Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division V

SEISMIC RESPONSE OF ISFSI SITE WITH THICK SOFT SOIL LAYER BELOW THE WATER TABLE

Taha AL-Shawaf[1], Benjamin Kennedy[2], Jamal Azmeh[3], and Si-Hwan Park[4]

[1] Technical Consultant, Orano Federal Services LLC, Charlotte, NC, USA
(Taha.AlShawaf@orano.group)
[2] Engineer IV, Framatome Inc., Charlotte, NC, USA
[3] Staff Engineer, NEXTERA ENERGY, Duane Arnold, Palo, IA, USA
[4] Principal Engineer, TN Americas LLC, Columbia, MD, USA

ABSTRACT

For DAEC the Design Basis Earthquake (DBE) is defined as an outcropping motion at the top of the bedrock at an elevation of 728 ft. Since the DBE is provided as a response spectrum, ground motion time histories in three spatial directions are developed. Consistent with the original Reactor Building seismic design the seed motions are taken from the El Centro seismic event. These recorded time histories are used to match horizontal and vertical DBE targets in accordance with NUREG-0800 (2014). Once the ground motion time histories are determined they are convolved through the strain-compatible soil column to the free field elevation at 828’ of the ISFSI yard using SHAKE software. The unique feature of the soil at the DEAC ISFSI yard is a sudden large increase in Poisson’s ratio and associated increase in compression wave velocity at the top of the stratum. Since the Poisson’s ratio of the clay is close to 0.5 numerical problems can be encountered while using SSI analysis software like SASSI (MTR/SASSI, 2013). In this paper a method to compute seismic responses for soft soils with large Poisson’s ratios is provided. Further, two different loading scenarios are studied whereby the behavior of a fully loaded ISFSI pad is compared to a partially loaded pad on which 30 of a possible 34 storage modules are installed and only 16 are loaded.

INTRODUCTION

A new Independent Spent Fuel Storage Installation (ISFSI) at the Duane Arnold Energy Center (DAEC) site is investigated. The new ISFSI has a 176’ long by 43’-4” wide by 3’ thick reinforced concrete pad, loaded with up to 34 NUHOMS® HSM-H storage modules, which acts as an extension of the existing ISFSI at the site. Recent site soil explorations in the ISFSI yard confirm the presence of an approximately 100’ thick soft subsurface (clay, clayey sand, and sandy clay soil layers). Settlement experiences over time from the existing ISFSI pad at the site have revealed challenges, requiring the design of the new ISFSI to be more robust against potential differential settlement. Therefore, a 3’ thick layer of Controlled Low Strength Material (CLSM) is placed under the new ISFSI pad. This paper is focused on the key aspects of the seismic design, namely, Soil-Structure Interaction (SSI) analyses of the new reinforced concrete pad, considering two different loading scenarios (fully loaded as depicted in Figure 1 and partially loaded as depicted in Figure 2).

