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AN ENHANCED EQUIVALENT LINEAR SOIL-STRUCTURE INTERACTION ANALYSIS APPROACH FOR SEISMIC APPLICATIONS

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ABSTRACT

This paper proposes enhancements to the equivalent linear approach of simulating the site soil response for the seismic soil-structure interaction analysis of structures in a nuclear power plant to better represent the physical behavior of soil. The equivalent linear site response approach in frequency domain is the state of practice which is widely used to estimate site effects due to its simplicity, low computational cost, and reliability at small soil strains; however, conventional applications of the equivalent linear approach have some limitations.

This paper offers a novel framework to enhance the conventional equivalent linear soil-structure interaction analysis in frequency domain by incorporating the effects of the soil shear strength correction, structure's weight and mass interacting with the soil, and biaxial degradation of the soil in the equivalent linear soil-structure interaction analysis.

In-Structure-Response-Spectra (ISRS) are compared with those obtained from the conventional equivalent linear and corresponding nonlinear models. A better agreement between the results from the enhanced equivalent linear and nonlinear models is observed because both approaches account for the above-mentioned physical phenomena. However, even after the proposed enhancements, the equivalent linear frequency domain approach cannot fully capture the physical behavior of the soil due to its inherent limitations to model the nonlinear and transient response of the soil-structure system.

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. However, conventional applications of the equivalent linear approach have some inherent drawbacks. The equivalent soil properties used in ELFD method are developed based on the 1D site response analysis (SRA) of a soil column without consideration for the static and dynamic effects of the structural mass. The soil layers below relatively heavy structures would experience significantly higher compressive and shear stresses compared to those at free-field, especially in the layers close to the foundation. Higher effective in-situ soil pressure due to the structure's weight would significantly enhance the shear strength and stiffness of granular materials present at many nuclear sites. On the other hand, higher soil shear stress demands due to structure inertia interacting with it may result in significant degradation of the soil layers below the structure. Additionally, decoupled 1D site response analyses used to calculate the equivalent linear soil properties do not account for biaxial shear loading of the soil in two directions during a seismic event. Finally, the soil stiffness degradation and damping curves used for site response analysis are usually based on dynamic laboratory tests at small strains without correction to the soil shear strength at high strains.

This paper proposes a method to address the drawbacks in the conventional application of equivalent linear approach. The proposed method is demonstrated for soil-structure interaction analysis of the reactor building of a nuclear power plant (Tehrani et al. 2018). For this study, modifications are made to the site soil profile to represent a more generic site condition with a deeper deposit on the bedrock. The seismic response of the modified soil-structure system is studied using the conventional and enhanced equivalent linear approaches in frequency domain using SC-SASSI (2016) as well as the nonlinear time domain approach using LS-DYNA (2006). The gravel site soil nonlinearity is incorporated in the nonlinear time domain approach through a 3D hysteretic plasticity model whose shear response is dependent on effective soil pressure. To calibrate the plasticity model, gravel's shear stiffness degradation curves are modified to produce shear strength values consistent with the laboratory-measured friction angles. Tehrani et al. (2018) showed that the conventional equivalent linear approach may result in significant overestimation of the ISRS especially at higher hazard levels.

CASE STUDY NUCLEAR POWER PLANT

The case study nuclear power plant has a central reactor building which is surrounded by other buildings around half of its footprint. 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. An isometric of the finite element (FE) representation of the reactor building and soil domain is shown in Figure 1. 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. Consistent with structural drawings, realistic embedment of the FE model is represented as no soil-structure interaction along the boundary with the neighbor buildings and full interaction along the remaining half of the foundation perimeter.

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 ground water table is at a depth of about 6.0m below surface (Tehrani et al. 2018). For this study, the original soil profile is extended by adding extra soil layers to the bottom of the soil domain to represent a more generic site. The soil profile depth is increased from 27.5m to about 87m. As such, the study in this paper is not intended to present any results for the seismic assessment of any particular reactor building. It is rather a hypothetical, yet realistic exercise focused on the improvement of seismic SSI analysis approaches that can be applied to any structure. The assumed site shear wave (V_s) and compression wave (V_p) velocities versus depth are shown in Figure 2. The results in this study are presented for a single ground motion which triggers relatively large shear strains in the soil for demonstration purposes.

