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Nonlinear Time Domain Seismic Soil Structure Interaction (SSI) Analysis for Nuclear Facilities and Draft Appendix B of ASCE 4

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Abstract

Seismic analysis of nuclear power plants is routinely carried out using guidance provided in "Seismic Analysis of Safety-Related Nuclear Structures and Commentary (ASCE 4, 1998)." This document, which is currently under revision, provides detailed guidance on linear seismic soil-structure-interaction (SSI) analysis of nuclear facilities using deterministic and probabilistic methods. However, a new Appendix in ASCE 4-2013 (draft) is being added to provide guidance for nonlinear time domain SSI analysis. Nonlinear seismic SSI analysis may be needed to model the following behaviors: material nonlinearity (in soil and/or structure), rocking or sliding of the foundation, static and dynamic soil pressure effects on deeply embedded structures, local soil failure at the foundation-soil interface, nonlinear coupling of soil and pore fluid, nonlinear effects of gaps between the surrounding soil and the embedded structure, and seismic isolation systems. Guidance is provided in Appendix B on development of finite element meshes, earthquake ground motion input, nonlinear constitutive models, assessment of analysis results, and verification and validation procedures.

This paper provides an overview of the proposed Appendix B to ASCE 4. The principles of nonlinear SSI analyses and technical bases for the recommendations on modeling, earthquake ground input motion and constitutive models are discussed.

Software codes are available to perform nonlinear SSI analysis such as the NRC ESSI simulator (Jeremic et al. 2012), and commercial codes such as ABAQUS, LS-DYNA, and ANSYS. The paper provides a brief overview of how to apply the guidance in Appendix B of ASCE 4 to perform nonlinear SSI analysis utilizing these codes.

Introduction

Seismic analysis in support of nuclear power plant (NPP), high-hazard nuclear waste facilities, and spent fuel storage systems is carried out using the guidance provided in ASCE 4 and generally performed using frequency domain software. Frequency domain software such as SASSI are linear analysis codes that when used in accordance with ASCE 4 and ASCE 43 should generally produce conservative NPP designs for low to moderate amplitude seismic events. ASCE 43 requires that NPP's be designed so that their structural response remains linear elastic during design basis earthquakes (DBE). However, ASCE 43 allows for some inelastic structural response for high-hazard nuclear facilities. For both NPPs and non power nuclear facilities there are nonlinearities that should be considered when performing analysis in support of design basis earthquakes (DBE), beyond design basis earthquakes (BDBE), and seismic fragility calculations. Nonmandatory guidance has been developed in Appendix B to ASCE 4 that provides a general framework for performing nonlinear analysis. The primary objectives of this paper are, 1) present the guidance provided in Appendix B, 2) discuss when nonlinear seismic soil structure interaction (SSI) analysis may be necessary for NPPs and high-hazard nuclear waste facilities, and 3) minimum acceptable analysis and peer review requirements.

Nonlinear analysis of structural/mechanical systems is routinely performed using implicit and explicit time domain finite element analysis (FEA) codes. These analyses include spent fuel canister drop analysis, missile impact analysis, and seismic analysis involving complicated systems with multiple contact interactions, such as spent fuel inside fuel storage racks. Nonlinear seismic SSI analysis has been performed for structures such as canal locks (Figure 1), bridges (Figure 2), and liquid natural gas storage platforms (Figure 3). These seismic SSI analyses used three different finite element codes, ABAQUS, ESSI, and LS-DYNA. Each analysis approach used different approaches for allowing wave passage (or absorbing) at the boundaries and different methods for applying the seismic motion.

