U.S. NUCLEAR REGULATORY COMMISSION

SAFETY EVALUATION FOR NUSCALE POWER, LLC,

LICENSING TOPICAL REPORT, TR-0118-58005, REVISION 2,

"IMPROVEMENTS IN FREQUENCY DOMAIN

SOIL-STRUCTURE-FLUID INTERACTION ANALYSIS"

1.0 INTRODUCTION

By letter dated July 26, 2018, (Agencywide Documents Access and Management System (ADAMS) Accession No. ML18208A362), NuScale Power, LLC (NuScale or the applicant), submitted Licensing Topical Report (TR)-0118-58005, Revision 0, "Improvements in Frequency Domain Soil-Structure-Fluid Interaction Analysis," (Reference 1) to the U.S. Nuclear Regulatory Commission (NRC) for staff review and approval. By letter dated November 28, 2018 (ADAMS Accession No. ML18331A404), NRC accepted the TR for review because the report provided sufficient technical information for the NRC staff to conduct a detailed technical review. By letter dated November 19, 2019, (ADAMS Accession No. ML19324E311), NuScale submitted TR-0118-58005, Revision 1, "Improvements in Frequency Domain Soil-Structure-Fluid Interaction Analysis," (Reference 2) to the NRC for staff review and approval. Revision 1 of the TR incorporates information provided in the NuScale response to the NRC staff request for additional information (Reference 3). Revision 2, submitted on September 2, 2020 (ADAMS Accession No. ML20246G848), of the TR incorporates additional information supporting the evaluation of the software (Reference 8).

The TR describes an enhanced workflow in the frequency-domain seismic analysis of a complex structural system considering the effects of coupled soil, structure, and fluid interaction. The report provides an improved methodology for the use of a nuclear power plant licensee or applicant in performing seismic analysis of structures, systems, and components (SSCs) important to safety in compliance with the applicable requirements of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic licensing of production and utilization facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," General Design Criteria (GDC) 2 "Design bases for protection against natural phenomena," and 10 CFR Part 50, Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants."

This safety evaluation (SE) is based on the information provided in TR-0118-58005, Revision 2. The staff has based its conclusions on its technical evaluation of the information provided and has identified limitations and conditions associated with the use of this methodology. The SE is divided into seven sections. Section 1, the current section, is the introduction; Section 2 presents the applicable regulatory requirements and guidance; Section 3 contains a summary of the technical information presented in the TR; Section 4 contains the staff's evaluation of the information; Section 5 presents the conclusions of this review; Section 6 contains the limitations and conditions on the use of the TR; and Section 7 lists the references.

2.0 REGULATORY REQUIREMENTS AND GUIDANCE

Requirements:

The requirements of the NRC regulations relevant to the review of the TR include the following:

- 10 CFR Part 50, Appendix A, GDC 2, requires that structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena including earthquakes without loss of capability to perform their safety functions.

- 10 CFR Part 50, Appendix S, requires that the safety functions of structures, systems, and components important to safety must be assured during and after the vibratory ground motion associated with the Safe Shutdown Earthquake ground motion through design, testing, or qualification methods and that the evaluation must take into account soil-structure interaction effects.

Relevant Guidance:

The following regulatory guidance is relevant to the review of the TR:

- "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," NUREG-0800, Section 3.7.2, "Seismic System Analysis," Revision 4, September 2013. (Reference 4)

3.0 SUMMARY OF TECHNICAL INFORMATION

The TR presents the purpose, scope, assumptions, and technical basis for the proposed methodology along with solutions to example problems to demonstrate the adequacy of the methodology for seismic soil-structure-fluid interaction analysis of nuclear power plant structures and major mechanical components and equipment. The report discusses efficiencies that can be gained from this new analysis workflow compared to the traditional method.

