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FREQUENCY- AND TIME-DOMAIN METHODS IN SOIL-STRUCTURE INTERACTION ANALYSIS

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ABSTRACT

Soil-structure interaction (SSI) analysis in the nuclear industry is currently performed using linear codes that function in the frequency domain. There is a consensus that these frequency-domain codes give reasonably accurate results for low-intensity ground motions that result in almost linear response. For higher intensity ground motions, which may result in nonlinear response in the soil, structure or at the vicinity of the foundation, the adequacy of frequency-domain codes is unproven. Nonlinear analysis, which is only possible in the time domain, is theoretically more appropriate in such cases. These methods are available but are rarely used due to the large computational requirements and a lack of experience with analysts and regulators.

This paper presents an assessment of the linear frequency-domain code, SASSI, which is widely used in the nuclear industry, and the time-domain commercial finite-element code, LS-DYNA, for SSI analysis. The assessment involves benchmarking the SSI analysis procedure in LS-DYNA against SASSI for linearly elastic models. After affirming that SASSI and LS-DYNA result in almost identical responses for these models, they are used to perform nonlinear SSI analyses of two structures founded on soft soil. An examination of the results shows that, in spite of using identical material properties, the predictions of frequency- and time-domain codes are significantly different in the presence of nonlinear behavior such as gapping and sliding of the foundation.

INTRODUCTION

Seismic probabilistic risk assessment is now being routinely used to assess the adequacy of new and existing nuclear power plants and safety-related nuclear structures in the United States. Soil-structure interaction (SSI) analysis is a key component of the risk assessment calculations because it influences demands on structural components and floor spectra with which equipment vulnerability is judged. Frequency-domain SSI analysis is routinely performed in the nuclear industry of the United States. SASSI (Lysmer *et al.*, 1999) is the most widely-used frequency-domain code and it uses equivalent-linear, strain-compatible soil properties. The frequency-domain methods should accurately predict responses for low-intensity ground motions involving almost linear response in the soil and the structure, and linear foundation-soil interaction. However, for intense earthquake shaking involving large soil strains or nonlinear foundation-soil interaction, especially at sites with a high seismic hazard or beyond-design basis shaking, nonlinear analysis methods using hysteretic soil models are theoretically more appropriate than equivalent-linear methods in the frequency domain. Nonlinear SSI analysis is only possible in the time domain and the numerical tools to perform these analyses have been developed only recently. Analysts and regulators will have to gain more experience with and confidence in nonlinear SSI analysis before it is widely used in the nuclear industry.

Advancing the use of nonlinear time-domain codes for SSI analysis requires their benchmarking against frequency-domain codes, and confirming that they result in similar predictions for cases involving linear response in the soil and the structure, and linear foundation-soil interaction. The predictions of these codes for cases involving larger soil strains, and nonlinear behavior in the material or the foundation, are expected to differ. For these cases the assessment studies should examine the differences and provide guidelines to analysts and regulators on the use of nonlinear codes.

To the knowledge of the authors, very few studies have been performed that assess frequency-domain and time-domain numerical SSI codes, mainly due to the newness of the time-domain methods. In one study Xu *et al.* (2006) compared predictions made using SASSI and LS-DYNA (LSTC, 2013) from the SSI analyses of deeply embedded nuclear structures. They observed that results calculated using SASSI and LS-DYNA differed considerably for both linear and nonlinear analyses. Although differences were expected between the linear and nonlinear analyses, their results of linear analyses performed using two codes also differed because the damping formulations in the two codes were not the same. Studies by Anderson *et al.* (2013) and Coronado *et al.* (2013) showed that the linear SSI analyses of deeply embedded nuclear structures using time-domain and frequency-domain codes resulted in very similar structural responses. Anderson *et al.* (2013) compared analysis results from SAP2000 (Computers and Structures Inc., 2011) and SASSI2010 (Ostadan and Deng, 2011). Coronado *et al.* (2013) compared results from the extended subtraction method in SASSI2010 to those calculated using the commercial finite-element code ANSYS (ANSYS Inc., 2013). Spears and Coleman (2014), in a comprehensive study, developed a methodology for nonlinear SSI analysis in the time domain, compared the SSI responses calculated using SASSI and time-domain codes, and identified some issues regarding the usage of these codes.

More studies that are comprehensive are required to support the widespread use of nonlinear, time-domain SSI analyses and to provide guidance for performing such analyses. These studies should examine cases involving material nonlinearities in the soil and the structure, as well as geometric nonlinearities, such as gapping and sliding of the foundation, neither of which can be explicitly simulated in the frequency-domain. The study presented in this paper assesses the industry-standard frequency- and time-domain codes for such cases. The frequency-domain code SASSI and the commercial time-domain finite-element code, LS-DYNA, are used for the assessment. Before performing nonlinear analyses, a few verification problems involving simple, idealized structures and soil profiles are solved to confirm that the direct method of analysis in LS-DYNA produces the same results as SASSI for linear elastic models. These verification problems and the corresponding results are presented in detail in Bolisetti *et al.* (2015) and Bolisetti and Whittaker (2015), and are not presented in this paper. The verified direct method is then extended to the nonlinear domain by using nonlinear hysteretic material models, and explicitly modeling the foundation-soil interface using contact elements to simulate gapping and sliding of the foundation. The SASSI analyses are performed using equivalent-linear properties for the soil layers. The SASSI and LS-DYNA results are compared and observations are made regarding the deviation of the equivalent-linear response from the nonlinear response at various ground motion intensities. The analyses performed as a part of this study revealed some practical problems that can be faced while using these codes. These problems and strategies to mitigate them are presented in Bolisetti *et al.* (2015) and Bolisetti and Whittaker (2015), and not here.

