## ACKNOWLEDGEMENTS AND DISCLAIMERS

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## DATA RIGHTS NOTICES

December 18, 2023

Subject: SMR, LLC Soil-Structure Interaction (SSI) Analysis Method

## 1. Introduction

This document has been crafted to facilitate discussions between the USNRC staff and Holtec's structural analysis team concerning the proposed nonlinear time-domain soil-structure interaction (SSI) analysis methodology. This methodology will be employed to assess the seismic responses of seismic Category I structures and neighboring structures of the SMR-300 design. The outcomes of the SSI analysis have direct implications for subsequent structural evaluations and defining seismic loads for assessing safety-related equipment and their supporting structures within seismic Category I buildings.

This white paper serves a dual purpose. Firstly, it offers an overview of the proposed SSI analysis methodology, complete with updates on our progress (including initial SSI analysis results) since our previous meeting on November 8, 2023. Secondly, it responds to the feedback provided by the NRC staff, addressing their expectations concerning the validation and verification (V&V) of the proposed SSI analysis method. The white paper discusses benchmarking and calibration of soil material models, while elucidating our V&V strategy and steps to ensure and demonstrate the accuracy of the proposed SSI analysis method.

Although a complete SMR SSI analysis involves various areas, such as the 12 aspects listed in Ref. [1], the scope of this white paper is limited to addressing the key portions of the proposed SSI analysis method. Therefore, the following sections also briefly touch on the design basis earthquake, generic site soil profiles, and the SSI analysis finite element model development.

## 2. SSI Analysis Method

In an NRC public meeting on September 27, 2022, Holtec proposed a nonlinear time-domain SSI analysis method for generating in-structure response spectra (ISRS) for the SMR-160. While the design has since been uprated to SMR-300, the preliminary results remain useful in evaluating the efficacy of the analysis method. This method is endorsed by ASCE 4-16, Ref. [2], for analyzing nuclear structures and has been applied in non-nuclear industries for decades. Illustrated schematically in Figure 1, this approach distinguishes itself from the conventional frequency-domain equivalent linear analysis method employed in the linear analysis code SASSI.

The proposed SSI analysis method using the LS-DYNA computer code and the traditional SASSI analysis approach share more common considerations than differences, as both methods employ finite element analysis techniques. The primary distinctions between the two approaches lie in two areas: (1) nonlinear vs. linear and (2) time domain vs. frequency domain. In comparison with the SASSI analysis approach, the Holtec proposed SSI analysis method is adept at explicitly capturing potential geometric nonlinearity (e.g., sliding and gapping) at the interfaces between deeply embedded seismic Category I structures and the surrounding soil. Additionally, the proposed SSI method can effectively model plausible pronounced soil nonlinearity expected to manifest near the embedded structures. Notably, both nonlinear effects can be of substantial significance in the SSI analysis scenarios involving high seismic intensity and/or weak soil conditions. In summary, the proposed LS-DYNA SSI analysis method, compared with the traditional SASSI analysis approach, can predict both linear and nonlinear seismic responses. Finally, while both time domain and frequency domain analyses are established numerical analysis techniques, the frequency domain analysis is limited to solving linear problems. The flowchart shown in Figure 2 outlines the procedure of the time-domain SSI analysis method. Note that the final two steps in the dashed-line box are only taken for the SSI analysis method verification phase as described in Section 6.