Nuclear power plants may include large, complex structures with soil, structure, and fluids interacting during an earthquake. As such, coupled soil-structure-fluid interaction effects need to be accounted for in the design of the SSCs. However, a single integrated frequency-domain analysis tool that can evaluate the effects of soil-structure-fluid interaction along with operating loads is not currently available. Therefore, the analysis of structures with soil-structure-fluid interaction and other operating loads is typically performed using a piecewise approach involving several labor-intensive steps. In the nuclear industry, seismic soil-structure interaction analysis is typically performed using the "System for Analysis of Soil-Structure Interaction" (SASSI) computer code (Reference 5). Since SASSI was first developed at the University of California at Berkeley in 1981, a number of SASSI versions have been issued by different entities with various added features. However, all of the SASSI versions, including SDE-SASSI used in the TR, are built upon the same source code as the original version. While SASSI has capabilities for handling the effects of soil-structure interaction, it does not provide an integrated analytical framework for considering the effects of fluid-structure interaction and other operating loads.

A traditional seismic analysis workflow is to develop and analyze a simplified seismic model for soil-structure interaction using SASSI, and then to export the response parameters into a separate detailed model of the building that also contains other loads. This model is analyzed using a commercial finite element analysis code, such as ANSYS. Detailed building response parameters are then further exported for seismic equipment qualification that considers all loads. Thus, multiple separate models must be maintained as the seismic design develops. To consider the effects of fluid-structure interaction, the analysis requires yet another step.

The TR proposes a methodology to perform seismic analysis in the frequency domain considering interactions among the structure, soil, fluid, and major equipment in a single, integrated analysis framework. The TR includes example problems to demonstrate the adequacy and applicability of the proposed workflow to perform the seismic soil-structure-fluid interaction analysis.

Section 3.0 of the TR discusses the assumptions involved in the development of the proposed methodology including the linear elastic material properties and linear boundary conditions and constraints. The TR also indicates that the site response analysis involved in the proposed workflow assumes one-dimensional vertically propagating seismic waves through layered half-space. Computer codes used in the development of the TR are also addressed in Section 3.0 of the TR.

Section 4.0 of the TR discusses the solution strategy for the proposed methodology. The elements of the proposed workflow consist of substructures representing interacting entities involved in the analysis - the soil substructure, building substructure, and fluid substructure. These substructures collectively represent a coupled soil-structure-fluid interactive system that is analyzed for a prescribed ground motion. Thus, different soil substructures, representing different site soil conditions, can be created and an integrated analysis can be performed for each different soil substructure without impacting the other substructures. The TR uses two computer codes to develop quantities representing these substructures (see "Computer Codes" in Section 4.0 of this SE for more details about the computer codes used in the TR). The TR uses SDE-SASSI to develop soil impedance matrices and seismic load vectors for the soil substructure, and then stores the calculated values of these parameters for different soil substructures in the Soil Library. The TR uses ANSYS to develop stiffness, mass, and damping matrices that represent the substructures of other interacting entities involved in the integrated analysis.

Section 5.0 of the TR discusses the theoretical basis for the proposed methodology. It describes the theoretical framework of the established SASSI methodology, and then describes enhancements to the established SASSI methodology that are applied to the new proposed methodology. These enhancements include the ability to solve a soil-structure interaction problem using an ANSYS substructure containing fluid-structure interaction; the ability to solve equations with non-symmetric mass and stiffness matrices associated with fluid-structure interaction problems; and the ability to reduce the impedance matrices and seismic load vectors through condensation of internal soil degrees of freedom that do not interact with the building. The applicant provided further details on the theoretical formulation for the soil-structure-fluid interaction analysis in Subsection 6.3.2 of the TR.

Section 6.0 of the TR contains example problems to demonstrate the implementation of the proposed methodology for frequency-domain soil-structure-fluid interaction analysis. The TR presents four different example problems. Example 1 deals with a surface-founded containment building, Example 2 deals with a partially-embedded box-shaped building with soil-structure interaction, Example 3 deals with a partially-embedded box-shaped building with soil-structure-fluid interaction, and Example 4 deals with a representative small modular reactor (SMR) building that is embedded in the soil and houses twelve reactor modules and a reactor pool.

Section 7.0 of the TR discusses implementation of the Soil Library and describes steps for calculating the soil impedance matrices and seismic load vectors, in addition to organizing the calculated Soil Library data by site and excavation geometry.

