Appendix B Nonlinear Time Domain Soil-Structure Interaction Analysis

B.1 Introduction

This non-mandatory appendix provides guidance for performing nonlinear three dimensional time domain soil-structure interaction analysis. Nonlinear time domain analysis involves nonlinearities in the materials and/or geometry such as loss of contact between soil and structure, and inelastic action in soil and structure. This may be useful when performing analyses for beyond design basis events (see Chapter 1), performing fragility analysis, and analyzing seismic isolation solutions. It is not anticipated to be used as the primary analysis method for new design at this time but may be used for evaluation of existing plants. This method may be used when any of the following behaviors are important to the analysis results:

- Material nonlinearity (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 is expected/present.
- Nonlinear effects involving gaping between the structure and surrounding soil at the soil-structure interfaces.
- Base isolation (as discussed in Section 7.7)

The analyst and reviewer must determine which of these nonlinear effects are important and model and simulate some or all as outlined in this Appendix. For example, if the goal of the nonlinear analysis is capturing gaping and sliding between soil and structure, nonlinear elements (contact) should be added to capture these effects and equivalent linear elements could be used to model the remainder. In this instance the equivalent linear elements modeled in time domain would be matched to the strain compatible soil properties, as outlined in Chapter 2 and 5, for the frequencies of interest. The method should be verified by matching the time domain model free field to frequency domain free field. Reference B-23 outlines an approach when performing a time domain analysis but matching strain compatible soil properties.

In the context of this standard, nonlinear soil-structure interaction (SSI) can be used to provide either 1) element forces and deformations for superstructure component checking and in-structure response spectra, or 2) foundation input motions which are the first step in a multistep analysis. . This appendix does not alter prior guidance in this Standard on the use of three soil columns (BE, LB, UB) for SSI analysis or peak smoothing and broadening of in-structure response spectra.

Guidance is provided in the following subsections on

- Development of finite element meshes for analysis
- Earthquake ground motion input
- Nonlinear constitutive models for soils and structures
- Analysis results and interpretation
- Verification and validation

In performing a nonlinear SSI analysis, the analyst should:

- Demonstrate that the soil domain modeled is sufficiently large that the predicted responses do not change significantly if the domain size is further increased.
- Account for local nonlinearities between the soil and the structure using contact algorithms or gap/frictional elements that can model possible gap opening and closing and frictional behavior (when gap is closed).
- Consider the effects of uncertainties in material parameters, properties of components and ground motion characteristics; sources of uncertainty should be identified and their effects quantified
- Account for buoyancy effects for embedded structures.

Energy dissipation (damping) is captured in nonlinear SSI analysis through the development of a model that includes; material nonlinear behavior (hysteretic energy dissipation), material viscous coupling behavior (pore fluid-soil and structure-fluid), Coulomb friction, and radiation damping.

When performing nonlinear analysis, unintended (numerical) damping (positive and/or negative) can arise within the numerical solution and its effect should be understood. The integration method chosen to advance the solution (e.g., Newmark and/or Hilber-Hughes-Taylor integration method, Ref B-4) may introduce non physical energy dissipation into the model. In addition, 'stiffness proportional' viscous damping must be specified carefully, since it intrinsically increases in proportion to frequency; higher frequencies can therefore often be heavily over-damped. Over-damping can also arise if materials soften beyond their initial elastic stiffness; therefore viscous terms should be based upon instantaneous tangent stiffness, not initial stiffness.

B.2 Development of Finite Element Meshes for Analysis

The extent of the finite element model and the size of individual elements must be selected carefully.

The extent of the finite element model is dependent on the chosen method of analysis; Section B.3 provides details.

The size of the finite elements should be sufficiently small to permit adequate transmission of seismic motions up to the cut-off frequency.

In general, the mesh density will depend upon the soil characteristics, the element formulation, the solution technique (implicit/explicit) and the cut-off frequency for which accurate representation is required. The analyst should demonstrate the mesh adequately transmits the seismic motions up to the cut-off frequency. One method for doing this is using small test models with mesh densities of increasing fineness in the software being used.

Some meshing considerations are:

- The mesh size should be sufficiently small to capture the nonlinear behavior of the effected region.
- The mesh 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 EQN B-1. The use of larger elements can lead to excessive artificial/numerical damping. (Ref. B-2, and B-3)

$$\Delta h \leq \frac{v_s}{10 * f_{max}} \quad \text{(B-1)}$$

where f_{max} is the maximum frequency of interest, and v_s is the smallest shear wave velocity of interest in a given area of the simulation (The maximum mesh 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 (Ref. B-2).

$$\Delta t < \frac{\Delta h}{v_s} \quad \text{(B-2)}$$

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

B.3 Ground Motion Input

Seismic motions should be input into the SSI model at the boundaries of the soil domain. Three-component sets of earthquake ground motions should be applied. Section 4.7.3 should be followed for development of the ground motion. Depending on the specific issues being investigated it may be necessary to represent body and surface waves, including inclined waves, as well as the effects of lack of correlation (termed incoherence in frequency domain).

The type and position of the boundaries must be selected such that radiation damping (radiation of seismic waves resulting from wave reflections and oscillations/vibrations of the structure(s), systems and components) is adequately accounted for.

