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Division V

SIMULATION OF SOIL STRUCTURE INTERACTION SUPPORTING SEISMIC SHAKE TABLE TESTS OF FULL-SCALE DRY STORAGE OF SPENT NUCLEAR FUEL

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ABSTRACT

Sandia National Laboratories (SNL), under the Spent Fuel Waste Disposition (SFWD) program, is planning to conduct a series of earthquake shake table tests to determine the strains and accelerations on fuel assembly hardware and cladding during earthquakes of different magnitudes to better quantify the potential damage an earthquake could inflict on spent nuclear fuel rods. The shake table experiments will include one dry cask sitting on a concrete pad poured over the platen of the shake table. The effects of the underlaying soil, as well as the neighboring casks as in an actual spent fuel storage installation, are numerically simulated through Soil-Structure Interaction (SSI) analyses and incorporated in the input motion to the shake table.

A set of SSI Analyses are performed with two main objectives: (1) generate (SSI) input motions for the shake table, and (2) simulate the seismic cask behavior to inform the experimental program. A phased implementation is used for seismic simulations. Equivalent linear SSI analysis is performed in Phase 1. The response output SSI motions are used as input motion for a Phase 2 model. Nonlinear structural analysis using the input motions obtained from Phase 1 SSI analyses are performed in Phase 2. Significant deviations from the structural response at the concrete pad with respect to the input motion invalidates the equivalent linear input motion. Valid equivalent linear SSI motions are used as shake table input motions. Critical cases, those for which the input motions display significant deviation thus invaliding the case for equivalent linear analysis, are evaluated in Phase 3. It is envisioned to perform nonlinear SSI analysis in Phase 3 for the selected critical cases identified in Phase 2. The output motions from the nonlinear SSI analyses performed in Phase 3 are to be used as shake table input motions.

INTRODUCTION

Currently, spent nuclear fuel (SNF) in the United States is stored in onsite independent spent fuel storage installations (ISFSIs), which are dry storage facilities, at 55 nuclear power plant sites. Because the SNF will be stored at ISFSIs for an extended period of time, there is growing concern with regards to the behavior of the SNF within these dry storage systems during earthquakes. While the seismic stability of spent fuel dry casks has been extensively investigated (NUREG 6865: Luk et al. 2005), very limited information is available about the seismic behavior of the spent fuel bundles and rods. To fill this gap, Sandia National Laboratories (SNL), under the Spent Fuel Waste Disposition (SFWD) program, is planning to conduct a series of earthquake shake table tests. The goal of this test program is to determine the strains and accelerations on fuel assembly hardware and cladding during earthquakes of different magnitudes to better quantify the potential damage an earthquake could inflict on spent nuclear fuel rods. Ground motions representative of different seismic, tectonic, and site conditions in the United States for seismic hazard levels from 1E-3 to 1E-5 mean annual frequency of exceedance have been developed for this test program to capture the seismic hazard for dry-cask storage (Gregor et al., 2021). A companion paper provides a summary of the ground motions developed for this effort (Kalinina et al., 2022).

It is widely known that soil-structure interaction (SSI) effects would alter the ground motions as they interact with the ISFSI concrete pad and dry storage system. These SSI effects should be considered to transfer the ground motions (free field motion of the rock or soil) to the top of the ISFSI pad which will serve as inputs to a shake table for an experimental program.

SSI SIMULATIONS

The shake table experiments will consist of one dry cask sitting on a concrete pad poured over the platen of the shake table. The effects of the underlaying soil, as well as the neighboring casks as in an actual ISFSI, are numerically simulated through SSI analyses and applied as input motion to the shake table. A set of SSI Analyses are performed with two main objectives: (1) generate (SSI) input motions for the shake table, and (2) simulate the seismic cask behavior to inform the experimental program.