TIME-DOMAIN NONLINEAR SSI ANALYSIS IN LS-DYNA

LS-DYNA is a commercial finite-element code capable of three-dimensional nonlinear analyses. It is equipped with a large number of material models that can be used to model the soil and structure, and several contact algorithms that can be used to model the foundation-soil interface. LS-DYNA is therefore a suitable choice for nonlinear SSI analysis, and has been used for some nonlinear site-response and SSI analyses of buildings and petrochemical structures in recent years (Willford *et al.*, 2010). Soil-structure interaction analyses in LS-DYNA can be performed using 1) the direct method, or 2) the effective seismic input method (Basu, 2011; Bielak and Christiano, 1984). The analyses of this study are performed using the direct method, as described below.

In the direct method, the whole soil-structure system is analyzed in a single step thereby circumventing the use of superposition, which is extensively used in traditional SSI analysis methods (including SASSI) and is restricted to linear analyses. This enables a more realistic simulation with the use of nonlinear material models for the soil and structure, and contact models that simulate separation and sliding at the foundation-soil interface. Soil-structure interaction analysis using the direct method can be performed using most commercial finite-element codes such as ABAQUS (Dassault Systèmes, 2005), ANSYS (ANSYS Inc., 2013), LS-DYNA, or the open source finite-element code, OpenSees (Mazzoni *et al.*, 2009). Figure 1 presents a sample finite-element model for SSI analysis using the direct method in LS-DYNA.

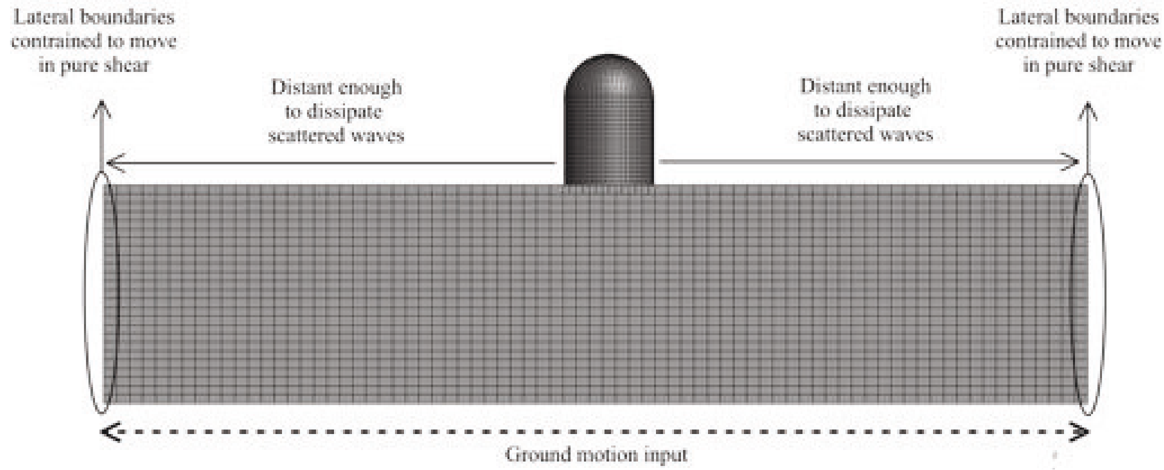

Figure 1: Finite-element model for soil-structure interaction analysis using the direct method

The direct method requires significant computational resources in comparison with the frequency-domain methods and has not seen widespread use in design practice. Consequently, nonlinear SSI analysis using the direct method is not yet well established, and some challenges still exist including: 1) specifying a three-dimensional ground motion input, and 2) simulating a horizontally infinite soil domain. The direct method is currently used only for cases involving vertically propagating shear or compressive waves. Ground motion input for these cases is applied either 1) as a force input (for viscoelastic bedrock) or 2) an acceleration input (for rigid bedrock) specified at the bottom of the soil domain (shown in Figure 1). Simulating a horizontally infinite soil domain is another major challenge in performing nonlinear SSI analysis using the direct method. An infinite soil domain can be simulated by building a finite domain that satisfies the following conditions: 1) effective damping of the waves radiating away from the structure so that they do not reflect back into the soil domain from the lateral boundaries, and 2) stress equilibrium at the lateral boundaries to account for the rest of the soil domain that is not included in the finite domain model. The former can be achieved by using absorbing boundary models at the lateral boundaries that absorb the incoming waves and minimize reflections. Absorbing boundary models have been developed and implemented in commercial finite-element codes. Examples include the viscous boundary model by Lysmer and Kuhlemeyer (1969) and, the more recent, Perfectly Matched Layer (PML) model of Basu (2009), both of which, have been implemented in LS-DYNA. However, these boundary models are limited to waves propagating in linear elastic materials. No absorbing boundaries have yet been developed for nonlinear materials, to the knowledge of the authors. Another approach to simulate radiation damping is to build a large soil domain with sufficient plan dimensions to dissipate the radiating waves before they reach the lateral boundaries. In this approach, the radiating waves are dissipated through hysteresis and viscous damping in the soil. The plan dimensions of the domain can be determined by a trial-and-error procedure, ensuring that the acceleration responses at the boundaries of the soil domain are equal to the free-field acceleration, which is calculated from a separate site-response analysis, and also by verifying that the structural response does not change with a further increase in the domain size. Stress equilibrium at the lateral boundaries can be obtained by constraining the boundary nodes at each elevation to move together in each direction. This enables the elements at the boundaries to move in pure shear, thus simulating a free-field condition (assuming that the input comprises vertically propagating shear waves), as shown in Figure 1.

