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SMR-300 Time-Domain LS-DYNA Soil Structure Interaction Analysis Methodology Licensing Topical Report

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Export Control restrictions do not apply to this record.

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Revision Log

Revision	Description of Changes
0	Initial Issue.

Executive Summary

This licensing topical report (LTR) presents a time-domain seismic system or soil-structure interaction (SSI) analysis methodology using the LS-DYNA finite element code that can be used for the SMR-300 small modular reactor (SMR) design, hereinafter referred to as the methodology. The methodology provides a modern alternative to traditional frequency-domain approaches such as SASSI by capturing nonlinear soil behavior, soil-structure interface effects, and fluid-structure interaction (FSI) with greater fidelity. Its purpose is to generate seismic input parameters, including in-structure response spectra (ISRS), for the qualification of safety-related systems, structures, and components (SSCs), and to support U.S. Nuclear Regulatory Commission (NRC) review and approval.

The methodology results in ISRS for Seismic Category I (SC-I) and Seismic Category II (SC-II) structures under generic Design Basis Earthquake (DBE) conditions and for site-specific Safe Shutdown Earthquake (SSE) analyses when the DBE does not provide bounding results. It employs fully coupled soil-structure-fluid models solved in the time domain, with linear hysteretic soil models used for DBE cases and nonlinear models applied for high-strain conditions. Safety-related buildings and major subsystems are modeled explicitly, while fluids are represented through an efficient simplified Lagrangian approach. Seismic input motions are derived from SHAKE2000 site response analyses, with multiple time histories applied in accordance with NRC guidance in NUREG-0800.

Validation of the methodology includes benchmarking soil models against SHAKE2000, confirming fluid-structure interaction results with annular tank tests, and comparing system-level predictions to the Lotung Large-Scale Seismic Test (LSST07). In each case, LS-DYNA results closely matched measured data and established frequency-domain analyses, demonstrating acceptable accuracy.

The methodology conforms to NRC requirements in 10 CFR Part 50, Appendix A (GDC 2) and Appendix S, as well as Standard Review Plan Section 3.7 and applicable ASCE/SEI standards. It also builds on NRC precedents that have accepted LS-DYNA time-domain SSI analyses for safety-related spent fuel storage systems and facilities.

In conclusion, the LS-DYNA time-domain SSI methodology is validated, technically sound, and compliant with regulatory requirements. It provides a robust analytical basis for seismic design of structures and ensures the plant can be deployed confidently across a wide range of seismic environments.

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1.0 INTRODUCTION

1.1 Purpose

The purpose of this Licensing Topical Report (LTR) is to describe and justify a time-domain seismic analysis methodology using the commercial finite element code LS-DYNA [1] to perform seismic analyses of a coupled soil-structure-fluid system, including relevant material models and assumptions. The results of this analytical procedure provide design parameters (e.g., in-structure response spectra) for the seismic qualification of safety-related systems, structures and components (SSCs).

The time-domain analysis approach offers a more realistic alternative to the conventional frequency-domain analysis methods due to its computational efficiency for deeply embedded structures and flexibility to incorporate more realistic complexities and/or design features in the analysis.

The seismic system analysis is performed using an established Design Basis Earthquake (DBE) condition, including representative generic soil profiles. This DBE condition is intended to bound the seismic demands at most potential reactor sites. If the loading demand of the site-specific Safe Shutdown Earthquake (SSE) ground motion is demonstrated to be bounded by the generic DBE conditions, a site-specific Soil-Structure Interaction (SSI) analysis is not needed. However, if this bounding seismic condition is not satisfied, site-specific SSI analyses must be performed.

Representative values and example data are provided in this LTR to demonstrate how the seismic analysis methodology could be applied to the SMR-300 design.

For illustrative purposes, the layout of the SMR-300 design is shown in Figure 1-1. The nuclear island includes two Reactor Buildings (RB), two Intermediate Buildings (IB), and a Reactor Auxiliary Building (RAB), with the southern portion of the RAB sharing a common basemat with the RBs and the northern portion founded at a higher elevation.

The methodology can be used to demonstrate that a reactor design is compliant with regulatory requirements of the United States Nuclear Regulatory Commission (NRC), including General Design Criterion (GDC) 2 in Appendix A to Title 10 of the Code of Federal Regulations (10 CFR) Part 50 [2], and Appendix S to 10 CFR Part 50 [3].

SMR, LLC requests NRC approval of the methodology as a reasonable and adequate way of meeting applicable regulations and guidance defined in Section 2.0 of this LTR.

1.2 Scope

The methodology can be used to determine the In-Structure Response Spectra (ISRS) of the seismic Category I (SC-I) and seismic Category II (SC-II) structures that are considered in the seismic system analyses due to:

- The seismic loading from the generic DBE or site-specific SSE defined in accordance with Appendix S to 10 CFR Part 50 [3].

- The effect of SSI during the earthquake including potential geometric nonlinearity at the soil-structure contact interface (i.e., gapping and sliding).
- The effect of Fluid-Structure Interaction (FSI) during the earthquake.

[[[redacted]]]

This LTR is independent of upstream analyses that provide inputs required to implement the methodology. The following supporting analyses are beyond the scope of this report:

- Site-specific seismic response analysis to develop performance-based response spectra (PBRS) at key elevations including foundation input response spectra (FIRS).
- Development of acceleration time histories per the generic seismic design response spectra (SDRS) or site-specific FIRS.

The methodology is site-independent and adheres to NRC guidance articulated in NUREG-0800, the Standard Review Plan (SRP), Section 3.7.2 [4] and other industry standards such as ASCE 4-16 [5].

1.3 Abbreviations and Definitions

The abbreviations used in this report are shown in Table 1-1. Definitions of common terms used in the report are shown in Table 1-2.

Table 1-1 Abbreviations

Term	Definition
AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
AR	Annular Reservoir
ASCE	American Society of Civil Engineering
BE	Best Estimate
CES	Containment Enclosure Structure
CFR	Code of Federal Regulations
CS	Containment Structure
CSSM	Concrete Strengthened Steel Module

DBE	Design Basis Earthquake
EPRI	Electric Power Research Institute
FE	Finite Element
FIRS	Foundation Input Response Spectra
FSI	Fluid-Structure Interaction
GDC	General Design Criterion
GMRS	Ground Motion Response Spectra
HDEC	Hyundai Engineering and Construction
IB	Intermediate Building
ISRS	In-Structure Response Spectra
LB	Lower Bound
LTR	Licensing Topical Report
LSST	Large-Scale Seismic Test
MPC	Multi-Point Constraint
NRC	Nuclear Regulatory Commission
NS	Non-Seismic
OBE	Operating Basis Earthquake
RAB	Reactor Auxiliary Building
RB	Reactor Building
PCMWT	Passive Core Water Makeup Water Tank
PBRS	Performance-Based Response Spectra
PEC	Palisades Energy Center
PSHA	Probabilistic Seismic Hazard Analysis
RCP	Reactor Coolant Pump
RPV	Reactor Pressure Vessel
SCCV	Steel Concrete Containment Vessel
SC-I	Seismic Category I
SC-II	Seismic Category II
SCV	Steel Containment Vessel
SDRS	Seismic Design Response Spectra
SEI	Structural Engineering Institute
SG	Steam Generator
SGES	Steam Generator Enclosure Structure
SMR	Small Module Reactor
SRA	Site Response Analysis
SRP	Standard Review Plan
SOE	Support of Excavation
SSC	Structures, Systems, and Components
SSE	Safe Shutdown Earthquake
SSI	Soil-Structure Interaction
SSSI	Structure–Soil–Structure Interaction

TPC	Taiwan Power Company
TG	Transfer Girder
UB	Upper Bound
UHS	Uniform Hazard Spectrum (UHS)
USDOE	U.S. Department of Energy
USNRC	United States Nuclear Regulatory Commission
ZPA	Zero Period Acceleration

Table 1-2 Definitions

Term	Definition
Containment Structure	SMR-300 containment structure consists of SCV, TG, SCCV, and containment basemat
Reactor Building	SMR-300 reactor building consists of CS, Containment Internal Structures, and CES

[[[redacted]]]

Figure 1-1: Pictorial View of SMR-300 Nuclear Island Structures

2.0 BACKGROUND

2.1 Regulatory Requirements and Guidance

The methodology detailed in this report can be used to demonstrate compliance with the following regulatory requirements and guidance documents.

Appendix A to 10 CFR Part 50 [2]: *General Design Criteria for Nuclear Power Plants*

GDC 2: *Design Bases for Protection Against Natural Phenomena*

Defines regulatory requirements for the design bases to protect safety-related SSCs against earthquakes and other natural phenomena.

Appendix S to 10 CFR Part 50 [3]: *Earthquake Engineering Criteria for Nuclear Power Plants*

Outlines the seismic and geologic siting criteria for nuclear power plants, specifying the requirements for evaluating and designing SSCs to withstand the effects of earthquakes and other related natural hazards. It ensures that nuclear facilities are designed to maintain safety during and after seismic events.

NUREG-0800: *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition*

Section 3.7.1, Revision 4 [6]: *Seismic Design Parameters*

Provides guidance on defining and applying seismic input parameters, such as ground motion response spectra and time histories, for the seismic analysis and design of nuclear power plant SSCs important to safety.