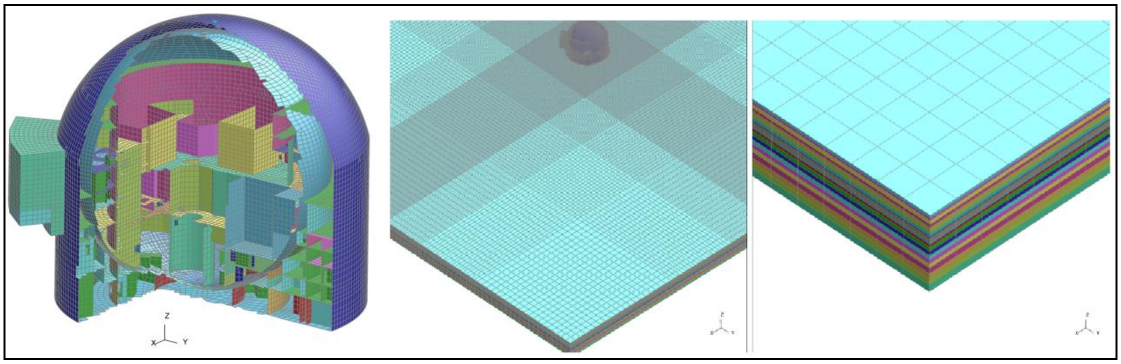

Figure 1: Isometric View of the Reactor Building FE Model (Left) and Soil FE Model (Middle and Right)

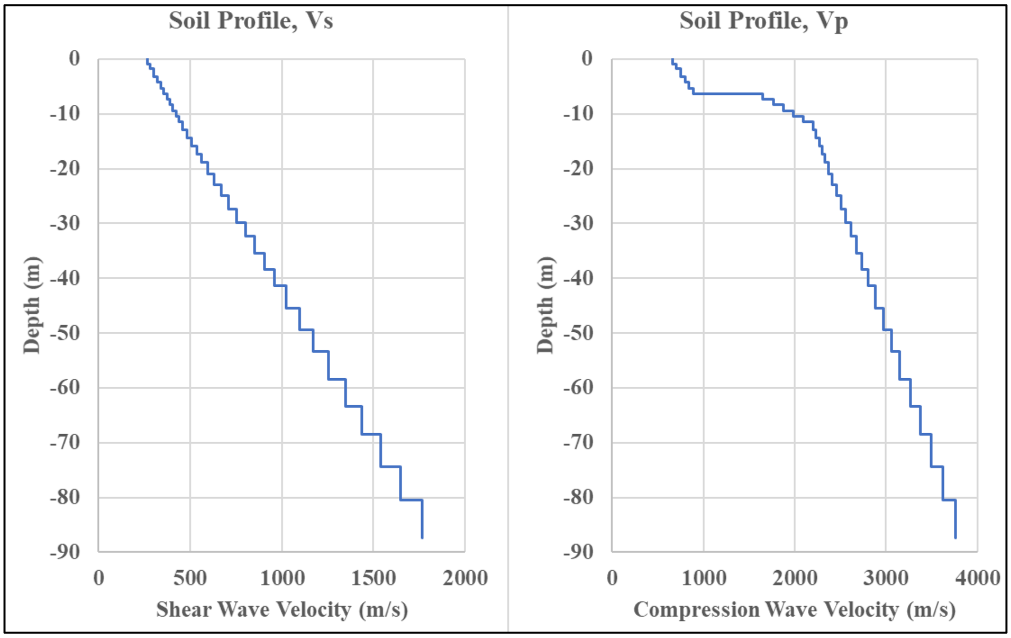

Figure 2: Soil Low-Strain Shear Wave Velocity (Left) and Compression Wave Velocity (Right) Profiles

EQUIVALENT LINEAR FREQUENCY DOMAIN (ELFD) APPROACH

In the ELFD approach, the soil-structure interaction problem is analyzed using a sub-structuring approach where the linear soil-structure system is subdivided into a series of simpler sub-problems (sub-structures). The soil system is discretized using thin layers, while the structure and the excavated soil (i.e. the soil replaced by the structure when embedment is considered) are discretized using finite elements. Interaction between the three sub-structures occurs at the common nodes (interaction nodes). The coupled soil-structure system is formulated and solved in the frequency domain using SC-SASSI (2016). The equivalent soil stiffness and damping used in the SC-SASSI (2016) model are obtained from 1D site response analyses performed in SHAKE 91 (1992).