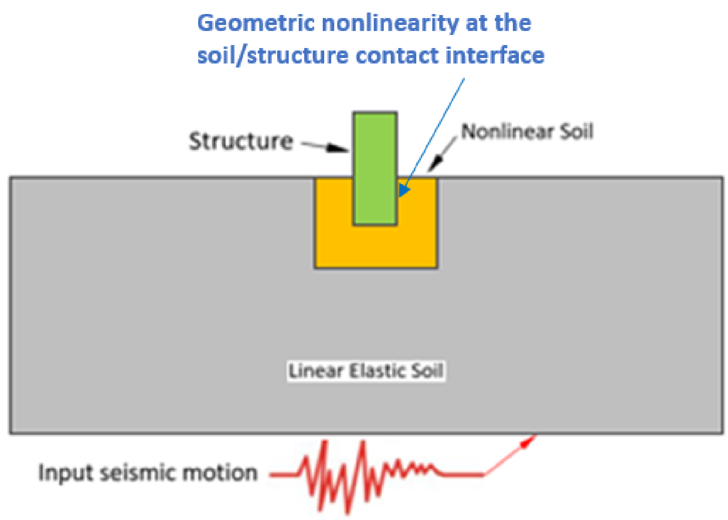


*Figure 1. Schematic description of nonlinear time-domain SSI analysis method*

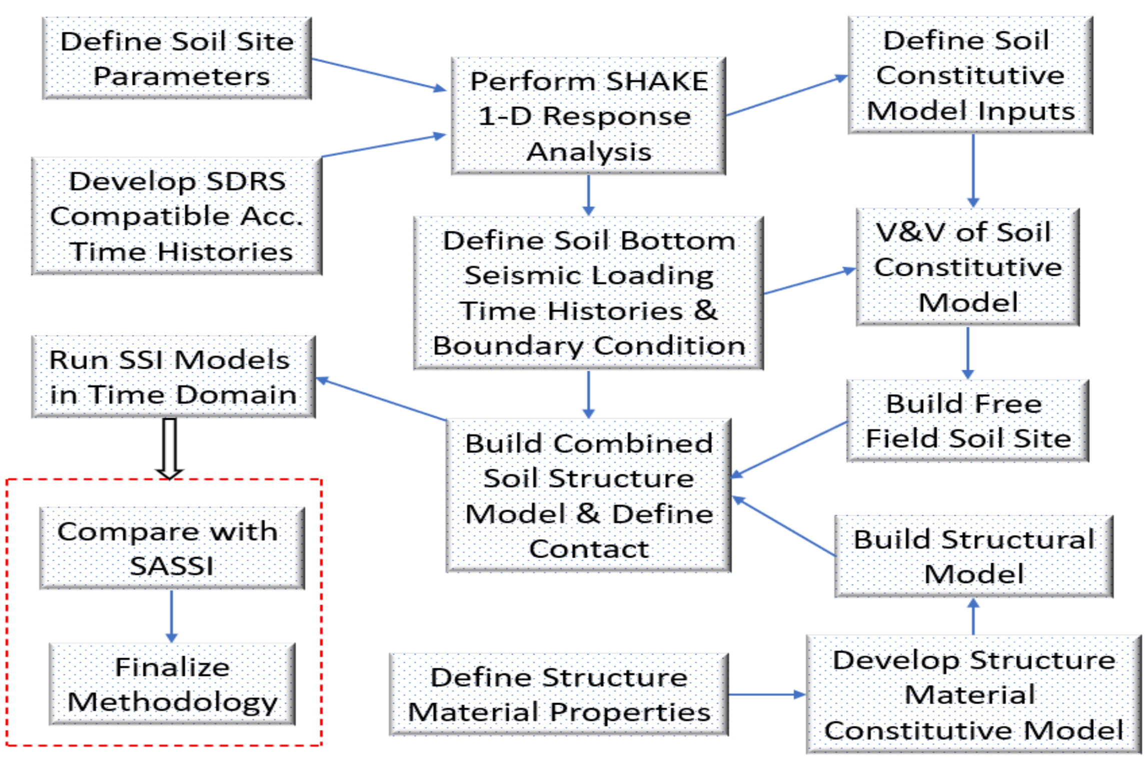


*Figure 2. Flow Chart Describing the Time-Domain SSI Analysis Procedure*

## 3. Design Basis Earthquake and Soil Profiles

Holtec intends to submit a construction permit application under 10 CFR 50 for a dual-unit SMR-300 plant at the current Palisades Nuclear Generating Station (PNGS) site. The dual-unit plant will be structurally qualified based on a generic design basis earthquake and three soil profiles that will bound the site-specific seismic condition. More specifically, to meet the intent of DC/COL-ISG-017, Ref. [3], site response analyses will be carried out to assure that the probabilistic performance-based foundation input response spectra (FIRS) of the PNGS site-specific seismic hazard are enveloped by the recovered free-field seismic responses at the SMR foundation from the input seismic motions used in the SMR SSI analysis. Furthermore, the "extended NEI Check," as detailed in Ref. [4], will be conducted as deemed appropriate.

The characterization of the SMR-300 design basis earthquake centers on the seismic design response spectra (SDRS), defined in the following tables. Notably, the hypothetical soil outcrop SDRS is specified at the elevation of the containment enclosure structure (CES) base.

Horizontal directions

| Frequency (Hz) | Acceleration (g) |
|---|---|
| 0.1 | 0.0192 |
| 0.25 | 0.12 |
| 1.0 | 0.48 |
| 3.5 | 0.92 |
| 12 | 0.92 |
| 50 | 0.4 |
| 100 | 0.4 |

Vertical Direction

| Frequency (Hz) | Acceleration (g) |
|---|---|
| 0.1 | 0.0133 |
| 0.25 | 0.08 |
| 1.0 | 0.36 |
| 3.5 | 0.88 |
| 12 | 0.92 |
| 50 | 0.4 |
| 100 | 0.4 |

*Table 1. Seismic Design Response Spectra*

The consideration of three soil profiles, which represent the best estimate (BE), lower bound (LB), and upper bound (UB) soil profiles of the site, is aligned with the guidance of NUREG-0800, SRP 3.7.2 for seismic analysis. The small-strain shear wave velocities of each soil profile are listed in Table 2 for a 170-foot-deep soil column (extending well below the depth of the deepest planned structure).

To facilitate the implementation of the time-domain SSI analysis, 3-D seismic acceleration time histories are generated at the base of the 170-foot soil column. This is achieved through a sequential process involving 1-D site response analyses conducted for each distinct soil profile, utilizing the SHAKE2000 software.