Section 3.7.2, Revision 4 [4]: *Seismic System Analysis*

Provides guidance on methods for evaluating the seismic response of nuclear power plant structures and systems to ensure their safety and functionality during and after seismic events.

Section 3.7.3, Revision 4 [7] *Seismic Subsystem Analysis*

Provides guidance on the analysis and evaluation of seismic responses for subsystems and components within nuclear power plants to verify their structural integrity and functional reliability during earthquakes.

Section 3.8.5, Revision 4 [8]: *Foundations*

Provides guidance for reviewing the design, analysis, and construction of nuclear power plant foundations to ensure they can support loads from structures and withstand seismic and soil-related effects while maintaining safety functions.

NUREG/CR-6896 [9]**:** *Assessment of Seismic Analysis Methodologies for Deeply Embedded Nuclear Power Plant Structures*

Assesses and benchmarks seismic analysis approaches for nuclear structures located at significant depth, to confirm whether existing NRC guidance and modeling tools are adequate or require adaptation.

NUREG/CR-7193 [10]**:** *Evaluations of NRC Seismic-Structural Regulations and Regulatory Guidance, and Simulation-Evaluation Tools for Applicability to Small Modular Reactors (SMRs)*

Evaluates NRC regulatory guidance in the seismic-structural area and several seismic-structural simulation tools used in NRC regulatory applications.

DC/COL-ISG-017 [11]**:** *On Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses*

Provides supplemental guidance to NUREG-0800 on acceptable methods for developing and applying seismic input motions and performing SSI analyses.

Regulatory Guide (RG) 1.122, Revision 1 [12]: *Development of Floor Response Spectra for Seismic Design of Floor-Supported Equipment or Components*

Describes methods acceptable to the NRC staff for developing two horizontal and one vertical floor design response spectra at various floors or other equipment-support locations of interest from the time-history motions resulting from the dynamic analysis of the supporting structure.

RG 1.61, Revision 2 [13]**:** Damping Values for Seismic Design of Nuclear Power Plants

Provides acceptable methods for determining damping values for use in the dynamic analysis of nuclear power plant SSCs to ensure their seismic adequacy.

ASCE/ANS Standards

ASCE/SEI 4-16 [5]: *Seismic Analysis of Safety-Related Nuclear Structures*

ASCE/SEI 43-19 [14]**:** *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities*

2.2 Seismic System Analysis Considerations

The seismic system analysis has significant implications for the structural design and construction of a nuclear power plant. The seismic responses of the nuclear island buildings, which are determined by the specified DBE or SSE, the site's soil properties, and effects such as SSI and FSI, are critical inputs for structural design and contribute substantially to overall construction cost. Consequently, employing a robust and reasonably conservative seismic system analysis method capable of realistically modeling complex design features and material behaviors is essential for advancing new reactor designs. For simplicity, seismic system analysis for structures with coupled soil, structure, and fluid behaviors is often referred to as SSI analysis.

The NRC outlines the specific elements of its seismic review process in SRP Section 3.7.2, "Seismic System Analysis" [4]. This SRP section addresses all aspects of seismic system analysis for the design of safety-related SSCs, including criteria for SSI analysis methods.

A "complete" SSI analysis is defined in SRP Section 3.7.2 [4] as one which accounts for both kinematic and inertial interactions (as applicable) for surface or embedded structures. Kinematic interaction refers to the alteration of free-field seismic waves caused by the geometry of the

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embedded portion of a structure and is therefore independent of the structure's inertial properties. Inertial interaction is associated with the dynamic response of the coupled structure-foundation system, which is governed by the inertial properties of the structure and foundation dynamic stiffness and damping. The SRP allows for any SSI analysis method, provided that: (a) the soil, foundation, and structure are properly modeled to capture spatial variation of ground motion, three-dimensional effects of radiation damping and soil layering, and nonlinear effects from site responses; and (b) ground motions input to SSI analysis are consistent with specified seismic response spectra. This regulatory flexibility provides a pathway for using a nonlinear SSI analysis methodology subject to case-by-case review under the SRP acceptance criteria, although the current criteria primarily address linear elastic seismic analyses.

Historically, the SSI analysis of nuclear structures has been performed using equivalent linear methods with the assumption that soil is bonded with structures throughout the earthquake. Therefore, SSI analyses are typically carried out using linear analysis tools, such as SASSI [15], that operate in the frequency domain. The equivalent linear analysis method is appropriate and acceptable for the seismic system analysis of reactors designed for low and moderate earthquakes.

[[[redacted] **]]**

To ensure analytical robustness in support of deploying the design at high-seismicity sites, the time-domain LS-DYNA method has been adopted for seismic system analysis, replacing the conventional SASSI approach. This shift addresses potential limitations of frequency-domain equivalent linear analysis, which may become invalid due to high soil strain levels, increased influence of near-field zone due to deep structural embedment, and other potential nonlinearity effects. The time-domain LS-DYNA method offers flexibility to model both geometric nonlinearity at the soil-structure interface and material nonlinearity of soil using a validated material model. These capabilities cannot be addressed by the conventional frequency-domain SASSI analysis method.

Figure 2-1 schematically compares the time-domain SSI analysis method and the conventional frequency-domain SSI analysis method, highlighting their capabilities and major differences.

Finally, the time-domain nonlinear SSI analysis method has been widely adopted across multiple industries and is now considered standard practice for the seismic design of tall buildings, bridges, and other infrastructure in regions of moderate to high seismic hazard. Its maturity is also recognized in consensus standards for the dynamic analysis of nuclear structures, such as ASCE/SEI 4-16 [5]. Moreover, the NRC has reviewed and accepted time-domain nonlinear SSI analyses performed by Holtec using LS-DYNA for the HI-STORM UMAX [17] and HI-STORE [18] underground spent fuel storage systems prior to issuing licenses for these facilities.

The remainder of this LTR presents a detailed description and technical justification of the SSI analysis methodology.

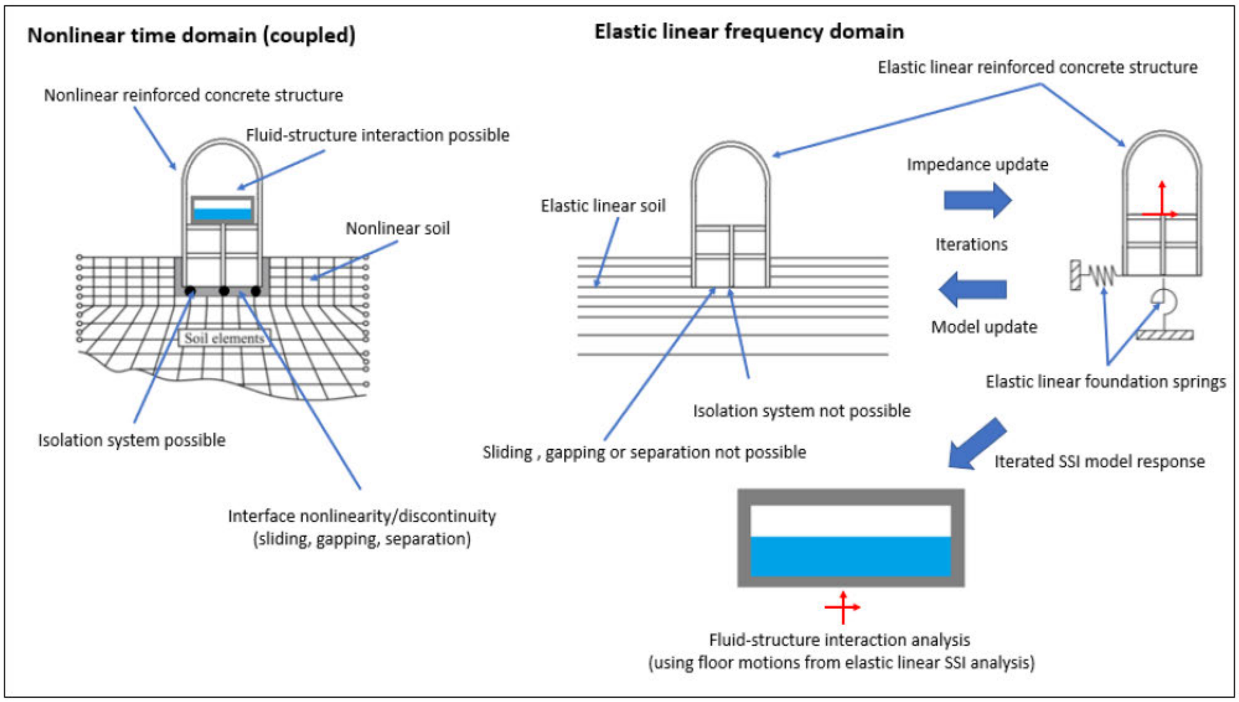

Figure 2-1: Coupled Time-Domain SSI Analysis vs Decoupled and Iterative Equivalent Linear Approach in Frequency Domain

3.0 ASSUMPTIONS AND SOFTWARE

3.1 Assumptions

This time-domain LS-DYNA analysis methodology is based on the following general assumptions. These are typical assumptions for a seismic analysis of nuclear structures and are discussed in ASCE/SEI 4-16 [5]. These general assumptions do not require validation.