NUMERICAL ANALYSES

Nonlinear SSI analysis is performed for two structures subjected to four ground motions. The soil profile, structural models and input ground motions are adopted from the NEES City Block project (Bray *et al.*, 2008), which involved the investigation of structure-soil-structure interaction (SSSI) in dense urban regions through centrifuge tests and numerical simulations involving several building models. Two of these building models are used for the nonlinear SSI analyses of this study: 1) a one-story, steel moment-resisting frame founded on footings and designed to develop plastic hinges in the beams and columns (hereafter referred to as MS1F_2), and 2) a two-story shear wall building founded on a basemat and designed to be elastic (hereafter referred to as MS2F). The 1st mode fixed-base time periods of MS1F_2 and MS2F are 0.13 sec and 0.47 sec, respectively, at the prototype scale. The building models are also designed to have a flexible-base time period close to 0.6 sec, which is equal to the first mode time period of the soil profile. Further details regarding the design of the experimental models are presented in Mason (2011) and Trombetta (2013).

The superstructures in both SASSI and LS-DYNA are modelled using finite elements. Both the structures are modelled using beam elements and lumped masses at the nodes. The footings of MS1F_2 and the basemat of MS2F are modelled with solid elements. The experimental models of the structures and the corresponding numerical models in SASSI are presented in Figure 2. The corresponding numerical models in LS-DYNA are almost identical. Specifications (dimensions, cross-section and material properties) of these numerical models are presented in Bolisetti *et al.* (2015).

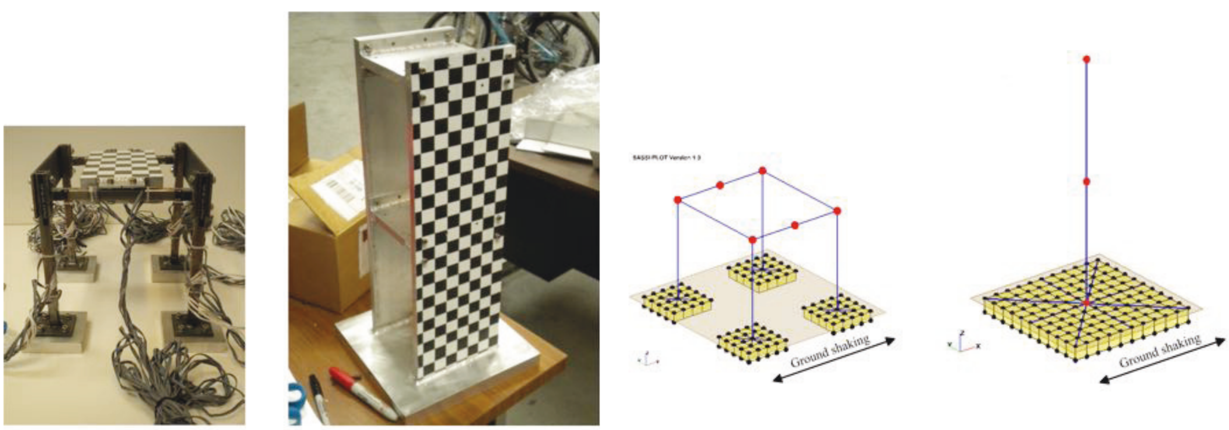

Figure 2: Photographs of experimental models of the structures (left) and the corresponding numerical models in SASSI (right)

The soil profile of the City Block project experiments is 29.5m deep at the prototype scale. This soil profile is modelled in both codes using 29 soil layers, which propagate a maximum frequency of about 8Hz assuming 10 layers per wavelength (Bolisetti *et al.*, 2015). Each layer in SASSI corresponds to a layer of solid elements in LS-DYNA. Since SASSI performs a linear analysis, the soil profile in SASSI is modelled using strain-compatible properties (shear modulus and damping ratio profiles) that are calculated from a separate SHAKE (Schnabel *et al.*, 2012) analysis for each input ground motion. The strain-compatible properties used for each ground motion in SASSI are presented in the left panel of Figure 3. The right panel of the figure presents the modulus reduction and damping curves used in the

SHAKE analyses for the calculation of the strain-compatible properties. These curves, developed for sands by Seed and Idriss (1970), are taken from the SHAKE database. The soil material in LS-DYNA is modelled using the *MAT_HYSTERETIC_SOIL model, which requires a backbone curve for input. The modulus reduction curves used in the SHAKE analyses are converted into stress-strain curves that are used as input for the LS-DYNA analyses.