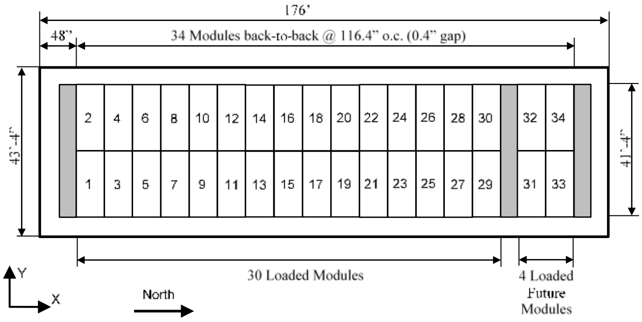

Figure 1. Fully Loaded ISFSI pad

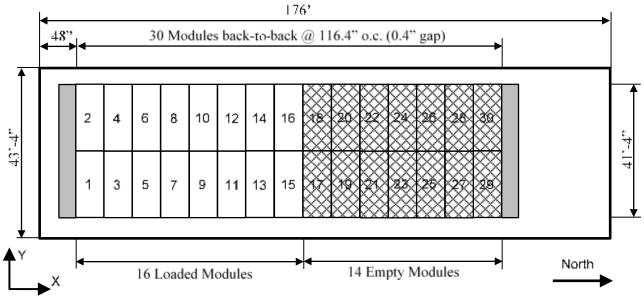

Figure 2. Partially Loaded ISFSI pad

INPUT MOTIONS

Free-field ground motions for the DAEC ISFSI yard for best estimate (BE) soil representations are developed. Consistent with the original Reactor Building seismic design the seed motions are taken from the El Centro seismic event. These recorded time histories are used to match horizontal and vertical DBE targets in accordance with NUREG-0800 (2014). Response spectra of these free-field ground motions compared against the outcropping motion at the bedrock are shown in Figure 8 through Figure 10. The positive X axis ground motion component is located such that it points in the north direction (Figure 1) for this analysis. Thus, the positive Y component points in the west direction and the Z component points up. These input motions have a time step size $\Delta t = 0.01$ s and a total duration of 40.96 s ($N = 4096$ time steps). The Nyquist frequency for the motions is $f_{ny} = 1 / (2\ \Delta t) = 50$ Hz. The upper bound for the frequency of interest for the ground motions is where the amplified spectral acceleration region drops down to the peak ground acceleration, and is at approximately 20 Hz horizontally and 50 Hz vertically.

SOIL MODELLING

Strain-compatible soil profiles for the DAEC ISFSI site are developed using SHAKE (SHAKE91, 1991) analyses and represent each of the soil conditions through a horizontally layered system on top of a halfspace (Figure 3). The soil conditions are characterized by a lower bound (LB), best estimate (BE), and upper bound (UB) realization that covers the expected variability in soil properties at the DAEC ISFSI site through a shear modulus variation of ±50%; however, only the BE properties are presented here.

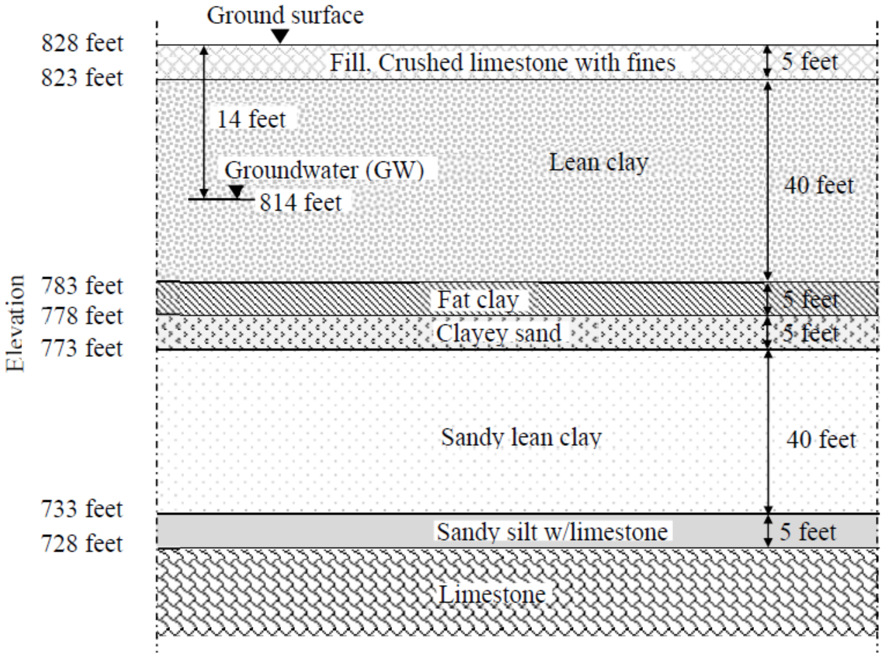

Figure 3. Subsurface Idealization

The ground elevation around the ISFSI pad is 828 ft. The top of concrete of the ISFSI expansion pad is 828'-4½" with a pad thickness of 3 ft. Since the centerline modeling technique is used for the pad, the analysis ground elevation is 826'-10½" (= 828'-4½" – 3'/2) which serves as the location of the control point. The minimum passing frequency is computed for each soil profile and layer using the following formula: $f_{pass} = V / 5 / h$ (MTR/SASSI, 2013), where V is the applicable wave velocity and h is the layer thickness. Soil layers with a passing frequency less than the frequency of interest are subdivided.

