December 18, 2023

Subject: SMR, LLC Responses to NRC Questions Concerning Soil-Structure Interaction (SSI) Analysis Method

NRC Question #1. *Boulanger and Beaty (2016) provide a checklist for the review of seismic deformation analyses of embankment dams. Twelve aspects for a review and associated questions are provided, some of which may be applicable to SSI analyses for nuclear facilities. The twelve aspects are: 1) Seismic Failure Modes and Important Behaviors, 2) Validation Record for the Numerical Model Procedure, 3) Site Characterization Basis for Material Parameters, 4) Calibration and Evaluation of the Constitutive Model, 5) Numerical Modeling Procedures, 6) Input Ground Motions, 7) Initial Static Stress Conditions, 8) Dynamic Response, 9) Post-Shaking Deformations, 10) Parametric Analyses, 11) Uncertainties and Limitations, 12) Reasonableness of Conclusions. Has SMR (Holtec) considered these aspects in its SSI analyses?*

Holtec Response: The majority of the twelve aspects outlined in the review checklist by Boulanger and Beaty are relevant to the proposed time-domain nonlinear SSI analysis method employed for predicting seismic responses in the critical structures of the Holtec SMR design. These aspects hold significance for any SSI analysis methodology. The current white paper acknowledges each aspect but does not address all aspects in detail; future submittals will more thoroughly address all aspects.

Accurate modeling of soil behavior in the time domain is essential to the success of the proposed LS-DYNA time-domain nonlinear SSI analysis method and is the focus of the Holtec white paper. The white paper validates two LS-DYNA soil material models chosen for the time-domain SSI analysis method through extensive benchmarking analyses, demonstrating their capability to predict nearly identical seismic response results as those obtained through established frequency-domain analysis or theoretical solutions. Given the Holtec white paper's primary focus on validating the time-domain analysis method and the associated soil material models, applicable aspects that have not been discussed are briefly addressed in the updated Holtec white paper.

NRC Question #2. *Given the substantial significance of the soil behavior surrounding the structure, what will you do to verify that the constitutive model properties and analytical soil behavior are consistent with site specific soil behavior? What plans do you have for soil testing or are soil testing results available to demonstrate that the soil constitutive model and chosen model parameters used result in behavior consistent with site soils?*

Holtec Response: It is widely acknowledged that the site-specific soil behavior can be effectively represented by its stiffness (i.e., shear wave velocity), Poisson’s ratio, and the strain-dependent modulus degradation and damping curves. These properties serve as the basis for defining the ideal hysteretic model utilized in frequency-domain analysis tools (e.g., SHAKE2000 and SASSI) and the two LS-DYNA hysteretic material models validated in the Holtec white paper for time-domain SSI analysis. The material model validation results presented in the Holtec white paper illustrate that the soil behavior from LS-DYNA, which is determined by constitutive model properties, aligns consistently with the actual soil behavior from SHAKE2000 concerning critical seismic responses, including acceleration, stress, and dissipated energy.

For a designated Holtec SMR site, soil properties will be acquired through a comprehensive geotechnical survey which includes soil testing. By performing 1-D seismic response analysis using SHAKE2000, the constitutive model properties consistent with the site-specific soil behavior can be obtained. Verification of the analytical soil behavior can be carried out by repeating the LS-DYNA analyses documented in the white paper using the site-specific soil properties.

NRC Question #3. *How will you consider uncertainty in soil behavior and constitutive model behavior in your analyses?*

Holtec Response: Holtec will conduct SSI analyses using conservatively defined soil profiles (Best Estimate, Lower Bound, and Upper Bound) to address concerns related to uncertainties in soil behavior. As demonstrated in the soil material model validation results, the uncertainty in the soil constitutive model is found to be minimal. To assure reliable SSI analysis results, however, the LS-DYNA SSI analysis of the Holtec SMR design will consider conservative soil properties and incorporate parametric studies. This approach is in accordance with the applicable guidance in NUREG-800, SRP 3.7.1 and SRP 3.7.2.