[[

[redacted]

[redacted]

[redacted]

[redacted]]]

3.2 Software

The following software is used to perform safety-related evaluations using this methodology:

1. SHAKE2000 Version 9.99.99 and 12.2.5 by GeoMotions [19]

   This software is employed for one-dimensional (1-D) analysis of geotechnical earthquake engineering problems. Specifically, SHAKE2000 is utilized to determine strain-compatible soil properties for the site and to evaluate the site's free-field seismic response under the defined SSE conditions. Results from the SHAKE2000 analysis are used to develop and validate the soil material model, as well as to define the input seismic motions for the SSI analysis.

2. LS-DYNA Revision 15 by ANSYS LLC [1]

   This general-purpose finite element program is used to perform seismic system analysis. To qualify this software for safety-related applications, validation efforts have been conducted across the following three key areas:

- Verification of the specific LS-DYNA soil material model employed in the analysis.
- Evaluation of whether the time-domain LS-DYNA SSI analysis method can produce acceptable results when applied to an instrumented SSI test subjected to an actual earthquake.

Assessment of whether the simplified FSI analysis approach provides reasonably accurate and conservative results for seismic system analysis.

The following software is used to perform auxiliary tasks in this methodology:

1. Python 3.13 by the Python Software Foundation

   Python is employed as a tool for performing basic numerical calculations, processing analysis results, and generating graphical presentations.

4.0 SOLUTION STRATEGY

This section presents an overview of the solution strategy for the seismic analysis of the coupled soil-structure-fluid interaction system. While current NRC documents do not provide comprehensive guidance on performing time-domain nonlinear SSI analyses for nuclear structures, information can be found in documents such as an Idaho National Laboratory report [20] and Appendix B to ASCE 4-16 [5]. These documents cover the development of the finite element mesh, ground motion input, and nonlinear material models, in addition to the assessment of the nonlinear analysis results along with the importance of the verification and validation of the nonlinear SSI numerical modeling.

4.1 Time Domain Solution

[[[redacted]

[redacted]]]

4.2 Procedure

The seismic system analysis is performed using an established DBE condition, including representative generic soil profiles. This DBE condition is intended to bound the seismic demands at most potential sites, thereby reducing the need for site-specific SSI analyses. However, if this bounding seismic condition is not satisfied, site-specific SSI analyses must be performed. Section 5.1.3 describes the method for determining whether the DBE bounds the SSE for a given site. In either case, the procedure for conducting the time-domain nonlinear SSI analysis remains essentially the same and consists of the following major steps:

1. Perform 1-D Site Response Analyses.

   Conduct 1-D seismic response analyses for the soil profiles of the site. The objective is to determine strain-compatible soil stiffness and damping properties, as well as to generate input motions at the base of the soil model used in the SSI analysis. Detailed guidance is provided in Subsection 5.2.1.

2. Prepare Input Data and Develop the Soil Model.

   [[[redacted]

[redacted]]]

3. Develop Structural Finite Element (FE) Models.

   [[[redacted]]

4. Execute SSI Analyses.

   The combined soil-structure model is analyzed separately for the best-estimate, lower-bound, and upper-bound soil profiles, consistent with SRP 3.7.2. For each profile, the model is first run under gravity loading only. This establishes the initial stress state for the subsequent dynamic analyses, each using one of the seven input seismic motion time histories (per SRP 3.7.1) developed for that soil profile in Step 1. Section 5.5 provides detailed instructions.

5. Process SSI Analysis Results.

   For each soil profile, the acceleration time histories extracted at designated structural locations (e.g., foundation, equipment supports) from the LS-DYNA SSI analyses are converted into response spectra at the selected locations. The response spectra are then averaged for each soil profile. The final ISRS are generated by taking the envelope (pointwise maximum) across the three soil profiles. Section 5.6 contains detailed guidance.

4.3 Utilization of SSI Analysis Results for Detailed Design Analyses

The results of the SSI analyses are used to define seismic loads for the structural models employed in detailed design analyses of all applicable load combinations. Potential applications include:

- ISRS for Substructures and Equipment

  Applying the in-structure response spectra obtained from SSI analyses at designated support locations for substructures and equipment that are not explicitly modeled in the SSI model.

- Response Spectra for Structural Analysis

  Utilizing the seismic response spectra generated at the structure foundation and other proper elevations from SSI analyses to perform seismic response spectrum analyses of the structure.

- Time History Input at the Perimeter

  Using seismic time histories obtained from SSI analyses at the structure's perimeter to conduct time history analyses. This approach is preferred for detailed design analyses when the preceding SSI analysis involves strong seismic motions and nonlinear

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behavior, as it preserves the high fidelity of the seismic loads produced by the nonlinear SSI analysis.

- Direct Use of SSI Demands

  For structures modeled with reasonable finite element meshes, directly applying the bounding structural demands obtained from SSI analyses in the detailed design evaluations.

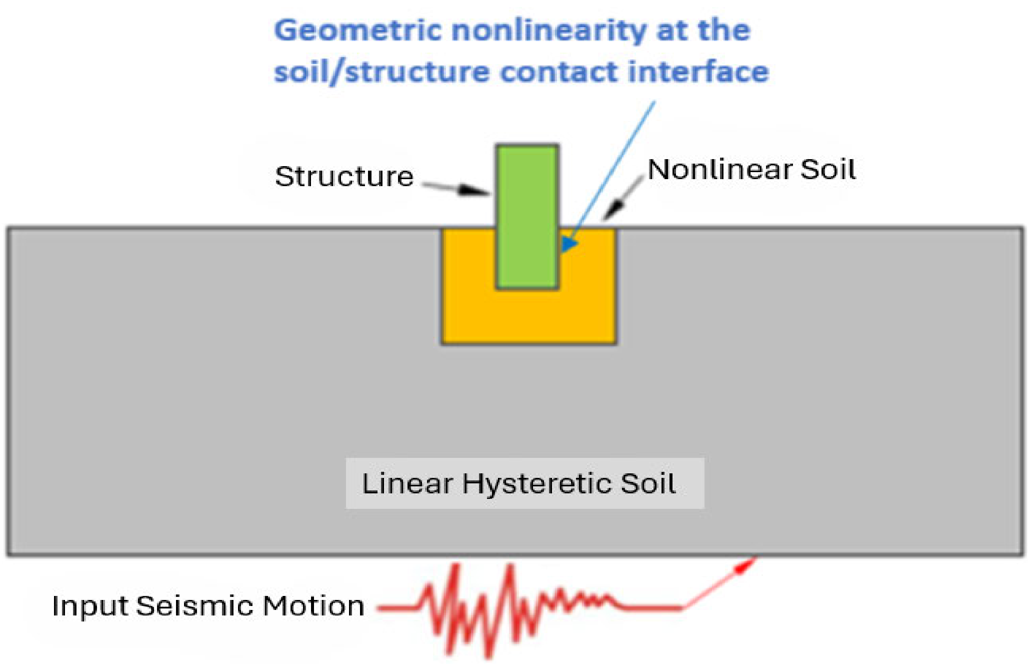

Figure 4-1: Schematic Description of Time-Domain Nonlinear SSI Analysis Method

5.0 REGULATORY COMPLIANCE

The SRP Section 3.7.2 acceptance criteria generally deal with linear elastic seismic system analysis. However, most of the areas of review are applicable to seismic system analysis that is performed in time domain with nonlinearity considered. This section discusses all applicable areas pertinent to seismic system analysis except for the time-domain analysis method discussed in Section 4.0. The discussion also addresses the feedback received from NRC on the SMR LLC white paper [21] regarding the time-domain nonlinear SSI analysis method.

5.1 Input of Ground Motions

As discussed in Section 4.2, this SSI analysis method is performed for an appropriately established DBE and representative generic soil profiles. The intent is to minimize the need for site-specific SSI analyses and subsequent structural design analyses, provided that the loading demand of the site-specific SSE ground motion is demonstrated to be bounded by the generic DBE condition.

5.1.1 Seismic Input Motions for DBE

The DBE can be defined by the SDRS, with spectral acceleration values at various frequencies. An example is provided in Table 5-1. The SDRS are developed to encompass the Ground Motion Response Spectra (GMRS) at the majority of U.S. nuclear power plant sites. Consistent with the guidance in SRP Section 3.7.2 [4], the generic DBE is represented by the foundation input response spectra, defined as the free-field outcrop response spectra per SRP Section 3.7.1 [6] at the elevation of the deepest safety-related building foundation base.

Table 5-2 presents representative generic soil profiles associated with the SDRS,**[[** [redacted] **]]** The generic soil profiles have been developed to represent typical soil conditions at U.S. nuclear power plant sites. In accordance with SRP Section 3.7.2 [4], the seismic system analysis considers three soil profiles: best estimate (BE), lower bound (LB), and upper bound (UB).