NONLINEAR TIME DOMAIN (NLTD) APPROACH

In the NLTD approach, the soil domain is discretized and represented via finite elements. The nonlinear response of the soil is simulated using a nested multi-surface hysteretic plasticity model, with effective pressure-dependent stiffness and strength. The three components of ground motions are applied simultaneously at the base of the soil domain as rock outcrop. Transmitting boundary conditions are applied at the base and sides of the soil domain to prevent the reflection of the outgoing seismic waves to efficiently model an “infinite” soil domain. The seismic waves propagate through the continuum soil domain and excite the structure through soil-structure interface.

ENHANCED EQUIVALENT LINEAR FREQUENCY DOMAIN (EELFD) APPROACH

The enhanced equivalent linear frequency domain (EELFD) model is developed from the conventional ELFD model by modifying the soil properties. 1D site response analyses are performed using SHAKE 91 (1992) to obtain the updated equivalent linear soil properties used in the EELFD model. Modifications made to the input G/G_{max}, damping curves and the soil column model are discussed in the following sections.

Effect of Soil Strength Correction on the Soil Properties

There are significant discrepancies between the soil shear strength implied based on G/G_{max} 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/G_{max} were made to limit the stress at high shear strains to cap it at correct shear strength of the soil. Figure 3 shows a representative soil shear response in terms of its modulus reduction and shear stress versus shear strain relationships. The shear strength is calculated based on the soil strength properties, i.e. friction angle and cohesion, and in-situ soil stresses.

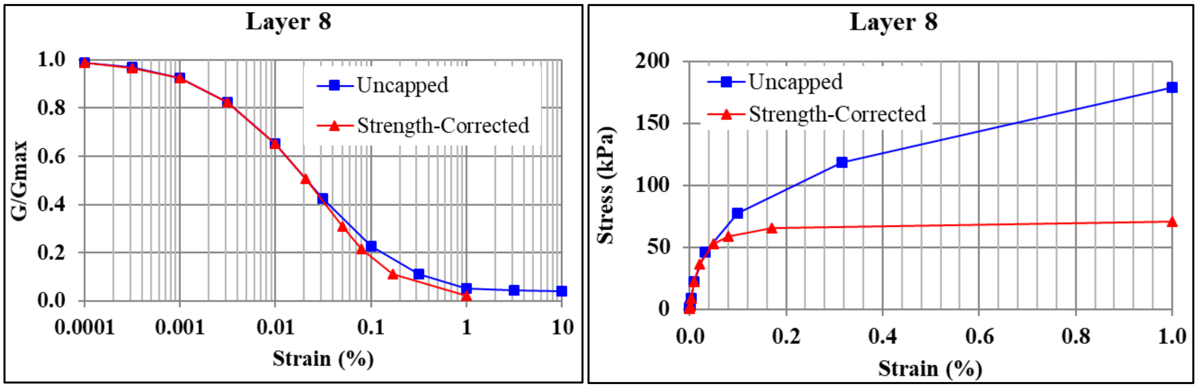

Figure 3: Representative G/G_{max} (Left) and Shear Stress-Shear Strain Curves (Right) – Uncapped versus Strength-Corrected

Effect of Structure Weight and Inertia on the Soil Properties

The soil layers below relatively heavy structures would experience significantly higher compressive stresses under gravity and significantly higher shear stresses due to inertial seismic loading from the excited structure compared to those at free-field especially in the layers close to the foundation. Higher effective in-situ pressure would significantly enhance the shear strength and stiffness of granular materials present at many nuclear sites. On the other hand, higher shear stresses due to structure inertia effects may result in significant degradation of the soil layers below the structure. Boussinesq's equation (1883) is used in this study to calculate the soil pressure distribution in the soil layers due to the structure weight. The increase in the soil pressure versus depth due to structure weight is calculated as a scale factor:

$$SF = \frac{P_{structure} + P_{soil}}{P_{soil-FF}}$$

where $P_{structure}$ is the soil pressure due to structure weight calculated using Boussinesq's equation, P_{soil} is the soil pressure due to its self-weight and $P_{soil-FF}$ is the free-field in-situ soil pressure (before excavation and construction). In other words, the scale factor is equal to the ratio of the soil effective pressure below the structure over the in-situ free-field effective pressure which is the reference pressure for calculation of soil shear response. Figure 4 compares the soil horizontal, vertical, and mean effective pressure distributions under the structure from LS-DYNA gravity analysis with a nonlinear soil domain and Boussinesq's equation. A good agreement is observed for the soil vertical effective stress distribution below the structure. The horizontal stress distribution calculated by Boussinesq’s equation follows a similar trend to that calculated from the FE analysis. However, the horizontal stress values calculated using Boussinesq’s equation are smaller. The latter is due to the underlying assumptions of the Boussinesq’s equation which is appropriate for a semi-infinite, linear elastic, homogenous, and isotropic domain. Nonetheless, the effective pressure values under the structure weight calculated using Boussinesq's equation are in reasonable agreement with the FE results. The scale factor is calculated for each soil layer underneath the structure. As expected, the scale factor reduces with depth with the maximum of 5.5 for the first layer below the structure. The strength-corrected soil curves are then scaled up based on the corresponding scale factors. Figure 5 shows soil stress-strain curves for Layer 8 (the layer immediately under the structure) and Layer 24 (at about 30m below the structure's foundation). The scaled strength-corrected curves are then used as an input to the 1D site response analysis. It should be noted that the scaled soil curve is assigned to the entire soil layer because of the infinite and horizontally layered assumption inherent in the frequency domain approach. Therefore, while this approach more accurately captures the behavior of the soil near the structure, it results in deviations to the soil properties away from the structure. The soil response far away from the structure is expected to have minimal effects on the SSI response of the structure.

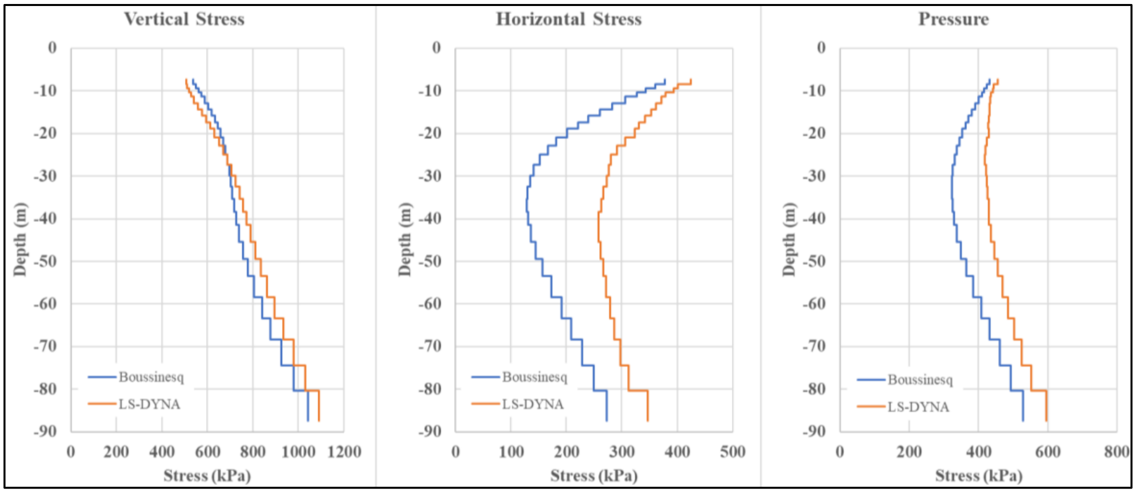

Figure 4: Soil Horizontal, Vertical and Mean Pressure Distribution due to Structure and Soil Weight from LS-DYNA FE Model Vs. Boussinesq's equation