For the frequency-domain SHAKE2000 analysis, a total of seven distinct sets of input acceleration time histories are employed at the CES basemat bottom elevation (i.e., EL -86'). These input histories are developed in accordance with the SDRS and are subsequently utilized in the analysis. The strain-dependent soil modulus degradation and damping ratio data, which also slightly vary with the depth of the soil, are taken from the 1993 Electric Power Research Institute (EPRI) document TR-102293. This nonlinear material behavior of the soil is effectively addressed through the equivalent linear analysis capabilities offered by SHAKE2000. This is achieved through a series of iterative solutions, enabling the derivation of strain-compatible soil modulus and damping ratio outcomes. These outcomes correspond to the seismic loading conditions attributed to the design basis earthquake.

Shear Wave Velocities

| Layer No. | Thickness (ft) | Depth (ft) | Shear Wave Velocity (ft/s) | | | Density (pcf) |
|---|---|---|---|---|---|---|
| | | | LB | BE | UB | |
| 1 | 2 | -2 | 635 | 900 | 1240 | 120 |
| 2 | 3 | -5 | 705 | 1000 | 1415 | 120 |
| 3 | 15 | -20 | 810 | 1150 | 1630 | 120 |
| 4 | 20 | -40 | 985 | 1400 | 1980 | 120 |
| 5 | 20 | -60 | 1130 | 1600 | 2265 | 120 |
| 6 | 20 | -80 | 1200 | 1700 | 2405 | 120 |
| 7 | 20 | -100 | 1255 | 1780 | 2520 | 120 |
| 8 | 20 | -120 | 1305 | 1850 | 2620 | 120 |
| 9 | 20 | -140 | 1360 | 1930 | 2730 | 130 |
| 10 | 30 | -170 | 1410 | 2000 | 2830 | 130 |

*Table 2. Shear Wave Velocities of Soil Profiles*

### 4. Validation and Verification of Soil Models

In the realm of geotechnical engineering, it is well-established that soil exhibits characteristics akin to those of a nonlinear and inelastic material. The nonlinearity observed in soil stress-strain behavior is a result of the ever-changing shear modulus. Furthermore, the inelastic nature of soil signifies that during unloading, the material follows a distinct trajectory compared to its loading path, effectively dissipating energy at the contact points between particles.

In practical computational applications, an equivalent linear analysis method is traditionally employed within the frequency domain. This approach offers computational convenience and is widely utilized for assessing 1-D soil seismic response (as exemplified by SHAKE2000 analysis) or the 3-D interaction between soil and structures (as demonstrated in SASSI analysis).

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## 5. Verification of the Nonlinear Time-Domain SSI Analysis Method

In addition to the soil material model benchmarking and calibration efforts detailed above, which can be considered as the first step of the two-step V&V of the proposed SSI analysis method, Holtec plans to embark on a supplementary validation and verification effort pertaining to a deeply embedded simple concrete structure subjected to soil-structure interaction. This effort entails both time-domain and frequency-domain SSI analyses, utilizing LS-DYNA for the former (employing *MAT_232 for soil modeling) and SASSI for the latter, to predict the seismic responses of the deeply embedded structure. The procedure outlined in subsection 4.1 to establish *MAT_232 input parameter data will be followed, and the same approach to impose the seismic input motion and the standard viscous boundary will be employed. The successful completion of this initiative serves as an indicator of a satisfactory V&V for the proposed SSI analysis method for SMR-300.

Figure 14 schematically illustrates the simple SSI problem slated for analysis in the second step of the V&V process for the proposed SSI analysis method.