A number of methods are available, including:

- Domain Reduction Method (Ref. B-1) 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 B-1).

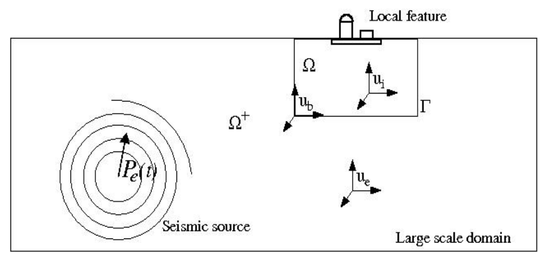

Figure B-1: Geometry of the Structure Foundation Structure system.

Such domain of interest includes soil/rock (adjacent to the NPP), the contact zone (between foundation and soil/rock) and the structure. While the domain of interest can have arbitrary inelastic (elastic-plastic, damage, etc) deformations (Ref. B-2, B-3), 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 "far enough" to be counted as a free field. Reference B-3 Chapter 14 provides information on modeling seismic motion using DRM.

- The Perfectly Matched Layer approach (Ref. B-13) or an approach that uses infinite elements (as described in Ref. B-11), which has certain qualifications related to the linear far field. These approaches provide methods for bounded domain modeling of wave propagation on unbounded domains.

- Modeling a very large nonlinear domain with imperfect boundaries constrained to move as the (nonlinear) free (far) field. The rock outcrop ground motions are applied to viscous dampers that represent the rock in the model. The motions could be applied as force histories. This method may be necessary when significant nonlinearity in the far field is expected (Figure B-2). This is the approach described in Ref. B-12.

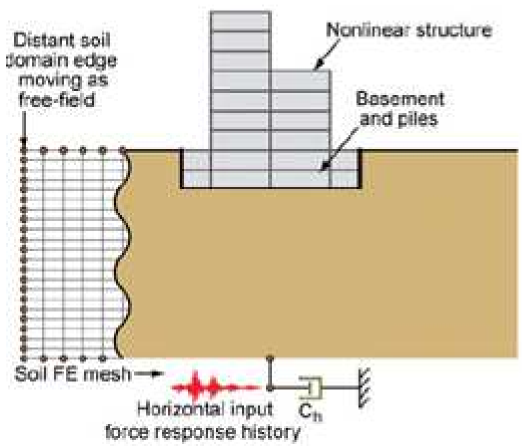

Figure B-2: Direct Approach

B.4 Nonlinear constitutive models

Nonlinear constitutive models for soil, concrete and other structural materials should capture appropriate nonlinear hysteretic behavior with increasing strains and during cyclic motions. The nonlinear constitutive laws and numerical procedures used to integrate constitutive equations should be verified and validated. For instance low aspect concrete shear walls have a pinching behavior that flexural elements will not capture. Section 4.7.2 provides guidance for developing nonlinear structural constitutive and component models.

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), and in contact regions (for example contact of foundation concrete with base soil/rock, Ref. B-4)

Viscous behavior can also 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.

Commercially available software packages such as LS-DYNA, ABAQUS and ANSYS (Refs. B-10. B-11, and B-14), as well as open source packages such as NRC ESSI Simulator (Ref. B-3) provide constitutive equations that can capture the nonlinear behavior of the soil.

The analyst must demonstrate that the nonlinear constitutive soil models are capturing the appropriate three-dimensional soil behavior by using verified and validated constitutive models or matching experimental results.

B.5 Analysis Results and Interpretation

Results from the analysis may include element forces and deformations for superstructure component checking and in-structure response spectra, or development of foundation input motion. These results should be developed using the deterministic approach outlined in Chapter 2; a minimum of five sets of acceleration time series and three sets of site-specific soil profiles with the appropriate COV. The analyst should take the results as the mean for each soil profile run of five sets of acceleration time series and then envelop these. It is anticipated that analyses that exhibit highly nonlinear behavior would need more than 5 sets of acceleration time series. The analyst should demonstrate that an adequate number of acceleration time series have been used.

A probabilistic approach as outlined in Section 5.5 is also an acceptable method for developing results. An alternate approach involves the use of stochastic elastic-plastic finite elements (Ref. B-15).

B.6 Verification and Validation

Developing confidence in accurate numerical predictions of the seismic response of nuclear facilities relies heavily on Verification and Validation (V&V) procedures. Verification and validation procedures are the primary means of assessing accuracy in modeling and computational simulations (Refs. B-5, B-6, B-7, B-8, B-9). Verification is the process of determining that a model implementation accurately represents the developer's conceptual description and specification. Verification provides evidence that the model is solved correctly. It is essentially a mathematics issue. Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. Validation provides evidence that the correct model is solved.

Three nonlinear behaviors that need to be separately validated are: 1) soil nonlinearity, 2) structural nonlinearity, and 3) 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 providing validation of soil, concrete, and contact nonlinearities and some experimental results are provided in References B-21 and B-22.

Chapter 5 Section 5.1.11 provides target validation goals that should be implemented when performing analyses in accordance with this Appendix. Additional considerations for model validation 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). These results should be compared to the results for similar models using procedures outlined in Chapters 2 and 5 of this Standard.

The burden of proof is on the analyst to perform the necessary verification and validation for the analysis.

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