Certain features of the pad-cask structural system prompt nonlinear behavior: globally through sliding/uplift of the unanchored cask over the pad, and internally through impact/bouncing caused by the gaps between the different components (Klymyshyn et al., 2022). Numerical models able to represent both SSI effects as well as nonlinear structural behavior are computationally expensive and can easily compromise the timeline of this project. Therefore, a phased implementation is used for the seismic simulations of this project to optimize the time and computational resources available.

The aim of Phase 1 is to generate SSI input motions for the shake table. Equivalent linear SSI analysis is performed with a soil model that represents the site conditions and a structural model that represents the ISFSI: concrete pad and casks. The SSI motions resulting from the equivalent linear analysis, i.e. acceleration time histories on the concrete pad (at the base of the casks), need to be further evaluated in Phase 2, to be used as input motion for the shake table. Because seismic motion can induce sliding and uplift displacements on the cask, which cannot be simulated with an equivalent linear model, the simulation of the seismic cask behavior is mainly left for a Phase 2 model.

The aim of Phase 2 is to assess the SSI input motions generated in Phase 1, as well as to simulate the seismic cask behavior. A two-step SSI analysis with a nonlinear structural analysis is performed in Phase 2. Input motions consist of response output motions (including SSI effects) from Phase 1. The site and SSI effects are only implicitly represented through input motions. A structural model that represents a concrete pad and a detailed model of one cask, including internals and fuel rods, is used. The interface between the cask and the pad is modeled with a nonlinear contact interface to explicitly simulate the potential relative displacement (sliding and/or uplift) between the cask and the concrete pad. Seismic behavior of fuel rods is explicitly simulated and evaluated. Significant deviations from the structural response at the concrete pad with respect to the input motion invalidate the equivalent linear input motion. Equivalent linear SSI motions that have not been invalidated are used as shake table input motions. Equivalent linear SSI motions from critical cases that are invalidated are evaluated in Phase 3.

The aim of Phase 3 is to generate SSI input motions for the shake table, as well as to simulate the seismic cask behavior. Nonlinear SSI analysis for the selected critical cases identified in Phase 2 is envisioned for Phase 3. A model for the SSI system which includes an explicit representation of the site and nonlinear structural model of the pad/cask system and their interface will be used. The output motions from nonlinear SSI analyses will be used as shake table input motions.

In this paper, a case study consisting of the seismic response simulation of one ISFSI on soil conditions representative of Central and Eastern US (CEUS), for both Phase 1 and Phase 2, is presented. The inputs to the simulations include an input ground motion, a soil profile, and the structures consisting of a concrete pad and casks.

Ground Motions

Acceleration time histories corresponding to a typical CEUS soil site ground motion, assigned at the ground surface, and corresponding to an annual frequency of exceedance (AFE) of $5x10^{-5}$ with PGA values presented in Table 1, are used as input motions for the case study. Details on the generation of the input motions are provided by Gregor et al. (2021).

Table 1. Peak Ground Accelerations of Input Ground Motion.

Site Condition	AFE	Ground Motion Peak Acceleration (g)		
		X	Y	Z
Soil	5×10^{-5}	0.62	0.50	0.37

Soil Properties

Representative CEUS Soil properties, which are generated as a hybrid profile between the Vogtle site (Southern Company, 2014b) and the Farley site (Southern Company, 2014a), are used to create generic site conditions for a relatively large geographic area and to keep realistic site characteristics. In detail, soil properties are generated taking as the base case the soil properties for the Vogtle site and linearly scaling the shear wave velocity (Vs) for the profile to cause the rock at approximately 300 m depth to have a Vs value of 1151 m/s. This is the Vs value for rock at 300 ft depth of the Farley site. The input soil properties used include layer thickness, unit weight, low-strain properties: shear wave velocity (Vs), compression wave velocity (Vp), and damping, as well as degradation curves: shear modulus G/Gmax vs shear strain, and damping vs shear strain.