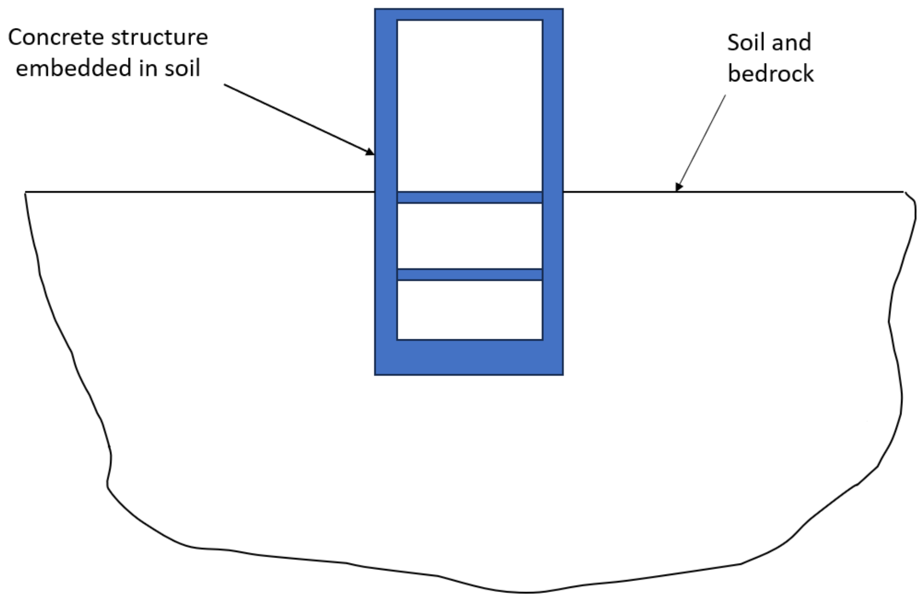


*Figure 14. Schematic of the Simple SSI Problem*

The primary objective of this second-step V&V effort is to confirm that, when analyzing the simple SSI problem as a linear system with the proposed time-domain LS-DYNA method, the predicted in-structure response spectra closely match those acquired through the conventional frequency-domain SASSI analysis approach. To align with this aim, the embedded concrete structure will be connected to the soil through shared nodes in the LS-DYNA model. The SSI analysis will be conducted for a mild or moderate seismic event (PGA ≤ 0.4~0.5g), as the precision of frequency-domain SSI analysis results obtained using SASSI for a high-intensity earthquake may be compromised due to significant soil and geometric nonlinearities.

To illustrate the ramifications of geometric nonlinearity, a specific modification will be introduced to the LS-DYNA model. This involves the dissection of finite element models representing both the soil and the embedded structure and the addition of surface-to-surface contact between the two models. The intention behind this alteration is to effectively capture potential instances of gapping and sliding at the interface of contact between the soil and the structure.

Through the execution of additional SSI analyses, the revised LS-DYNA model is expected to yield seismic response predictions that exhibit progressively discernible deviations from the outcomes derived through the frequency-domain SASSI solutions. Such deviations are anticipated to become more pronounced as the intensity of the seismic activity escalates. The evaluation initiative outlined in this section serves not only to authenticate the precision of the proposed time-domain SSI analysis method but also to showcase its efficacy in handling SSI events characterized by pronounced nonlinearity.

## 6. SMR SSI Model Development

The preliminary SSI analysis considered the single-unit SMR-160 design, available prior to the finalization of the uprated dual-unit SMR-300 design. This preliminary analysis was conducted using the explicit finite element software, LS-DYNA. The LS-DYNA SSI model is composed of several key parts, encompassing the soil, seismic Category I structures, and adjacent non-seismic Category I structures.

Within the LS-DYNA SSI model for SMR-160, the array of structures includes the deeply embedded CES, which houses the steel containment structure (CS) including the concrete structures inside the CS, the reactor auxiliary building (RAB), and the control building (CB), as well as surface-supported structures such as the radioactive waste building (RWB), the turbine building (TB), and the auxiliary building (AB).

The LS-DYNA model is characterized by the following attributes:

- Solid elements are used to model soil and thick civil structure components (e.g., basemats). Solid elements are also used to model water in the annular reservoir and in the spent fuel pool through a simple fluid material model which has no shear capacity. Note that the simple fluid model does not simulate water sloshing, which has only secondary effects on SSI analysis results.

- Shell or thick shell elements are used to model walls and slabs of civil structures or thin steel equipment/structures.

- Beam elements are used to model beams and columns of civil or steel structures and certain equipment.

- Mass elements are used to account for equipment of significant mass.

- Structures are placed at the center of SSI model with a significant distance from the soil lateral periphery.

- The soil model periphery nodes at the same elevation are constrained to move together to simulate the free field soil behavior. The standard viscous boundary condition is applied to the soil bottom surface to fully absorb the energy from the reflected seismic stress waves.

- The maximum element size is limited to ensure the SSI model can capture the appropriate frequencies.

- All elements are connected except at soil/structure interfaces, where LS-DYNA automatic surface-to-surface contacts are defined to capture potential geometric nonlinearity.

The following figures show the relevant LS-DYNA models.

