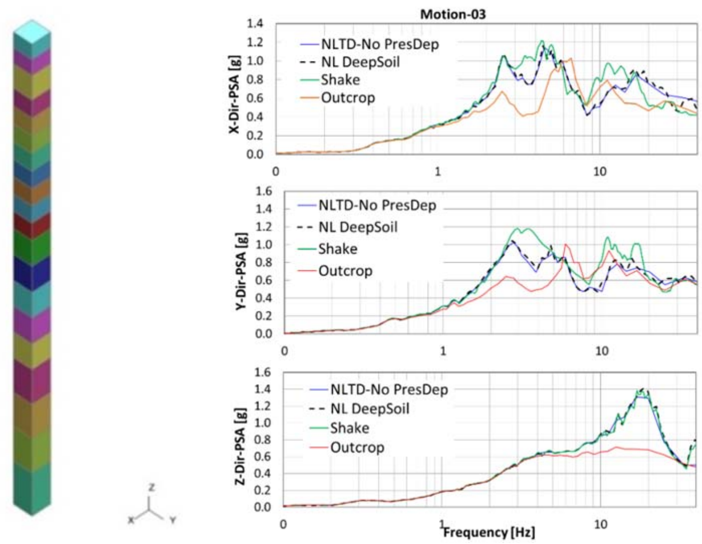

Figure 10: Comparison of 1D Nonlinear Site Response Analysis Results - Motion-03 1E-5 UHS

Nonlinear Soil-Structure Interface

The nonlinear soil-structure interface was modeled using contact surfaces. A penalty-based algorithm was used to couple the soil-structure response normal to their interface which allows for gapping. A coulomb friction formulation was used to couple the soil-structure response in tangential direction which allows for sliding. In the latter formulation, an exponential decay function is used to transition from static to dynamic friction coefficient. The static coefficient of friction was considered to be 0.55 and 0.45 for the mat foundation (mass concrete) and walls (formed concrete) against gravel, respectively, consistent with reference [15]. The dynamic coefficient of friction was assumed to be 0.4.

NLTD and ELTD SSI Results Comparison

Prior to studying the effects of different nonlinearities on the in-structure response, soil domain extent verification study was conducted to assure that the domain boundaries were modeled far enough from the structure so that the SSI response was not adversely affected by the wave reflections from the boundaries. The free-field response of the 3D SSI models at the foundation elevation obtained from a node close to the soil side boundaries was compared to the response from 1D site response analyses at the same elevation at 1E-5 UHS hazard level. Excellent agreement between the responses obtained from the two sets of analyses verifies that the soil side boundaries are modeled far enough from the structure for both equivalent linear and nonlinear 3D soil domains as shown in Figure 11.

The effects of different nonlinearities (i.e. soil, interface, and structure) on the seismic response are studied by comparing ISRS from ELTD and corresponding NLTD models at several component locations. Results for two representative component locations, at FE node 30681 (low elevation and close to the center) and FE node 52596 (high elevation and close to the perimeter), are presented in the following sections.