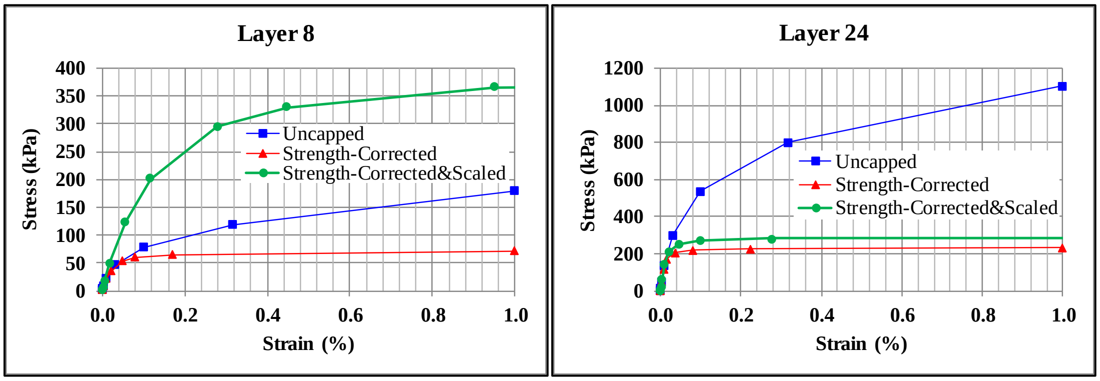

Figure 5: Representative Soil Shear Stress-Shear Strain Curves and their Adjustments for a Layer right below the Foundation (Layer 8) and a Layer 30m Below the Foundation (Layer 24)

The effect of the interacting structure mass on the soil shear response during shaking is included in the 1D site response analysis in SHAKE by adding an extra mass modeled via a thin layer on top of the soil column. Figure 6 compares the shear strain profiles for the ELFD and EELFD soil columns. The ELFD model represents a full-height soil column at free-field while the EELFD is for a truncated soil column under the structure foundation. In addition to the structure mass added to top of the EELFD soil column, the input soil curves are scaled to account for the building weight effect and strength-corrected. Therefore, the EELFD soil column response includes the combined effects of all the soil properties enhancements discussed previously with exception of biaxial loading (next section). In general, the soil layers in the EELFD model experience larger strains due to interaction with the structure mass. For the layers closer to the foundation, sudden shear strain increase at 10m depth in the ELFD model are due to differences between the soil degradation curves selected for above and below the 10m elevation. In the EELFD model, although the soil curves are scaled and therefore are stiffer and stronger, the soil layers still experience relatively large strains which is due to the structure mass interacting with the soil that is more pronounced for the Y component of the ground motion.