Concrete Pad and Cask Loading Configuration

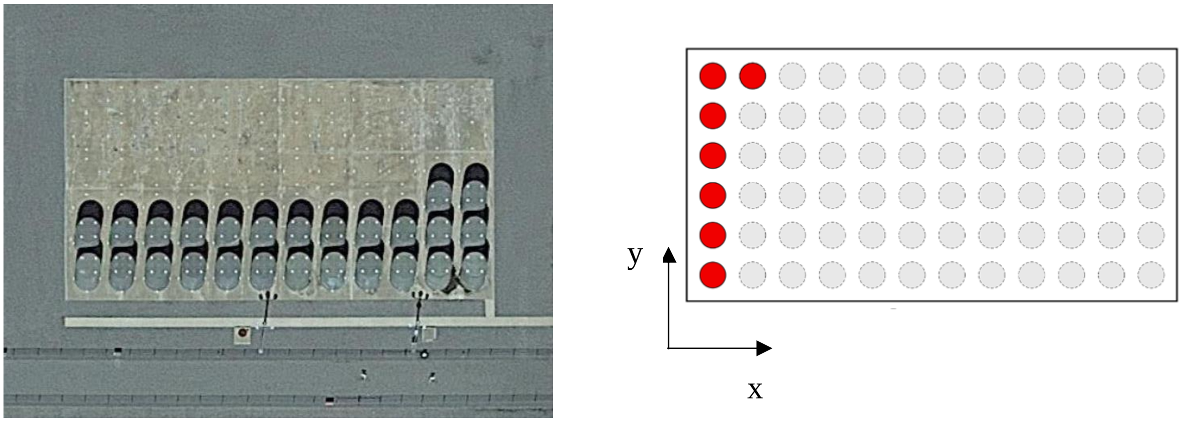
The cask properties for the simulations are given in Table 2. These properties are consistent with those of the cask which will be tested on the shake table. For the cask configuration analyzed here, a 5 m cask center-to-center distance is considered. The pad, shown in Figure 1b, has 12 columns by 6 rows of casks for a capacity of 72 casks, and dimensions of 58 m x 29 m. An image of a representative ISFSI is provided in Figure 1a. Four different loading configurations were initially analyzed. The cask configuration capturing the ISFSI pad at the governing load case is considered in this case study and shown in Figure 1b. The concrete pad properties used in this study are summarized in Table 3.

Table 2: Test Cask Key Dimensions and Weight.

Cask Outer Diameter	Cask Base Height	CG Height	Cask Mass
3.47 m	0.30 m	2.61 m	152,385 kg

Table 3: Reinforced Concrete Pad Dimensions.

Thickness	Length	Width
0.91 m	58.5 m	29.3 m



a) Google Image of a Representative ISFSI   b) ISFSI Cask Loading Configuration Used

Figure 1. ISFSI Pad with Vertical SNF Dry Storage Casks.

Cracked reinforced concrete section properties are considered consistent with the ground motion amplitudes and stress level expected. Material properties for the reinforced concrete of the pad are provided in Table 4.

Table 4: Reinforced Concrete Properties.

f'c	Ec	Unit Weight	Poisson's Ratio	Damping
27.58 MPa	24,855 MPa	2400 kg/m^3	0.25	7%

PHASE 1: EQUIVALENT LINEAR SSI ANALYSIS

Seismic Soil-Structure Interaction (SSI) analyses for Phase 1 are performed using an equivalent linear approach in the frequency domain using the software SC-SASSI (SC Solutions, 2018). Expanded SASSI capabilities via High Performance Computing capabilities (HPC) as implemented in SC-SASSI provide two primary advantages: (1) no limitations on model sizes (i.e. larger number of interaction nodes); and (2) drastically reduced analysis run-time. These two primary advantages allow direct and rigorous treatment of SSI phenomena.

Input ground motion is prescribed at the ground surface. Calculations are performed in the frequency range of 0 to 50 Hz. Response acceleration time histories are output at selected structural locations, and response spectra is calculated in the range of 0 to 100 Hz.