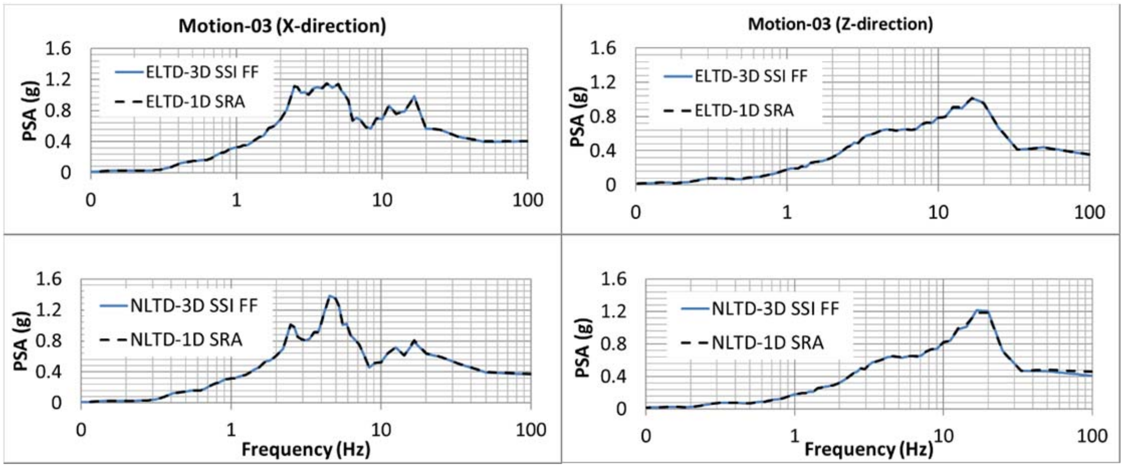

Figure 11: ELTD (Top) and NLTD (Bottom) 3D SSI Model Soil Response at Free Field (FF) vs. 1D SRA Response (1E-5UHS)

Effects of Soil Nonlinearity on the Response

The ISRS results from the NLTD model with soil nonlinearity are compared with those obtained from the ELTD model as shown in Figure 12. The full embedment configuration was selected for this comparison to better isolate the compression-only response of the nonlinear soil from the interface gapping.

The NLTD model shows significantly smaller responses in horizontal directions compared to the ELTD model. This significant deamplification is a result of substantial energy dissipation in the nonlinear soil layers due to the development of large plastic strains. The soil layers below the structure experience significantly higher shear strains compared to those at free-field especially in the layers close to the mat foundation. This is primarily due to direct inertial interaction between the heavy structure and the soil despite the soil shear strength enhancement due to the pressure dependency of gravel response. On the other hand, the ELTD soil damping only accounts for the energy dissipation due to seismic wave propagation and the soil damping due to local shearing resulted from direct inertial soil-structure interaction is ignored. Additionally, the equivalent soil damping included in the ELTD approach usually does not account for biaxial loading of the soil in two directions.

The vertical response of the two models is similar because the volumetric response of the nonlinear soil material model is linear as opposed to its nonlinear deviatoric response.

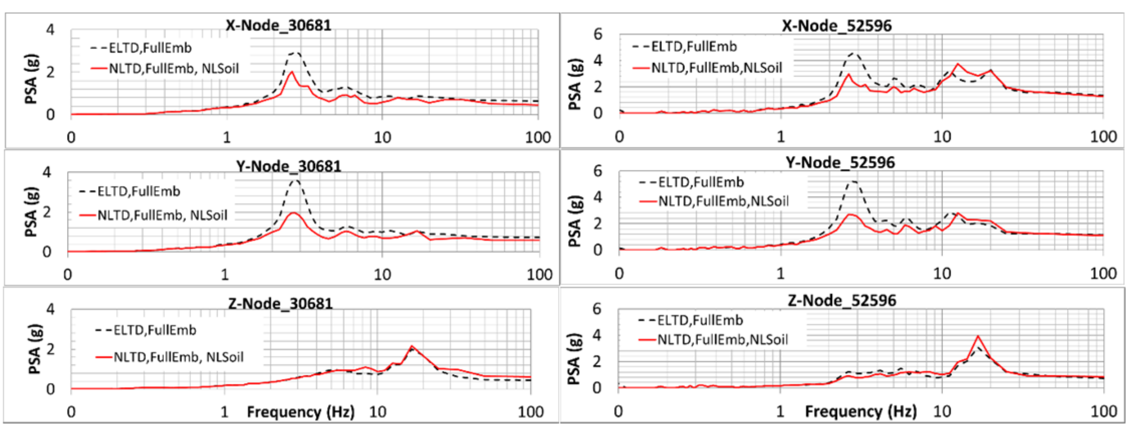

Figure 12: Effects of Soil Nonlinearity- ELTD Vs. NLTD ISRS – Motion-03 (1E-5 UHS)