Because the SSI analysis is performed in the time domain, the baseline corrected (limited to no drift), statistically independent three orthogonal input seismic motion time histories are derived from the 1-D seismic site response analysis described in Section 5.2.1 and applied at the base of the soil model. Moreover, seven sets of input seismic motion time histories are generated for each soil profile per SRP 3.7.1 Section II.1.B Option 2 [6], since the SSI analysis is nonlinear. Using seven sets of input seismic motion time histories in the SSI analysis allows for averaging structural response quantities obtained from the seven solutions. The above requirements are also applicable to the generation of site-specific seismic input motions.

5.1.2 Seismic Input Motions for Site-Specific SSE

When the seismic demand from the SSE is not bounded by that of the generic DBE per the criteria set forth in Subsection 5.1.3, seismic input motions corresponding to the site-specific SSE are used to perform site-specific SSI analyses.

The site-specific SSE, developed in accordance with RG 1.208 [22], is a performance-based ground motion response spectrum (GMRS) that satisfies 10 CFR Part 100 [23]. The GMRS is derived from the uniform-hazard response spectra (UHRS), which in turn are obtained from a probabilistic seismic hazard analysis (PSHA) based on geologic, seismologic, and engineering investigations, consistent with requirements of Appendix S to 10 CFR Part 50 [3].

The seismic input motions used for the site-specific SSI analysis are baseline-corrected, statistically independent three orthogonal time histories at the base of the SSI analysis soil model. Seismic input motions are developed based on the site-specific FIRS, which are transferred from the GMRS, by performing 1-D seismic site response analyses using the three deterministic soil columns (LB, BE, and UB) of the site.

To ensure hazard-consistent seismic input as required by the interim staff guidance DC/COL-ISG-017 [11], the seismic input motions used for site-specific SSI analyses must pass the "extended NEI Check" [24], as illustrated in Figure 5-1. The effect of incompatibility between the probabilistic site response and deterministic SSI analyses becomes more significant with increasing depth of embedment. The "extended NEI check" described in [24], originally proposed by the NRC staff in the Design-Specific Review Standard for NuScale SMR Design [25], assesses the adequacy of the deterministic soil columns and associated input motions used in the SSI analysis. **[[** [redacted] **]]**

5.1.3 Decision Criteria for Waiver of Site-Specific SSI Analysis

A generic DBE, represented by an SDRS and generic soil profiles, can be used to design a reactor for a variety of sites and avoid a site-specific SSI analysis. The DBE can be selected so that it is more seismically challenging than most potential candidate sites.

The decision criteria for waiving a site-specific SSI analysis are established based on (1) the regulatory position in DC/COL-ISG-017 [25] regarding comparison of the certified seismic design response spectra (CSDRS) with the site-specific seismic demand to determine the applicability of a certified design, and (2) the "extended NEI check" [24] proposed by the NRC staff for seismic input motions used in site-specific SSI analyses of deeply embedded structures, as summarized in Subsection 5.1.2.

The design is qualified for a DBE defined by an SDRS anchored at the elevation of the deepest safety-related foundation. To fully characterize the seismic demand for the safety-related structures that are deeply embedded into the soil, envelopes of SDRS-based site response spectra at the other safety-related foundation elevations and the ground surface must also be developed for all generic soil profiles described in Subsection 5.1.1. These elevations collectively constitute the complete set of "extended NEI check" locations.

[[[redacted]]]

5.2 Modeling of Supporting Soil

For a time-domain SSI analysis, achieving a realistic soil model is of paramount importance, as the seismic response of the soil has a substantial impact on the accuracy of in-structure responses.

[[[redacted]

[redacted]

[redacted]

[redacted]]]

The following subsections describe the key topics in the modeling of the supporting soil.

5.2.1 1-D Soil Seismic Response Analysis

[[[redacted]]]

5.2.2 Soil Material Models

5.2.2.1 [[[redacted]

[redacted]

[redacted]]]

Validation of this soil material model for SSI analyses is discussed in Subsection 6.1.1.

5.2.2.2 [[[redacted]]]

[[[redacted]

[redacted]]]

Validation of this soil material model for SSI analyses is discussed in Subsection 6.1.2.

5.2.3 Soil Model Boundary Conditions

[[[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]]]

The soil model boundary conditions described above are employed in the validation analyses presented in Section 6.0.

5.2.4 Soil Model

[[[redacted]]]

5.3 Modeling of Structures

Nuclear facility structures are categorized based on their safety function and role in accident mitigation. These categories affect their design standards, regulatory requirements, and seismic/structural qualifications. Safety-related structures are required to maintain the integrity of the reactor core and prevent significant release of radioactive material and to remain functional during and after a design basis event, including the SSE. Based on their need to withstand seismic events, structures are also categorized as SC-I, SC-II, and NS structures. SC-I structures are required to remain structurally and functionally intact during and after the SSE while SC-II structures are not required to function during an SSE but must not impair the operation of SC-I structures. These classifications are consistent with the definition of safety-related in 10 CFR 50.2, "Definitions," and the guidance of RG 1.29 [30].

[[[redacted]]]

5.3.1 System Structure Models

The SSI model considers all safety-related buildings, which are SC-I structures supporting various subsystems. In addition, the SSI model also considers the influence from any nearby non-safety-related buildings which have a significant mass that may affect the seismic response of adjacent SC-I buildings.

5.3.1.1 Safety-Related Buildings

[[[redacted]

[redacted]

[redacted]

[redacted]]]

5.3.1.2 Non-Safety-Related Buildings

[[[redacted]]]

5.3.2 Subsystem Structure Models

[[[redacted] **]]**

5.3.2.1 Reactor Coolant System Model

[[[redacted] **]]**

Figure 5-7 shows a representative RCS finite element model.

5.3.2.2 Representation of Floor Loads, Live Loads, and Major Equipment

In accordance with the guidance of SRP 3.7.2 for modeling of structures, the following loads are treated as inertial mass and incorporated into the finite element (FE) models developed for SSI analyses: **[[**

- [redacted]
- [redacted]
- [redacted]
- [redacted] **]]**

5.3.3 Damping of Structures

All SC-I, SC-II buildings, and the RCS considered in the SSI analysis are modeled by linear elastic materials in the forms of shell, solid, and beam finite elements. The energy dissipation during the seismic event is accounted for by assigning appropriate damping to the structural model.

Table 5-3 specifies the damping values for SSCs analyzed for the generic DBE or site-specific SSE condition. These generic damping values are consistent with the those specified in RG 1.61 [13], Table 1 for the SSE condition, and those specified in ASCE/SEI 43-19 [14], Table 3-2 and ASCE/SEI 4-16 [5], Table 3-1 for Response Level 2 condition.

[[[redacted]]]

5.4 Modeling of Fluids

[[[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]]

5.5 Soil-Structure Interaction

In addition to the major constituent parts of the SSI system described in Sections 5.1through 5.4, the complete SSI analysis model also incorporates several other important components, which are discussed in the following subsections.

5.5.1 Soil–Structure Interface Contact Modeling

[[[redacted]

[redacted]

- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]]]

5.5.2 Modeling of SOE Walls and Backfill

[[[redacted]

[redacted]

[redacted]

[redacted]]]

5.5.3 Consideration of Proper Variation of Parameters

5.5.3.1 Uncertainty of Soil Properties

To meet regulatory expectations, the methodology accounts for uncertainties in soil properties by evaluating three representative soil profiles: LB, BE, and UB.

Table 5-2 provides examples of representative soil profiles that could be used for generic SSI analyses under the DBE. The coefficient of variation (COV), used in the following formulas to characterize the deviations in the strain-compatible shear modulus from the BE soil profile, exceed the minimum value of 0.5 as required by SRP 3.7.2 [4].

$$G_{LB} = G_{BE}/(1 + COV) \quad \text{(Eq. 5.5-1)}$$

$$G_{UB} = G_{BE} \times (1 + COV) \quad \text{(Eq. 5.5-2)}$$

Where:

G = the strain-compatible shear modulus for a given soil profile

For a particular site, the three representative soil profiles are developed based on geophysical and geotechnical investigations conducted in accordance with RGs 1.132 [36] and 1.138 [37], followed by site response analyses. The BE, LB and UB soil profiles, initially generated from at least 60 randomized soil columns at the mean, mean minus one standard deviation, and mean plus one standard deviation values, may be adjusted to ensure compliance with the COV criteria specified in Equations 5.5-1 and 5.5-2 for site-specific SSI analyses. For well-characterized sites, a minimum COV of 0.5 for the strain-compatible shear modulus is required. For sites that are not well investigated, a more conservative minimum COV of 1.0 must be used.

5.5.3.2 Water Table

A sensitivity study is required to evaluate the effects of groundwater level.

[[[redacted]

[redacted]]]

5.5.3.3 Concrete Cracking

The concrete in SC-I buildings may crack before or during a seismic event, necessitating the use of effective stiffness factors to account for changes in structural behavior. Accordingly, the stiffness of the finite elements representing the structures must be adjusted based on the dominant response parameter.

[[[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]]]

5.5.3.4 Phasing of Input Motions

[[[redacted]]]

5.6 Development of In-Structure Response Spectra

This section describes the methodology and procedure used to generate the ISRS for SC-I structures, based on results from detailed time-domain nonlinear SSI analyses. The generated ISRS are used to support the seismic qualification of safety-related SSCs in accordance with applicable NRC regulatory requirements and guidance, including 10 CFR Part 50, Appendix S [3], SRP 3.7.3 [7], and ASCE/SEI 4-16 [5].