Site Response Analysis

Site response analyses are performed to calculate strain-compatible soil properties (Vs and damping). A soil column consisting of the low-strain soil properties is subjected to ground motions prescribed at the ground surface (top of the soil column), consistent with the ground motion generation conditions (Gregor et al. 2021). Strain-compatible soil properties are calculated in the frequency domain using the software SHAKE2000 (Ordonez, 2014). Compression wave velocity is back calculated from the degraded Vs and Poisson's ratios. Strain-compatible properties are used as site inputs for the soil-structure interaction analysis. Strain-compatible Vs properties are shown in Figure 2.

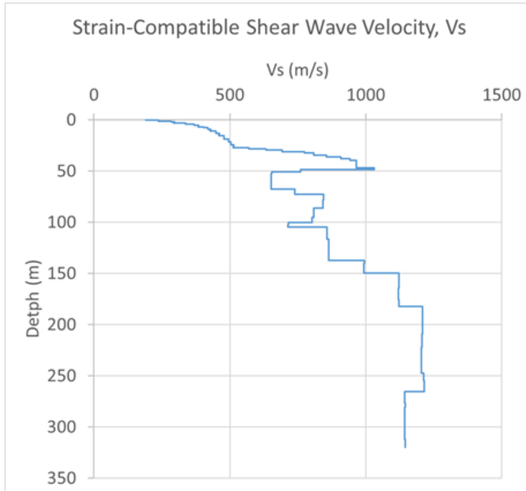


Figure 2. Strain-Compatible Shear Wave Velocity associated with Soil Profile.

Model Generation

The dry cask consists of the following main components: vertical concrete cask (VCC), canister, basket, and fuel assemblies. With the exception of the fuel assemblies, the other components are relatively stiff. A detailed description of the geometry and stiffness of the dry casks is provided in a companion paper by Klymyshyn et al. (2022). A simplified model to represent the global behavior of the dry cask system is used.

The dynamic behavior for the storage casks is characterized by the fundamental frequency for the following components: for the fuel basket, the lowest natural frequency is 83 Hz; and for the cask, the lowest natural frequency is 177 Hz per NUHMOS FSAR (TN Americas, 2017); and both are considered to be rigid for this SSI analysis up to 50 Hz. The finite element (FE) model for individual casks is shown in Figure 3.

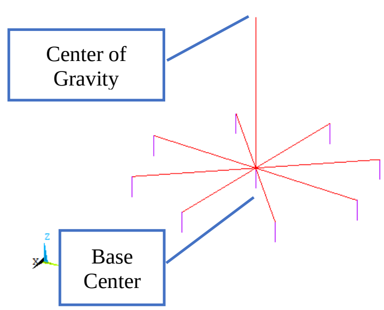


Figure 3. Single Cask Model.

The storage casks are represented with a single vertical rigid beam element with the cask mass lumped at its center of gravity and 8 horizontal rigid beam elements representing the contact area with the concrete pad. The horizontal rigid beam elements representing the cask base are connected to the pad with 8 vertical stiff springs having a length of half the pad thickness to locate the casks at the pad surface. The horizontal rigid beam ends connected to the vertical springs have rotational end releases. This configuration minimizes the effect of stiffening of the concrete pad due to the connection of the rigid beam members to the concrete pad. Horizontal forces and moments are transferred between the cask and the pad via the short element at the center of the cask, connecting the cask single vertical rigid beam element with the concrete pad.

The concrete ISFSI pad is modeled using 4-node shell finite elements at the center of the pad thickness, with the X-axis oriented parallel to the EW axis, the Y-axis oriented parallel to the NS axis, and the vertical direction along the Z-axis in the global Cartesian coordinate system. The loaded pad with the casks it is supporting is shown in Figure 4.

