ACKNOWLEDGEMENTS AND DISCLAIMERS

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DATA RIGHTS NOTICES

1. Introduction

This document has been crafted to facilitate discussions between the USNRC staff and Holtec's structural analysis team concerning the proposed time-domain nonlinear 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 Holtec's SMR design. The regulatory endorsement of this non-conventional SSI analysis approach holds significant importance for the success of the SMR program. The outcomes of the SSI analysis have direct implications for subsequent structural evaluations, encompassing the qualification of designs for these structures, as well as defining seismic loads for assessing safety-related equipment and their supporting structures within the said edifices.

This white paper serves a dual purpose. Firstly, it seeks to offer a succinct yet comprehensive overview of the proposed SMR Soil-Structure Interaction (SSI) analysis methodology, complete with updates on our progress since our previous meeting. Secondly, and of greater significance, it responds to the valuable feedback provided by the NRC, addressing their expectations concerning the validation and verification of our proposed time-domain nonlinear SSI analysis approach.

Aligned with the central objective, the white paper delves into critical components, notably the benchmarking and calibration of soil material models, while elucidating our strategy to ensure and to demonstrate the accuracy of the intended SSI analysis approach. Additionally, this document presents initial findings from the SSI analysis and outlines our future analysis plans. We place great importance on any insights, feedback, and guidance provided by the USNRC staff, and we remain fully committed to thoughtfully incorporating the staff's input into our forthcoming analytical efforts.

2. Background

During an NRC public meeting on 09/27/2022, Holtec introduced a novel time-domain nonlinear SSI analysis methodology for the SMR-160. This methodology is anticipated to be applicable to Holtec's uprated SMR design that is currently in development. Illustrated schematically in Figure 1 on the following page, this approach distinguishes itself from the conventional frequency-domain equivalent linear analysis employed in the linear analysis code SASSI.

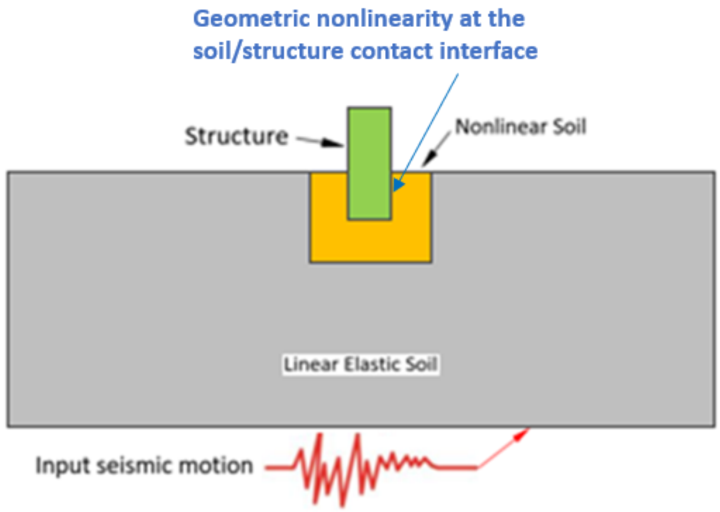

Figure 1. Schematic description of non-linear approach.

Unlike the conventional approach, Holtec's SSI analysis method is adept at explicitly capturing geometric nonlinearity at the interfaces connecting deeply embedded seismic Category I structures with the surrounding soil. Additionally, it can effectively model the pronounced soil nonlinearity that is anticipated to manifest in close proximity to these embedded structures. Notably, both these nonlinear effects can have substantial significance in scenarios involving strong seismic activity and/or weakened soil conditions.

3. Design Basis Earthquake and Soil Profiles

Holtec intends to submit a construction permit application under 10 CFR 50 for a standard dual-unit plant at the current Palisades Nuclear Generating Station (PNGS) site. The standard 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, 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.

The characterization of the SMR design basis earthquake revolves around the seismic design response spectra (SDRS), which are detailed in Table 1. Notably, the SDRS is anchored at the base of the containment enclosure structure (CES) at an elevation of almost 90 feet below grade.