Following the SSI analysis, acceleration time histories are extracted at the critical locations, including the ones below, for ISRS generation:

- SC-I building foundation bottom levels
- Equipment anchor/support points at basemat and intermediate floor elevations
- SC-I building floors housing safety-related SSCs
- Containment penetrations, crane supports, and equipment support platforms
- Cable trays and high-energy piping support elevations, and spent fuel pool support level

[[[redacted]

[redacted]

[redacted]

[redacted]

[redacted]]

5.7 Effects of Inclined Waves

The potential impact of inclined seismic waves on SSI analyses is an important consideration, as non-vertically propagating waves can introduce additional complexities in the dynamic response of structures and the surrounding soil medium. The significance depends on specific site conditions and seismic wave propagation paths. To address this issue, Subsection 5.7.1 presents a Snell's law–based evaluation method. Subsection 5.7.1.1 provides corresponding sample calculations that show inclined wave effects are not a realistic concern for the Palisades SMR-300 site. Subsection 5.7.2 outlines a more general methodology for evaluating inclined wave effects, offering a framework that can be applied to other sites where such considerations may warrant further analysis.

5.7.1 Evaluation of Inclined Wave Effects Using Snell's Law

[[[redacted]

[redacted]]

1. Sensitivity Study 1: Surface-to-Depth Refraction Using Snell's Law.

[[[redacted]

[redacted]]

2. Sensitivity Study 2: Raytracing .

[[[redacted]

[redacted]

[redacted]]]

5.7.1.1 Example Sensitivity Studies Performed for the Palisades Site

[[[redacted]

[redacted]

[redacted]

[redacted]

[redacted] **]**

5.7.2 General Methodology for Evaluating Inclined Wave Propagation Effects

The following outlines a general framework for assessing and accounting for the potential impact of inclined seismic waves. **[[**

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]]]

Table 5-1: Representative Data SMR-300 Seismic Design Response Spectra for the Generic DBE

[[[redacted]]]

Table 5-2: Representative Data SMR-300 Seismic Design Generic Soil Profiles (LB, BE, and UB)

[[[redacted]]]

Table 5-3: Generic Damping Values for SSI Analyses

Material	Critical Damping
Reinforced Concrete or Masonry	7%
Prestressed Concrete	5%
Steel-Plate Composite Structures	5%
Welded Steel or Bolted Steel with Friction Connections	4%
Bolted Steel with Bearing Connections	7%
Piping Systems	4%
Mechanical and Electric Components	3%
Cable Tray Systems[1]	7%
Conduit Systems[2]	7%
HVAC Duct Systems[3]	4%
Notes: 1. May increase to 10% for cable trays that are 50% or more full; 2. Use 5% for empty conduit systems; 3. May increase to 7% and 10% for companion angle and pocket lock, respectively.	

Table 5-4: Angles of Incidence of Horizontal Shear-Wave Propagation for Palisades SRA Logic Tree Profile P1

[[[redacted]]]

Table 5-5: Angles of Incidence of Horizontal Shear-Wave Propagation for Palisades SRA Logic Tree Profile P2

[[[redacted]]]

[Not Export Controlled]

Table 5-6: Angles of Incidence of Horizontal Shear-Wave Propagation for Palisades SRA Logic Tree Profile P3

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[redacted]

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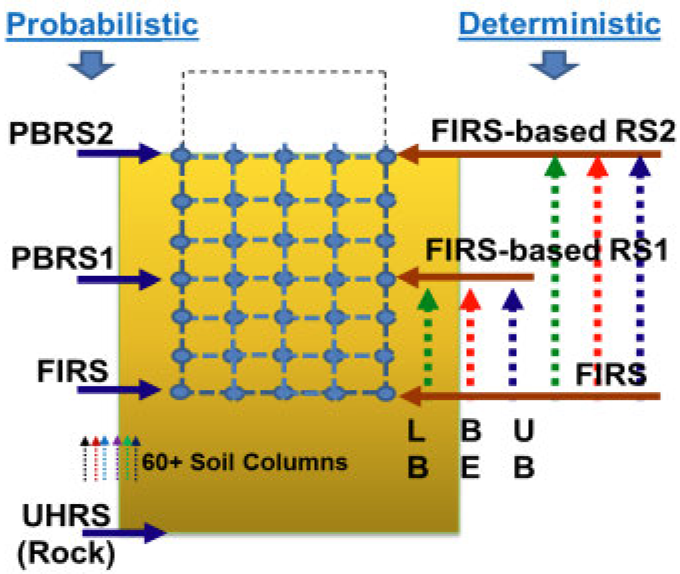

Figure 5-1: Illustration of the “Extended NEI Check”(Reproduced from [24])

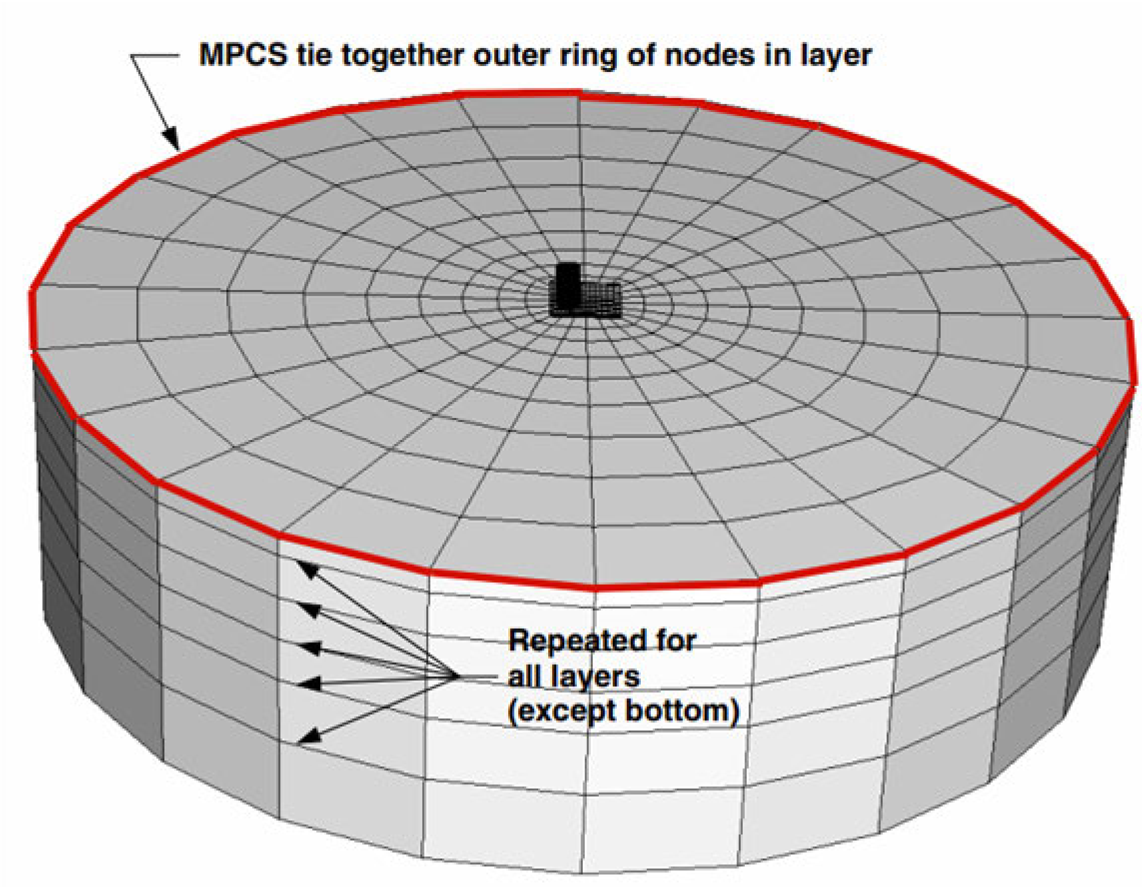

Figure 5-2: Multi-Point Constraints Applied to the Site Boundary of the Supporting Soil Model for SSI Analysis (Reproduced from [29])

[[

[redacted]]]

Figure 5-3: Overall View of the LS-DYNA Soil Model for the SMR-300 SSI Analysis

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Figure 5-4: Meshed LS-DYNA Soil Model Around Embedded Buildings

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Figure 5-5: LS-DYNA Model of the SMR-300 Safety-Related Buildings for SSI Analysis

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[redacted]

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Figure 5-6: LS-DYNA Model of the SMR-300 Safety-Related Buildings Showing the Internals of RBs

[[[redacted]]]

Figure 5-7: RCS Finite Element Model Used in the SMR-300 SSI Analysis

[[[redacted]]]

Figure 5-8: Source-to-Site Travel Paths for a Point Source Located 120 km from the Palisades Site at a Depth of 12 km

[[

[redacted]

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Figure 5-9: Summary of Incident Angles Encountered at the Ground Surface for All Considered Scenarios at the Palisades Site

[[

[redacted]

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Figure 5-10: Summary of Incident Angles Encountered at a Depth of 75 feet for All Considered Scenarios at the Palisades Site

6.0 VALIDATION OF SMR-300 SSI ANALYSIS METHODOLOGY

To support the application of the time-domain LS-DYNA SSI analysis methodology, validation efforts have been undertaken across key aspects of the approach. These include benchmarking the soil models against SHAKE2000 and theoretical solutions, verifying fluid-structure interaction results using U.S. Department of Energy (USDOE) annular tank test data, and comparing system-level predictions to actual seismic test results.