4.0 Technical Evaluation

Assumptions

In Section 3.0 of the TR, the applicant states that the proposed analysis methodology is based on the assumptions that: (1) material properties are linear elastic during the analysis, (2) the behavior of boundary conditions and constraints is linear, and (3) the seismic load is represented by vertically propagating shear and compression waves.

The staff has reviewed and determined that the applicant's assumptions on the linearity of material properties and boundary conditions and on vertically propagating seismic waves are consistent with the established state-of-the-practice in SASSI analysis for nuclear structures. Further, while the staff has not endorsed American Society of Civil Engineers Standard 4-16 (Reference 6), that standard represents a consensus of expert civil engineering opinion in regard to the assumptions stated above and accepts them as applicable for the type of analysis described in the TR. The staff, however, does note that certain site-specific considerations may invalidate the applicability of any one of these conditions for a particular analysis. Accordingly, the staff finds these assumptions to be acceptable, provided that each of these assumptions becomes a condition and limitation on the applicability of the TR for any particular analysis as delineated in Section 6 of this SE.

Computer Codes

In Section 3.0 of the TR, the applicant indicates that it used two computer codes in the development and evaluation of the proposed analysis methodology. They are ANSYS, Version 18.1, and SDE-SASSI, Version 2.1.1.

ANSYS is a commercially available general-purpose finite element code that has been widely scrutinized and accepted by the engineering community. In particular, the nuclear industry, with the NRC's consent, has employed ANSYS in applications similar to that for which the TR is intended, and the NRC staff's experience is that the results obtained have been acceptable. Accordingly, the staff has determined that ANSYS Version 18.1 can be accepted for use in the TR without further validation.

The applicant also used SDE-SASSI in the development and evaluation of the proposed methodology in the TR. The staff conducted a regulatory audit (Reference 7) to review the report, "SDE-SASSI Version 2.1.1 Acceptance Testing Report," that is not docketed with the NRC, but was made available by the software's vendor (Carl J. Costantino and Associates, LLC) for the staff's review in the vendor's electronic reading room. The staff noted that the report documents the example problems considered and vendor's evaluations of the test results to demonstrate the accuracy of the solutions from SDE-SASSI against the established benchmark solutions. Solutions evaluated include soil impedances, stiffnesses, and transfer functions. The report also includes example problems to demonstrate the equivalency between the proposed Soil Library solutions and the standard SASSI solutions.

However, during this audit, the staff found that information needed to summarize key evaluation findings and conclusions in SDE-SASSI v2.1.1 Software Acceptance Testing Report, which is not docketed with the NRC, was not captured in the TR. Therefore, the staff requested the applicant to add the relevant information from the testing report to Section 3.2, "Software," of the TR. On September 2, 2020, the applicant submitted Revision 2 of the TR (ADAMS Accession No. ML20246G848, Reference 8) and the staff verified that it contained the necessary, additional information regarding software acceptance testing to validate the use of the software for the proposed frequency-domain methodology for soil-structure-fluid interaction analysis.

The staff reviewed the additional information provided in Section 3.2 of the TR, Revision 2, and finds the information accurately captures what the staff reviewed in the Software Acceptance Testing Report during the audit. Specifically, NuScale added a description of the types of problem sets and their respective testing purposes, and a statement that the results of the tests were shown to be essentially equivalent to established benchmark solutions.

The staff's review determined that the SDE-SASSI V.2.1.1 code is adequate for use in developing the TR because: (1) the vendor's selection of test problems is adequate as the range of input parameters considered in these test problems covers the range of input parameters expected in the application of the analysis methodology proposed in the TR; (2) the methods of modeling and analysis employed for the test problems conform to the guidance in NUREG-0800, SRP Section 3.7.2; and (3) the solutions from SDE-SASSI are shown to be comparable with the benchmark solutions from established theory and numerical methods.