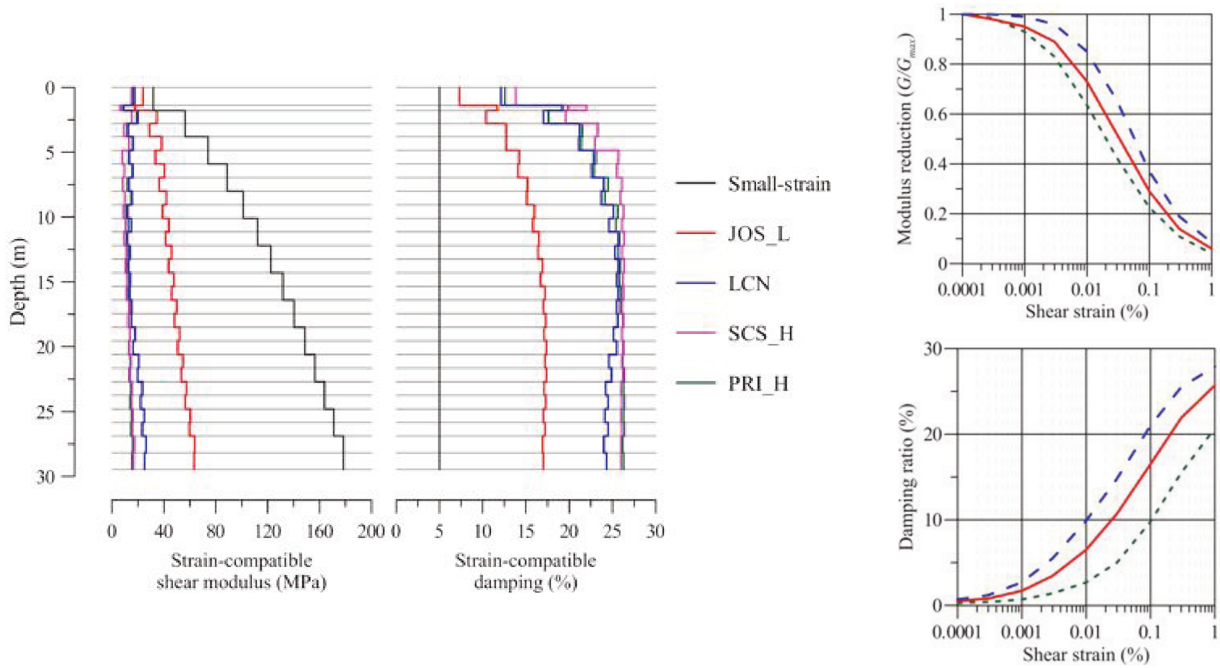

Figure 3: Strain-compatible shear modulus and damping ratio profiles used in SASSI (left) and the modulus reduction and damping ratio curves used in the SHAKE and LS-DYNA analyses

The LS-DYNA analyses are performed using a soil domain of size 218m × 118m (218m in the shaking direction, X) in plan and 29.47m deep. The SSI model for the analysis of MS2F is presented in Figure 4. The LS-DYNA analyses are performed for two cases: 1) foundations are tied to the surrounding soil, without allowing gapping and sliding, and 2) separation is allowed at the foundation-soil interface, allowing gapping and sliding. A comparison of the results from these two cases provides an understanding of the importance of geometric nonlinearities in the calculation of structural response.

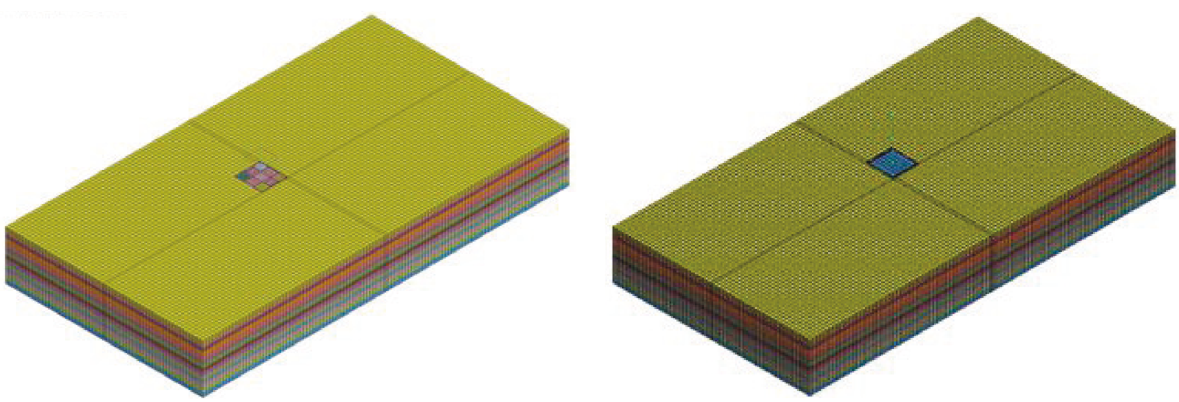

Figure 4: Finite element model for the nonlinear SSI analysis of MS1F_2 (left) and MS2F (right) in LS-DYNA