NRC Question #4. *What studies will be completed to evaluate the sensitivity of the structure, system, and component loading/response to variability/uncertainty in the constitutive model and model parameters?*

Holtec Response: 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. Linear elastic material models are employed to simulate structures, maintaining consistency with traditional frequency-domain SASSI analysis. The revised white paper includes the sensitivity study discussion.

The input parameters of the soil material model *MAT_232 are derived from SHAKE solutions, with the exception of the dominant excitation frequency. The impact of this frequency on the 1-D soil seismic response results are detailed in the revised white paper. No sensitivity studies are planned for the nonlinear material model *MAT_079 input parameters, as crucial parameters (e.g., stress-strain curve and damping vs shear strain curves) are predefined. Note that *MAT_079 includes additional input parameters for advanced modeling capabilities, which are disabled in the benchmarking analysis for comparison with the theoretical solution documented in the white paper. These parameters will also be disabled if *MAT_079 is used in the Holtec SMR SSI analyses.

NRC Question #5. *The white paper only indicates using the EPRI modulus reduction and damping curves to describe the nonlinear behavior of the soil. Have you considered modulus reduction and damping curves measured using soil samples from the site? What is the basis for the decision to not use modulus reduction and damping curves obtained from site specific soil and other generic curves for soil testing?*

Holtec Response: The structural evaluation of the Holtec SMR design involves a generic and appropriately conservative SSI analysis. This analysis utilizes EPRI soil modulus reduction and damping curves, in conjunction with the specified Seismic Design Response Spectra (SDRS) and soil profiles. The purpose of this approach is to generalize the Holtec SMR design process for numerous candidate sites; by demonstrating that the generic analysis is conservative compared to a candidate site, SMR may avoid comprehensive site-specific SSI analyses.

For site-specific applications, the actual soil modulus reduction and damping curves, along with other geotechnical properties and seismic hazard information specific to the site, will be considered. These site-specific parameters will be utilized in the "extended NEI Check," as outlined in the SMiRT-24 paper titled "Seismic Soil-Structure Interaction Analysis of Deeply Embedded SMRs and Associated Challenges," authored by NRC staff Sunwoo Park and Sujit

Samaddar. This analysis aims to demonstrate the suitability of the Holtec SMR standard design for the specific site. The "extended NEI Check" represents a reasonable expansion of the requirements outlined in DC/COL-ISG-17 for deeply embedded structures.

NRC Question #6. *I understand that *MAT_232 is a linear hysteretic soil model. Are the shear modulus and damping values used to define the model behavior determined from equivalent linear site response analyses for an appropriate loading/strain level?*

Holtec Response: Yes, the strain-compatible modulus and damping ratio values derived from equivalent linear site response analyses are used to define the model behavior of the linear hysteretic soil model *MAT_232. However, it is crucial to make slight adjustments to those values before incorporating them as input parameters for the material model. The adjustments ensure that *MAT_232 can accurately predict site responses, aligning closely with those predicted by SHAKE2000. The need for adjustments stems from the inherent differences between the ideal hysteretic model employed in the frequency-domain equivalent linear site response analysis code, like SHAKE2000, and the time-domain hysteretic model (*MAT_232).

NRC Question #7. *Will you use anything in addition to modulus reduction and damping curves to calibrate the *MAT_079 parameters?*

Holtec Response: The modulus reduction and damping curves play a crucial role in defining the stress-strain curve and non-Masing damping curve of the soil, serving as the primary *MAT_079 input parameters. Another essential input parameter for the LS-DYNA material model *MAT_079 is the bulk modulus, which correlates with the Poisson's ratio and elastic modulus of the soil. While *MAT_079 does have additional input parameters for characterizing soil in alternative ways or addressing specific soil behaviors, it's important to note that these parameters are not used in the *MAT_079 benchmarking analyses.