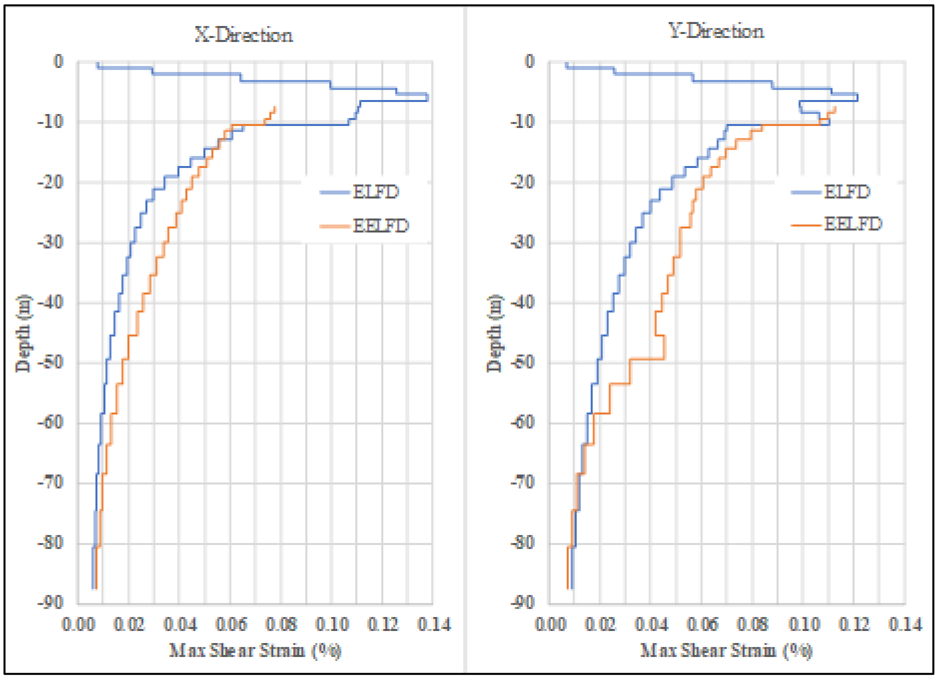

Figure 6: The Effect of Structure Mass on the Site Response Performed in SHAKE

Effects of Biaxial Loading on the Equivalent Soil Properties

The degraded soil properties used in the equivalent linear approach, usually obtained from 1D site response analyses, do not account for biaxial shear loading of the soil in two directions. The site response analysis is performed for motions in two horizontal directions separately. The strain time histories obtained from the two SRAs may be combined using SRSS approach. The maximum strain values calculated for each layer can then be used to obtain the equivalent linear soil properties used in the EELFD model. Figure 7 shows the degraded shear wave velocity profiles obtained from the 1D site response analyses performed for two horizontal input motions in X and Y directions. The biaxially-degraded shear wave velocity profile used in the EELFD SSI model is also included in the figure. It should be noted that for this particular site and considered ground motion, there are slight differences between the 1D and biaxially degraded shear wave velocities for the soil layers close to the foundation. More importantly, the biaxially degraded velocity is similar to the 1D SRA results in Y direction due to much larger strains observed in Y direction for the ground motion considered in this study.

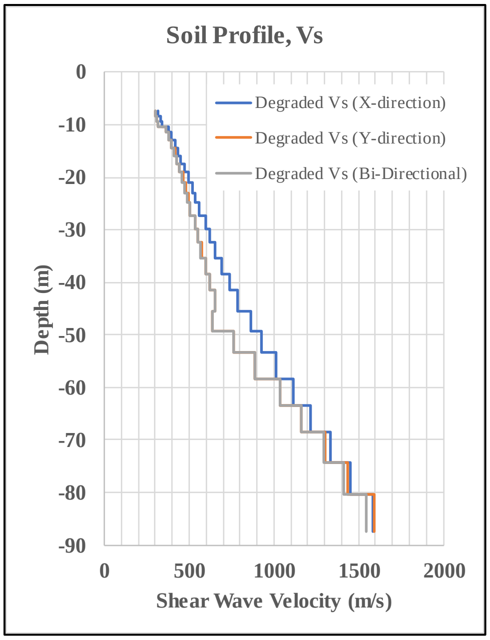

Figure 7: Degraded Shear Wave Velocity Profiles - Uni-directional versus Bi-directional

Combined Effects of Soil Properties Enhancements

The combined effects of equivalent soil properties enhancements discussed in the previous sections are shown in Figure 8 where the degraded shear wave velocity and damping profiles used as input to the ELFD (average of X and Y responses) and EELFD models are compared. The ELFD model represents a full-height soil column at free-field while the EELFD is for a truncated soil column under the structure. In general, more soil degradation is observed for the EELFD soil layers which is mainly driven by the dynamic interaction of the structure mass and soil layers below the building foundation.