Horizontal Directions

Frequency (Hz)	Acceleration (g)
0.10	0.0192
0.25	0.12
1.0	0.48
3.5	0.92
12	0.92
50	0.40
100	0.40

Vertical Direction

Frequency (Hz)	Acceleration (g)
0.10	0.0133
0.25	0.08
1.0	0.36
3.5	0.88
12	0.92
50	0.40
100	0.40

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 requirement 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.

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.

To facilitate the implementation of the time-domain SSI analysis, 3-D seismic acceleration time histories are generated at the base of the 170' 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 an elevation (EL) of -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.

4. SMR SSI Model Development

The preliminary SSI analysis considers the initial single-unit SMR-160 design, available prior to the finalization of the enhanced standard dual-unit SMR design. This preliminary analysis is conducted using the explicit finite element software, LS-DYNA. The LS-DYNA SSI model is composed of several key components, encompassing the soil, seismic structures, and adjacent non-seismic structures.

Within the LS-DYNA SSI model, 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), as well as water in the annular reservoir and in the spent fuel pool through a simple fluid material model which has no shear capacity.
- 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 the masses of equipment of significant weight.

The following figures show the relevant LS-DYNA models.

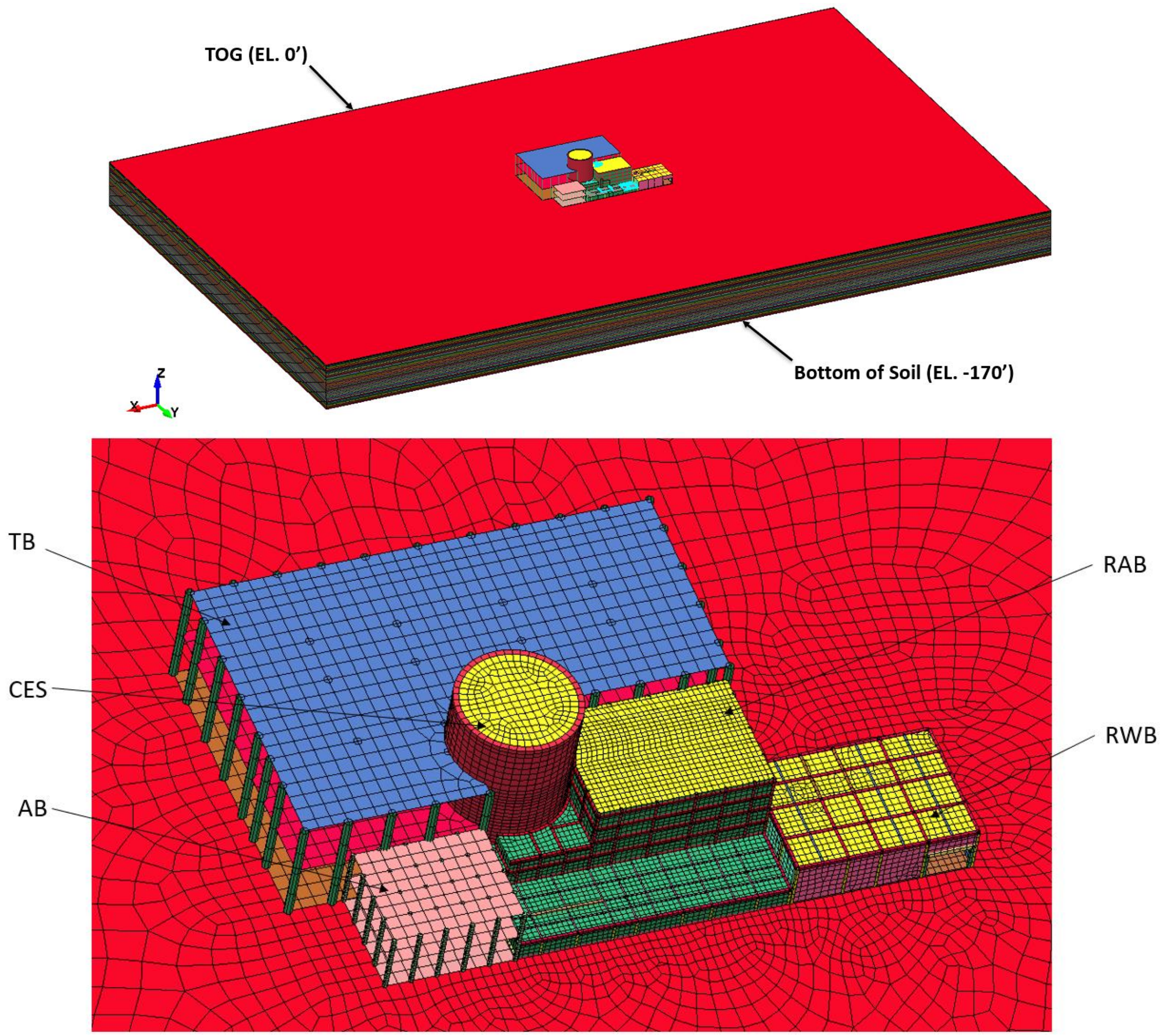

Figure 2. LS-DYNA model of overall SMR site.