Solution Strategy

In Section 4.0 of the TR, the applicant discusses the solution strategy for the proposed analysis workflow. A soil-structure interaction problem is typically solved in the frequency domain because the soil damping and modulus are frequency dependent, hence a frequency-by-frequency solution scheme for the soil-structure interaction is more convenient. However, the properties of the fluid are not frequency dependent in general and are commonly represented using acoustic elements, hence a fluid-structure interaction problem can be solved in either the time or the frequency domain.

The applicant proposed that the workflow leads to the development of a model that integrates all the interacting entities in the frequency domain for solution using the SASSI or ANSYS solver. The complex frequency response analysis is used to obtain a time-domain response to transient loading such as seismic ground motion. The applicant demonstrates through the solved example problems that the results obtained from either the SASSI or the ANSYS solver are practically the same.

The applicant also discusses that the coupled soil-structure-fluid interaction problem is solved in the frequency domain and involves the soil substructure, building substructure, and fluid substructure. Equipment substructure(s) may also be included, as needed. The applicant proposed a Soil Library that contains a series of pre-calculated soil impedance matrices and seismic load vectors for soil substructures. The soil impedances and load vectors are frequency dependent and are calculated at each analysis frequency using SDE-SASSI. The excavated soil impedances are then developed by assembling the soil flexibility matrix for a layered half-space, inverting the flexibility matrix into an impedance matrix for the layered half-space, and then deducting the dynamic stiffness of the excavated soil volume. Much of the SASSI computational effort is exerted on the numerical process of inverting the flexibility matrix of the layered half-space into the impedance matrix.

The staff reviewed the applicant's approach to handling a soil-structure-fluid interaction problem in the frequency domain and finds it acceptable because the frequency-domain solution method can be applied to both the soil-structure interaction and fluid-structure interaction problems. In addition, the staff determined that the applicant's proposed Soil Library tool provides a convenient method for calculating and storing the excavated soil impedances and seismic load vectors separately from the other quantities involved in a soil-structure-fluid interaction analysis. As such, the staff finds that the Soil Library, as used in the TR, is acceptable because the parameters used in the Soil Library are derived and evaluated within the framework of the established SASSI methodology.

The applicant describes the details of the established SASSI methodology analysis tools and the steps involved in developing the Soil Library, in addition to utilizing it to solve a soil-structure-fluid interaction problem in the frequency domain. The applicant explains that the soil impedances and load vectors are calculated using SASSI. The SASSI HOUSE module is used to generate the stiffness of the excavated soil volume, and the response of the layered half-space is solved using the SASSI SITE module. The SASSI POINT3 module is then used to develop flexibilities for the axisymmetric or asymmetric point response model. The flexibilities are assembled and inverted in the SASSI ANALYS module into soil impedances for the layered half-space. The stiffness of the excavated soil volume is then subtracted from the layered half-space impedances and the resulting excavated soil impedances are stored in the Soil Library.

Of particular interest to the staff was that the applicant proposed to condense the internal soil degrees of freedom that do not interact with the building out of the impedance matrices and load vectors to reduce the size of storage for the Soil Library. This condensation occurs at each analysis frequency and the reduced impedance matrices and load vectors are stored in the Soil Library. Either the ANSYS or SASSI solver may be used in solving the resulting equations; however, the applicant notes that the extensive ANSYS tools available for modeling and post-processing makes ANSYS the preferred solver. In the TR, the applicant used both ANSYS and SASSI solvers for demonstrating their functional equivalency.

The staff reviewed the analysis procedures involved in the development of the Soil Library and finds them acceptable because the applicant uses the established analytical procedures and computational modules of SASSI, which is a software that performs seismic analysis that conforms to the acceptance criteria of SRP Section 3.7.2. Moreover, the engineering community has accepted SASSI and used it in nuclear applications to obtain results that are acceptable in the staff's experience. The applicant's proposed method for the condensation of the internal degrees of freedom for the excavated soil impedance matrices and load vectors is also acceptable because the staff has determined that the mathematical operations involved in the condensation process conform to established mathematical principles. More detail on this topic is discussed in the "Theoretical Basis" subsection of this SE below.