NRC Question #8. *Can you provide reasons for some differences in SHAKE2000 and LS-DYNA results? For example, in Figure 8, there is a large spectral acceleration spike in the LS-DYNA results compared to the SHAKE2000 results. What is the reason for the much larger LS-DYNA spectral acceleration between 2 and 3 Hz? [Note that Figures 7-15 in the prior revision have been replaced by Figures 4-6 in the revised white paper.]*

Holtec Response: As explained during the meeting on November 8, 2023, Figures 7 through 15 in the white paper were derived from preliminary benchmarking analyses for material model *MAT_232 by directly utilizing strain-compatible modulus and damping values as the corresponding input parameters. Subsequent examination of the ideal hysteretic model in SHAKE 2000 and the Biot hysteretic model implemented in the LS-DYNA material model *MAT_232 revealed the need for minor adjustments to the strain-compatible modulus and damping values before their incorporation as input parameters for *MAT_232. The latest benchmarking analysis results have successfully addressed the previously observed amplified responses between 2 and 3 Hz, eliminating them from the presented figures in the revised white paper. See Figures 4-6 for these updated results.

NRC Question #9. *How will soil behavior/response in the SSI analyses be used to assess reasonableness of the SSI results?*

Holtec Response: The soil response in the SSI analysis exhibits variations based on the proximity to the structures, with the response of far-field soil (located at a considerable distance from the structures in the SSI model) expected to resemble that of free-field soil predicted by the 1-D site response analysis. While a reasonable soil response serves as a positive indicator for accurate SSI results, the validity of the SSI outcomes is further ensured through the successful validation and verification of the proposed time-domain SSI analysis method. As outlined in the white paper, benchmarking analyses have been conducted for the two LS-DYNA hysteretic soil material models and will be done for a simplified SSI model featuring a deeply embedded structure. These analyses aim to demonstrate that the time-domain LS-DYNA SSI analysis approach yields seismic response results closely aligned with those obtained from conventional methods.

NRC Question #10. *It is not clear whether the FEM model shown in Figure 2 can produce results for overturning, sliding and flotation checks under load combinations as provided per Section 3.8.5 in NUREG-0800. [Note that this figure is Figure 15 in the revised white paper.]*

Holtec response: As clarified in the November 8, 2023 meeting, the finite element model illustrates that meshing is not continuous at the interfaces between soil and structures. See Figure 15 of the revised white paper. This aligns with the description of the proposed time-domain nonlinear LS-DYNA SSI analysis method, where automatic surface-to-surface contacts are employed to model potential sliding, gaping, and overturning (i.e., geometric nonlinearity) during earthquakes. Consequently, the overturning, sliding, and flotation checks, as required per Section 3.8.5 of NUREG-800, are inherently addressed by utilizing the proposed time-domain nonlinear LS-DYNA SSI analysis method.

NRC Question #11. *The White Paper discusses nonlinear soil models in detail; however, it does not provide sufficient details on the proposed nonlinear time-domain SSI analysis methodology and corresponding results. Will there be additional preapplication interactions, a future White Paper or Topical Report that provides descriptions and evaluations of some key elements of the proposed methodology including, but not limited to, the following:*

- *Modeling of structure-soil interface including gapping and sliding.*
- *Soil boundaries – location and type of the lower boundary; location and type of lateral boundaries; handling of radiation damping and description of transmitting boundaries if used.*
- *Element size – sufficiently refined finite elements; soil discretization ensuring frequency transmission up to the cutoff frequency.*
- *Boundary motion input – compatibility of soil boundary input motions with the design ground motion specified at the control point; treatment of non-vertically propagating waves if considered.*
- *Solution scheme and time step – integration time step ensuring stability and accuracy of the solution.*
- *Fluid effects (if applicable) – modeling of the fluid and the fluid-structure or fluid-structure-soil interaction effects.*
- *Probabilistic SSI analysis (if applicable) - analysis parameters treated as random variables, sampling method used, the number of simulations and statistical properties evaluated, discussion of treatment of uncertainties.*

Holtec response: The primary objective of this white paper is to offer a concise overview of the proposed nonlinear time-domain SSI analysis methodology, with a specific focus on benchmarking the two soil hysteretic material models designed to simulate soil behavior during earthquakes. While the revised white paper will touch on various items identified in this comment, comprehensive details and corresponding results will be extensively covered in separate licensing documentation, such as a topical report or PSAR.