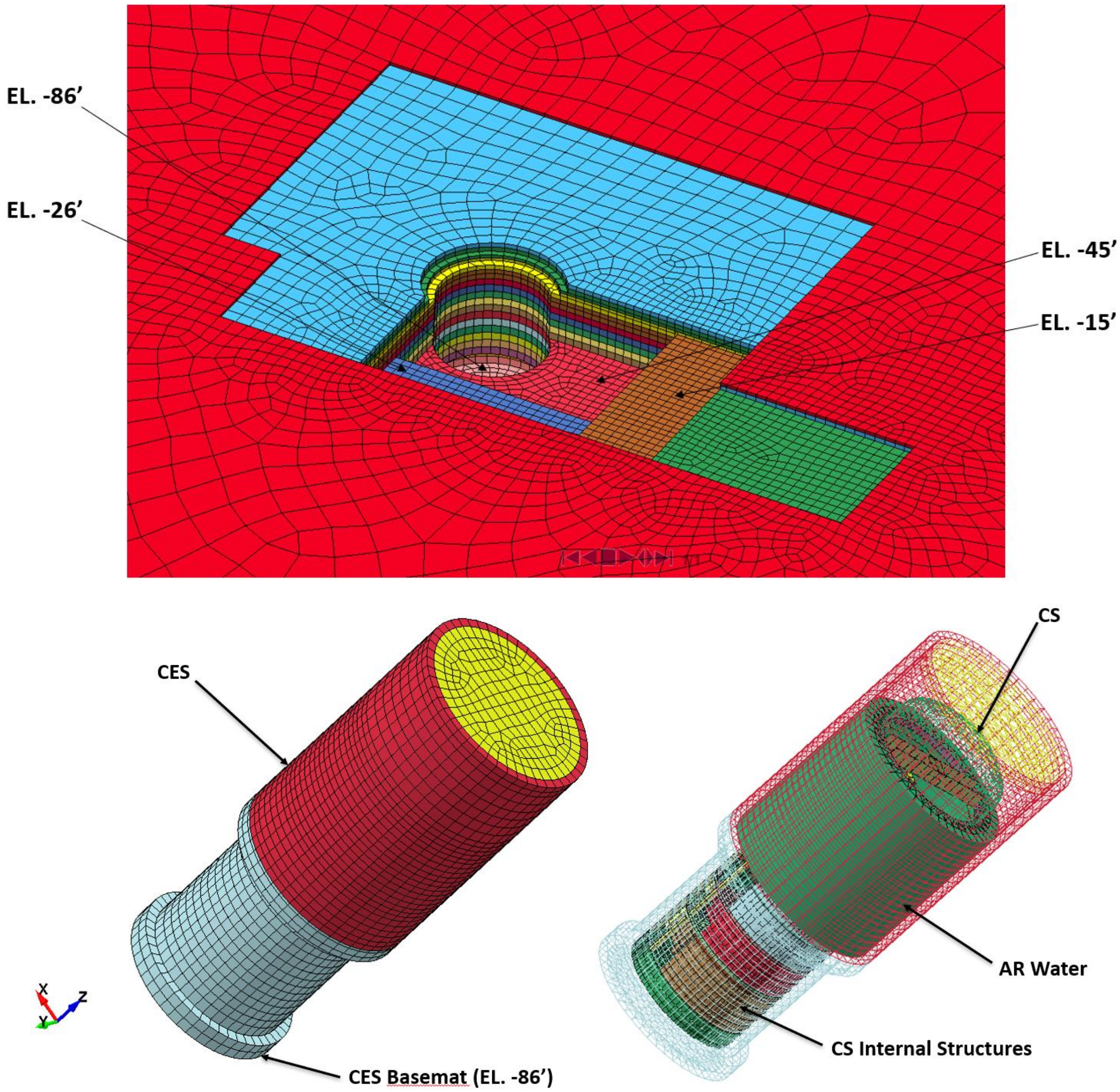

Figure 3. LS-DYNA model of SMR site, showing CES excavation, CES, and CS.