Figure 4 and Figure 5, respectively, show the shear wave velocity V_s and compression wave velocity V_p profiles for the BE soil cases. The relation between V_s and V_p for linear elastic wave propagation depends on the Poisson's ratio: $V_p = V_s\ [\ (2 – 2\upsilon) / (1 – 2\upsilon)\ ]^{0.5}$. If the Poisson's ratio, υ approaches 0.5, V_p tends to infinity. Such a situation would pose a numerical challenge for the finite element software and make the solution process unstable. To avoid erroneous results, a case limiting the Poisson's ratio to 0.485 (with reduced V_p) is also considered.

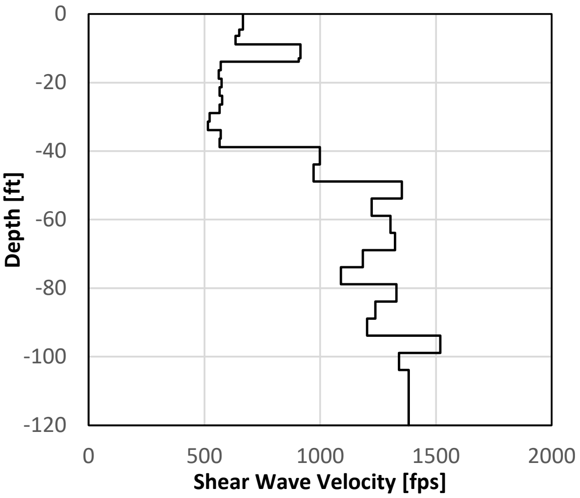

Figure 4. V_s Profile

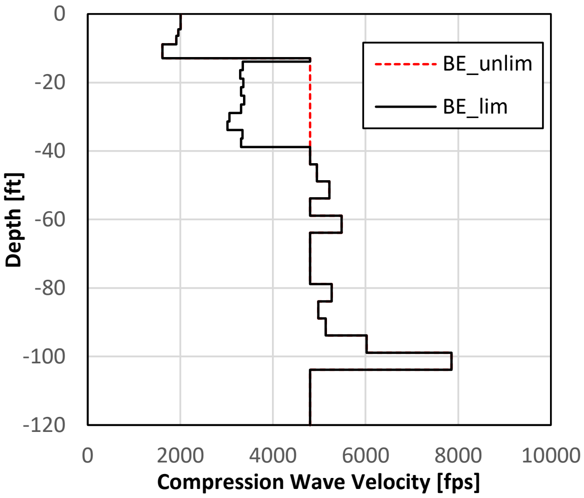

Figure 5. V_p Profile

Due to the Poisson's ratio limitation several soil layers are affected along with the vertical response (between depths of approximately 14' and 40'). Since large Poisson's ratios are natural in clay soils the effect of the Poison's ratio limitation on the response is evaluated utilizing a SHAKE analysis. Similarly to the first SHAKE analysis, the input motions are propagated from the top of the bedrock through the limited soil profile (as opposed to the unlimited profile) to the ground elevation. Figure 6 shows the response spectra comparison between the unlimited and limited (reduced V_p between 14' and 40' depth) soil profile.