Four ground motions with different intensities and frequency characteristics are applied as input for the SSI analyses. These ground motions are applied at the base of the soil profile as acceleration inputs, assuming that the soil profile lies atop rigid bedrock. Results for two of the ground motions are presented in this paper. These ground motions, referred to as JOS_L and PRI_H, have peak accelerations of 0.06g and 0.64g, respectively. JOS_L is an ordinary ground motion, whereas PRI_H is a near-fault, pulse-like ground motion. Further details of the ground motions, including a description of their selection process is presented in Bolisetti and Whittaker (2015).

RESULTS

The SSI responses calculated using SASSI and LS-DYNA are compared in this section. The responses are compared for 1) linear elastic analyses in SASSI and LS-DYNA, and 2) linear analyses in SASSI with strain-compatible properties for the soil and nonlinear analyses in LS-DYNA. The linear elastic analyses are performed to verify that the frequency- and time-domain responses are almost identical and to eliminate errors from the SASSI and LS-DYNA models. The nonlinear analyses are then performed in LS-DYNA by changing material properties and incorporating contact models at the foundation-soil interface.

The differences in the structural responses calculated using SASSI and LS-DYNA are a result of 1) nonlinear site response, 2) foundation hysteresis, and 3) geometric nonlinearities such as gapping and sliding of the foundation. An assessment of frequency- and time-domain codes in calculating the nonlinear site response is performed in a different study by Bolisetti *et al.* (2014). The study presented here focuses on the nonlinearity from foundation hysteresis and geometric nonlinearities. The structural responses calculated for comparison include the response spectra for 1) total acceleration at the roof, 2) relative (to the free field) acceleration at the roof of MS1F_2, and 3) rocking acceleration at the roof of MS2F. The relative and total accelerations are included to eliminate (as much as possible) the free-field acceleration from the comparisons. The accelerations calculated using LS-DYNA are low-pass filtered with a cut-off frequency of 10Hz to remove numerical noise from the contact elements.

MS1F_2

Figure 5 presents 5% damped response spectra of the accelerations relative to the base, and the total accelerations at the roof of MS1F_2 for linear elastic and nonlinear analyses. The figure shows that SASSI and LS-DYNA predict almost identical responses in a linear elastic analysis, verifying that the SSI models of MS1F_2 in the two codes are equivalent.

The figure also presents the results of nonlinear analysis for the ground motions JOS_L and PRI_H for the two scenarios of foundation-soil contact, referred to 'LS-DYNA (tied)' and 'LS-DYNA (separation allowed)'. There are significant differences in the SASSI and LS-DYNA results for both relative and total acceleration responses. The differences are significant even for the low-intensity JOS_L ground motion, which results in similar free-field accelerations in SASSI and LS-DYNA [free-field results are presented in Bolisetti and Whittaker (2015)]. The peaks in the relative acceleration spectra calculated using LS-DYNA (separation allowed) occur at longer periods than those calculated using SASSI, indicating that the differences arise from increased flexibility either at the foundation or in the superstructure, due to nonlinear behaviour. Since the fuses of MS1F_2 did not yield for the first three ground motions, the differences in the structural responses are attributed here to nonlinear behaviour in the soil near the footings. This hypothesis is confirmed by performing a separate nonlinear analysis in LS-DYNA, with the soil in the vicinity of the footings modelled with linear elastic material, and with a tied foundation condition. The results of this analysis, presented in Bolisetti *et al.* (2015), show that the SASSI and LS-DYNA responses are virtually identical, and confirm that differences in the structural responses for the JOS_L ground motion in Figure 5 are due to nonlinear soil behaviour in the vicinity of the footings. Figure 5 also shows that preventing separation at the foundation-soil interface in the LS-DYNA model by using a tied foundation condition significantly changes the response. Specifically, the peaks of the relative acceleration spectra occur at a shorter period (which is still longer than the period corresponding to the SASSI responses), and the amplitude of these peaks is smaller as compared with the LS-DYNA case that allows separation at the foundation. This indicates that a significant amount of nonlinear behaviour at the foundation is due to the gapping and sliding of footings, and partly due to the hysteretic behaviour of the soil. However, the difference between the LS-DYNA results for the tied interface and the SASSI results indicates that the nonlinear response due to soil hysteresis is still significant. Therefore, the results presented in Figure 5 show the significant impact of secondary nonlinearities, including sliding and gapping of the footings and hysteretic behaviour of soil at the footing vicinity, on the MS1F_2 response. These nonlinearities result in larger peak spectral accelerations that occur at longer periods than those calculated using equivalent-linear properties.