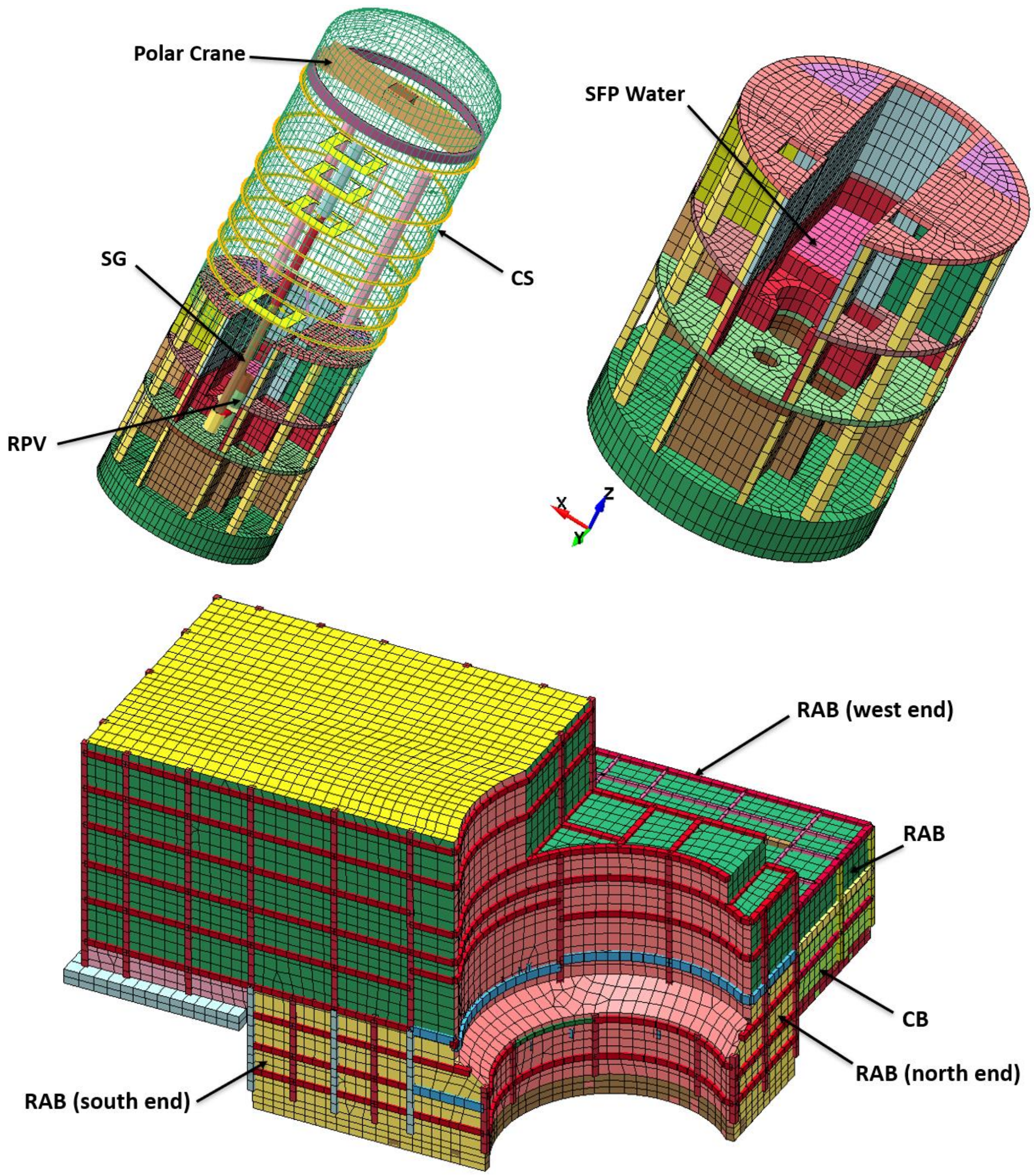

Figure 4. LS-DYNA model of CS and surrounding buildings.

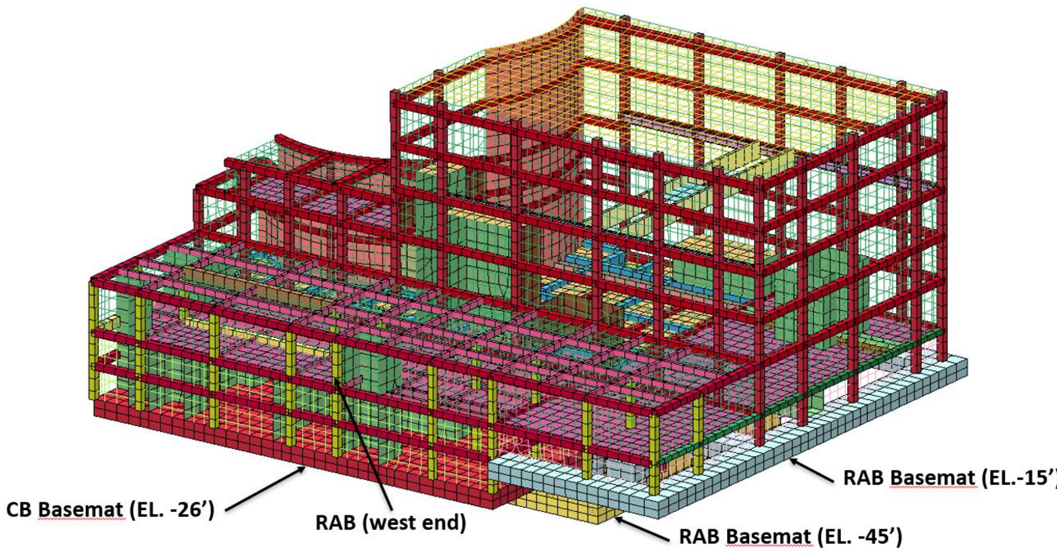

Figure 5. LS-DYNA model of RAB.

The standard dual-unit SMR design maintains consistency with 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 standard dual-unit SMR design will be consistent with the approach utilized in the preliminary SSI analysis performed for the single-unit design.

5. Benchmarking 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, the 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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6. Verification of Time Domain SSI Analysis Method

In addition to the soil material model benchmarking and calibration efforts detailed above, Holtec is poised to embark on a supplementary validation effort pertaining to a deeply embedded simple concrete structure subjected to soil-structure interaction. This comprehensive validation entails both time domain and frequency domain 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 structure.

The primary objective of this validation initiative is to compare seismic responses for the concrete structure, which is intimately linked with the soil through shared nodes, as predicted by both time-domain and conventional frequency-domain methods. This assessment will be carried out for a mild or moderate seismic event.