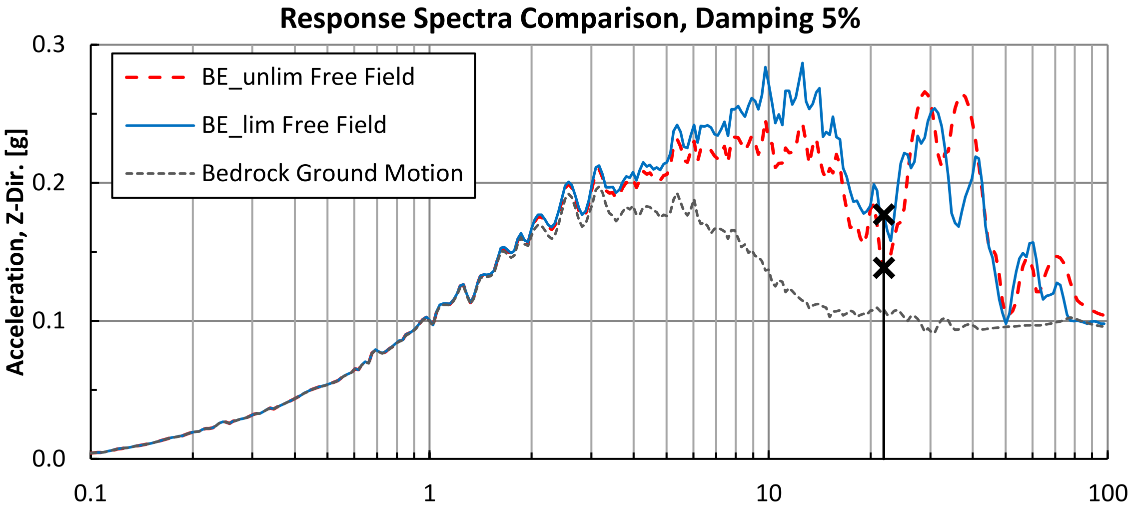

Figure 6. Free Field Response Spectra Comparison – Limited vs. Unlimited

To avoid unconservative vertical responses a scale factor (SF) which is computed from the maximum spectral ratio of the limited over the unlimited spectral response over the entire frequency range is used (Figure 6). The scale factor of 1.28 (at 21.9 Hz) is applied to the vertical SSI input motion for the BE soil case.

STRUCTURAL MODELLING

The concrete support pad is 176' long by 43'-4" wide by 3' thick. The shield walls of the HSM-H storage modules at the ends of the pad and south of the future modules are 41'-4" long by 18'-6" tall by 3' thick. In the fully loaded condition, the pad supports 34 storage modules. In the partially loaded condition, the pad supports 16 loaded storage modules (1 through 16), 14 empty storage modules (17 through 30), and the future storage modules (31 through 34) are not installed. The structural model consists of a 3-D lumped mass stick model for each storage module (loaded or empty), 3-D lumped mass stick models for the shield walls, and a finite element model for the support pad (plate elements). The material properties of the pad, shield wall, and HSM-H concrete are listed in Table 1.

Table 1: Concrete and CLSM Material Properties

Material Property		Structural Element
28 day compressive strength of concrete:	$f'_c = 4{,}000$ psi	pad, shield wall
	$f'_c = 5{,}000$ psi	HSM-H
	$f'_c = 850$ psi	CLSM
Unit weight of concrete:	$w_c = 150$ pcf	pad, shield wall
	$w_c = 145$ pcf	HSM-H
	$w_c = 135$ pcf	CLSM
Modulus of Elasticity:	$E_c = w_c^{1.5} \cdot 33 \cdot f'^{0.5}_c = 552{,}133$ ksf	pad, shield wall
	$E_c = w_c^{1.5} \cdot 33 \cdot f'^{0.5}_c = 586{,}696$ ksf	HSM-H
	$E_c = w_c^{1.5} \cdot 33 \cdot f'^{0.5}_c = 217{,}313$ ksf	CLSM
Poisson's ratio:	$\nu = 0.17$	
Shear Modulus:	$G_c = E_c / (2[1+\nu]) = 235{,}954$ ksf	pad, shield wall
	$G_c = E_c / (2[1+\nu]) = 250{,}725$ ksf	HSM-H
	$G_c = E_c / (2[1+\nu]) = 92{,}869$ ksf	CLSM
Concrete damping:	$d_c = 7\%$	