In the case of utilizing the ANSYS solver, the applicant retrieved the impedance matrix and load vector from the Soil Library and combined them with the dynamic stiffness of the building-fluid interaction model. ANSYS is then used to solve for the transfer function at each analysis frequency. The transfer functions between the selected calculated frequencies are interpolated using the same interpolation algorithm used in SASSI. Finally, the time domain solution is obtained through the complex frequency response analysis using the same method as in

SASSI. The applicant notes that the ANSYS frequency domain solution using the Soil Library is functionally equivalent to the SASSI frequency domain solution. Results from the ANSYS solver are included in the example problems discussed in Section 6.0 of the TR, to demonstrate functional equivalency between the ANSYS and SASSI solvers.

In the case of utilizing the SASSI solver, the applicant exported the building substructure in the form of mass, damping, and stiffness matrices from ANSYS and combined them with the soil impedance matrix and seismic load vectors at a given frequency. Alternately, the building model can be assembled using the SASSI HOUSE module and combined with the soil impedance matrix and seismic load vectors. The combined equations are then solved using the SASSI ANAL16 module, which yields the transfer function for a given frequency. The transfer functions at different analysis frequencies are then combined and post-processed as in the established SASSI routine. The applicant indicates that the ANSYS solver is the preferred one and will be used in production analysis; however, the SASSI solver is used in the report only to provide a check on the ANSYS solver. The staff's review of these solvers finds that the applicant's use of either the ANSYS or SASSI solver is acceptable because they follow essentially the same computational procedures.

In summary, the staff reviewed the applicant's solution strategy and method for the proposed improvements in frequency-domain soil-structure-fluid interaction analysis and finds it to be acceptable because the method is based on the established analytical procedures used in the SASSI methodology, which supports the performance of a seismic analysis that conforms to the guidance in SRP Section 3.7.2. The adequacy of the solution method is further validated through the example problems reviewed in "Example Problems" subsection of this SE below.

Theoretical Basis

Section 5.0 of the TR discusses the theoretical basis for the proposed improvements in frequency-domain soil-structure-fluid interaction analysis. The applicant provides a theoretical background and basis for development of the Soil Library and enhancements to the capabilities of a conventional SASSI code to support the proposed soil-structure-fluid interaction analysis methodology. The applicant discussed key elements of the SASSI methodology, including time-domain equations of motion, frequency-domain complex response analysis, development of material parameters including the stiffness, mass and damping matrices, mesh size criteria for soil elements, development of soil impedances for layered half-space, development of seismic load vectors, computation of transfer functions, and interpolation of transfer functions. The staff reviewed the theoretical basis discussed in the TR and finds it acceptable because it is based on the established SASSI methodology, which performs seismic system analysis in accordance with the guidance in SRP Section 3.7.2.

As a way of improving the efficiency with respect to the storage requirements of the Soil Library, the applicant presented a method through which the size of the soil impedance matrices and seismic load vectors is reduced through the process of internal condensation. The applicant notes that storing the full impedance matrices for a moderately-sized problem can be resource intensive and that internal soil impedance degrees of freedom that do not interact with the building can be condensed out of the impedance matrices and load vectors without affecting the outcome. This then results in a substantial saving of the space for the Soil Library. The condensation takes place for each frequency and the applicant demonstrated that condensation does not affect the outcome through a comparison of the results from analyses with and without condensation.

The staff reviewed the analytical steps involved in the condensation and finds them to be acceptable because the staff verified that they conform to the established mathematical principles concerning algebraic operations of matrices and because the building degrees of freedom interfacing with the soil are kept in the equations of motion. The staff also notes, in Example 2 discussed in "Demonstration Problems" subsection of this SE below, that the applicant performed and compared a solution based on the established SASSI methodology to a Soil Library solution that uses reduced impedances and load vectors. The staff verified that the results of the two solutions are equivalent, thus demonstrating the accuracy of the methods that use reduced impedances and load vectors from condensation.