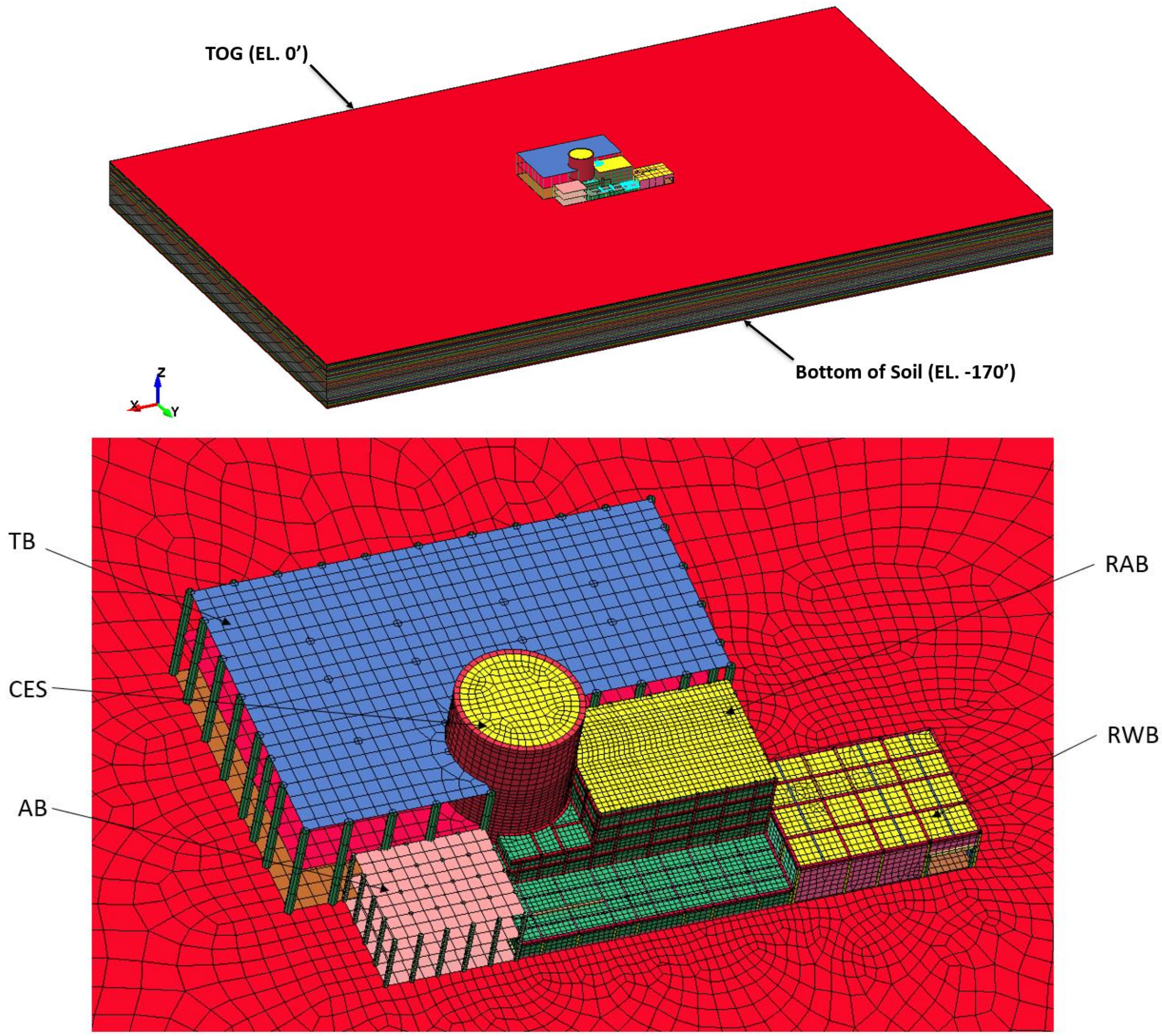


*Figure 15. LS-DYNA SSI Model of Overall SMR-160 Site*