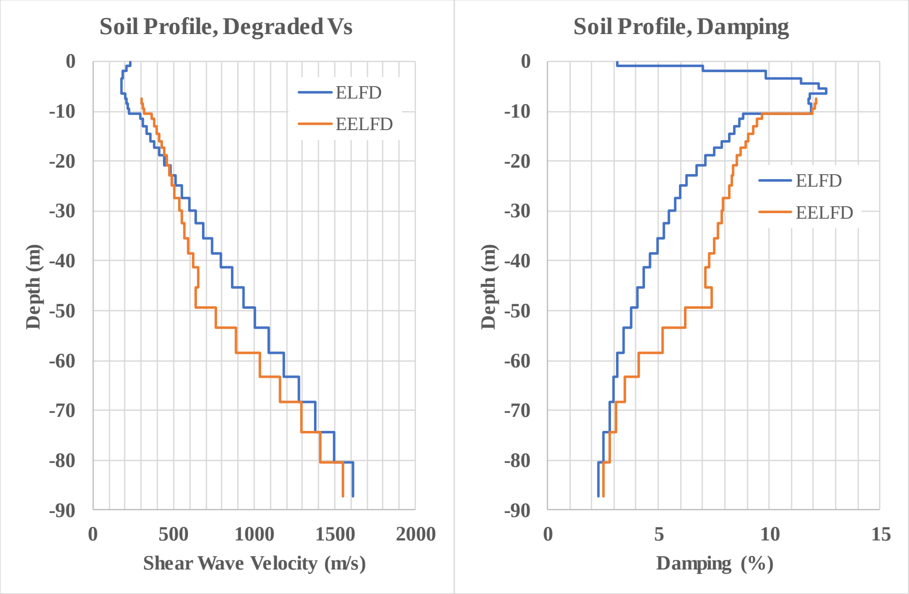

Figure 8: Degraded Shear Wave Velocity and Damping Profiles- ELFD vs. EELFD

RESULTS

The enhanced equivalent linear frequency domain (EELFD) SSI model of the reactor building was developed from the conventional ELFD model by implementing the updated soil properties obtained by following the steps discussed in previous sections and as presented in Figure 8. The equivalent linear frequency domain models (ELFD and EELFD) were analyzed in SC-SASSI (2016) and the nonlinear time domain model (NLTD) was analyzed using LS-DYNA. The ISRS results from the EELFD model are compared with those from the conventional equivalent linear frequency domain (ELFD) and nonlinear time domain (NLTD) analyses as shown in Figure 9. Results are presented for two representative component locations at FE Node 30681 (low elevation and close to the center of the structure) and FE Node 52596 (high elevation and close to the perimeter of the structure).

As shown in Figure 9, the NLTD model results in significantly smaller responses in horizontal directions compared to the ELFD 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. The EELFD model shows horizontal responses in better agreement with those obtained from the NLTD model because both approaches account for the soil shear strength correction, effective pressure dependency, direct inertial interaction, and biaxial degradation of the soil. The enhancements made to the ELFD approach has reduced the peak response by an average of about 22% in X direction and 24% in Y direction. The vertical response of the three models are similar, since the volumetric response of the nonlinear soil material model is linear as opposed to its nonlinear deviatoric response.

The EELFD approach seems to have significantly improved the structural response by incorporating the often-ignored physical response phenomena, however, it still cannot fully capture the physical behavior of the soil due to its inherent linear and frequency domain solution limitations. The equivalent soil stiffness and damping used in the linear frequency domain models are constant values set at the onset of the analysis, while in reality, the stiffness and damping of the soil are functions of instantaneous shear strain demands. Moreover, the same equivalent soil properties are used for seismic analysis in both horizontal directions which lead to similar seismic responses in both directions as shown in Figure 9. In contrary and consistent with the uni-directional strain profiles shown in Figure 6 for EELFD with all corrections before combining strains via SRSS, the NLTD approach shows smaller response in Y direction compared to the X direction. Larger strains in Y direction should result in larger damping and consequently smaller responses in Y direction. The NLTD model, even if not yet fully validated, captures the above-mentioned physical phenomena that is routinely ignored in the equivalent linear approaches in frequency domain. Additionally, it addresses the inherent limitations of the equivalent linear frequency domain solutions even after the proposed enhancements.