Effects of Interface Nonlinearity on the Response

The ISRS results from NLTD model with interface nonlinearity are compared with those obtained from the ELTD model with partial embedment configuration in both analyses as shown in Figure 13. Included in the figures are also the results of the NLTD model with lower coefficient of friction (0.4 for static and 0.3 for dynamic) for the mat foundation on soil. The NLTD models show smaller responses in horizontal directions, especially in Y-direction for this motion, as a result of significant energy dissipation at the soil-structure interfaces due to sliding and gapping. In the vertical direction, NLTD models show similar responses to those of the ELTD model as there is no significant nonlinear energy dissipation at the interface in vertical direction. As expected, NLTD model with lower coefficient of friction produces smaller responses in comparison to the model with higher coefficient of friction.

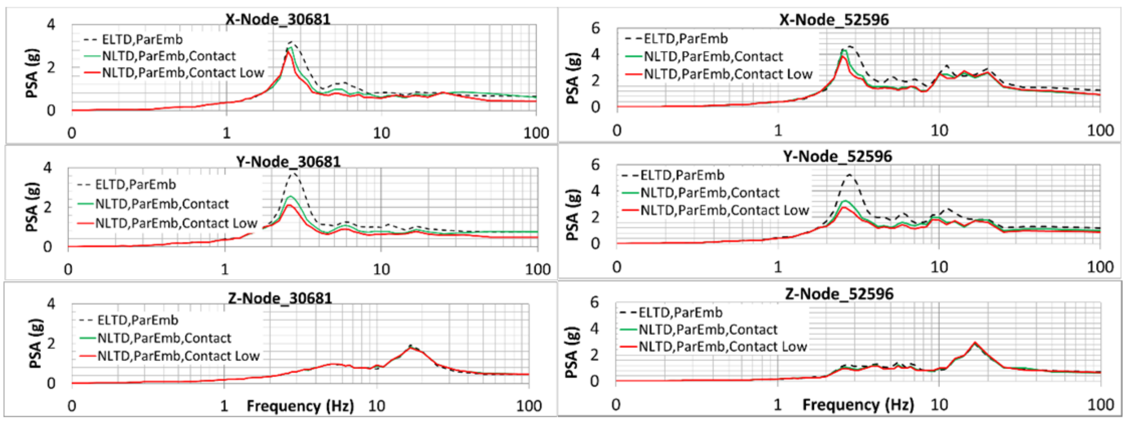

Figure 13: Effects of Interface Nonlinearity –ELTD Vs. NLTD ISRS – Motion-03 (1E-5UHS)

Effects of Structural Nonlinearity on the Response

The ISRS results from NLTD model with structural nonlinearity were compared with those obtained from the ELTD model with partial embedment configuration in both analyses as shown in Figure 14. From the comparison plots, it can be concluded that the structural nonlinearity has no significant effect on the global response of this structure at 1E-5 hazard level as the main lateral force resisting system components remain essentially uncracked after the seismic event. However, extensive local cracking may affect the ISRS at some isolated locations within the structure.