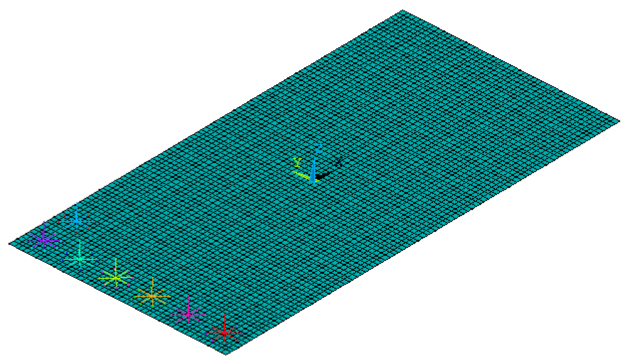
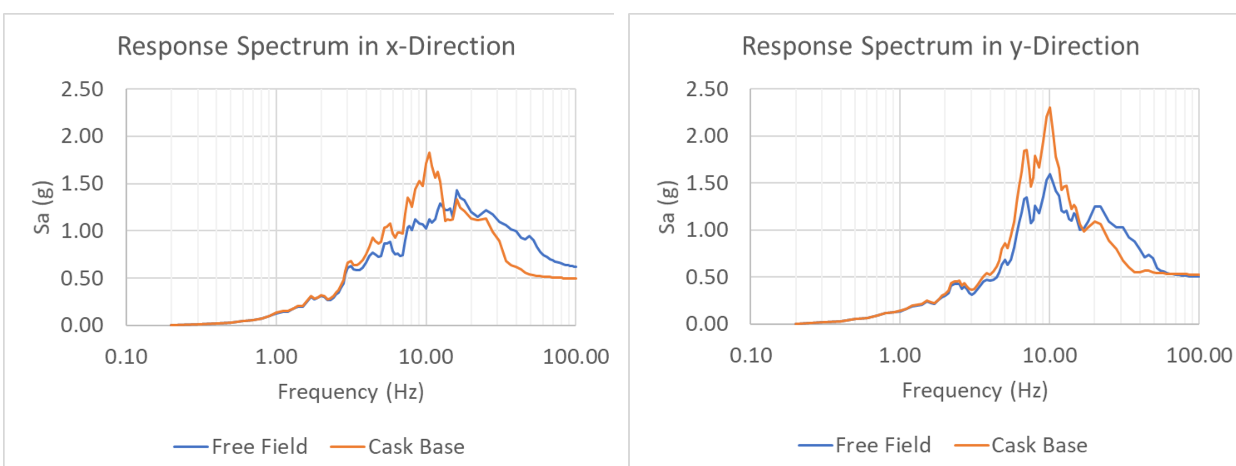


Figure 4. ISFSI Model Used for SSI Analysis.

The model assumes that the pad-cask system is linear. The casks are assumed to neither shift nor tip on the pad. Thus, friction is not included in this model.

Representative Results

The acceleration response spectra on the pad at the cask base center, located at the corner of the L-shaped cask loading (NW corner), are shown in Figure 5.



a) Response Spectrum in x-Direction b) Response Spectrum in y-Direction

Figure 5. Acceleration Response Spectra on the Pad at the Base Center of Cask of Interest.

The response spectrum at the cask base is characterized by frequency content and spectral amplitudes that are different than the free field response spectrum (representing the input ground motion), which shows the significance of the SSI effects. In the x-direction, response amplification is identified for frequencies lower than 15 Hz (similar amplification occurs below approximately 18 Hz in the y-direction), with peak spectral amplitudes around 10 Hz (for both x- and y-directions).

PHASE 2: NONLINEAR STRUCTURAL ANALYSIS

As stated above, certain features of the pad-cask structural system prompt nonlinear behavior: sliding/uplift of the unanchored cask over the pad, as well as impact/bouncing caused by the gaps between the different components. A companion paper describes a nonlinear detailed structural model and the corresponding seismic analyses performed for this project (Klymyshyn et al, 2022).