The stick models of the storage modules are shown in Figure 7. Each stick model consists of a 1.5' long rigid beam from Node 101 (half of the pad thickness) to 201 and a shear beam from Node 201 to 301 to represent the empty module. If the module is loaded then the rigid beam is connected to a shear beam from Node 201 to 401 to represent the loaded module. Either the empty module or the loaded module of the shear beam is used. The lumped mass at Node 301 is equal to $m_{301} = 9.506$ k-sec^2/ft (empty module). The lumped mass at Node 401 is equal to $m_{401} = 12.398$ k-sec^2/ft (loaded module). The section and material properties of the shear beams are selected such that the frequency of the stick representing the module closely matches those of the module (23.2 Hz and 28.4 Hz for vibrations in the lateral (X) and longitudinal (Y) directions, respectively, and 53.5 Hz for vertical vibrations). The base of the stick model (Node 101) is connected to 6 radiating horizontal rigid beams which are located at the pad centerline elevation, resembling the footprint of the modules on the pad. The outer ends of the rigid beams lie along the perimeter of the footprint of the module, and are pin-connected to the 6 nodes on the pad.

The shield walls at both ends of the pad and south of the future modules consist of 4 panels each that are not structurally connected to the pad but stand on the pad while laterally connected with anchor bolts to the outer walls of the modules. For the shield wall stick which represents 2 panels each, the lumped mass of 5.345 k-sec^2/ft is located at 9.25' from the pad top. The connection from the shield wall to the storage module side wall is approximated by three components of equivalent springs between the shield wall and end module sticks. The shield wall and end module are expected to behave like one integral structure and their seismic responses are not expected to be sensitive to the values of the spring stiffness.

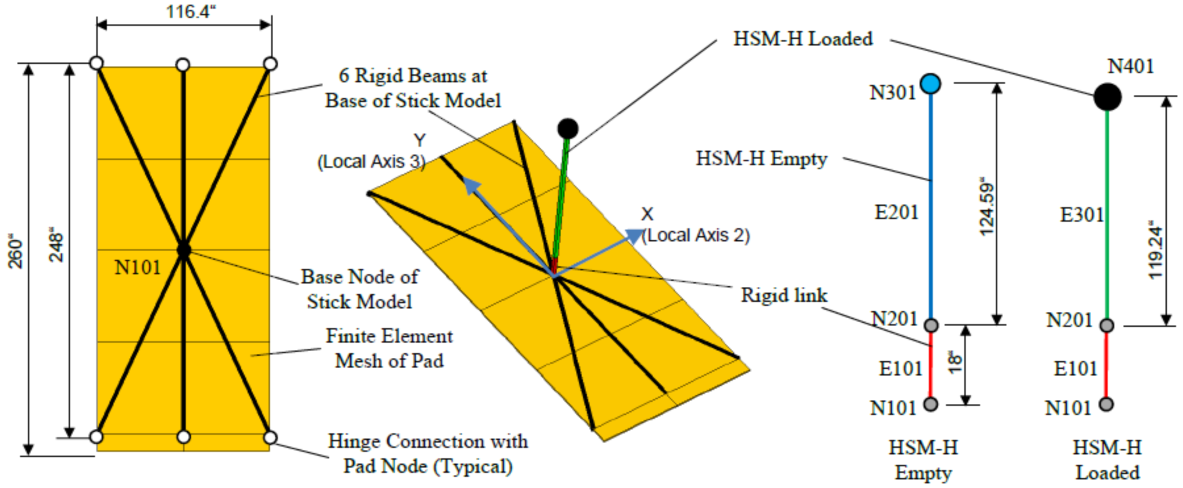

Figure 7. Stick Modelling of Modules

Two loading scenarios that cover potential installation patterns are considered in this analysis:

A) Fully loaded pad, The HSM-H modules 1-34 are installed and loaded. The shield walls are installed at the outer walls of the modules at both ends of the pad as well as after HSM29 and HSM 30 (Figure 1).