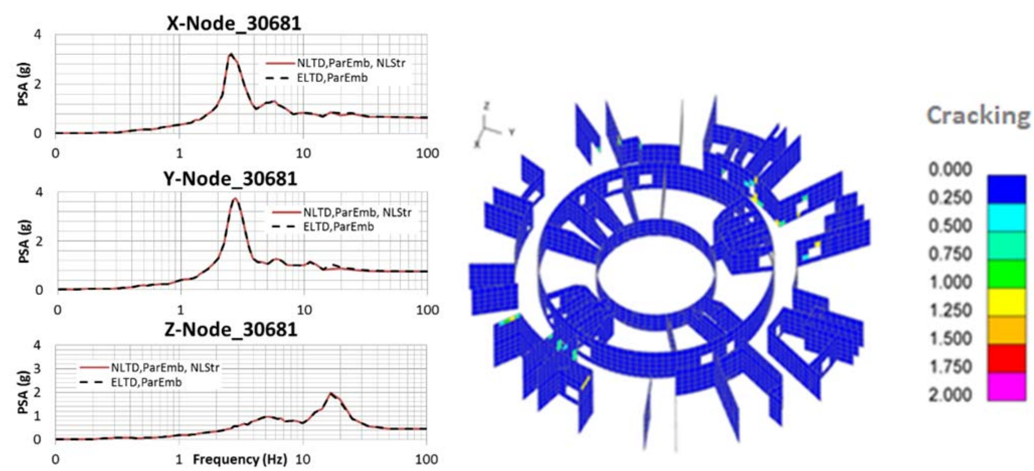

Figure 14: Effects of Structural Nonlinearity – ELTD Vs. NLTD ISRS (Left), Extent of Concrete Cracking in the Basement Walls (Right) with 0 and 2 Indicating Uncracked and Fully Cracked Sections Respectively – Motion-03 (1E-5 UHS)

Effects of Combined Nonlinearities on the Response

The ISRS results from the NLTD model with combined soil and interface nonlinearities were compared with those obtained from the ELTD model as shown in Figure 15. Also included in the plots are the results of the NLTD model with nonlinear soil which are very similar to those of the NLTD model with combined soil and interface nonlinearities. Since the nonlinear model of the gravel soil does not take any tension, interface gapping is naturally included in the model with the nonlinear soil. It is also observed that the sliding on the nonlinear soil is much smaller in comparison to the sliding on the equivalent linear soil. The latter is due to significant softening of the nonlinear soil in direct interaction with the heavy structure. Consequently, the addition of the interface nonlinearity to the model with nonlinear soil does not have any significant effect on the results. These results show that nonlinear effects interact with each other so they cannot be studied in isolation and subsequently added together.

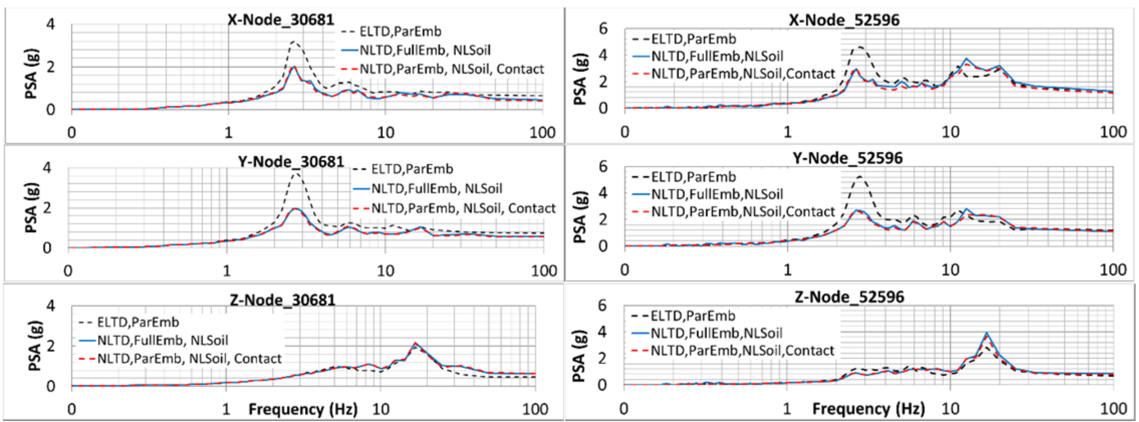

Figure 15: Effects of Combined Soil and Interface Nonlinearities – ELTD Vs. NLTD ISRS – Motion-03 (1E-5UHS)

Finally, the ISRS obtained from the model with all nonlinearities combined (nonlinear soil, structure, and interface) were very similar to the results shown in Figure 15 for the combined soil and interface nonlinearities. The latter is due to insignificant effect of structural nonlinearities on ISRS for this building at this specific hazard level and site condition.

It should be also noted that the response from the NLTD model is higher in comparison to that of the ELTD at some (higher) frequencies (for an example, look at the horizontal responses at node 52596 at frequencies between 10Hz and 20Hz); so, it cannot be generalized that ELTD response is conservative at all frequencies.