It's worth noting that radiation damping, a geometric effect causing energy loss from the structure through the radiation of waves away from the footing, is automatically addressed by the time-domain LS-DYNA SSI analysis model where the soil lateral boundary is sufficiently far away from modeled structures and the impact of the bedrock half space is considered through a standard viscous boundary at the bottom surface of the soil.

Furthermore, although the proposed method can be extended beyond deterministic SSI analysis, the intricacies of applying it to probabilistic SSI analysis are beyond the scope of this white paper.

NRC Question #12. *The proposed nonlinear SSI analysis methodology is a first-of-a-kind application to new reactor license application. NUREG-0800, SRP criteria generally deal with linear elastic analysis, and SRP Section 3.7.2 also states that "the staff conducts a detailed review of all inelastic/nonlinear analyses." Therefore, the staff believes that additional information and evaluations beyond the usual scope of linear analysis should be included in the paper for staff's detailed review of the proposed methodology, such as the following:*

- *Verification and validation of the models and methods, including benchmarking against the established solutions (e.g., SASSI frequency-domain linear elastic solutions; theoretical/closed-form solutions, experimental data) to demonstrate reasonableness of the proposed methodology.*
- *Uncertainty and sensitivity analysis for the models, material properties, input ground motions, and other key parameters involved.*
- *An independent peer review by those with appropriate geotechnical and structural engineering experience to support reliability and accuracy of the results.*

Holtec Response: Holtec acknowledges the SRP 3.7.2 requirement mentioned in the comment. Although this proposed SSI analysis method might be a first-of-a-kind for new reactor applications, it has been accepted by ASCE 4 since 2016 for seismic analysis of safety-related nuclear structures and has been successfully utilized in other industries, such as bridge SSI analyses, for decades. Moreover, a similar LS-DYNA SSI methodology was employed in Holtec's underground spent fuel storage system (HI-STORM UMAX) license application and received approval from the USNRC in 2015.

The proposed LS-DYNA SSI analysis method and the traditional SASSI analysis approach share more common considerations (such as those listed in Question 11) than differences. The primary distinctions between the two approaches lie in two areas: (1) nonlinear vs. linear and (2) time domain vs. frequency domain. As noted in the white paper, potential geometric nonlinearity at the structure/soil contact interface is automatically captured through a simple surface-to-surface contact definition in LS-DYNA. In contrast, the traditional SASSI analysis is constrained by assuming that geometric nonlinearity (i.e., gapping, sliding at the contact interface) does not exist. Additionally, the traditional SASSI analysis relies on the assumption that the soil behaves linear elastically. Those assumptions become questionable for situations involving strong earthquakes and/or weak soil.

Validation and verification of the proposed SSI methodology is being carried out in two steps. First, the linear hysteretic soil material model (*MAT_232) and the nonlinear hysteretic soil material model (*MAT_079) were benchmarked against the SHAKE2000 solution and the theoretical solution, respectively (as discussed in the white paper). Subsequently, a simple SSI problem for a deeply embedded nuclear structure will be analyzed using the proposed time domain SSI analysis methodology to demonstrate that the obtained in-structure responses align well with results from the traditional SASSI linear SSI analysis performed in the frequency domain. Although Holtec has not obtained results from the second step analysis at this point, promising conclusions from the use of the nonlinear time domain analysis method have been reported in several publications. Evaluations beyond the usual scope of linear analysis will also be included in the second step analysis to showcase the capabilities of the proposed SSI method, as noted in the white paper.

Like the traditional SASSI analysis or any generic finite element analysis, the proposed time domain nonlinear SSI analysis method will consider uncertainty and sensitivity analyses involving material properties (e.g., site soil properties) and certain model input parameters.

Finally, Holtec has engaged SC Solutions under contract to provide independent peer review and consulting services for the Holtec SMR SSI analysis.

NRC Question #13. *Discuss the implications of nonlinear SSI analysis on seismic risk assessment of SSCs in the context of risk-informed performance-based design.*

Holtec Response: Compared with the traditional equivalent linear SSI analysis approach using SASSI, the proposed nonlinear SSI analysis methodology is expected to yield more realistic seismic responses required for the seismic risk assessment of SSCs in the context of risk-informed performance-based design. Not considering nonlinear behavior for sites that have moderate to high ground motions may produce overly conservative in-structure analysis results. In seismic risk space, this conservatism may cause nuclear facility owner/operators to overdesign some structures to mitigate the perceived seismic risk.