The applicant added other enhancements to the established SASSI methodology to support the proposed soil-structure-fluid interaction analysis. These enhancements include the ability to solve a soil-structure interaction problem using an ANSYS substructure incorporating fluid-structure interaction and the ability to solve problems with non-symmetric mass and stiffness matrices resulting from the fluid-structure interaction formulation. The staff recognizes that these enhanced features of SDE-SASSI provide essential tools that support the improved frequency-domain soil-structure-fluid interaction analysis proposed in the TR. The staff reviewed the theoretical basis for these enhancements provided in the TR and further reviewed the evaluation of these enhanced features provided in the SDE-SASSI Acceptance Testing Report (Reference 7).

Based on its review, the staff finds that the theoretical basis for the proposed enhanced features is acceptable because: (1) the mathematical procedures involved in the enhancements to the established SASSI methodology conform to the established mathematical principles, and (2) its validity is demonstrated through the example problems provided in the TR.

In Subsection 6.3.2 of the TR, the applicant further provided an analytical formulation and the corresponding equations of motion for fluid-structure interaction analysis. The applicant then incorporated the fluid-structure interaction formulation into the seismic soil-structure interaction analysis framework, resulting in an explicit set of equations of motion for a coupled soil-structure-fluid interaction system subjected to an earthquake ground motion. The staff reviewed the procedures involved in the derivation of the formulation and finds it to be acceptable because: (1) the equations and parameters involved correctly reflect the established principles in the dynamics of fluid-structure and soil-structure interactive systems, and (2) the algebraic operations performed correctly follow established mathematical principles.

In summary, the staff's review of the applicant's theoretical basis for the proposed methodology for the soil-structure-fluid interaction analysis finds it to be acceptable because it conforms to the theoretical basis used in the established SASSI methodology and is consistent with the established mathematical principles.

Demonstration Problems

Section 6.0 of the TR contains example problems used to demonstrate the application of the Soil Library methodology. The example problems presented in the TR cover four different types; Example 1 evaluates a surface-founded containment building, Example 2 evaluates a partially-embedded box-shaped building with soil-structure interaction, Example 3 evaluates a partially-embedded box-shaped building with soil-structure-fluid interaction, and Example 4 evaluates a representative SMR building that houses twelve reactor modules and a pool and taking into account the effects of seismic soil-structure-fluid interaction.

(a) Example 1

This example includes the calculation of soil impedances and seismic response for a surface-founded pressurized-water reactor (PWR). The PWR containment and reactor internals are represented by lumped mass stick models supported on a rigid foundation resting on the surface of an elastic half-space. The applicant included this example to demonstrate the use of the Soil Library to develop the soil impedance matrices and seismic load vectors for a surface foundation.

The applicant calculated the seismic response of the model using both SDE-SASSI and ANSYS. The ANSYS solution uses the Soil Library, ANSYS structural elements, frequency domain solver, complex frequency response analysis method, and transfer function interpolation, and generates in-structure response spectra and structural force time histories. The staff reviewed this information and determined that there is good agreement between the SASSI and ANSYS results, which demonstrates that the ANSYS frequency domain solution using the Soil Library is functionally equivalent to the SASSI frequency domain solution.

(b) Example 2

This example demonstrates the use of the Soil Library to develop the impedances and load vectors for a partially embedded reinforced concrete building. The applicant used transfer functions to quantify the building's seismic response to a unit sinusoidal input for selected frequencies. The applicant calculated the response of the building using both SDE-SASSI and ANSYS. The ANSYS solution uses the Soil Library, ANSYS structural elements, and the frequency domain solver, and incorporates transfer function interpolation. The staff reviewed this information and notes that there is good agreement between the SASSI and ANSYS results, which demonstrates that the ANSYS frequency domain solution is functionally equivalent to the SASSI frequency domain solution.

ANSYS uses a moderately thick-shell element formulation with a consistent mass matrix. The applicant compared the response from a model using this ANSYS thick-shell element to the response from a model using the SDE-SASSI thin-shell element with a lumped-mass matrix. The staff reviewed the comparison and noted that responses generally diverge in the high frequency regions while the low frequency responses agree well between the two models. The staff determined that the ANSYS thick shell formulation would yield more accurate results than the thin-shell element implemented by SDE-SASSI because the thick shell is able to represent the mechanical behavior of the structural element more accurately than the thin shell.