6.1 Soil Material Model Validation

6.1.1 Linear Hysteretic Material Model

[[[redacted]

[redacted]

[redacted]

[redacted]]]

6.1.2 Hysteretic Plasticity Material Model

[[[redacted]

[redacted]

[redacted]]

6.2 Validation of Simplified FSI Simulation Approach

The FSI modeling method described in Section 5.4 for seismic system analysis has been validated in two steps.

Step 1: Validation Against Theoretical Solution

[[[redacted]

[redacted]

[redacted]]]

Step 2: Simplified FSI Model for Efficiency

[[[redacted]

[redacted]

[redacted]

[redacted]]]

6.3 Validation of Time-Domain SSI Analysis Method

[[[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]]

The validation of the time-domain LS-DYNA SSI analysis methodology is documented in detail in the proprietary Holtec Report HI-2251120.

Table 6-1:[[[redacted]]]

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[redacted]

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Table 6-2: Input Data of the Annular Water Tank

Outer radius of the outer tank wall	0.76 m
Thickness of the outer tank wall	7.9 mm
Outer radius of the inner tank wall	0.684 m
Thickness of the inner tank wall	7.9 mm
Height of the annular tank	2.0 m
Height of the annular tank water	1.62 m
Density of the contained water	1000 kg/m^3
Density of annular tank	7850 kg/m^3

Table 6-3: Results of LS-DYNA FSI Analysis (Penalty-Based Lagrangian Formulation)

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[redacted]

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Table 6-4: Results of LS-DYNA FSI Analysis (Simplified FSI Analysis Method)

[[[redacted]]]

Table 6-5: Small-Strain Shear Wave Velocity Profile (Lotung LSST)

Soil Layer	Thickness (ft)	S-Wave Velocity (ft/s)	P-Wave Velocity (ft/s)	Mass Density (kip/ft^3)
1	4	400.3	1273	0.134
2	4	400.3	1273	0.134
3	4	436.2	1273	0.134
4	3	465.9	1273	0.134
5	4.6	465.9	1273	0.134
6	5	518.4	1735	0.134
7	5.5	556.1	1735	0.123
8	6	593.8	1735	0.123
9	5	625.0	3280	0.123
10	5	656.2	3280	0.128
11	5	662.7	3280	0.128
12	5	662.7	3280	0.128
13	9	813.6	6521	0.128
14	9	813.6	6521	0.128
15	8	767.7	6521	0.128
16	8	767.7	6521	0.128
17	8	903.9	6521	0.128
18	8	1040.0	6521	0.128
19	8	1040.0	6521	0.124
20	8	853.0	6521	0.117
Half space		853.0		0.117

Table 6-6: Soil Shear Modulus Degradation Data (Lotung LSST)

Strain (in/in)	G/Gmax		
	0-20 ft sandy soils	20-111 ft sandy soils	Below 111 ft clay soils
0.0001	1.0	1.0	1.0
0.0003	0.983	1.0	1.0
0.001	0.913	0.968	0.998
0.003	0.768	0.851	0.967
0.01	0.584	0.668	0.856
0.03	0.417	0.468	0.614
0.1	0.243	0.272	0.326
0.3	0.125	0.147	0.186
1.0	0.043	0.043	0.10

Table 6-7: Strain Dependent Soil Damping Data (Lotung LSST)

Shear Strain (in/in)	Damping Ratio (%)	
	0-111 ft sandy soils	Below 111 ft clay soils
0.0001	1.17	1.17
0.0003	1.37	1.37
0.001	1.66	1.66
0.003	1.99	1.99
0.01	3.22	3.22
0.03	6.07	4.88
0.1	11.2	7.5
0.3	15.7	10.7
1.0	18.6	13.5

[[

[redacted]

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Figure 6-1: LS-DYNA Soil Column Model for Seismic Response Analysis

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[redacted]

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Figure 6-2: Sample Benchmarking Result of the SSI Analysis Soil Model – X direction

[[

[redacted]

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Figure 6-3: Sample Benchmarking Result of the SSI Analysis Soil Model – Y direction

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[redacted]

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Figure 6-4: Sample Benchmarking Result of the SSI Analysis Soil Model – Z direction

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[redacted]

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Figure 6-5: Comparison of the TOG Seismic Response Spectrum in Lateral Direction Predicted by SHAKE2000 and those by LS-DYNA using [[[redacted]

[[

[redacted]

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Figure 6-6: Comparison of the TOG Seismic Response Spectrum in Longitudinal Direction Predicted by SHAKE2000 and those by LS-DYNA using [[[redacted]]]

[[[redacted]]]

Figure 6-7: Comparison of the TOG Seismic Response Spectrum in Vertical Direction Predicted by SHAKE2000 and those by LS-DYNA using [[[redacted]

[[[redacted]]]

Figure 6-8: Inputs Used for Benchmark Analysis of the Soil Model[[[redacted]]]

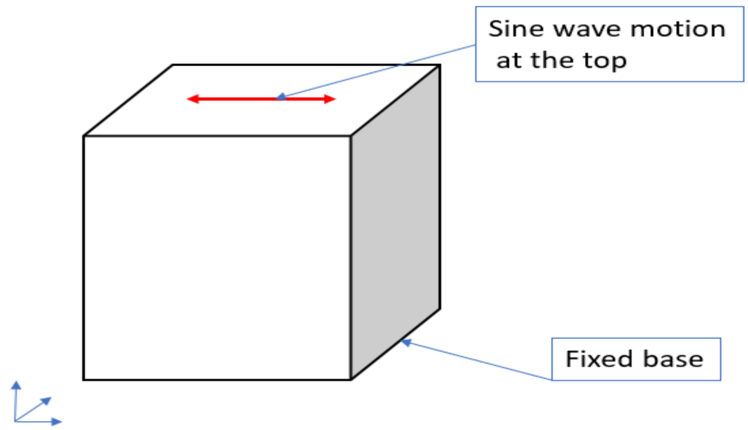

Figure 6-9: Schematic of LS-DYNA Soil Cube Model

[[[redacted]]]

Figure 6-10: Input Stress-Strain Curve Plotted Alongside Predicted Hysteretic Loop

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Figure 6-11: Input Damping Ratios Plotted Alongside Predicted Damping Ratios

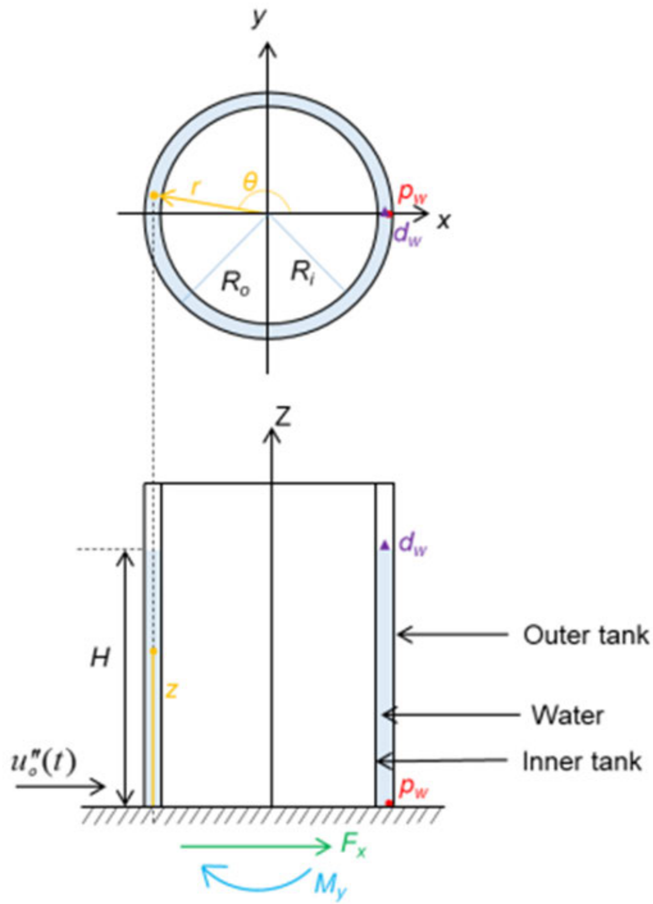

Figure 6-12: Plane and Sectional Views of the Base-Supported Steel Annular Water Tank Subject to A Horizontal Seismic Acceleration Time History (Reproduced from [42])