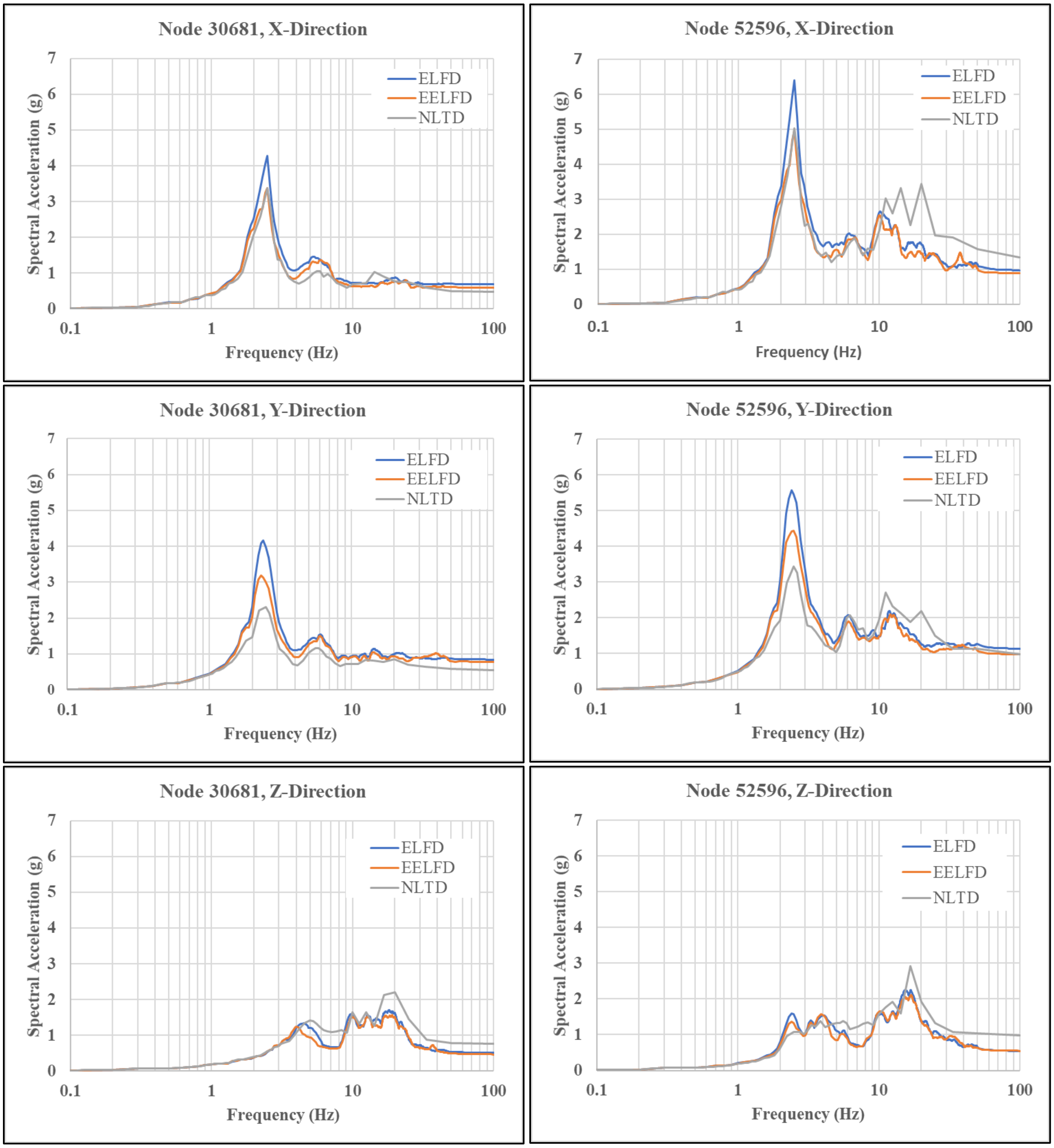

Figure 9: ISRS Results for EELFD Vs. ELFD Vs. NLTD

CONCLUSION

This paper proposes a framework to enhance the equivalent linear soil-structure interaction analysis in frequency domain by incorporating the effects of physical phenomena that are absent in conventional equivalent linear soil-structure interaction analysis. The proposed approach is used for soil-structure interaction analysis of the reactor building of a nuclear power plant on a generic site. The In-Structure-Response-Spectra (ISRS) are compared with those obtained from the conventional equivalent linear (ELFD) and corresponding nonlinear (NLTD) models.

The proposed enhanced equivalent linear model (EELFD) in frequency domain shows horizontal responses in better agreement with those obtained from the NLTD model because both approaches account for the soil shear strength correction, effective pressure dependency, direct inertial interaction, and biaxial degradation of the soil. While the proposed EELFD approach significantly improved the seismic response assessment of the structure, it still could not fully capture the nonlinear behavior of the soil due to its inherent linear and frequency domain solution limitations such as setting the soil properties as constant values prior to the analysis. Additionally, the frequency domain approaches use the same soil properties in both horizontal directions that may lead to response overprediction in one direction and underprediction in the other direction. Finally, there are inherent limitations associated with the proposed techniques to incorporate each physical phenomenon in the EELFD approach.

The proposed EELFD approach, even with its inherent limitations, offers significant improvements to the seismic response assessment of the structure. Incorporation of fundamentally accepted phenomena discussed in this paper into the well-established and accepted ELFD approach results in responses closer to those obtained via NLTD approach. The NLTD approach explicitly incorporates those physical phenomena based on the principles of mechanics.

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