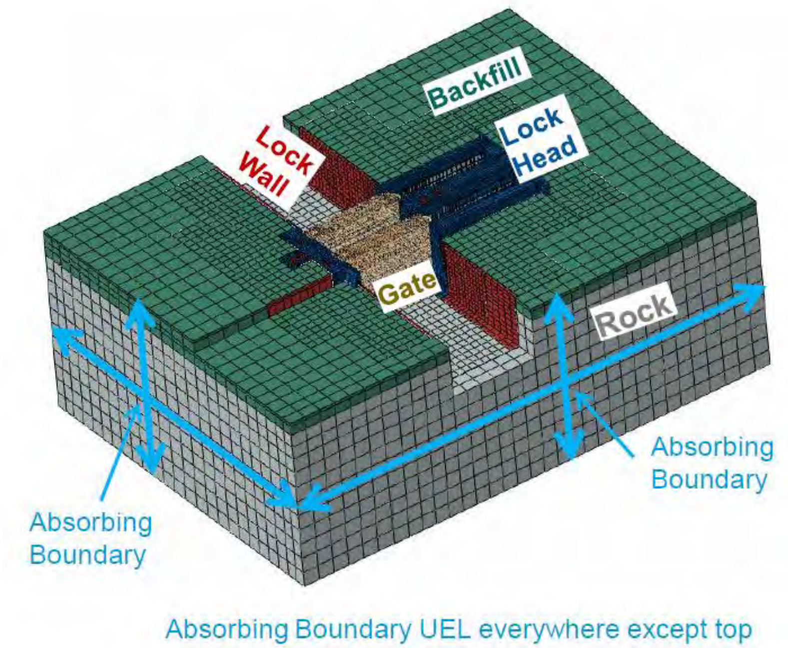

Figure 1: Finite Element Model of Panama Canal 3rd set of Locks, Barry (2012)

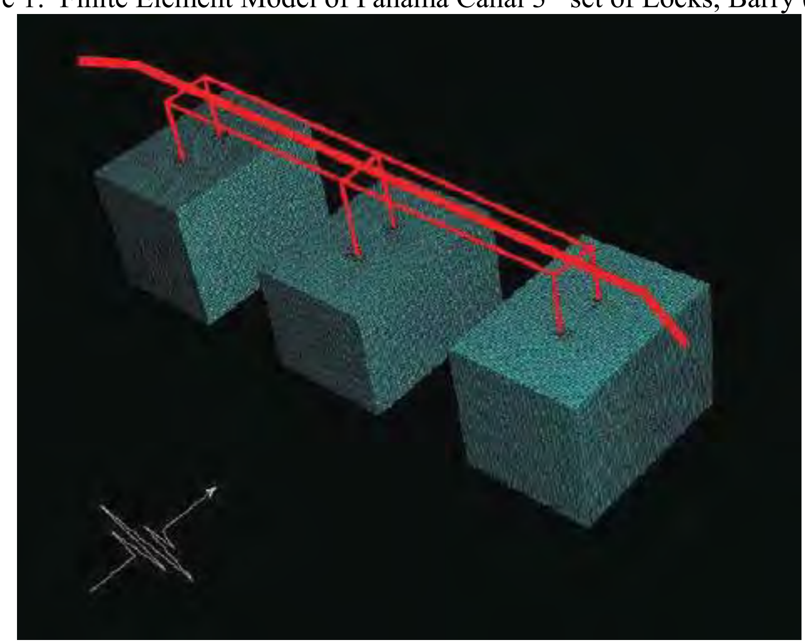

Figure 2: Detailed Three Bent Prototype Soil-Structure-Foundation Interaction Finite Element Model, Jeremic et al. (2009)