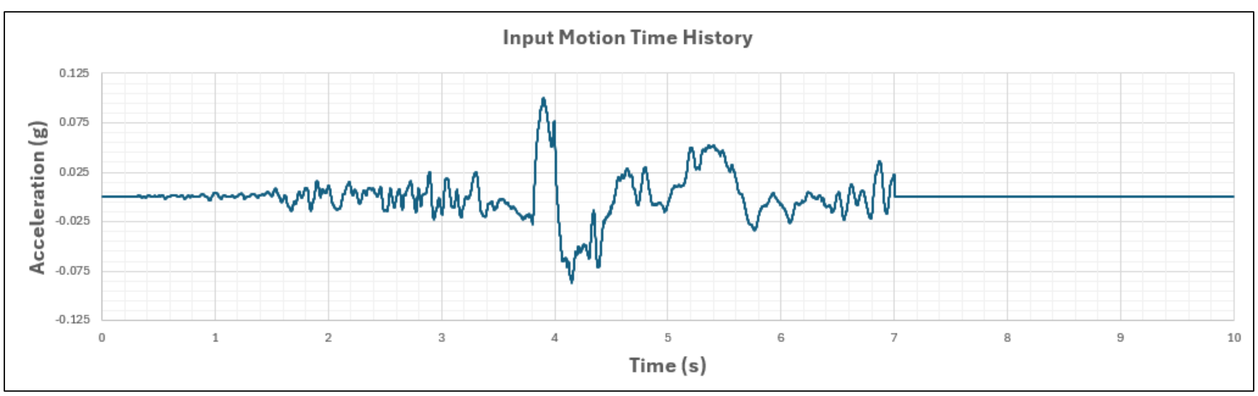

Figure 6-13: Input Acceleration Time History of the Annular Water Tank

[[[redacted]]]

Figure 6-14: Annular Water Tank FSI Analysis LS-DYNA Model with Water Surface Nodes Marked for Wave Height Measurement

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Figure 6-15: Water Wave Height Time History During Earthquake

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Figure 6-16: Annular Tank (Half Model) Base Reaction Force Time History

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Figure 6-17: Derived Annular Tank (Half Model) Base Reaction Moment Time History

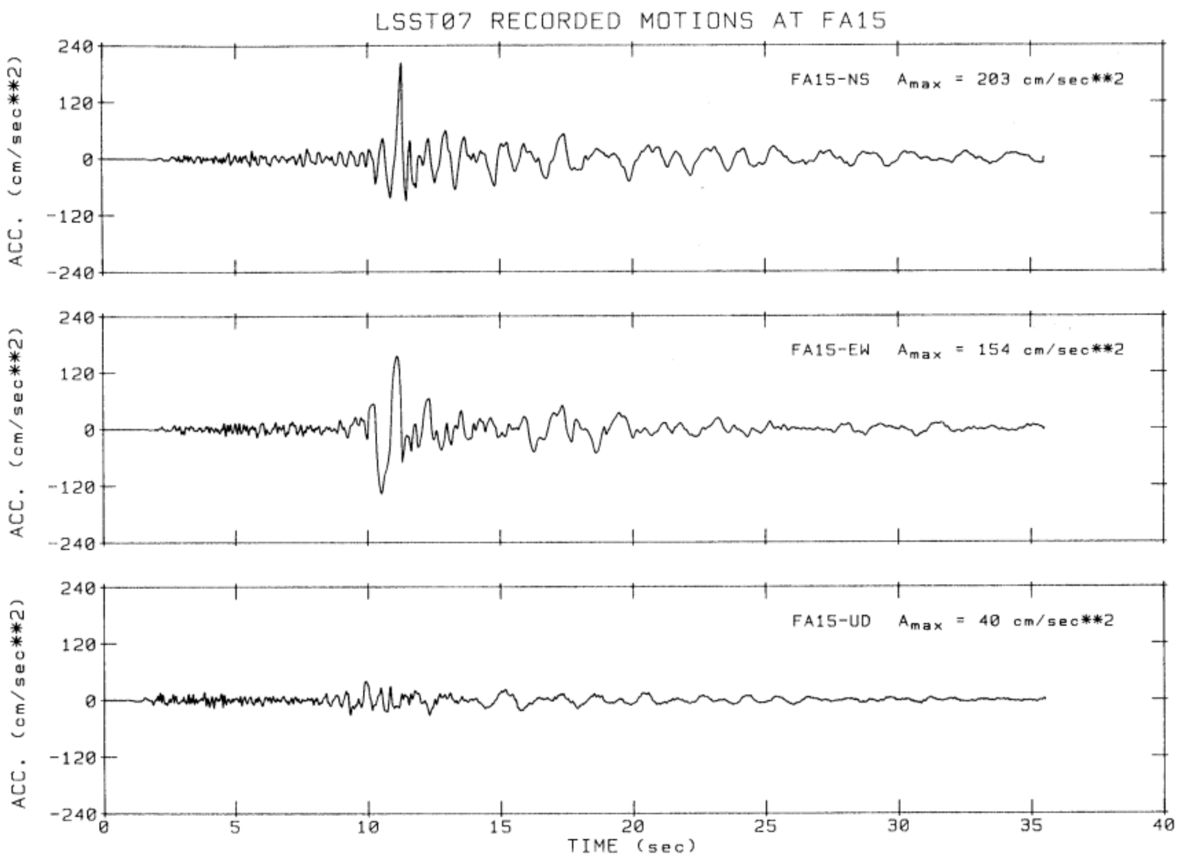

Figure 6-18: Three-Component Acceleration Time Histories Recorded at FA1-5 for Event LSST07 (Reproduced from Figure 4-2(a) of [44])

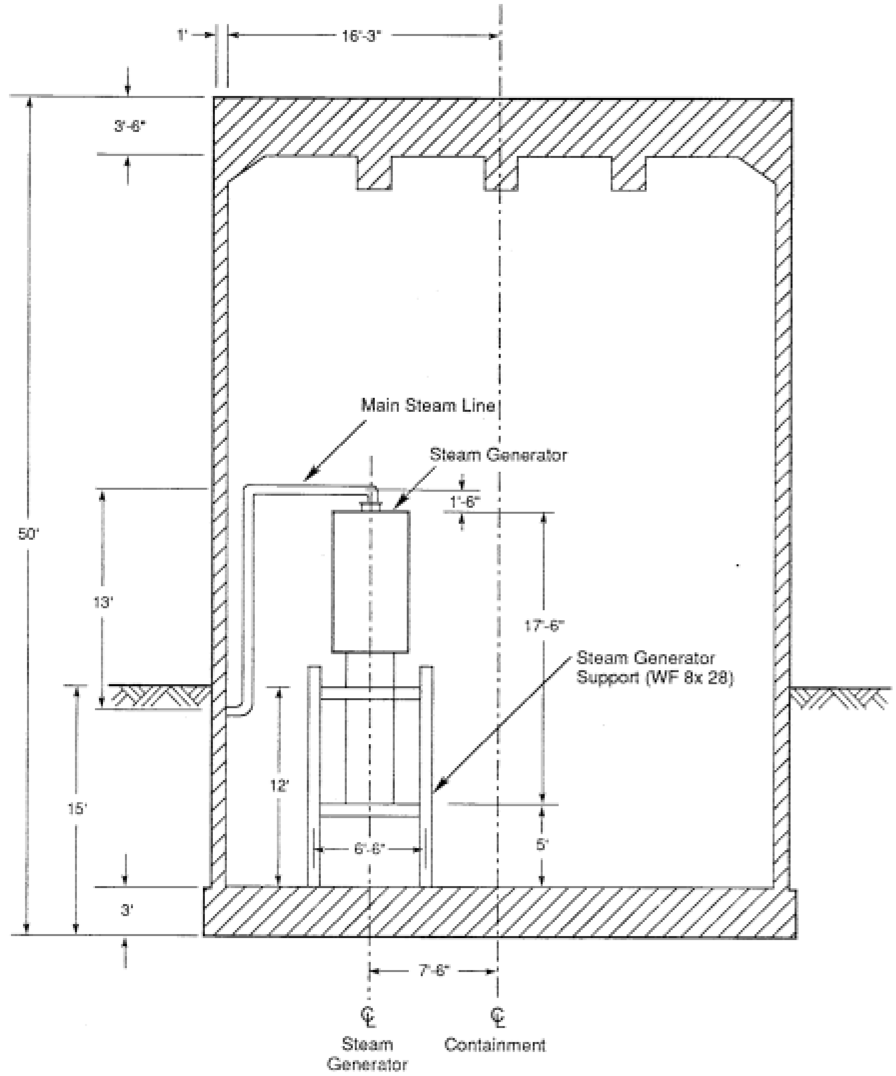

Figure 6-19: **Vertical Cross-Section of 1/4–Scale Containment Model (Reproduced from Figure 2-1 of [44])**