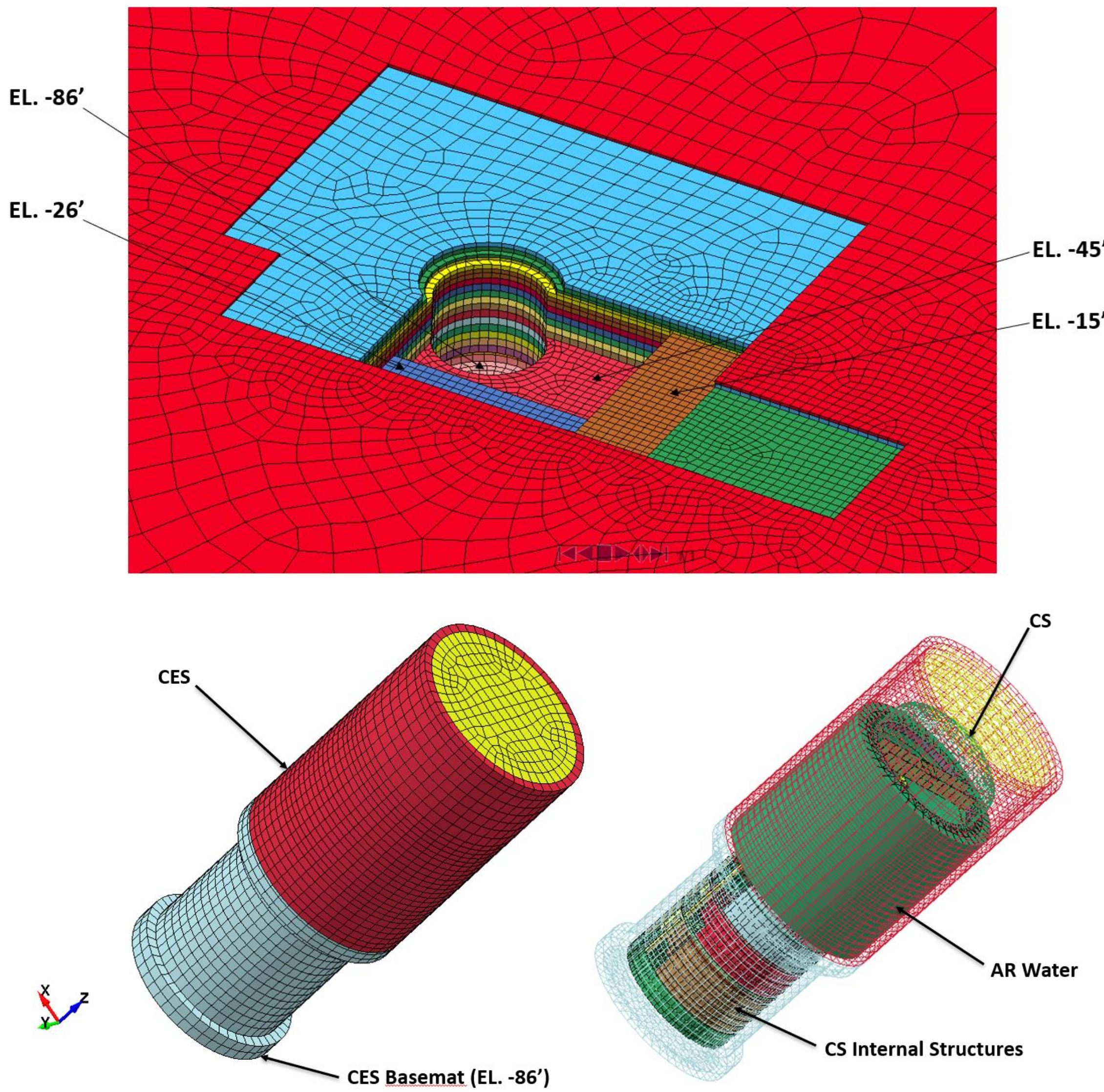


*Figure 16. LS-DYNA SSI Model of Overall SMR-160 Site, Showing CES Excavation, CES, and CS*