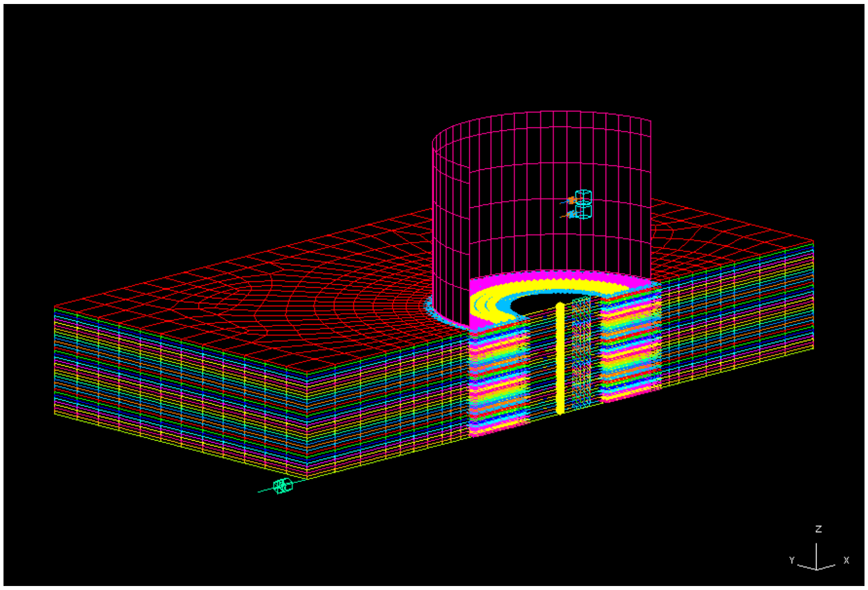

Figure 3: Liquid Natural Gas Tank SSI Simulation Finite Element Model including Fluid and Tank Wall Uplift, Willford et al, (2010)

Nonlinear Time Domain per ASCE 4

Nonlinearities in the soil and structure become more pronounced with increasing intensity of earthquake shaking. It is important to provide realistic analysis tools to assess the performance of nuclear facilities and spent fuel storage systems [Figure 4 shows the movement of a cylindrical cask after the North Anna earthquake] during DBE and BDBE. Time domain analytical solutions can be used for this purpose. Appendix B of ASCE 4-2013 provides non-mandatory guidance for performing nonlinear, three dimensional time domain soil-structure interaction analysis. Nonlinearities in the materials and/or

Figure 4: TN-32 cask movement after the North Anna earthquake

geometry such as loss of contact between soil and structure, and inelastic action in soil and structure can be considered explicitly. Appendix B notes that nonlinear response of a nuclear facility or spent fuel storage system should consider the following behaviors; material nonlinearity, hysteretic behavior (in soil and/or structure), significant uplift or sliding of the foundation, static and dynamic soil pressure effects on deeply embedded structures, local soil failure at the foundation- soil interface, nonlinear coupling of soil and pore fluid, nonlinear effects involving gaping between the structure and surrounding soil at the soil-structure interfaces, and if seismic base isolation is used the nonlinear behavior of the isolators. Nonlinear soil-structure interaction (SSI) can be used to provide element forces and deformations for superstructure component checking and in-structure response spectra, or foundation input motions, which are the first step in a multistep analysis.

Appendix B of ASCE 4does not alter other guidance on the use of three soil columns (BE, LB, UB) for SSI analysis or peak smoothing and broadening of in-structure response spectra. Appendix B provides information on:

- Development of finite element meshes for analysis
- Ground motion input
- Nonlinear constitutive models
- Analysis results and interpretation
- Verification and validation

Development of Finite Element Meshes for Analysis

This sub-section in Appendix B provides general guidance on developing finite element meshes that can appropriately pass seismic waves. The accuracy of a time-domain solution depends on the size of the finite element and the time step of the model. The extent of the finite element model is dependent on the chosen method of analysis such as domain reduction method (DRM), and absorbing boundary condition formulations such as perfectly matched layer (LS-DYNA) or ABC (ABAQUS).

The required mesh density in the finite element model will depend upon the soil characteristics, the element formulation, the solution technique (implicit/explicit) and the cut-off frequency. The analyst should demonstrate the mesh adequately transmits the seismic motions up to the cut-off frequency. Some meshing considerations are:

- The element size should be small enough to capture the nonlinear (i.e. geometric material behavior and/or soil behavior) behavior of the affected region.
- The element size should be small enough to capture the appropriate frequencies. For linear displacement interpolation elements, the longest side of each element (Δh), is defined by equation 1 (Jeremic et al. (2009)).

$$\Delta h \leq \frac{v_s}{10 * f_{\max}} \tag{1}$$

where $f_{\max}$ is the cutoff frequency, and v_s is the smallest shear wave velocity of interest in a given area of the simulation (The maximum element size should be considered for each layer since it is dependent on the shear wave velocity in the soil layers).

- The time step Δt used for solving the equations of motion depends on the solution technique. Explicit solvers will automatically select a timestep required for numerical stability. For implicit solvers, the timestep should be limited to the smaller of a) 10 percent of the smallest natural period of the system being considered, and b) the ratio of the shortest side of any element in a layer to its corresponding shear wave velocity see equation 2 (Jeremic et al. (2009)).

$$\Delta t < \frac{\Delta h}{v_s} \tag{2}$$

where Δh is the maximum grid spacing and v_s is the highest shear wave velocity.