A two-step analysis is performed. The output accelerations (translational and rotational) at the top of the concrete pad (at the base of the cask of interest) of the equivalent linear SSI model discussed in the previous section are provided as input motion for the fixed-base nonlinear detailed model, i.e., an input ground motion including SSI effects is generated and applied. Seismic analysis for the nonlinear detailed structural model is performed in the time domain and reported in a companion paper (Klymyshyn et al, 2022). As described by Klymyshyn et al. (2022), a detailed canister model more accurately represents the canister internals and it is expected to provide a better estimate of system behavior at relatively expensive computational cost. Results for the nonlinear detailed structural model are presented and discussed in the following section.

RESULTS COMPARISON

Despite the significant differences in modeling assumptions, as well as model resolution between the model for equivalent linear SSI analysis and the detailed model for the nonlinear analysis, results from both models are compared. Results from the time-domain nonlinear detailed model have had a low-pass filter applied to remove spurious high frequency content above 100 Hz. As described by Klymyshyn et al. (2022), the nonlinear detailed model reported cask base sliding motions, but not a significant amount of tipping for the input ground motion considered.

Acceleration time histories at the cask center of gravity in the y-direction are shown in Figure 6.

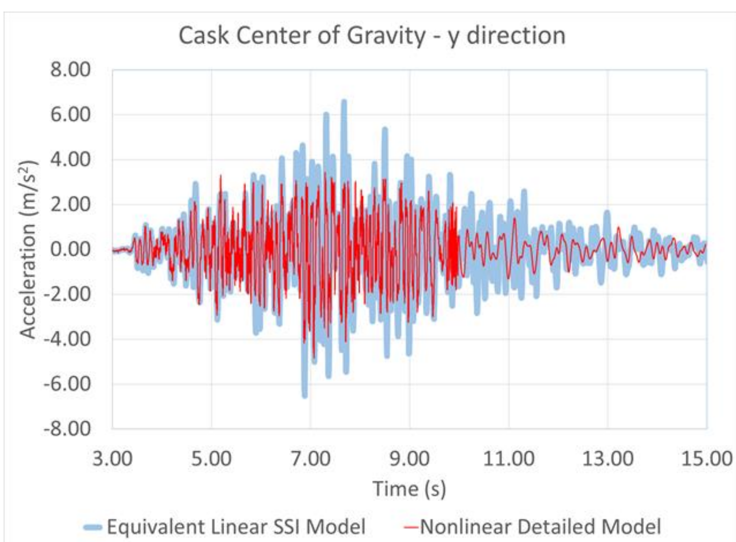


Figure 6. Comparison of Acceleration Time Histories Responses at Cask Center of Gravity.

The two sets of time histories in Figure 6 show fair agreement initially for the 3-5 sec. time segment, indicating relatively low influence of the nonlinear features of the detailed model for the early ground motion amplitudes. However, after 5.0 s, response of the nonlinear detailed model deviates significantly from the response of the equivalent linear SSI model, indicating the contribution of the nonlinear features (cask sliding as well as multiple gaps between the cask internals) for middle and late ground motion amplitudes to the attenuation of the cask response of the nonlinear detailed model.

Response spectra at the cask center of gravity in the y-direction are shown in Figure 7. The response spectra of the two models show significant differences in the frequency content and amplitudes. The equivalent linear SSI model shows spectral amplification mainly around 10 Hz, corresponding to a relatively simple structural system. The nonlinear detailed model shows multiple amplification peaks, consistent with a more complex structural configuration and local resonances. Both models show the highest spectral amplitudes around 10 Hz; however, the nonlinear detailed structural model shows smaller amplitude than the equivalent linear SSI model at 10 Hz, consistent with the additional energy dissipation through the interface's nonlinearities of the detailed model.