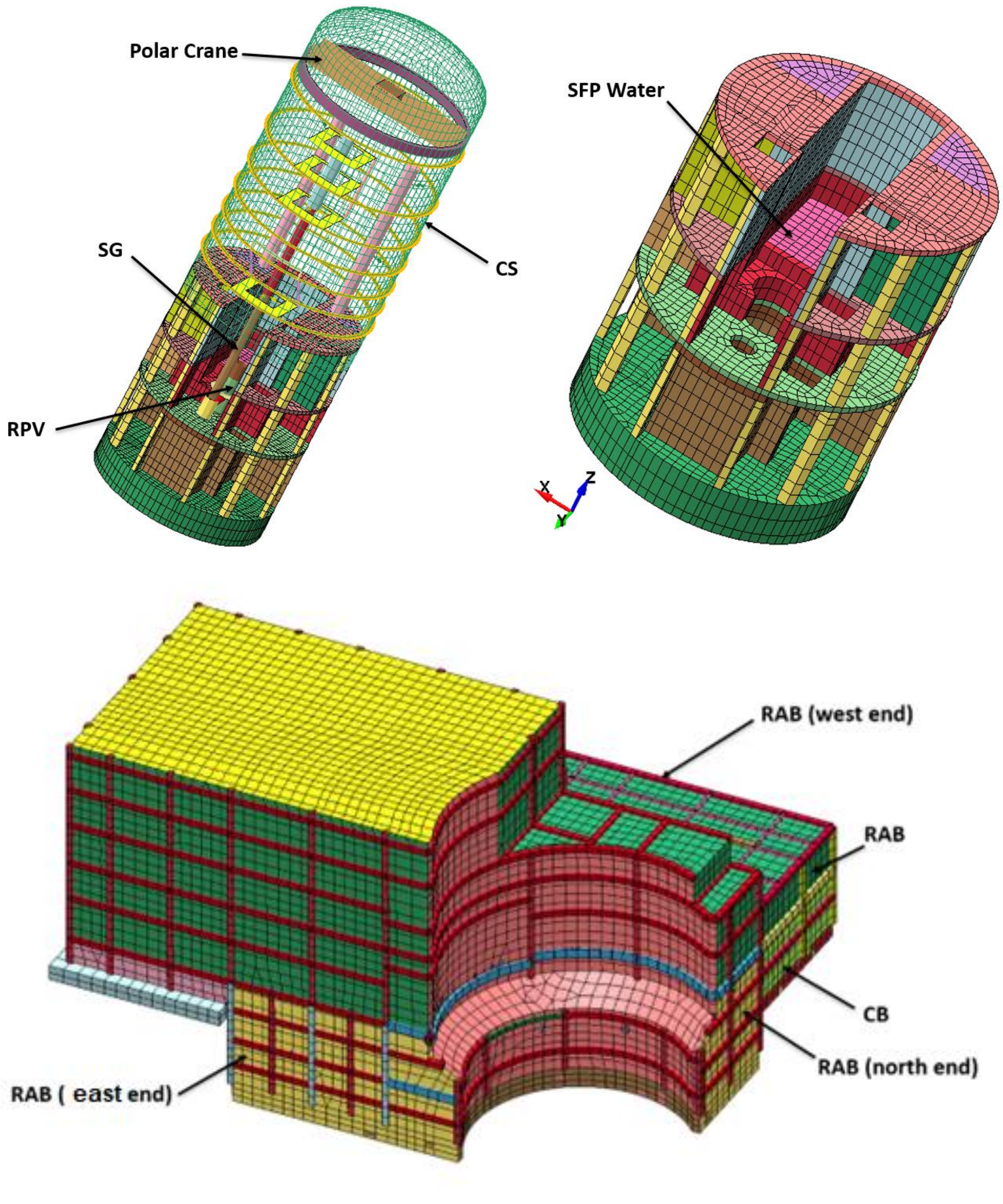


*Figure 17. LS-DYNA SSI Model of SMR-160 CS and Surrounding Structures*

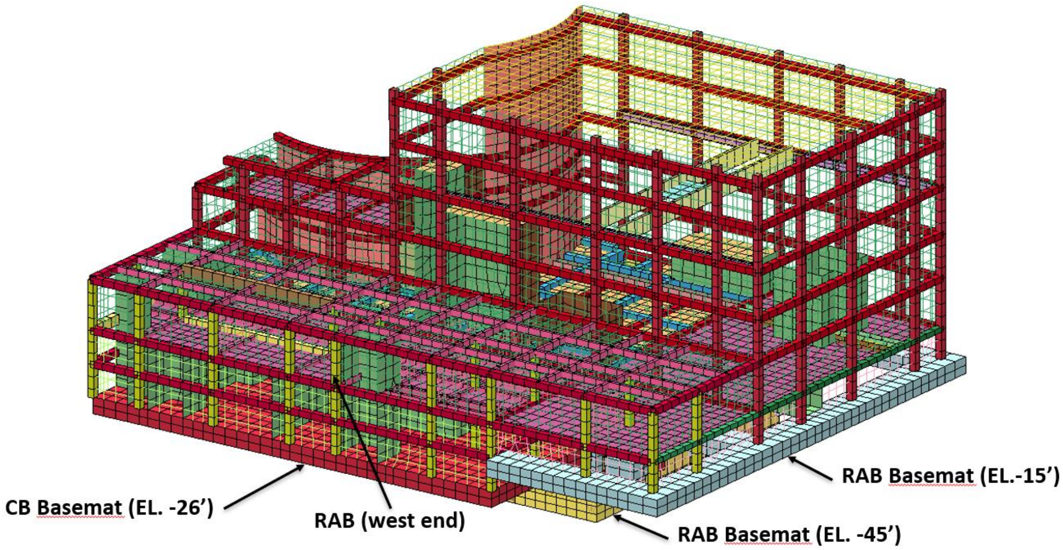


*Figure 18. LS-DYNA SSI Model of SMR-160 RAB*

The dual-unit SMR-300 design is similar to the initial single-unit plant design in terms of the overall building configuration and the layout of equipment. The modeling and analytical methodology employed for the dual-unit SMR-300 design will be consistent with the approach utilized in the preliminary SSI analysis performed for the single-unit SMR-160 design.

## 7. Preliminary SSI Analysis

The LS-DYNA models developed for the SMR-160 design and presented in Section 6 were used to perform a preliminary SSI analysis, which served to ensure that the time-history analysis can be executed smoothly and efficiently. Namely, the existing computer hardware can support the SSI analysis, and the total run time for a realistic earthquake duration is acceptable.

The LS-DYNA SSI analysis was carried out in two stages. Firstly, the complete SMR LS-DYNA SSI model was subjected solely to the gravity load over an extended duration (30s). This time span is long enough to allow for the settling of any significant oscillations in predicted deformation, stress, and the hydrostatic pressure affecting embedded structures. Subsequently, the second stage of analysis began with a full-deck restart of the LS-DYNA simulation, preserving the solutions from the first stage as the initial conditions for the second stage. The equivalent seismic force time histories in three orthogonal directions, which were derived from the preceding SHAKE2000 analysis, were employed as the seismic input motion for the SSI analysis.

The nodal acceleration time histories obtained from the second-stage analysis can be employed to generate in-structure response spectra for the SMR structures. For instance, Figure 19 illustrates the polar crane support acceleration time history along the horizontal (x-) direction predicted by the LS-DYNA SSI analysis for the best estimate soil profile and the first of seven earthquakes. The corresponding response spectrum plot is depicted in Figure 20. The ultimate in-structure response spectra at this location should be derived from the averaged SSI analysis results of all seven earthquakes and should envelop the response spectra of all three soil profiles. Note that the LS-DYNA generated time history results may need to be filtered to remove high-frequency fictitious numeric noise that contains little energy (determined by FFT analysis).