Ground Motion Input

Seismic motions should be input into the SSI model and applied at the boundaries of the soil domain using three-component sets of earthquake ground motions. The boundary conditions used in the model must allow for passage of waves so that the seismic waves are not reflected back into the model. Development of ground motion should follow Section 4.7.3 of ASCE 4. Some methods are available for applying seismic motions to the soil model boundaries, including:

- Domain Reduction Method (Bielak et al. 2003) that analytically replaces motions from the hypocenter with a set of time varying forces applied on a single layer of linear finite elements encompassing the domain of interest (Figure 5). While the domain of interest can have arbitrary inelastic (elastic-plastic, damage, etc) deformations, a degree of approximation still exists in the use of free field motions for load application to the model, at the single layer of elements that are a sufficient distance away from the structure so that the response in the soil is linear.

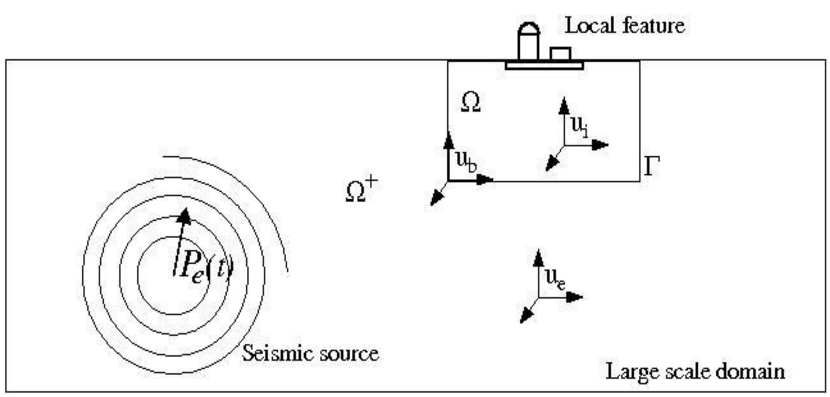

Figure 5: Geometry of the soil-foundation-structure system (Jeremic et al. 2012).

- The Perfectly Matched Layer approach (Basu, 2008) or an approach that uses absorbing boundary conditions (Barry et al., 2012) along the edges of the soil model. These approaches provide methods for bounded domain modeling of wave propagation on unbounded domains. In this approach a three component set of acceleration time series are applied to the base of the soil model, see Figure 6.

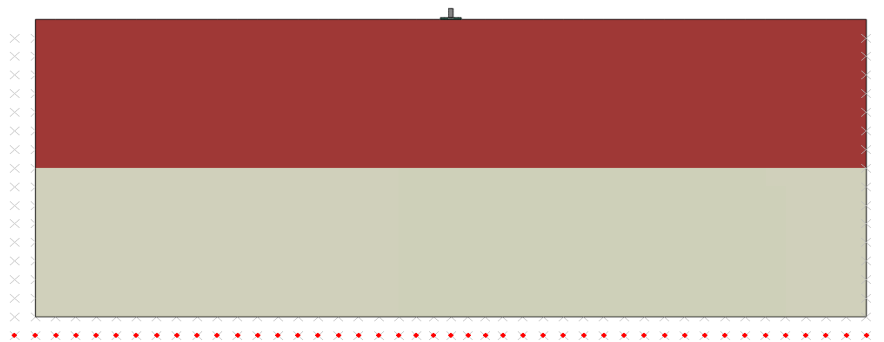

Figure 6: ABAQUS model of spent fuel cask on concrete storage pad resting on a two layer soil column. The three component acceleration time series are applied to the red nodes shown.

Nonlinear constitutive models

If nonlinear constitutive models are required, because nonlinear response is expected, then these materials should capture appropriate nonlinear hysteretic behavior with increasing strains during cyclic motions. Nonlinear constitutive models provide one source of energy dissipation (damping) in time domain SSI analysis. This nonlinear behavior (elasto-plasticity, frictional dissipation, displacement proportional) results in cyclic, hysteretic energy dissipation within the material itself (solids and structures).