Yielding of the beam fuses is also observed in the LS-DYNA response to the PRI_H ground motion when separation at the foundation-soil interface is allowed. However, no yielding is observed in the corresponding LS-DYNA response for the tied foundation case, indicating that gapping and sliding of the footings result in increased inelastic deformation demands in the roof beams. No yielding is observed in the beams for the other ground motions for both the LS-DYNA cases. SASSI cannot directly capture yielding in a superstructure.

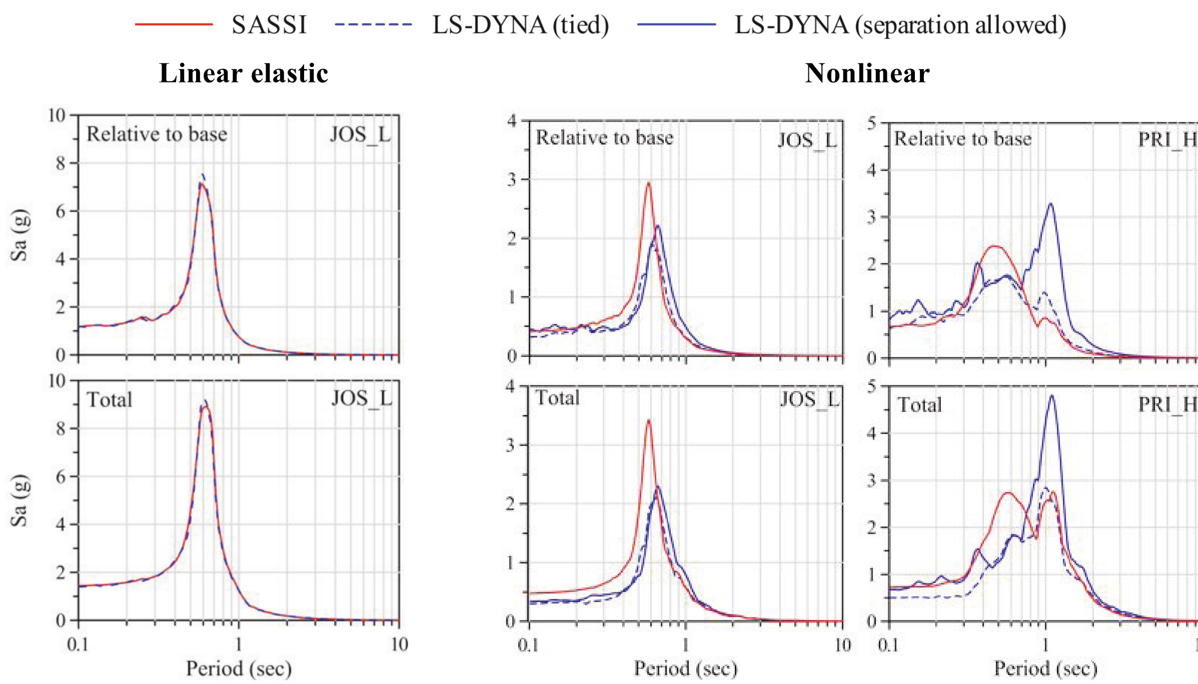

Figure 5: Results of SSI analysis of MS1F_2 using SASSI and LS-DYNA

MS2F

Figure 6 presents the 5% damped response spectra of the accelerations relative to the base, and the rocking accelerations at the roof of MS2F for linear elastic analyses. The figure shows that SASSI and LS-DYNA predict almost identical responses in a linear elastic analysis, verifying that the SSI models of MS2F in the two codes are equivalent for linear elastic analysis.

Figure 6 also presents the results of nonlinear SSI analysis for the ground motions JOS_L and PRI_H. The SASSI and LS-DYNA responses calculated from a nonlinear analysis are closer than those calculated for MS1F_2 and presented in Figure 5. The LS-DYNA responses for the two contact conditions are also closer than those calculated for MS1F_2. There is a small increase in the peak spectral accelerations calculated using LS-DYNA when separation is allowed at the foundation-soil interface. This increase is due to the sliding of the basemat from loss of contact with the surrounding soil. This increase is much smaller than that observed for MS1F_2, indicating that the degree of sliding and gapping in MS2F is smaller. Figure 6 also shows that, although the SASSI and LS-DYNA responses are close for the JOS_L ground motion, the peak spectral responses of the total acceleration are smaller than those calculated using SASSI for the other three ground motions. This is due primarily to LS-DYNA predicting smaller free-field response than SASSI [free-field results are presented in Bolisetti and Whittaker (2015)]. The peak spectral acceleration of the rocking response calculated using LS-DYNA is also slightly smaller than the corresponding SASSI response for the PRI_H ground motions because of the hysteretic response of the soil in the vicinity of the basemat that involves softening of the soil and damping of the rocking response of MS2F. However the comparatively small difference between the SASSI and LS-DYNA responses for MS2F, as compared with MS1F_2, indicates that the secondary nonlinearities for the basemat are smaller than those observed for the footings.