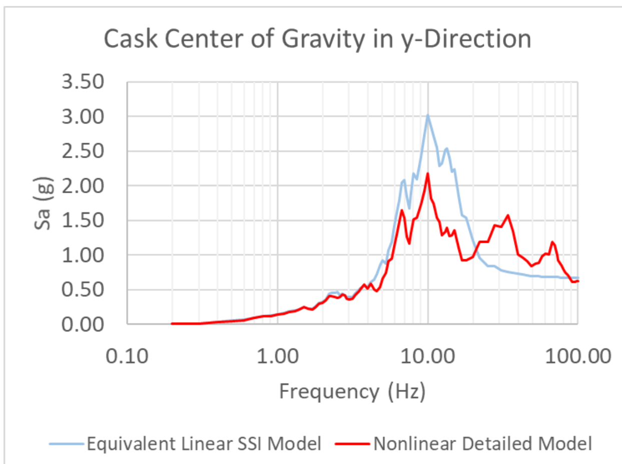


Figure 7. Comparison of Acceleration Response Spectra at Cask Center of Gravity.

Two different approaches are used to estimate sliding displacements. As described above, the equivalent linear SSI model is not able to predict sliding. However, the approximate method and formulae to estimate sliding of an unanchored rigid body provided by ASCE 4-16 (ASCE, 2017) is used and applied to this case. Second, the cask-pad sliding displacement predicted by the nonlinear detailed model is extracted. The results of the sliding displacements between cask and concrete pad estimated by the two methods indicated above are listed in Table 5. A reasonable agreement is found between the sliding displacement results predicted by the approximate method from ASCE 4-16 and those by the nonlinear detailed model.

Table 5: Sliding Displacement between Cask and Concrete Pad.

Approximate Method from ASCE 4-16	Nonlinear Detailed Model
(mm)	(mm)
6.3	4.3

FUTURE WORK: NONLINEAR SOIL-STRUCTURE INTERACTION ANALYSIS AND EXPERIMENTS

This paper is an in-progress report for the seismic simulations supporting the future shake table test program. The next phases of the project include nonlinear explicit SSI analysis, as needed, as well as the assessment and verification of the different stages of seismic simulation models using the upcoming experimental results.

As stated above, the two-step SSI analysis performed with the nonlinear detailed structural model is aimed at: a) confirming the applicability of equivalent linear SSI modeling assumptions for the shake table input motion generation, as well as b) predicting and simulating the seismic cask behavior to inform the experimental program. If cases are identified, where significant inconsistency between the results from the equivalent linear SSI model and the nonlinear detailed model exist, a third phase would be implemented for those cases.

The model used for Phase 3 would consist of a nonlinear detailed structural model augmented by a soil model. Seismic analysis would be performed in the time domain to generate acceleration time histories (translational and rotational) at the top of the pad and at the location of the base center of the casks of interest, to be used as input motion for the shake table.

Additionally, the future shake table testing program, as described in a companion paper (Kalinina et al., 2022), will be instrumental to assess and verify the phased SSI simulations and their underlining assumptions described in this paper.

SUMMARY AND CONCLUSIONS

A series of earthquake shake table tests are planned to investigate the seismic behavior of spent nuclear fuel storage systems including the spent nuclear fuel rods. A set of SSI Analyses are performed with two main objectives: (1) generate (SSI) input motions for the shake table, and (2) simulate the seismic cask behavior to inform the experimental program. To optimize the time and computational resources available, a phased implementation of SSI analysis is used for seismic simulations. The phased SSI analyses span from equivalent linear SSI analysis with simplified structural models and decoupled nonlinear cask/internals structural analysis, to fully integrated and nonlinear soil-structure system analysis. Equivalent linear SSI models are used in Phase 1 to generate SSI input motions to be used as input for shake table experiments. The aim of Phase 2 is to assess the SSI input motions generated in Phase 1, as well as to simulate the seismic cask behavior, using a two-step seismic analysis with an input motion including SSI effects and a nonlinear detailed structural model. The detailed model is able to predict nonlinear cask stability behavior including sliding and uplift, as well as nonlinear behavior of the cask internals. However, computation times are much larger compared to equivalent linear SSI models.