B) Partially loaded pad, The HSM-H modules 1-30 are installed (future modules 31-34 are not installed) with modules 1-16 being loaded and modules 17-30 remaining empty. The shield walls are installed at the outer walls of the modules at both ends of the pad (Figure 2).

The interaction nodes in the structure and the excavated soil volume are reviewed to determine a representative distance amongst them. A representative average distance (element size) in the X direction of x = 4.89 ft and in the Y direction y = 5.4 ft at elevation -2.25 ft is selected. This distance is used in the SASSI POINT module to derive the flexibility matrix and thereafter the soil impedance. An average distance between the nodes $h_{ave} = (x + y) / 2 = 5.145$ ft is used where the POINT load radius is about 4.6 ft ($0.9h_{ave}$). In order to derive the minimum passing frequency that can be transmitted into the structure, the maximum interface element size h = 5.64 ft is used. Table 2 shows the minimum passing frequencies calculated for the SSI analysis models. The analysis models have a minimum passing frequency of 24 Hz and 71 Hz in the horizontal and vertical direction, respectively. Since the amplified region of the input motion is less than these passing frequencies for each component, the SSI analysis models are adequate.

Table 2: Minimum Passing Frequency (Hz)

	Passing frequency due to			Minimum
	Time History	Soil Layer	Interface	
Horizontal	50	39	24	24
Vertical	50	81	71	71

A 3 ft thick layer of CLSM is placed below the ISFSI pad. This layer is explicitly modeled using solid elements, incorporating a bottom flared 8” horizontally for every 12” depth. To accommodate the 3 ft CLSM layer the first soil layer thickness is adjusted to a thickness of 4.5 ft (half of the pad thickness plus 3 ft of CLSM). The material properties of the CSLM are varied for the LB, BE, and UB cases with the BE values provided in Table 1.

Due to the centerline modeling technique the CLSM solid elements start at SSI model elevation +0.0 ft and extend down to -4.5 ft. As a result, the first CLSM solid element layer would add too much mass to the system (half of the pad thickness). Therefore, the density of the first CLSM layer is reduced to account for this effect (to 47.5 pcf).

Since the CLSM layer is embedded into the soil the response of the corresponding outcrop needs to be subtracted from the free-field response. That step is internally performed in SASSI through the definition of an excavated soil volume.

The SSI analyses are performed using MTR/SASSI Version 9.4.5, which operates in the frequency domain and outputs the seismic responses in the time domain. A total of 148 analysis frequencies are selected to compute transfer functions starting at sample frequency 1 at 0.0244 Hz (= 1 / ($\Delta t \cdot N$), $\Delta t = 0.01$ s and N = 4096 time steps) and as shown in Table 3. The analysis is performed utilizing the Direct Method where 3598 interaction nodes are used.

Table 3: Analysis Frequencies

Frequency Range (Hz)	Frequency Increment (Hz)
0 to 10	0.1221
10 to 15	0.2441
15 to 25	0.4883
25 to 50	0.9766

Acceleration response spectra are produced for the C.G. of the storage modules for 5% damping. A total of 298 response spectra sample frequencies are selected to compute the response spectra. The sample frequencies are defined by 100 uniformly spaced points per frequency decade (3 frequency decades minus 2 shared points at 1 Hz and 10 Hz = 298 sample frequencies).

RESULTS AND CONCLUSIONS

In-Structure Response Spectra (ISRS) comparisons for the C.G. of storage module 5 in each direction are presented in Figure 8, Figure 9, and Figure 10 between the fully loaded analysis (A) and the partially loaded analysis (B). While only module 5 is presented here as a representative result, it is apparent from the plots and comparisons for other locations that the loading scenario/pattern does not affect the overall response of the storage modules significantly. This is concluded from the almost identical response in the amplified region as well as in the zero period region of the spectra.