NRC Question #14. *In Section 2, Background, it is stated that the "SSI analysis method is adept at explicitly capturing geometric nonlinearity at the interfaces connecting deeply embedded seismic Category I structures with the surrounding soil." However, in Section 4, SMR SSI Model Development, there is no mention of a contact element available in LS-DYNA used in this Finite Element (FE) model, shown in Figures 2 through 5. It is also not clear whether the results shown in Figure 23 include the geometric nonlinearity of the interface. [Note that Figures 2-5 are Figures 15-18 in the revised white paper. Figure 23 is now Figure 21.]*

Holtec Response: As clarified during the meeting on November 8, 2023, the SMR SSI analysis LS-DYNA model employs automatic surface-to-surface contacts at all structure/soil interfaces. This can be visually confirmed in Figure 15 of the revised white paper, where the finite element models of the structures and the soil model do not share nodes at any structure/soil contact interface. The above statement is incorporated into Section 4 of the revised white paper.

NRC Question #15. *Figure 1 shows a zone of soil that exhibits nonlinearity. It is not clear how the nonlinear response of the soil was accounted for in the FE model. Is it through the soil shear stress–shear strain hysteretic loop (e.g., as shown in Figures 20 and 21) or the material model itself is nonlinear? [Note that Figures 20 and 21 are Figures 11 and 12 in the revised white paper.]*

Holtec Response: The zone marked as the nonlinear soil in Figure 1 illustrates that relatively large soil strain typically occurs in the region adjacent to the embedded structure during an earthquake. Consequently, it may be necessary to utilize an LS-DYNA nonlinear soil material model (*MAT_079) in that specific region to accurately capture the local nonlinear behavior of the soil.

NRC Question #16. *Clarify whether the soil layer represented by different color elements corresponds to the layers given in Table 2.*

Holtec Response: As clarified during the meeting on November 8, 2023, the soil layers listed in Table 2 have been further divided into 35 layers, each represented by different colors in the LS-DYNA soil model shown in Figure 3.

NRC Question #17. *Clarify whether the labeling of RAB (north end) and RAB (south end) is correct in Figure 4. [Note that this is Figure 17 in the revised white paper.]*

Holtec Response: As clarified during the meeting on November 8, 2023, there is an error in the labeling of RAB (south end) in the figure. The correct label should be RAB (east end), which is corrected in the revised white paper (Figure 17).

NRC Question #18. *Although two LS-DYNA soil material models (*MAT_232 and *MAT_079) were discussed in Section 5, Benchmarking of Soil Models, *MAT_079 element was not discussed later. Confirm whether this material model will also be used in the analysis and discuss the scenarios where one would be preferred over the other. Are there any differences between the responses from these two material models observed?*

Holtec Response: Benchmarking *MAT_079 against the theoretical solution was conducted at the element level, as detailed in the latter part of Section 5, including Figures 7-13 and Table 3. This soil material model is intended for application in regions where soil strain exceeds 0.3%, marking the threshold for significant soil nonlinearity. Employing *MAT_079 in these soil zones is appropriate, as it enables the capture of realistic responses, such as permanent soil deformation, within the SSI analysis model. Limited information from literature suggests that the nonlinear material model *MAT_079 yields soil responses that are essentially bounded by those predicted by SHAKE2000 (and consequently *MAT_232).

NRC Question #19. *What is Set 1 earthquake in Figure 7? [Note that this is Figure 4 in the revised white paper.]*

Holtec Response: In compliance with the pertinent SRP 3.7.1 guidance for nonlinear seismic analysis, seven (7) sets of seismic acceleration time histories are generated, based on the specified seismic design response spectra (SDRS) for the Holtec SMR standard design. The term "Set 1 earthquake" refers to the first set of acceleration time histories corresponding to the SDRS.