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 solutions. Such deviations are anticipated to become more pronounced as the intensity of the seismic activity escalates. This comprehensive validation initiative 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.

7. Preliminary SSI Analysis Results

The preliminary SSI analysis exclusively employs the linear hysteretic soil model *MAT_232 for soil representation. This analysis is carried out in two stages. Firstly, the complete SMR LS-DYNA SSI model is subjected solely to gravity load over an extended duration (30s). This time span allows for the settling of any significant oscillations in predicted deformation, stress, and the hydrostatic pressure affecting embedded structures.

Subsequently, the second stage of analysis begins 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 3-D soil column base acceleration time histories derived from the preceding SHAKE2000 analysis are employed as the seismic input motion for the SSI analysis. The nodal acceleration time histories obtained through the second stage analysis can be utilized to generate the in-structure response spectra for the SMR structures.

Published literature suggests that substantial soil nonlinearity becomes prominent when the shear strain surpasses 0.3%. The preliminary SMR SSI analysis affirms that the soil near embedded structures does indeed encounter greater strains compared to other areas. This is depicted in Figure 23 showing the soil strain distribution; the red region signifies strains exceeding 0.3%.

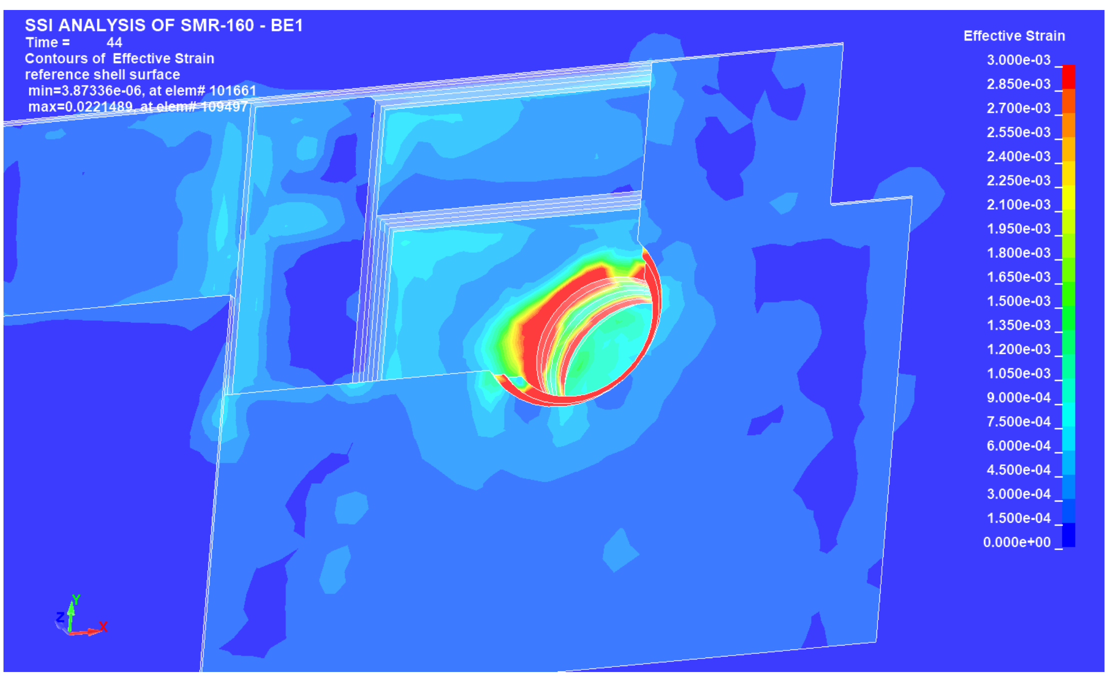

Figure 23. Soil strain distribution.

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.

8. Conclusions

Holtec intends to use the non-linear SSI method described above to perform seismic analysis of SMR 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.

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