If viscous behavior is important, it can be captured in nonlinear constitutive models by incorporating pore fluid (water usually), interaction of solids and structures with surrounding fluids (water, air, etc,), or both. This may be an important energy dissipation source to capture in the model.

Analysis Results and Interpretation

The results from an analysis may be developed using the deterministic approach outlined in ASCE 4 Chapter 2; a minimum of five sets of acceleration time series and three sets of site-specific soil profiles with the appropriate COV. It is anticipated that analyses that exhibit highly nonlinear behavior would need more than 5 sets of acceleration time series. It is the responsibility of the analyst to demonstrate that an adequate number of acceleration time series have been used to meet the intent of ASCE 4, which is 80th percentile nonexceedance probability.

A probabilistic approach as outlined in ASCE 4 Section 5.5 is also an acceptable method for developing results. An alternate approach that involves the use of stochastic elastic-plastic finite elements, which adds additional stochastic degrees of freedom to the nodes, could be used to quantify uncertainty in material properties (Sett et al., 2011).

Verification and Validation

Developing confidence in accurate numerical predictions of the seismic response of nuclear facilities relies heavily on the Verification and Validation (V&V) process. Verification and validation procedures are the primary means of assessing accuracy in modeling and computational simulations. Verification provides evidence that the model are mathematically solved correctly by using closed form problems with known solutions Validation provides evidence that the correct model is solved, and this typically involves experiments.

There are three nonlinear behaviors that should be separately validated: soil nonlinearity, structural nonlinearity, and contact interface nonlinearities (sliding and/or separation). Validation could be achieved by comparing results of the analytical model with experimental data or verification using closed form solutions (if available). Possible references for validating soil, concrete, and contact models and some experimental results are provided in *Practitioners' Guide to Finite Element Modeling of Reinforced Concrete Structures* (2008). ASCE 4 Chapter 5 Section 5.1.11 provides validation goals that should be implemented when performing nonlinear time-domain analyses. Additional validation considerations are:

- Sensitivity analyses should be performed on key nonlinear behaviors that significantly impact the time-domain SSI responses.
- The time-domain SSI analysis should first be validated with a representative model using low amplitude seismic events that are expected to produce linear behavior (in soil and structure) and comparing the results with frequency domain models. The time-domain model should match the frequency domain model for the frequency range of interest.
- To confirm that the meshed soil domain is appropriately passing the seismic waves, a free-field analysis should be performed using the project specific material properties, boundary conditions, and input to verify that the analysis method can replicate the free-field response.

Nonlinear Seismic SSI Considerations and Applications

It is important that the analyst and peer reviewer determine which nonlinear effects should be modeled and consider only those effects that are important. One example of capturing the nonlinear behaviors of interest is provided in Abatt et al. (2006) where the goal of the analysis was to include the sliding interfaces and fluid sloshing in a double shell tank. In this model the nonlinear behaviors were gaping and sliding between the soil and the structure, and fluid sloshing. A time-domain model was developed for the site-response analysis and compared to the generally accepted frequency domain site response analysis for the frequencies of interest. Once the site-response time-domain and frequency domain solutions matched in the frequency ranges of interest, the time-domain site response soil model was used in the nonlinear time domain solution so that the nonlinear geometric behavior (i.e. contact between the water and structure) are captured.

Damping in frequency domain codes is based on empirical data and may not be representative of the real-world damping for large earthquake events but provides a simplistic method for applying damping to a model. A time domain model may provide a more realistic method for representing damping but may be more complicated. The analyst should provide a model that captures damping (energy dissipation) by considering the following types of damping; material nonlinear behavior (hysteretic energy dissipation), material viscous coupling behavior (pore fluid-soil and structure-fluid), Coulomb friction, and radiation damping. The analyst must benchmark the damping parameters in the model with known experimental and/or mathematical results.

Conclusion

Nonmandatory guidance has been developed in Appendix B of ASCE 4 to provide a general framework for performing nonlinear time-domain soil structure interaction. Additional work is required to establish standard methods for performing nonlinear time domain seismic SSI analysis for nuclear facilities.

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