Furthermore, by visually comparing the free field response at the site with the response of the storage modules, it is evident that both responses are similar especially in the horizontal direction, implying that the soil column response dominates the response of the pad.

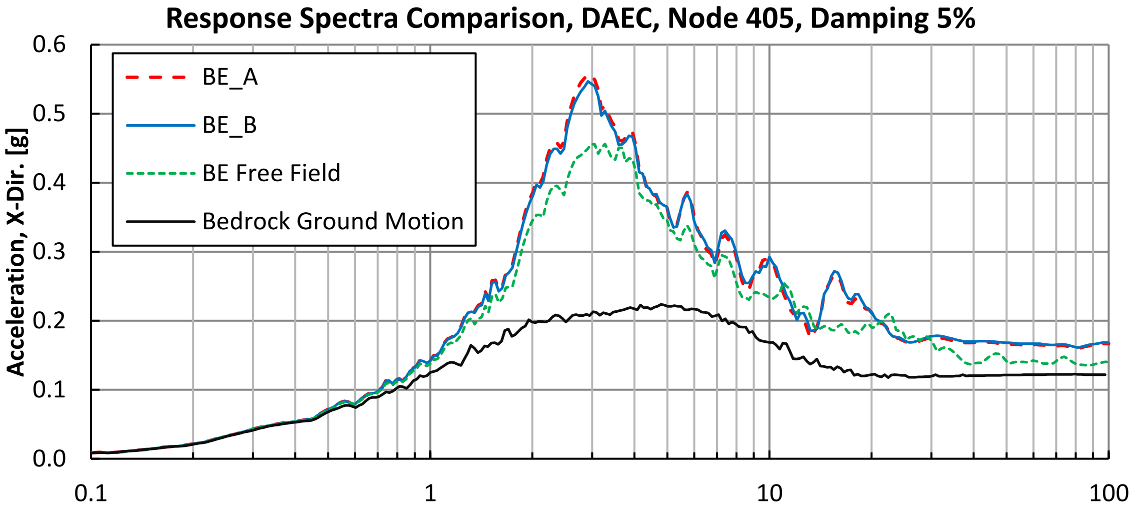

Figure 8. Best Estimate Soil Profile X-Direction Response Spectrum Comparison between A: Fully Loaded, B: Partially Loaded, Free Field, and Bedrock Ground Motion