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*Figure 19. Polar Crane Support Horizontal (X-) Direction Acceleration Time History*

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Figure 20. *Polar Crane Support Horizontal (X-) Direction Response Spectrum*

Information from the literature suggests that significant soil nonlinearity becomes prominent when the shear strain exceeds 0.3%. This is supported by observations indicating a significant difference between response spectra predicted by the equivalent linear analysis method and those by the nonlinear analysis method for maximum shear strains greater than 0.3% (Ref. [9]). The preliminary SMR SSI analysis affirms that the soil near embedded structures indeed encounters greater strains compared to other areas. This is depicted in Figure 21, which displays the soil strain distribution, where the red region signifies soil with strains exceeding 0.3%. This strain indication of local soil nonlinearity is also consistent with the design basis earthquake peak ground acceleration (PGA), i.e., 0.4~0.5g per Figures 4 to 6. Published studies (e.g., Ref. [10]) suggest that the nonlinear threshold value of the PGA is around 0.4 g.

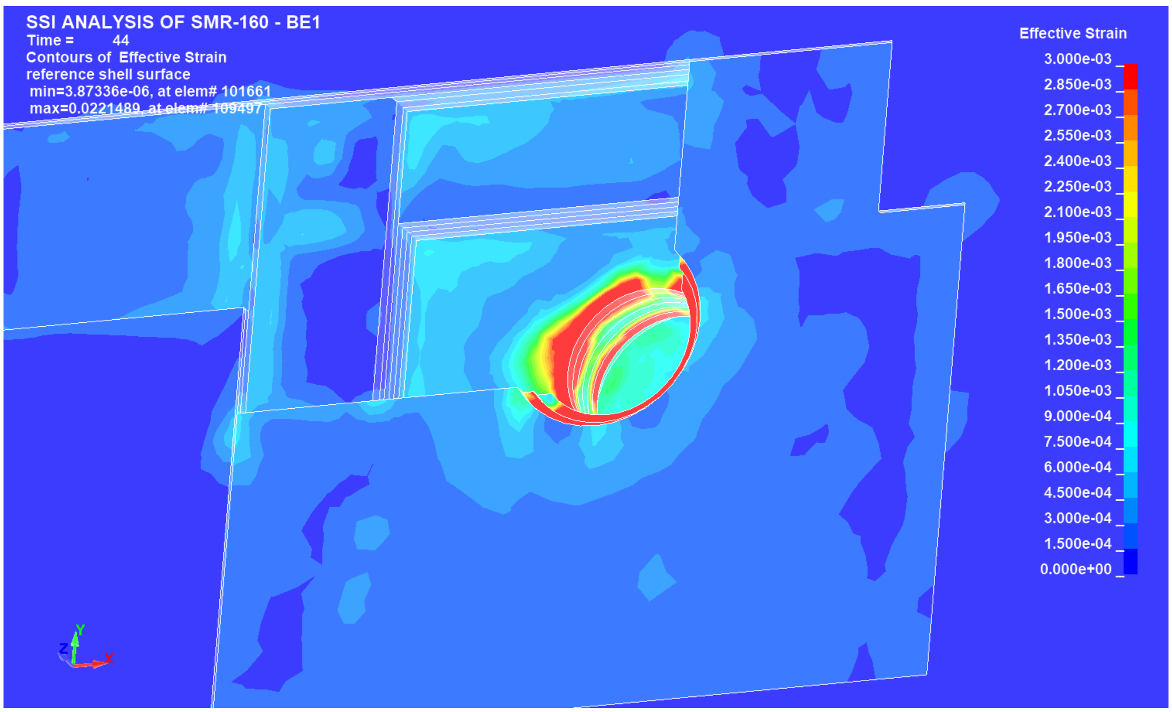


*Figure 21. SMR-160 Site Soil Strain Distribution*

The preliminary SSI analysis exclusively employs the linear hysteretic soil model *MAT_232 for soil representation. By employing *MAT_079 to model the soil adjoining embedded structures, it becomes possible to account for the heightened energy dissipation. This adjustment would lead to seismic response outcomes for SMR structures that are more realistic than would be expected from a purely linear approach. Information from the literature (e.g., Ref. [11]) suggests that the nonlinear material model *MAT_079 yields soil responses that are essentially bounded by those predicted by *MAT_232.

## 8. Other SSI Analysis Considerations

Sensitivity studies will be conducted to assess the influence of the friction coefficient at the structure/soil contact interface and the water table elevation on the results of the SSI analysis. This ensures a conservative approach in subsequent structural analyses of structures, systems, and components.

## 9. Conclusions

Holtec intends to use the nonlinear time-domain SSI analysis method described above to generate in-structure response spectra for SMR-300 structures. Comparison to existing models provides confidence that the method is valid, and additional studies will be completed to demonstrate its applicability to a broader range of conditions. Holtec anticipates that use of this method will provide meaningful improvement in the accuracy of seismic response predictions. This white paper continues Holtec's effort to provide early and detailed descriptions of the method. Holtec welcomes and appreciates questions and comments from the NRC staff.

## 10. References

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