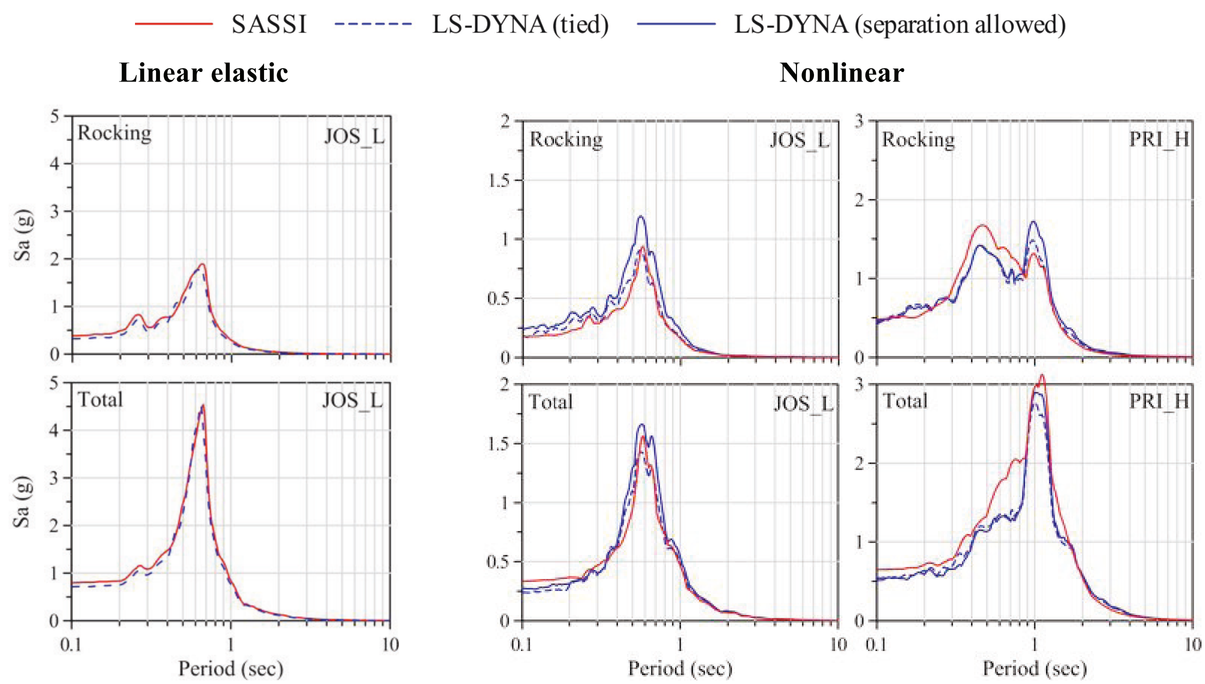

Figure 6: Results of SSI analysis of MS2F using SASSI and LS-DYNA

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This paper presents an assessment of the industry-standard SSI analysis codes, SASSI and LS-DYNA. The assessment involves linear and nonlinear analyses of realistic soil-foundation-structure systems that exhibit nonlinear behavior. The nonlinear SSI responses are calculated for a one-story steel-moment resisting frame building founded on spread footings and a two-story shear-wall building founded on a basemat, subjected to four recorded input ground motions of different intensities. The responses are calculated in SASSI using strain-compatible moduli and damping ratios for the soil. LS-DYNA analyses are performed using two foundation-soil interfaces: 1) a tied interface that does not allow separation between the soil and the foundation, and 2) an interface that allows separation between the soil and the foundation. The responses calculated using SASSI and LS-DYNA are compared for all the ground motions, and challenges and pitfalls in performing SSI analyses using these codes are identified.

The following conclusions can be drawn from the studies presented in this paper:

1. The frequency-domain code, SASSI and the direct method in the time-domain code, LS-DYNA, result in almost identical responses for linear SSI analyses. This is an important result in the benchmarking of time-domain codes against the frequency-domain codes for linear analysis.
2. The predictions from time-domain nonlinear SSI analysis can be significantly different from those made using linear frequency-domain codes. The differences are greatest for cases with significant nonlinearities, such as nonlinear site response (primary nonlinearities) and nonlinear behaviour at the foundation (secondary nonlinearities), namely, soil hysteresis, and gapping and sliding underneath the foundation. In the study presented in this paper, the responses of a one-story footing structure calculated using SASSI and LS-DYNA differed considerably even for a very low-intensity ground motion due to nonlinear soil behaviour at the vicinity of the footings.
3. Nonlinear response in the vicinity of the foundations (secondary nonlinearities) can be significant in buildings. This nonlinear response can lead to an increase in superstructure demands. A considerable increase in the roof accelerations of the one-story structure is observed when modelled with a soil-footing interface that simulates gapping and sliding, as opposed to an interface that does not allow separation between the soil and the footing. Ignoring secondary nonlinearities such as gapping and sliding can result in low predictions of superstructure response. In the context of performance-based design, nonlinear SSI effects should therefore be considered if accurate estimates of loss and risk are required.
4. Structures with spread footings are susceptible to an increase in inelastic deformation demands due to footing spreading: residual displacements of the footings away from each other. Connecting the footings with grade beams will eliminate footing spreading and reduce ductility demands in the superstructure, as shown by Bolisetti and Whittaker (2015).
5. The results of this study are significant for the SSI analysis of nuclear structures because they characterize the possible effects of gapping and sliding, which cannot be captured by frequency-domain analysis. These effects could have a significant impact on risk and loss calculations. Nonlinear time-domain analysis should be used for SSI analysis where gapping and sliding is possible.