The applicant used the ANSYS element formulation in the final comparison. The applicant also performed a solution without the Soil Library to demonstrate that the Soil Library solution and a solution from the established SASSI methodology are equivalent. The Soil Library solution used the reduced impedance matrices and load vectors obtained through the condensation of the interaction degrees of freedom that are not on the basement boundary. The staff reviewed the results and determined that the building response with and without the Soil Library compare well. Accordingly, the staff finds that the use of the Soil Library is functionally equivalent to an analysis based on the established SASSI methodology.

(c) Example 3

In this example, the applicant calculates the seismic response of a reinforced concrete building with an internal pool and considers the interaction among soil, structure, and fluid substructures. The example is to demonstrate that the SDE-SASSI and ANSYS frequency domain solutions are functionally equivalent for soil-structure-fluid interaction problems. Example 3 extends the soil-structure interaction response considered in Example 2 to include the fluid-structure interaction effects. Since the building footprint and soil properties for Example 3 are the same as for Example 2, the applicant used the Soil Library developed for Example 2 for Example 3. The applicant incorporated acoustic fluid interaction into the formulation by adding ANSYS acoustic elements to the structural model and adding pressure degrees of freedom as solution variables. The applicant notes that the stiffness and mass matrices that consider the acoustic coupling are not symmetric and therefore both SDE-SASSI and ANSYS use a solver for matrices that are not symmetric.

The applicant calculated the seismic response using both SDE-SASSI and ANSYS and used transfer functions to quantify the seismic response of the building and fluid. The ANSYS solution uses the Soil Library, ANSYS structural elements, and frequency domain solver, and incorporates transfer function interpolation. The SASSI solution uses the Soil Library and the ANSYS-generated structural elements. The applicant compared the in-structure response spectra for selected structural components and compared acoustic pressure time histories at different depths in the pool. The staff reviewed the results and determined that there is good agreement between the SASSI and ANSYS results. Accordingly, the staff finds that the ANSYS frequency-domain solution is functionally equivalent to the SASSI frequency-domain solution.

(d) Example 4

This example problem involves a representative SMR building that includes twelve nuclear power modules and a reactor pool. The applicant computed the dynamic response of a combined soil-structure-fluid substructure system subjected to earthquake ground motions using ANSYS and compared the results with those from SASSI. The purpose of this example problem is to illustrate the implementation of the Soil Library methodology using a complex structural model and to demonstrate that the ANSYS and SASSI solutions are equivalent. The applicant developed the Soil Library using SDE-SASSI with inputs taken from a soil profile and geometry of the reactor building excavation. The applicant used postulated input ground motions developed using actual recorded ground motion for a particular site as the seed time history. The analysis model includes the reactor building, twelve nuclear power modules, the reactor pool, and backfill soil. The ANSYS solution uses the Soil Library developed for the soil profile considered, ANSYS structural elements, and frequency domain solver, and incorporates the SASSI transfer function interpolation algorithm. The SASSI solution uses the ANSYS-generated mass, damping, and stiffness matrices.

The applicant compared the results, including transfer functions, time histories, and in-structure response spectra, calculated using ANSYS with the Soil Library to the results calculated using SASSI. The response parameters compared included: (1) acceleration transfer functions, (2) acceleration time histories, (3) in-structure response spectra, (4) fluid pressure transfer functions, (5) fluid pressure time histories, (6) relative displacement transfer functions, (7) relative displacement time histories, (8) reactor module lug force transfer functions, (9) reactor module lug force time histories, (10) reactor module base support force transfer functions, and (11) reactor module base support force time histories.

The staff reviewed the results from ANSYS and SASSI and their comparisons and verified agreement between them. Accordingly, the staff finds that the ANSYS frequency-domain solution is functionally equivalent to the SASSI frequency-domain solution for Example 4. The staff also observed good agreement between the transfer functions from ANSYS and SASSI. The applicant reported occasional spikes in transfer function plots, which it explained as artifacts of the transfer function interpolation algorithm implemented. The applicant noted that none of these interpolated spikes contain sufficient volume to affect the results. The staff evaluated this information and recognizes that such spikes in transfer functions are commonly encountered in frequency-domain solutions from SASSI, and the differences in solutions due to the spikes are usually inconsequential.