NRC Question #20. *Please define what is meant by mild or moderate seismic events. It is not clear why the seismic response of the concrete structures will be conducted for only mild and moderate seismic events.*

Holtec Response: The first LS-DYNA SSI verification analysis, with the geometric nonlinearity feature turned off as explained in Section 6 of the white paper, aims to demonstrate that the conventional equivalent linear SSI analysis conducted in the frequency domain using SASSI produces nearly identical in-structure seismic responses compared to those derived from the LS-DYNA time-domain SSI analysis method. Results obtained from the abovementioned SSI analysis are reliable if the earthquake intensity is not high. With escalating earthquake intensity, soil nonlinearity and geometric nonlinearity could become substantial, casting doubt on the reliability of SASSI analysis results as the software assumes the SSI response is linear. Defining a precise threshold for mild or moderate earthquakes is challenging due to the influence of overall soil profile and stiffness on nonlinear responses. As per published research, significant geometric and soil nonlinearity may manifest if the ZPA of the earthquake exceeds 0.4 ~ 0.5g. Additional LS-DYNA SSI verification analyses, also outlined in Section 6 of the white paper, will specifically address conditions of intense earthquakes, illustrating the growing disparities between the in-structure response results obtained from the two methods. The revised white paper emphasizes these distinctions to prevent any potential confusion.

NRC Question #21. *Section 6, Verification of Time Domain Analysis Method, mentions a surface-to-surface contact model used in the analysis. However, the desired contact behavior (e.g., only sliding, sliding with separation, etc.) or the specific contact model of LS-DYNA used was not mentioned. Please clarify.*

Holtec Response: As clarified during the meeting on November 8, 2023, the LS-DYNA SSI model incorporates automatic surface-to-surface contacts, enabling unmerged Lagrangian elements to interact seamlessly. Consequently, the LS-DYNA SSI model can capture various contact behaviors induced by simulated earthquakes at structure/soil interfaces, including pure sliding, sliding with separation, and more. The revised white paper aims to clarify this point.

NRC Question #22. *It is not clear in Section 6, Verification of Time Domain Analysis Method, what is meant by the revised LS-DYNA model. Please clarify what would be the new model and why would it be necessary.*

Holtec Response: In the initial LS-DYNA SSI method verification analysis proposed in Section 6, the nonlinearity capacity of the LS-DYNA SSI model is disabled by merging nodes at the structure/soil interfaces. The aim is to demonstrate that the linear time-domain LS-DYNA SSI analysis yields essentially identical in-structure responses as the frequency-domain SASSI analysis. Subsequent LS-DYNA SSI verification analyses outlined in Section 6 involve modifications to the LS-DYNA SSI model. These modifications reintroduce geometric nonlinearity, where automatic surface-to-surface contacts replace merged nodes at soil/structure interfaces. The “new model” refers to the LS-DYNA SSI model with nonlinear capability.

When modeling high-intensity earthquakes (where nonlinear behavior is expected), SMR anticipates differences between the in-structure responses from the nonlinear LS-DYNA SSI model and SASSI. The LS-DYNA model is expected to provide a more realistic description of in-structure responses in such cases.

NRC Question #23. *In Section 4, SMR SSI Development, it is stated that the “Solid” elements of the LS- DYNA were used to model soil, concrete, and water in the annular reservoir and in the spent fuel pool through a simple fluid material model which has no shear capacity. It is not clear whether the selected solid element with fluid characteristics can simulate water “sloshing” when subjected to a dynamic (seismic) motion. Please clarify. In addition, please discuss the interaction of the element with “Fluid” material model with the “Solid” element.*

Holtec Response: As clarified during the meeting on November 8, 2023, the water solid elements, characterized by a simple fluid material model with no shear capacity, are used to capture the inertial effect of water in the SSI analysis. It is important to note that the simple fluid model does not simulate water sloshing, which is considered to have secondary effects on SSI analysis results. Furthermore, the water in the annular reservoir between the Containment Structure (CS) and the Containment Enclosure Structure (CES) is not anticipated to undergo significant sloshing during an earthquake due to the small width-to-depth ratio. However, structural analyses of the CS, CES, and spent fuel pool will consider the impact of water sloshing loads. Finally, the water elements are connected to other structural solid elements. The above clarification is included in the revised white paper.