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REFERENCES

Anderson, L. M., Elkhoraibi, T., and Ostadan, F. (2013). "Validation of SASSI2010 Solution Methods through Independent Verification Using SAP2000 for Deeply Embedded Structures with Large Footprints." *22nd International Conference in Structural Mechanics in Reactor Technology - SMiRT 22*, August 2013, San Francisco, California.

ANSYS Inc. (2013). Computer Program: ANSYS 13.0. ANSYS Inc., Canonsburg, Pennsylvania.

Basu, U. (2009). "Explicit Finite Element Perfectly Matched Layer for Transient Three-Dimensional Elastic Waves." *International Journal for Numerical Methods in Engineering*, 77, 151-176.

Basu, U. (2011). "Soil-Structure Interaction." http://www.lstc.com/applications/soil_structure.

Bielak, J., and Christiano, P. (1984). "On the Effective Seismic Input for Nonlinear Soil-Structure Interaction Systems." *Earthquake Engineering & Structural Dynamics*, 12(1), 107-119. http://dx.doi.org/10.1002/eqe.4290120108

Bolisetti, C., Whittaker, A. S., Mason, H. B., Almufti, I., and Willford, M. (2014). "Equivalent Linear and Nonlinear Site Response Analysis for Design and Risk Assessment of Safety-Related Nuclear Structures." *Nuclear Engineering and Design*, 275, 107-121. 10.1016/j.nucengdes.2014.04.033

Bolisetti, C., and Whittaker, A. S. (2015). "Site Response, Soil-Structure Interaction and Structure-Soil-Structure Interaction for Performance Assessment of Buildings and Nuclear Structures." MCEER-15-0002, Multidisciplinary Center for Earthquake Engineering Research (MCEER), University at Buffalo, The State University of New York, Buffalo, NY.

Bolisetti, C., Whittaker, A. S., and Coleman, J. L. (2015). "Frequency- and Time-Domain Methods in Soil-Structure Interaction Analysis." *Nuclear Engineering and Design*, Under Review.

Bray, J., Kutter, B. L., Hutchinson, T. C., Whittaker, A. S., Fiegel, G. L., and Reitherman, R. (2008). "NEESR-SG: Seismic Performance Assessment in Dense Urban Environments." Funded Research Proposal to the US National Science Foundation, University of California, Berkeley, California.

Computers and Structures Inc. (2011). Computer Program: SAP2000 - Structural Analysis Program, Version 11.0.0. Computers and Structures, Inc., Berkeley, California.

Coronado, C., Anderson, L. M., and Ostadan, F. (2013). "Verification of SASSI Extended Subtraction Method for Computing the Seismic Response of Deeply Embedded Structures." *22nd International Conference in Structural Mechanics in Reactor Technology - SMiRT 22*, August 2013, San Francisco, California.

Livermore Software Technology Corporation (LSTC). (2013). "LS-DYNA Keyword User's Manual - Version R 7.0." Livermore, California.

Lysmer, J., and Kuhlemeyer, R. L. (1969). "Finite Dynamic Model for Infinite Media." *Journal of Engineering Mechanics Division, ASCE*, 95, EM4, 859-877.

Lysmer, J., Ostadan, F., and Chin, C. (1999). Computer Program: SASSI2000 - A System for Analysis of Soil-Structure Interaction. University of California, Berkeley, California.

Mason, H. B. (2011). "Seismic Performance Assessment in Dense Urban Environments." Ph.D. Dissertation, University of California, Berkeley, California.

Ostadan, F., and Deng, N. (2011). Computer Program: SASSI2010 - A System for Analysis of Soil-Structure Interaction, Version 1.1. Geotechnical and Hydraulic Engineering Services, Bechtel National Inc., San Francisco, California.

Schnabel, P. B., Lysmer, J., and Seed, H. B. (2012). Computer Program: SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites. University of California, Berkeley, California.

Seed, H. B., and Idriss, M. (1970). "Soil Moduli and Damping Factors for Dynamic Response Analysis." Earthquake Engineering Research Center, University of California, Berkeley, California.

Spears, R., and Coleman, J. (2014). "Nonlinear Time Domain Soil-Structure Interaction Methodology Development." INL/EXT-14-33126, Idaho National Laboratory, Idaho Falls, Idaho.

Trombetta, N. W. (2013). "Seismic Soil-Foundation Structure Interaction in Urban Environments." Ph.D. Dissertation, University of California, San Diego, California.

Willford, M., Sturt, R., Huang, Y., Almufti, I., and Duan, X. (2010). "Recent Advances in Nonlinear Soil-Structure Interaction Analysis using LS-DYNA." *Proceedings of the NEA-SSI Workshop*, October 6-8, Ottawa, Canada.

Xu, J., Miller, C., Costantino, C., and Hofmayer, C. (2006). "Assessment of Seismic Analysis Methodologies for Deeply Embedded Nuclear Power Plant Structures." NUREG/CR-6896, U.S. Nuclear Regulatory Commission, Washington, District of Columbia