For results produced in Phase 1 by equivalent linear SSI analysis, the differences between the response spectra at the concrete pad (at the cask base) and the response spectra of the free field motion demonstrate the significance of the SSI effects for this case study.

Comparison of resulting acceleration time histories at the cask center of gravity between an equivalent linear model and a nonlinear detailed model indicate relatively low influence of the nonlinear features of the detailed model for the initial early ground motion amplitudes, but a higher contribution of the nonlinear features (cask sliding as well as multiple gaps between the cask internals) for middle and late ground motion amplitudes represented by the attenuation of the cask response on the nonlinear detailed model.

Comparison of resulting acceleration response spectra at the cask center of gravity between an equivalent linear model and a nonlinear detailed model indicate significant differences in the frequency content and amplitudes. While the equivalent linear SSI model shows mainly one spectral amplification peak, consistent with a relatively simple structural system, the nonlinear detailed model shows multiple amplification peaks, consistent with a more complex structural configuration and local resonances. In addition, the nonlinear detailed structural model shows smaller amplification than the equivalent linear model for the first resonance, indicating the additional energy dissipation of the nonlinear detailed model through the interface's nonlinearities.

Results from the detailed nonlinear structural model of Phase 2 indicate occurrence of sliding displacements for the amplitudes of the ground motion of this case study. Inclusion of nonlinear features for the cask-pad interface to a model able to represent the SSI effects will improve its capabilities to simulate the seismic behavior of the system subjected to ground motion amplitudes capable of inducing cask sliding.

The next phases of this in-progress project will include nonlinear explicit SSI analysis, as needed, as well as the assessment and verification of the different stages of seismic simulations models using the upcoming experimental results from the future shake table test program.

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REFERENCES

American Society of Civil Engineers, (2017). *Seismic Analysis of Safety-Related Nuclear Structures, ASCE/SEI 4-16*, Reston, VA, USA.

Gregor, N. and Atik, L.A. (2021). *Ground Motions for Shake-Table Testing of Dry Casks*, SC Solutions Project Report, Sunnyvale, CA, USA.

Kalinina, E. A., Ammerman, D. (2022) "Planning for Seismic Shake Table Test of a Full-Scale Dry Storage of Spent Nuclear Fuel." Paper to be presented at SMiRT-26 Berlin/Potsdam, Germany, July 10-15, 2022.

Klymyshyn, N., Kadooka, K., Fitzpatrick, J. (2022). "Pretest Predictions of Spent Nuclear Fuel in a Seismic Shake Test". Paper to be presented at SMiRT-26 Berlin/Potsdam, Germany, July 10-15, 2022.

Luk, V.K., Spencer, B.W., Lam, I.P., and Dameron, R.A. (2005). *Parametric Evaluation of Seismic Behavior of Freestanding Spent Fuel Dry Cask Storage Systems*, NUREG/CR-6865, SAND2004-5794P, Sandia National Laboratories, Albuquerque, NM, USA,

Ordonez, Gustavo A. (2012). *SHAKE2000 – A Computer Program for the 1-D Analysis of Geotechnical Earthquake Engineering Problems*. Geomotions, Lacy, WA, USA.

SC Solutions, Inc. (2018). *SC-SASSI Manual, Version 2.3.2*, Sunnyvale, CA, USA.

Southern Company (2014a), *Joseph M. Farley Nuclear Plant – Units 1 and 2 – Seismic Hazard and Screening Report for CEUS Sites*, Birmingham, AL, USA.

Southern Company (2014b), *Vogtle Electric Generating Plant – Units 1 and 2 – Seismic Hazard and Screening Report for CEUS Sites*, Birmingham, AL, USA.

TN Americas, LLC. (2017), *Updated Final Safety Analysis Report (UFSAR), for the Standardized NUHOMS Horizontal Modular Storage System for Irradiated Nuclear Fuel*, NUH003, Rev. 16, Columbia, MD, USA.