Effects of Motion Intensity on the Response

The effects of the ground motion intensity on the seismic response were studied by comparing ISRS at 1E-5 and 1E-4 UHS from the ELTD and NLTD (combined all nonlinearities) models as shown in Figure 16. A distinct reduction of the fundamental frequency of the structure is observed for 1E-5 results as the soil response becomes softer under higher demands from a larger motion. As expected, the global response of the structure is amplified over a wide range of frequencies when the structure is shaken by a larger motion. Similar observations are made from the ELTD results. Furthermore, it can be observed that the deamplifications due to nonlinear effects (ELTD versus NLTD at each hazard level) are much more pronounced at higher (1E-5) hazard level. The latter is particularly evident in the Y-response at the representative location. Consequently, the nonlinear effects become more important as the ground motion intensity increases.

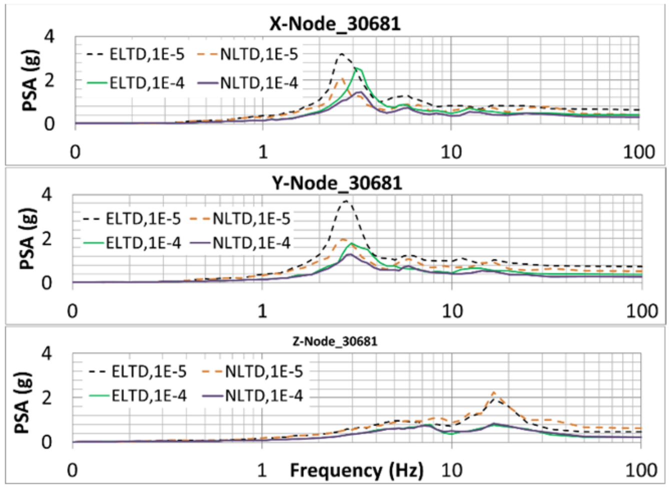

Figure 16: ISRS Comparison for NLTD Vs. ELTD- 1E-4 UHS Vs. 1E-5 UHS

Conclusions

The results of Soil-Structure-Interaction (SSI) analysis for the reactor building of the Gösgen Nuclear Power Plant obtained from Equivalent Linear Time Domain (ELTD), Equivalent Linear Frequency Domain (ELFD) and Nonlinear Time Domain (NLTD) approaches were compared.

Comparison of ELTD and ELFD ISRS extracted at selected component locations showed a very good agreement in the resonance frequency predictions but with some response amplitude differences which were small in comparison to the structural response variability observed due to the different ground motions.

Comparison of ELTD and NLTD ISRS showed significant effects of the soil and interface nonlinearities and minimal effects of the structural nonlinearities on the response of the structure under study. In general, NLTD models show smaller responses in horizontal directions compared to ELTD models. The equivalent soil damping included in the ELTD approach usually does not account for biaxial loading of the soil in two directions. Furthermore, the ELTD soil damping only accounts for the energy dissipation due to seismic wave propagation and the soil damping due to local shearing resulted from direct inertial soil-structure interaction is ignored. The latter can be a great source of energy dissipation. The response of the NLTD model at some frequencies may be higher than that of the ELTD so it cannot be generalized that ELTD approach would always result in conservative responses.

The results from the model with combined soil and interface nonlinearities showed that the effects of the interface nonlinearity are dissolved in the nonlinear soil effects. Sliding on the nonlinear soil is much smaller in comparison to that on the equivalent linear soil due to local soil nonlinearities resulting from direct soil-structure interaction at the interface.

The response of the structure is amplified and shifted over a wide range of frequencies as the ground motion intensity increases. Response de-amplifications due to nonlinear effects are much more pronounced at higher hazard level.

This study demonstrated successful application of the nonlinear SSI analysis approach to study the in-structure response spectra within a commercial reactor building. It highlighted the shortcomings of the commonly used equivalent linear approach in capturing the true physical behavior of a coupled soil-structure system. It also highlighted the importance of considering the nonlinear effects and their combinations especially at higher hazard levels.

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