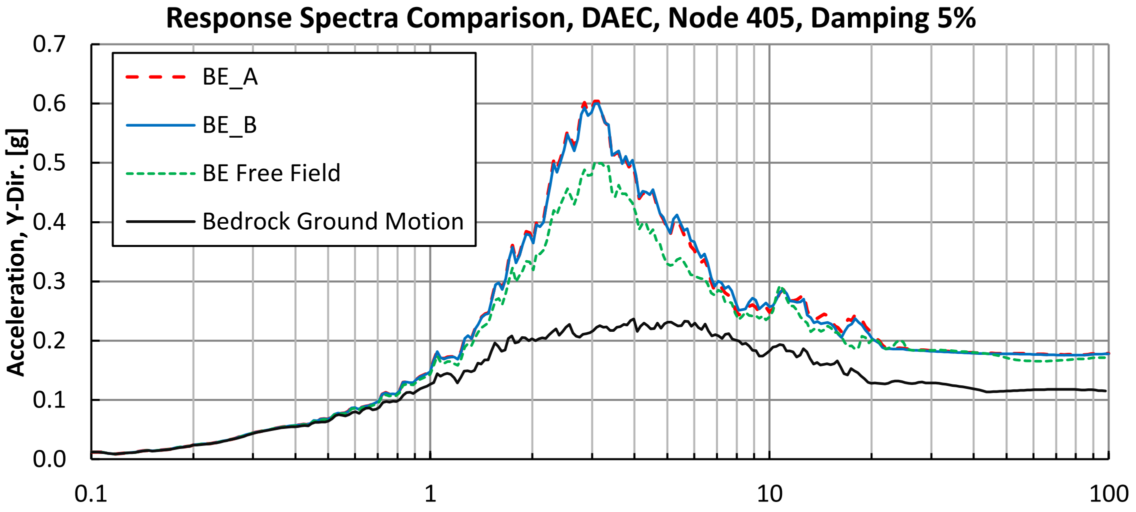

Figure 9. Best Estimate Soil Profile Y-Direction Response Spectrum Comparison between A: Fully Loaded, B: Partially Loaded, Free Field, and Bedrock Ground Motion

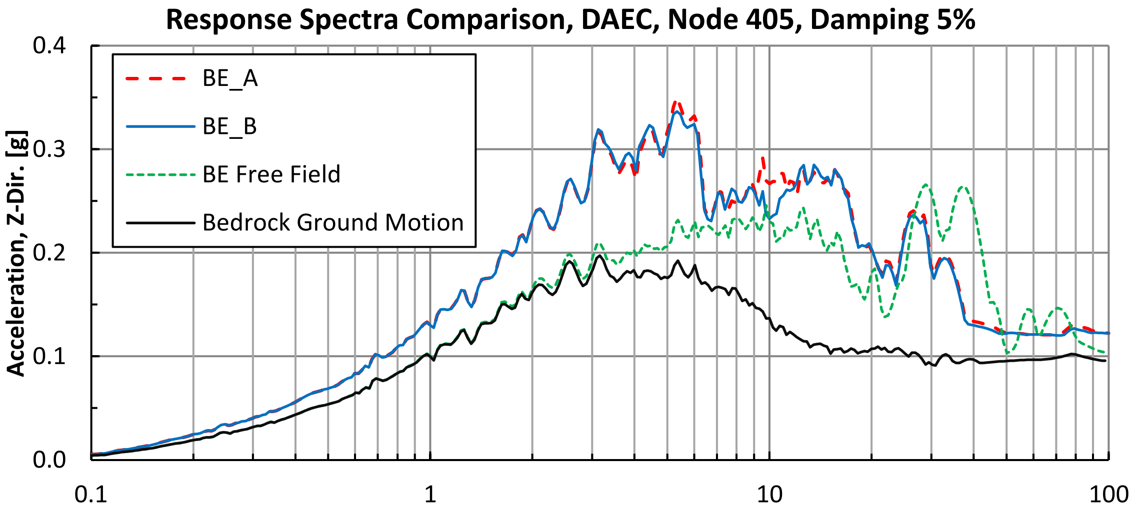

Figure 10. Best Estimate Soil Profile Z-Direction Response Spectrum Comparison between A: Fully Loaded, B: Partially Loaded, Free Field, and Bedrock Ground Motion

Scaling the vertical input motion to compensate for numerical issues that arise from large Poisson's ratio is conservative because the maximum spectral ratio is used to scale all frequency components of the respective input time history.

The high vertical ground motion in frequencies above 33 Hz has been previously reported and discussed by Tsai and Liu (2017), particularly in wet soils.

Different bounding loading scenarios for the DAEC ISFSI expansion pad are analyzed in this paper. It is concluded that the seismic response of the storage module and pad is insensitive to the different loading scenarios or installation patterns associated with the NUHOMS® HSM-H modules.

REFERENCES

MTR/SASSI. (2013). “System for Analysis of Soil-Structure Interaction,” Version 9.4.5.

NUREG-0800. (2014). “Standard Review Plan, Chapter 3, Section 3.7.1 Seismic Design Parameters, SRP 3.7.1,” Revision 4.

SHAKE91. (1991). “A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits,” Version 1.10.

Tsai, Chi-Chin and Liu, Hsing-Wen. (2017). “Site Response Analysis of Vertical Ground Motion in Consideration of Soil Nonlinearity,” *Soil Dynamics and Earthquake Engineering*, Elsevier, UK.