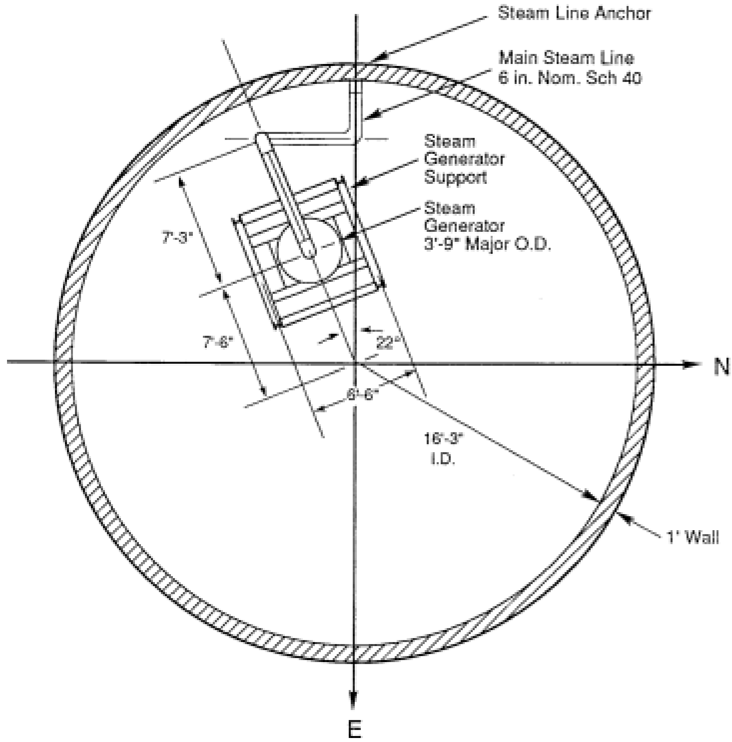

Figure 6-20: **Horizontal Cross-Section of Containment Model**
(Reproduced from Figure 2-2 of [44]**)**

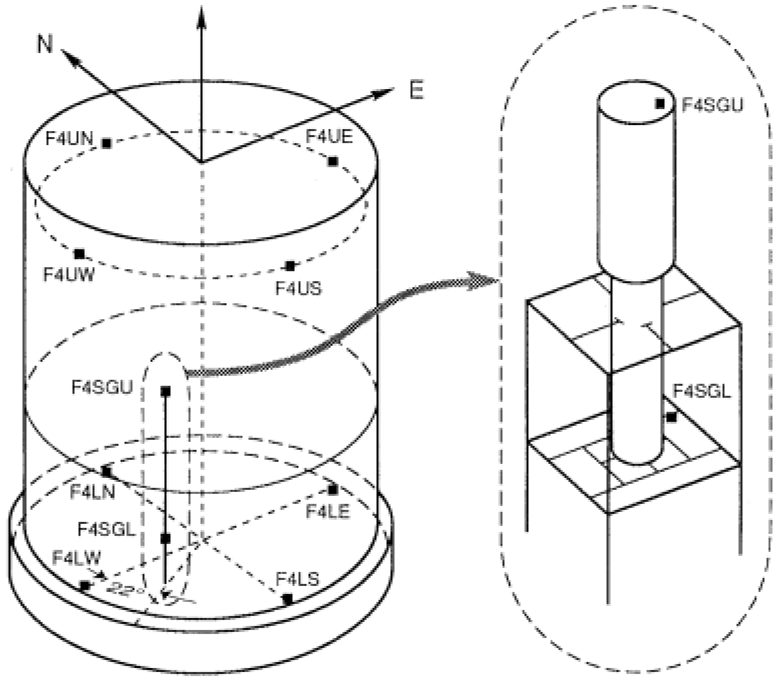

Figure 6-21: **Containment Model Accelerometer Layout (Reproduced from Figure 2-4 of** [44]**)**

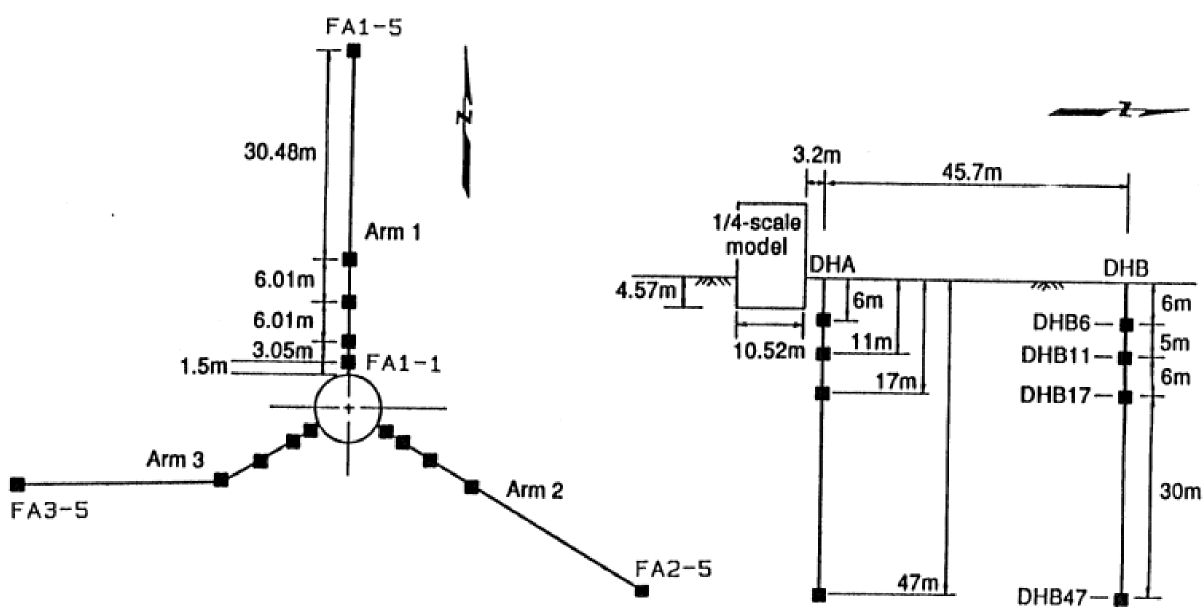

Figure 6-22: **Locations of Accelerometers of Surface Array and Downhole Array (Reproduced from Figure 2-5 of** [44]**)**

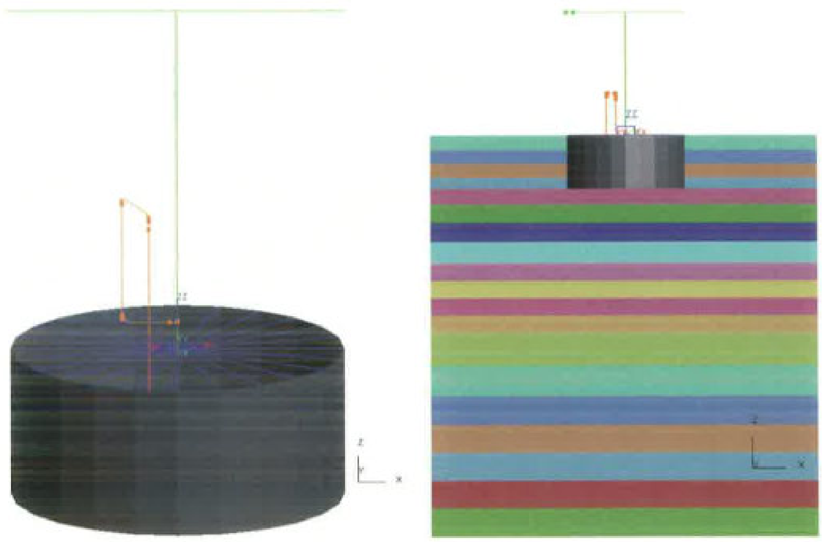

Figure 6-23: Stick Model Used in SASSI Analysis (Reproduced from Figure 2 of [42])

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Figure 6-24: **LS-DYNA SSI Analysis Model for the LSST07 Seismic Event**

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Figure 6-25: LS-DYNA Model of the 1/4–Scale Containment Internal Structures

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Figure 6-26: **Comparison of Far-Field Ground Surface Seismic Response Spectra Between Accelerometer Measurement and LS-DYNA Prediction**

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Figure 6-27: Comparison of Containment Base Seismic Response Spectra Between the Recorded, LS-DYNA Prediction, and SASSI Prediction

[[

[redacted]

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Figure 6-28: Comparison of Steam Generator Base Seismic Response Spectra Between the Recorded, LS-DYNA Prediction, and SASSI Prediction

[[
[redacted]
]]

Figure 6-29: Comparison of Steam Generator Top Seismic Response Spectra Between the Recorded, LS-DYNA Prediction, and SASSI Prediction

[[

[redacted]

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Figure 6-30: Comparison of Containment Top Seismic Response Spectra Between the Recorded, LS-DYNA Prediction, and SASSI Prediction

7.0 CONCLUSION

This topical report describes and substantiates a methodology that can be employed to analyze the SSI consequences of the SMR-300 design. The site-independent SSI analysis methodology incorporates the state-of-the-art modeling and computational capacities of the finite element code LS-DYNA. The SSI analysis methodology can conveniently analyze various nonlinearities involved in the seismic event which cannot be handled by the conventional frequency-domain SSI analysis approach. The methodology conforms to NRC regulatory guidance provided in NUREG-0800, SRP 3.7.2 and industrial standard ASCE 4-16 for performing seismic system analyses, as well as other regulatory guidance and standard(s) listed Section 2.1.

The methodology can be used to demonstrate that the SMR-300 design is compliant with the NRC regulatory requirements in GDC 2 in Appendix A and Appendix S to 10 CFR Part 50.

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