Soil Library Implementation

In Section 7.0 of the TR, the applicant discusses implementation of the Soil Library and describes steps for calculating the soil impedance matrices and seismic load vectors. It also describes the organization of the calculated Soil Library data, including detailed data structure by site and excavation geometry. The staff reviewed the information provided and finds it to be acceptable because the information on Soil Library implementation is consistent with the technical information reviewed and accepted by the staff above in this SE. The staff also recognizes that neither the specific organization, nor the data structure of the Soil Library for implementation affects the technical adequacy of the proposed analysis methodology, and, accordingly the applicant may choose the organization and data structure of the Soil Library at its own discretion.

5.0 Staff Conclusions

The staff has completed its review of the subject TR (Revision 2) and concludes that, subject to the limitations and conditions as specified in Section 6.0 of this SE, the frequency-domain analysis methodology described in this TR is acceptable to perform seismic soil-structure-fluid interaction analysis to establish seismic demands for seismic qualification of nuclear safety-related structures, systems, and components, in accordance with the guidance in NUREG-0800, SRP Section 3.7.2; and is thus in compliance with the applicable regulatory requirements delineated in Section 2.0 of this SE. The example problems provided in the TR demonstrate that the new analysis methodology provides computational efficiencies over the existing methodology. The staff's conclusions for specific technical topics are found within the respective technical evaluations in Section 4 of this SE.

6.0 Limitations and Conditions

The staff's approval of this TR is limited to the proposed analysis methodology applied to problems that satisfy the assumptions set forth by the applicant in Section 3 of the subject TR (Reference 2), specifically that: (1) all material properties are linear-elastic during the analysis, (2) the behavior of boundary conditions and constraints is linear, and (3) the seismic load is represented by vertically propagating shear and compression waves. A licensee or applicant who applies the analysis methodology approved in this SE to a site-specific problem must consider the applicability of these limitations to the specific site conditions, and the NRC staff will verify that each of these conditions has been satisfied in its review of a site-specific application.

7.0 References

1. NuScale Power, LLC Submittal of Topical Report TR-0118-58005, “Improvements in Frequency Domain Soil-Structure-Fluid Interaction Analysis,” Revision 0, dated July 26, 2018 (ADAMS Accession No. ML18208A362).

2. NuScale Power, LLC Submittal of Topical Report TR-0118-58005, “Improvements in Frequency Domain Soil-Structure-Fluid Interaction Analysis,” Revision 1, dated November 19, 2019 (ADAMS Accession No. ML19324E311).

3. NuScale Power, LLC Response to U.S. Nuclear Regulatory Commission, Request for Additional Information No. 9676 on the NuScale Topical Report, "Improvements in Frequency Domain Soil-Structure-Fluid Interaction Analysis," TR-0118-58005, Revision 0 (ADAMS Accession No. ML19168A249).

4. U.S. Nuclear Regulatory Commission, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition,” NUREG-0800, Section 3.7.2, “Seismic System Analysis,” Revision 4, September 2013 (ADAMS Accession No. ML13198A223).

5. Lysmer, J., Tabatabaie-Raissi, M., Tajirian, F., Vahdani, S., and Ostadan, F., “SASSI – A System for Analysis of Soil-Structure Interaction,” Report No. UCB/GT/81-02, Geotechnical Engineering, University of California, Berkeley, CA, April 1981.

6. American Society of Civil Engineers (ASCE) Standard 4-16, Seismic Analysis of Safety-Related Nuclear Structures, 2016.

7. NRC Staff Regulatory Summary Audit Report on Software Acceptance Testing Report for NuScale Licensing Topical Report, TR-0118-58005, July 13, 2020 (ADAMS Accession No. ML20195B116).

8. NuScale Power, LLC Submittal of Topical Report TR-0118-58005, “Improvements in Frequency Domain Soil-Structure-Fluid Interaction Analysis,” Revision 2, dated September 2, 2020 (ADAMS Accession No. ML20246G848).